Insights from an Integrated Deterministic Probabilistic Safety Analysis (IDPSA) of a Fire Scenario

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Abstract: For assessing the performance of fire fighting means with emphasis on human actions, an integrated deterministic probabilistic safety analysis (IDPSA) was performed. This analysis allows for a quite realistic modelling and simulation of the interaction of the fire dynamics with relevant stochastic influences which refer, in the presented application, to the timing and outcome of human actions as well as to the operability of technical systems. For the analysis, the MCDET (*M*onte *C*arlo *D*ynamic *E*vent *T*ree) tool was combined with the FDS (*F*ire *D*ynamics *S*imulator) code. The combination provided a sample of dynamic event trees comprising many different time series of quantities of the fire evolution associated with corresponding conditional occurrence probabilities. These results were used to derive exemplary probabilistic fire safety assessments from criteria such as the temperatures of cable targets or the time periods with target temperatures exceeding critical values. The paper outlines the analysis steps and presents a selection of results which also includes a quantification of the influence of epistemic uncertainties. Insights and lessons learned from the analysis are discussed.

Keywords: IDPSA, Aleatory and Epistemic Uncertainty, Fire PSA, MCDET, FDS.

1. INTRODUCTION

Fire in a nuclear power plant (NPP) can deteriorate or even damage the required function of systems, structures and components (SSC) which are important to safety. Therefore, the investigation of the fire protection concept of a plant is an important issue of nuclear safety analyses. A recent research project at GRS aimed at demonstrating how a combination of the MCDET tool [1] and the deterministic fire simulation code FDS [2] can be used to perform an IDPSA in the frame of a probabilistic fire risk analysis.

An IDPSA is particularly suitable for those aspects of a probabilistic fire risk analysis which require a realistic modelling and assessment of the interaction between the fire dynamics and stochastic influencing factors in the course of time. Such stochastic factors refer to the timing and outcome of the human actions performed for fire fighting as well as to the operability of those systems and components which are designated to be applied for fire detection, alarm, confinement and suppression. An IDPSA permits to derive safety assessments from process criteria such as the temperatures of cable targets or the time periods with target temperatures exceeding critical values.

For the IDPSA presented in this paper, a combination of the MCDET tool and the FDS code was applied. With MCDET, a mixture of Monte Carlo (MC) simulation and the Dynamic Event Tree (DET) approach can be performed. What makes the MCDET tool particularly useful for fire risk analysis is its Crew Module which allows for considering the human actions performed for fire fighting as a dynamic process [3].

The fire scenario selected to be analyzed deals with the fire fighting means designated to be applied in a reference NPP once a fire occurs for any reason. One major assumption is the failure of the automatic actuation of the fixed fire extinguishing system in the compartment where the fire starts. This implies that fire fighting mainly depends on the operability of the fire detection and alarm system, the performance of human actions as well as on the operability of active fire barrier elements (e.g. fire dampers and fire doors) and of the fire extinguishing systems which can be manually actuated.

The first steps of the analysis which were already presented in [4] mainly focused on the performance of the human actions to be applied for fire fighting without running the FDS code. In those situations where human actions had to be considered as dependent on the fire evolution, case-by-case analyses were performed. For instance, human actions were analyzed for the cases that smoke is visible or not, when the shift personnel reach the fire compartment. The computational effort of those case-by-case analyses was negligible, since the MCDET tool making use just of the Crew Module without applying another dynamics code runs very fast. Results of the analyses were conditional distributions referring to the timing of human actions such as the distribution of the time period between fire alarm and the arrival of fire fighters at the fire compartment door or the distribution of the time period between the arrival at the fire compartment door and the beginning of fire extinguishing. These distributions express the stochastic variability (aleatory uncertainty) of corresponding time variables and were used as input to the analysis presented in this paper.

Subject of the exemplary IDPSA presented here was the interaction of the fire dynamics as simulated by FDS with the main stochastic factors affecting the fire over time. Results provided by the analysis include the distribution of the time elapsed from fire ignition to its successful suppression and, what is even more interesting, distributions referring to the temporal evolution of the temperatures of safety related targets (e.g. cable targets). The influence of epistemic uncertainties (due to lack of knowledge) on these distributions is considered.

Chapter 2 of this paper gives an overview on the method and the modules of the MCDET tool. Chapter 3 presents information on the fire scenario including the scenario-specific model specified as input to FDS and the fire fighting means investigated in detail. The steps of the IDPSA and a selection of analysis results are described in Chapter 4. Conclusions are presented in the last chapter.

