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PROBABILISTIC SIMULATION OF CABLE FIRES IN A CABLE TUNNEL

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ABSTRACT

The reliability of the nuclear power plant safety systems relies strongly on the concept of redundancy. In some plant designs, cables of two subsystems can exist in the same room. In this work, Monte Carlo fire simulations of this kind of cable tunnel are performed. The goal of these simulations is to estimate the time dependent probabilities of cable failures and other events in case of a cable fire starting from the power cables of one sub-system. The simulations compare consequences with and without an operating sprinkler system.

INTRODUCTION

The reliability of the nuclear power plant safety systems relies strongly on the concept of redundancy. In some plant designs the reliability is increased by having four redundant sub-systems but these sub-systems are paired, which means that components of two sub-systems exist in the same place. The interesting questions are: What is the probability of a cable failure, given a fire in one sub-system, and, which variables correlate most with the cable failures?

In this work, fires in a cable tunnel including power and instrumentation and control (I&C) cables of two sub-systems are modelled. The power cables are modelled by one-dimensional heat conduction solver and pyrolysis models associated with the estimated material parameters. The failure probabilities are determined by Monte Carlo (MC) simulations, varying several variables, such as the size and location of the initial fire, and the characteristics of the materials in the tunnel. The simulations are made by using Fire Dynamics Simulator (FDS), Version 5 (FDS 5) [1], [2].

The sprinkler system is also modelled, and the nozzle parameters estimated by simulating simple ‘bucket test’. The MC simulations are made both with and without operating sprinkler system to find out the effectiveness of the sprinkler system in protecting the second sub-system.

MODEL

Cable Tunnel

The fire room was a long cable tunnel including power and I&C cables of two sub-systems. The real tunnel has some corners, but to simplify the computations, it was approximated by a long straight tunnel. To save computing time, only the first 15 m are filled with cables and simulated with a sufficiently fine spatial resolution (10 cm) for cable simulations .The remaining 80 m are empty with coarser grid. In reality, the fire can naturally spread beyond the first 15 m, but this spreading was not considered relevant for the events and measurements near the ignition point, where the failures were assumed to take place. The tunnel is 2.7 m wide and 5.6 m high. There are 10 I&C cable trays and 5 power cable trays of A and C sub-systems on the opposite sides of the corridor.

Cable Material

The I&C cables were modelled simply as a non-reacting PVC (*p*olyvinyl*c*hloride) material, with a steel cover. The power cable was modelled using the pyrolysis model of

FDS and the experimental data from NOKIA AHXCMK 10 kV 3 x 95/70 mm^2 cable. The components and the mass fractions of the cable are listed in Table 1. Components of others include plastic and crepe paper. TGA experiments were performed for the sheath, filler and insulation materials, and cone calorimeter experiments at 50 kW/m^2 heat flux level for sheath, filler rods, insulation with conductor and the complete cable. The model parameters were estimated by searching for a good fit between simulated and experimental data using a genetic algorithm [3].

Table 1 Components and mass fractions of the sample cable

Component	Mass fraction [kg/kg]
Sheath (PVC)	0.228
Copper binding	0.15
Filler rods	0.08
Insulator (PEX)	0.25
Conductor	0.27
Others	0.022

The sheath material undergoes three consecutive reactions yielding char. The filler and insulation materials in turn are modelled with only one reaction with no residue. The model of the complete cables in cone calorimeter was built using the parameters for the components. Some thermal and geometric parameters were adjusted to provide better fit in the cone calorimeter results. Both mass ratios and the actual masses correspond well to the real cable. The model has four layers:

1. Sheath (1.25 mm, 0.1 kg/kg)
2. Insulation and filler (6 mm, 0.34 kg/kg)
3. Sheath (2.5 mm, 0.21 kg/kg)
4. Metal (4.234 mm, 0.35 kg/kg)

The thicknesses are determined so that the predicted mass loss and heat release rate curves would be as accurate as possible. The layer model is very simple, assuming homogeneous layers in a plane. The thicknesses listed here are roughly half of the real ones, to conserve mass in a FDS model. In FDS, a cable tray is effectively a rectangle box that has the same cable surface at every side. This means, that if the actual layer thicknesses were used, there would be about twice as much mass to burn as in a real cable. A comparison of the experimental and simulated mass loss rates is shown in Figure 1. The parameters are listed in Table 2.