2. MCDET TOOL

2.1. Method

Coupled with a deterministic dynamics code such as FDS, the MCDET tool performs a combination of the Dynamic Event Tree (DET) approach and Monte Carlo (MC) simulation [1]. This combination is able to treat any kind of uncertainty. Aleatory uncertainties due to stochastic influences referring to discrete quantities (e.g. success/failure of the fire detection and alarm system to operate; success/error of human actions) are handled by the DET approach, whereas aleatory uncertainties referring to continuous quantities (e.g. execution times of human actions) are handled by MC simulation. MC simulation is also applied to consider epistemic uncertainties (due to lack of knowledge). The sampling of values for continuous aleatory variables is not performed a priori, i.e. before the calculation of a DET is launched. It is performed when needed in the course of the calculation. In this way, it is possible to treat the influence of the dynamic process on aleatory uncertainties and to consider, for instance, a higher failure rate of a component, if a high temperature seriously aggravates the condition of the component.

Output of MCDET simulations is a large spectrum of different sequences, for instance, of the evolution of the fire. It can be considered as a sample of individual DETs, each constructed from a set of values sampled for the continuous aleatory variables. From the time series of safety relevant process quantities (e.g. temperatures of cable targets) and the corresponding likelihoods available for each sequence, conditional DET-specific and, by the application of statistical methods, unconditional scenario-specific likelihoods of damage states can be calculated.

2.2. Modules

The Probabilistic Module of the MCDET tool implements algorithms referring to the evaluation of the simulation state, the sampling of points in time for branching points with run-time failures, the generation of the initial states of new simulation paths and the calculation of corresponding occurrence probabilities. The module is linked to the Scheduler Module supervising all simulation processes of a deterministic code. The MCDET Scheduler can be coupled with any dynamics code which allows somehow for reading and modifying the simulation state and which is able to terminate a simulation early, because for instance a probabilistic cut-off criterion is pending. The Driver Module implements a generic interface for communicating with the simulation process and maps the abstract interface commands to whatever is needed, making the simulator process perform the requested action.

While the new version of the Scheduler Module allows for performing parallel and distributed simulations on multicore workstations and cluster environments [5], the previous version just permits to calculate the branches of a DET in one process. The sequential calculation of the branches of a DET is performed according to the last-in-first-out principle. Different DETs can be calculated in parallel – each on a separate computing node. Simulations with the old version of the Scheduler Module make extensive use of the restart capabilities of the applied dynamics code.

The extra Crew Module of the MCDET tool allows for simulating human actions as a dynamic process which evolves over time within a context given, for instance, by the intermediate results of a deterministic dynamics code [3], [4]. With the combination of the Crew Module and the deterministic code, an integral simulation of the mutual dependencies between human actions, the system behavior and the process dynamics can be performed. Parameters of the Crew Module which are subjected to epistemic or aleatory uncertainty can be easily handled by the Probabilistic module of MCDET.

The execution of the Crew Module requires a compilation of the action sequences potentially applied during a scenario. An action sequence is composed of one or more simple basic actions, each defined by an ID and additional information on the crew member performing the action, the time needed to execute the action, and on the system, component or operator somehow affected by the action. An action sequence is activated, if the condition attached to the sequence is fulfilled. A condition is defined, for instance, by the state of alarms and indicators in the control room, the system state or by the action sequence previously performed. Information on alarms and indicators has to be provided in an appropriate dataset of the Crew Module.

The post-processing modules of the MCDET tool are useful for evaluating the huge amount of data from MCDET simulations. They can provide graphical representations of the sequences of a DET in the time-event space (temporal order of the events of each sequence) or in the time-state space (temporal evolution of a sequence with respect to a process quantity). In addition, they can calculate and graphically represent the conditional DET-specific distribution and the unconditional application-specific distribution of a process quantity.

3. FIRE SCENARIO

Subject of investigation are the fire fighting means designated to be applied in a German reference NPP in case of fire. The fire was assumed to initially occur in a compartment with cooling and filtering equipment for pump lubrication oil. Besides this process equipment, the compartment is equipped with electrical cables routed below the ceiling. These cables partly carry out safety related functions.

It was assumed that malfunction of the oil-heating system designated to heat up the pump lubrication oil in the start-up phase of the NPP leads to an ignition of the oil. The evolution of the fire was considered to depend on the leakage rate of the oil. The heat release rate may be limited by the oxygen available in the compartment.

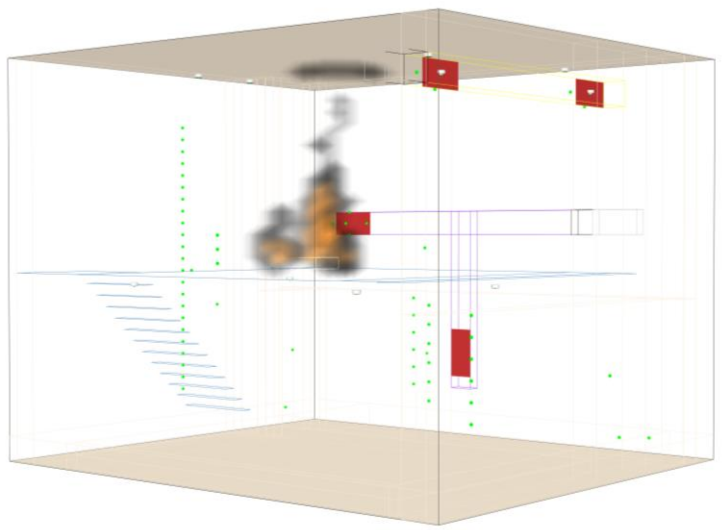
The dimensions of the compartment are about w x l x h = 8 m x 6.2 m x 6 m. Compartment walls are made from concrete. The compartment is divided into a lower and an upper level by a steel platform at a level of 2.4 m. The steel platform can be reached by steel stairs. The three compartment doors lead into the lower level of the compartment. It was assumed that one of those doors is left in open position with a reference probability of 0.005 (see Table 1). The mechanical air exchange by an inlet air duct and an outlet duct was supposed to be 800 m^3/h. The fire damper at the outlet duct was supposed to close after melting of a fusible link at 72 °C. This mechanism was assumed to fail with a reference probability of 0.01 (see Table 1). If the outlet damper is closed, the mechanical air supply into the room was considered to be reduced to 400 m^3/h. That value was chosen to account for increased pressure losses, if the inlet air leaves the room by other leaks.

The fire was assumed to start on the steel platform at the electrical oil heater. The evolution of the fire was considered to be linear with the time. The characteristic time to reach 1 MW heat release rate was varied from 250 s to 700 s (see Table 1). In the upper layer cable tray, the cable targets were exposed to hot smoke and radiation.

3.1. Scenario-specific Model

The fire simulation was performed with FDS (FDS 6.0) [2]. The compartment was discretized in one mesh with a grid solution of 0.2 m in all three directions (see Figure 1).

Figure 1: Snapshot of the Compartment Layout by FDS



The air inlet duct (violet in Figure 1) has one diffusor above the fire and one into the lower level. The outlet duct (yellow) sucks from the upper layer by two diffusors which can be closed by the fire damper. The mechanical air supply was assumed to allow for a heat release rate of about 800 kW inside the compartment that is reduced to 400 kW after shutting the damper. The inlet air damper was supposed not to close, because the soldered strut is kept cold.

The thermal penetration of the cable material was described by the model for thermally induced electrical failure (THIEF) implemented in FDS. The THIEF model predicts the temperature of the inner cable jacket under the assumption that the cable is a homogeneous cylinder with one-dimensional heat transfer. The thermal properties – conductivity, specific heat, and density – of the assumed cable are independent of the temperature. In reality, both the thermal conductivity and the specific heat of polymers are temperature-dependent. In the analysis, conductivity, specific heat, density, and the depth of the cable insolation were considered as uncertain parameters with relevant influence (Table 1).

The local optical density D of the smoke at 3.20 m height of the fire compartment was assumed to be an important factor affecting the time needed to suppress the fire. For optical densities below D = 0.1 m^{-1}, it was assumed that the personnel in charge of fire fighting can detect the fire and start to suppress it by means of a portable fire extinguisher after a delay of 10 s. For 0.1 m^{-1} < D < 0.4 m^{-1}, it is assumed that the delay time until the fire source is detected and the suppression can be started increases, when the optical density rises. The delay time was assumed to be D times 100 in seconds. For D ≥ 0.4 m^{-1}, fire suppression with a portable fire extinguisher and without any personal protective equipment was supposed to be impossible. More details are given in section 3.2. The threshold value of 0.4 m^{-1} for the optical density was considered as a relevant parameter subjected to epistemic uncertainty (Table 1).

Once the fire suppression was started, the simulation of a fire sequence was stopped as soon as the temperature inside the cable jacket fell below 120 °C. Otherwise, a sequence was calculated up to 1800 s after fire ignition.

3.2. Fire Fighting Means

If equipment and procedures work as intended, fire fighting is a rather short process, because the compartment where the fire is assumed to occur is equipped with a fixed fire extinguishing system which suppresses the fire with a sufficiently large amount of water after actuation by the fire detection and alarm system. However, one major assumption of the analysis presented here was the failure of the automatic actuation of the fixed fire extinguishing system. This implies that the fire has to be extinguished by manual fire fighting means performed by the plant personnel in charge.

Three states of the fire detection and alarm system can be assumed as decisive for the human actions to be performed for fire fighting, namely at least two detectors, only one detector or none of the detectors indicating an alarm signal to the control room. If at least two fire detectors send an alarm signal, the control room operator (shift leader) immediately instructs the shift fire patrol and the on-site plant fire brigade to inspect the compartment and to perform the necessary steps for fire suppression. If there is a signal by only one detector, the signal might be a faulty or spurious one (e.g. due to dust, steam, etc.). This is why the fire patrol trained for fighting incipient fires is instructed to inspect the fire compartment and to verify the fire. Suppose the fire patrol verifies the fire, the shift leader who is immediately informed calls the fire brigade. In the meantime, the fire patrol tries to suppress the fire either by a portable fire extinguisher or by manually actuating the stationary fire extinguishing system from outside the fire compartment. If none of the fire detectors sends an alarm, the detection of the fire depends on the shift patrol inspecting the compartment at a random time once during a shift.

The fire patrol is always the first person who arrives at the fire compartment. His/her success of suppressing the fire with a portable fire extinguisher was assumed to be depending on the local optical density D of the smoke at 3.20 m height (0.80 m above the level of the platform). If the optical density is too high (see section 3.1), fire suppression by the fire patrol inside the compartment is assumed to be impossible due to reduced visibility and irritant smoke effects on eyes and breathing organs. The fire patrol does not wear personal protective equipment. In this case, his only chance of successfully fighting the fire is to manually actuate the fixed fire extinguishing system. If it does not operate as intended, the fire brigade has to extinguish the fire with their equipment.

Besides the reliability of the fire detection and alarm system and the performance of human actions, the success of fire fighting mainly depends on the reliability of active fire barrier elements such as fire dampers or doors and of the fire extinguishing systems which can be manually actuated.

4. EXEMPLARY IDPSA

4.1 Steps of the Analysis

In the first steps of the analysis, the human actions designated to be applied in case of a fire were investigated in detail [4]. The dynamic model of these actions was constructed on the basis of documents from the reference NPP and walk-talk-throughs at locations relevant for fire fighting. After the model was encoded in the corresponding datasets of the Crew Module, the relevant parameters of the Crew Module which are subjected to epistemic or aleatory uncertainty were identified and the corresponding probabilistic information used to express the uncertainty (distributions and branching information) was specified. The list of relevant parameters included, for instance, time periods needed to execute simple basic actions or discrete parameters referring to the outcomes of basic actions (success/error). If feasible, the probabilities of human errors were derived from the methods ASEP (*A*ccident *S*equence *E*valuation *P*rogram, [6]) and THERP (*T*echnique for *H*uman *E*rror *R*ate *P*rediction, [7]) which are recommended by the technical document on PSA methods [8] supplementing the German PSA Guide. Uncertain parameters and the corresponding probabilistic data were entered as input to the Probabilistic Module of MCDET.

The subsequent simulations were performed without running the FDS code. They were performed just by the combination of the Crew Module, Probabilistic Module and the Scheduler Module of MCDET. That combination ran very fast and provided more than 100 Dynamic Event Trees (DETs) for each of several conditions. Those conditions identified as being decisive to the human actions of the fire fighting process were given by relevant states of the fire detection and alarm system (none, only one or at least two of the detectors operate as required) as well as by the fire progression (e. g. visibility of smoke in front of the door when shift personnel reaches the fire compartment or production of smoke in the fire compartment).

From the DETs resulting from the MCDET simulations, various conditional distributions could be derived by using the corresponding post-processing module of the MCDET tool. The distributions refer to the timing of human actions such as the time period between fire alarm and the arrival of fire fighters at the fire compartment door or the time period between the arrival at the fire compartment door and the start of fire suppression. They express stochastic variability and were used as input to the simulations performed in the following analysis steps.

Those analysis steps dealt with the modelling, simulation and evaluation of the interaction of the fire dynamics with relevant stochastic factors affecting the fire dynamics. The stochastic factors taken into account refer to the timing and outcome (success/error) of tasks of human actions affecting the evolution of the fire, the operability of the fire detection and alarm system as well as to the functioning of active fire barrier elements (i. e. fire dampers and fire doors) and of the fire extinguishing systems to be manually actuated. Modelling information on the dynamics-stochastics interaction was specified as input to FDS as well as to the Probabilistic Module of MCDET. The input of the Probabilistic Module includes the parameters subjected to stochastic variability (aleatory uncertainty) as well as the distributions and branching information expressing the stochastic variability. It also comprises information on the relevant parameters subjected to epistemic uncertainty. Corresponding information is given in Table 1.

The calculations of FDS and those of the Probabilistic Module were supervised by the old version of the MCDET Scheduler Module allowing for calculating each DET in one process. The simulation approach made extensive use of the restart capabilities of FDS. The fire scenario was calculated up to 1800 s (0.5 h) after ignition.The output of the simulations comprises data of approx. 2400 different fire sequences from a sample of 120 individual DETs. These data were evaluated by using corresponding post-processing modules of the MCDET tool.

Table 1: Epistemic Parameters and Specified Probability Distributions

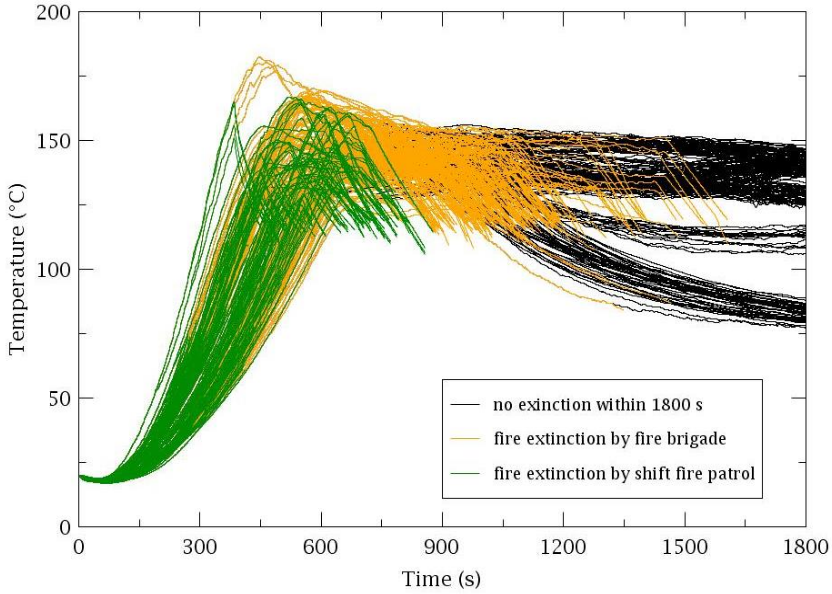
Epistemic Parameter	Reference Value	Distribution	Distribution Parameters
Value of optical density at which emerging smoke is visible under fire compartment door [1/m]	0.3	uniform	Min = 0.2, Max = 0.4
Response time index for activation temperature of fire dampers [$\sqrt{m \cdot s}$]	125	uniform	Min = 50, Max = 200
Threshold value of optical density D below which fire compartment can be entered [1/m]	0.4	uniform	Min = 0.3, Max = 0.5
Fraction of fuel mass (oil) converted into smoke	0.097	uniform	Min = 0.095, Max = 0.099
Time to reach 1 MW heat release rate [s]	425	uniform	Min = 250, Max = 700
Conductivity of cable [W/m*K]	0.275	uniform	Min = 0.15, Max = 0.4
Specific heat of cable [kJ/kg*K]	1.225	uniform	Min = 0.95, Max = 1.5
Depth of cable isolation [m]	0.0016	uniform	Min = 0.0012, Max = 0.002
Cable density [kg/m^3]	1131	uniform	Min = 833, Max = 1430
Specific heat of concrete [kJ/kg*K]	0.65	uniform	Min = 0.5, Max = 0.8
Conductivity of concrete [W/m*K]	1.75	uniform	Min = 1.4, Max = 2.1
Thickness of concrete walls in the fire compartment [m]	0.37	uniform	Min = 0.32, Max = 0.42
Probability that a fire door falsely stays open	0.005	beta	α = 1.5, β = 236.5
Probability that fire damper fails to close	0.01	beta	α = 1.5, β = 117.5
Failure temperature of I&C cables [°C]	170	uniform	Min = 145, Max = 195
Critical time periods [s] with temperatures of I&C cables between:			
145 °C - 150 °C	360	uniform	Min = 300, Max = 420
150 °C - 160 °C	240	uniform	Min = 200, Max = 280
160 °C - 170 °C	180	uniform	Min = 150, Max = 210
170 °C - 180 °C	120	uniform	Min = 90, Max = 150
> 180 °C	40	uniform	Min = 20, Max = 60

4.2 Results of the Analysis

The safety related targets which could be damaged and, therefore, were selected to be considered in this analysis, are I&C cables routed below the ceiling of the fire compartment. The fire was regarded as successfully suppressed as soon as the temperature inside the cable jacket fell below 120 °C after the fire fighters started to extinguish the fire.

Figure 2 shows the temporal evolution of the temperature inside the cable jacket for those sequences from all DETs for which the fire detection and alarm system operates as required. Differences between the sequences are due to the combined influence of aleatory and epistemic uncertainties. Distinct colors used in Figure 2 indicate which sequences lead to successful fire suppression (green and red curves) and which not (black curves). Successful fire suppression can be performed either by the fire patrol (green curves) or by the fire brigade (red curves). The fire patrol can extinguish the fire by a portable fire extinguisher or by manually actuating the stationary fire extinguishing system from outside the fire compartment (see section 3.2). If the fire detection and alarm system operates as required, the fire patrol can suppress the fire mostly within 800 s (~ 13 min) after fire ignition. If the patrol fails to suppress the fire, the fire brigade can extinguish the fire with their equipment. If the fire brigade succeeds to suppress the fire, mostly 800 to 1200 s (~ 13 to 20 min) – in some cases 1200 to 1500 s (20 to 25 min) - elapse after fire ignition.

Figure 2: Temperature inside the Cable Jacket



For sequences without any fire extinction within 1800 s (black curves), three distinguished temperature clusters are clearly visible in Figure 2. In the first cluster, the temperature inside the cable jacket decreases below 100 °C within 1800 s after ignition. The associated sequences are characterized by the corresponding fire damper operating as demanded and the fire door being closed (see Chapter 3). The same is true for the sequences of the second cluster with a temperature on a level between 105 °C and 120 °C. Main reasons for a smaller temperature decrease compared to that of the first cluster seem to be higher values of the depth of cable jacket material combined with lower values of the cable density. Both parameters are considered as subjected to epistemic uncertainty (see Table 1). In the third cluster, the temperature remains at a rather high level between 125 °C to 150 °C up to the end of simulation time (1800 s). This is the consequence of an open fire damper or an open fire door.

Figure 3: Distribution of the Time Elapsed from Fire Ignition to Successful Fire Suppression

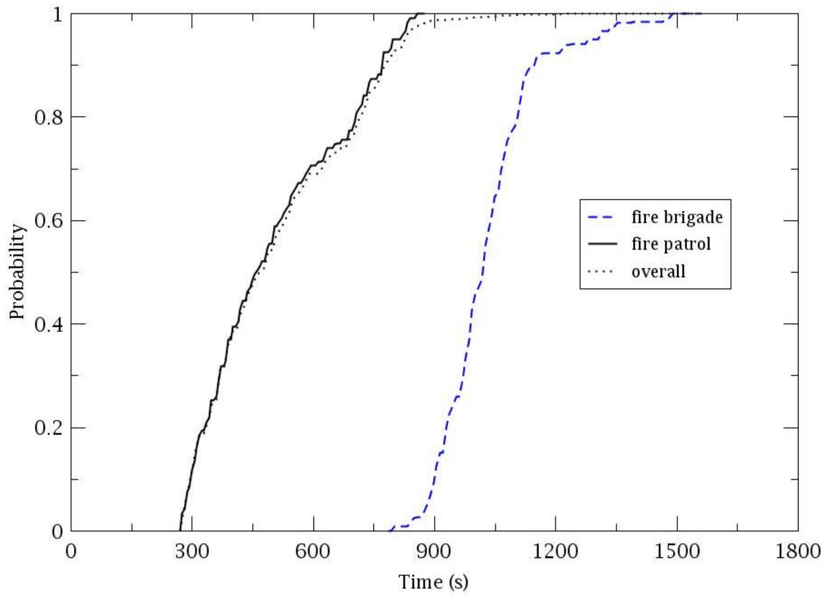


Figure 3 shows the overall distribution and two conditional distributions of the time elapsed from fire ignition to successful suppression, if the fire detection and alarm system operates as required. The conditional distributions refer to the conditions that either the fire patrol or the fire brigade suppresses the fire successfully. The distributions underline the results which could be derived from Figure 2. If the fire patrol is able to extinguish the fire, this happens within 780 s (13 min) after ignition with a mean probability of 0.92. If the fire brigade has to extinguish the fire, suppression is successful 13 min after ignition at the earliest. The fire brigade arrives at the fire compartment approx. 3 to 16 min later than the fire patrol with a mean probability of 0.95. The brigade is able to suppress the fire between 780 and 1320 s (13 and 22 min) after ignition with a mean probability of 0.95.

Obviously, the overall distribution and the conditional distribution referring to fire suppression by the fire patrol are quite similar. This is due to the fact that successful fire suppression (within 1800 s) by the fire patrol occurs with a high probability of 0.994. The mean conditional probability that the fire brigade is able to extinguish the fire within 1800 s after fire ignition is 0.999 given the fire patrol is not successful. Reasons why the fire brigade cannot extinguish the fire within 1800 s are recovery actions performed e.g., if the fire fighters misunderstand the correct fire location, if the equipment is defect or if the water supply for fire extinguishing is not available. All these situations were considered in the model of human actions applied for fire fighting (see section 4.1).

Figure 4: Distribution of the Maximum Temperature inside the Cable Jacket

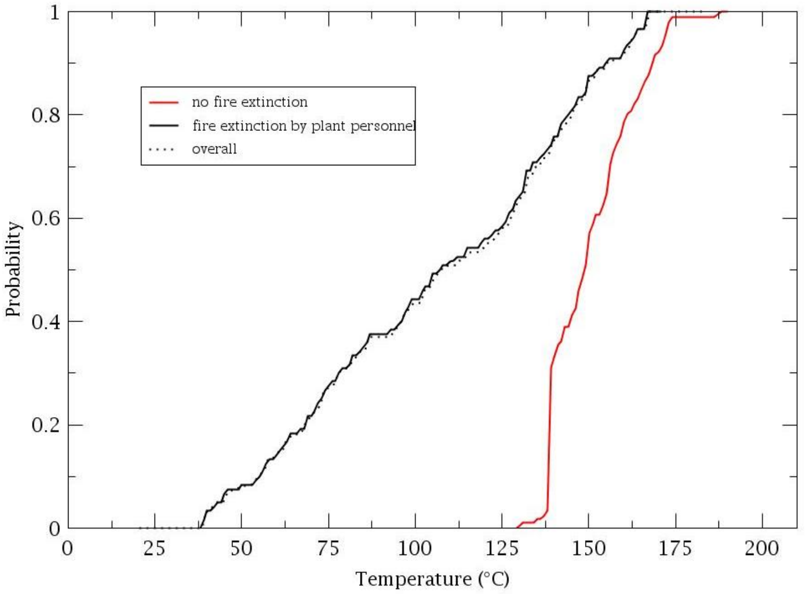
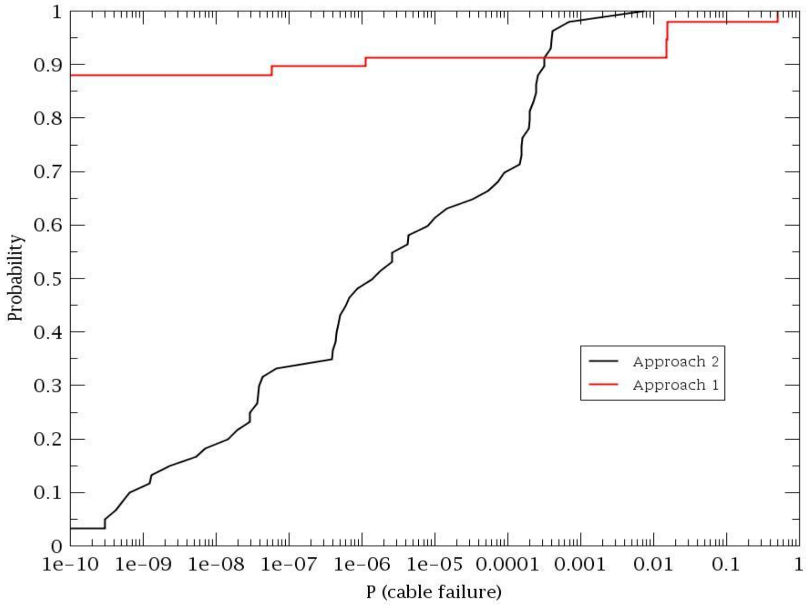


Figure 4 shows the overall distribution and two conditional distributions of the maximum temperature inside the cable jacket. The conditional distributions refer to the conditions, if the fire is successfully extinguished by the plant personnel or not. If the fire can be successfully suppressed, the maximum temperature can be reduced below 150 °C with a mean probability of about 0.87. If the fire cannot be suppressed, the mean probability of a maximum temperature below 150 °C is approx. 0.51. The main effect on the maximum temperature results from the actions of the fire patrol, because he/she can start the fire suppression quite early and therefore avoid a higher temperature maximum inside the cable jacket. The overall distribution and the conditional distribution referring to fire suppression by the plant personnel are nearly identical. This is due to the very high conditional probability for successful fire suppression within 1800 s. The mean value is 1.0 - 5.97 E-06.

Estimates of the probability of I&C cables to be damaged by the fire were derived based on two different failure criteria. According to failure criterion 1, the cables were assumed to be damaged, if the temperature inside the cable jacket exceeds a critical value. With criterion 2, the failure of a cable was supposed to be determined by both a high level of the temperature inside the cable jacket and a critical time period with the temperature on a high level. Reference values and uncertainty quantifications referring to the failure temperature (criterion 1) and the critical time periods (criterion 2) are specified in Table 1. It is emphasized that the specifications are used only for demonstration purposes. They were derived from available experimental data on failure temperatures of I&C cables [9] and should be checked for real applications, in particular, with respect to the critical time periods for given temperature levels.

Figure 5: Epistemic Uncertainty of the Conditional Probability of Damaged I&C Cables



The mean conditional probability that an I&C cable in the fire compartment is damaged during the fire scenario was estimated to be 1.76 E-02 based on failure criterion 1 and 2.08 E-04 based on criterion 2. Figure 5 shows the epistemic uncertainty of the cable damage probability for each criterion. It can be seen that the epistemic probability distributions due to both criteria differ significantly. Since just rather limited sample data were available from the MCDET-FDS simulations (a sample of 60 values is available to express the epistemic uncertainty of the cable damage probability), the one-sided upper (95 %, 95 %)-tolerance limit was calculated as an estimate of the 95 %-quantile of the cable damage probability. With failure criterion 1, the (95 %, 95 %)-tolerance limit is 0.5 which would certainly not be acceptable. The (95 %, 95 %)-tolerance limit based on criterion 2 is 7.5 E-03 which seems to be more reasonable.

The results clearly show the effect of different failure criteria on the calculated cable damage probability. They underline what intuitively seems to be more realistic, namely to consider both high temperature and the exposure time to high temperature as a criterion for assessing targets as deteriorated or damaged. To this purpose, corresponding data should be made available. As demonstrated, the MCDET method can use this data in order to provide corresponding risk assessments.

5. CONCLUSIONS

An exemplary IDPSA of a fire scenario was performed to demonstrate its modelling capacity and evaluation options in the frame of a probabilistic fire risk analysis. The necessary simulations were carried out by a combination of the MCDET tool and the FDS code. This combination allowed for a quite realistic simulation of the interaction between the fire dynamics and relevant stochastic influencing factors over time.

What made the MCDET tool particularly useful for the analysis was its extra Crew Module which permitted to consider the human actions designated to be performed for fire fighting as a dynamic process. MCDET simulations performed just with the Crew Module without running FDS provided a huge amount of data for generating conditional distributions of the timings of human actions. Those distributions were used as input to the IDPSA performed with the combination of FDS and MCDET. Besides the timings of human actions, the individual performances of all systems and components designated to be applied for fire detection, alarm, confinement and suppression were considered as subjected to aleatory uncertainty. Epistemic uncertainties were taken into account as well. Those ones which were considered as potentially important refer to parameters of the FDS code and failure criteria specified for cable targets.

From the huge amount of output data provided by the FDS-MCDET simulations, the distribution of the time elapsed from fire ignition to its successful extinction and - what is even more interesting - distributions referring to the temporal evolution of the temperature inside the jacket of the cable targets could be calculated. Based on these distributions, quantifications useful for fire risk assessment were derived, e.g. the conditional probability of safety related I&C cables to be damaged by the fire. The results clearly showed the effect of different failure criteria on the calculated cable damage probability. They also underlined the necessity of getting more time-dependent data on the reliability of SSC in order to be able to provide more realistic safety assessments by means of an IDPSA method.

The main lesson learned was the importance of having a well validated dynamics model when performing an IDPSA. Since the scenario-specific model did not exist initially, it had to be created as input to FDS just in the course of the IDPSA project. The amount of work necessary to make that model applicable in combination with the MCDET tool was higher than initially expected. A lot of activities had to be spent to find a way of how to handle the limited restart capabilities of FDS in order to make the code running in combination with MCDET while simultaneously avoiding extensive calculation time and data storage. Corresponding commands implemented in the Driver Module of MCDET finally made the communication between FDS and MCDET practicable.

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