Sprinkler System

The sprinkler system consists of triplets containing a control valve (Walther HVS 57C NW 20, type slow) and two open nozzles (Walther LU 25 NW 15, K-factor 25 L/min.bar$^{1/2}$). The distance between the control valves is 3.5 m. For the nozzle, bucket and flow tests were performed at VTT, and the FDS model (Figure 2) was built according to experimental results (Table 3). The spray was not smooth, and therefore the flow has lots of variations depending on the angle. To simplify the model, the nozzle parameters are chosen so that the average flow at each distance is more or less correct and the total amount of water is the same. The spray is divided so that 20 % of the water flow leaves in an angle of 40 – 50 º and the rest 80 % in an angle of 50 – 75 º.

The RTI value150 $(ms)^{1/2}$ was assumed for the control valve. Its water flow is expected to be similar to the open nozzles, but the droplet velocity is smaller, as well as the spray angle.

The nozzles are installed in the middle of the corridor at about 2.3 m height, spraying towards the cable trays. The real pressure in the water pipes depends on how many sprinklers are operating at the same time. That is now possible to model in FDS, by setting a pressure ramp according how many sprinklers are operating. Accurate information was not available, but as the operating pressure at the plant is 10 bar, the pressure was specified as a ramp giving 10, 8 or 6 bar, at 1, 4 and 7 open nozzles, respectively.

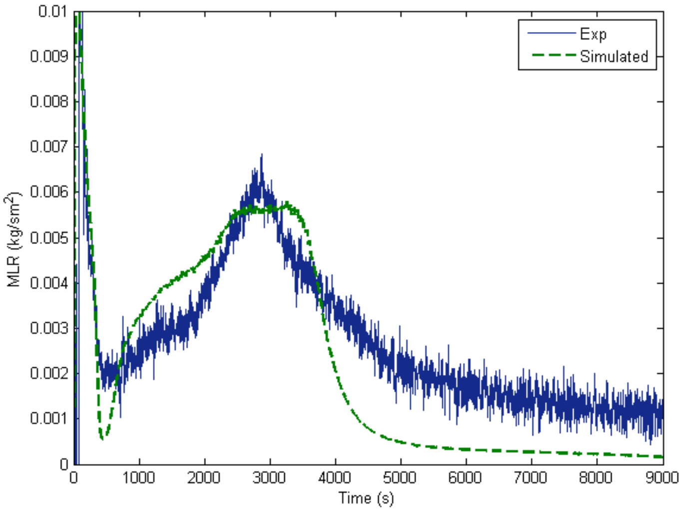

Figure 1 The mass loss rate in cone calorimeter for a complete power cable

Table 2 Material parameters for the sample cable

Material	Layer	P [kg/m³]	A [s⁻¹]	E [kJ/mol]	N	residue	K [W/m K]	c_p [kJ/kg·K]	ΔH [kJ/kg]	ΔH_c [MJ/kg]
Sheath 1 (56 %)	1, 3	1501	$1.78\cdot10^{9}$	127	1	0	0.1	2.5	200	-
Sheath 2 (11 %)	1,3	1501	$8.64\cdot10^{12}$	290	1	0.474	0.05	1.0	300	20
Sheath 3 (33 %)	1, 3	1501	$6.61\cdot10^{8}$	159	1	0.618	0.05	1.0	1700	50
Insulation	2	1039	$6.53\cdot10^{12}$	218	0.308	0	0.2	3.5	2500	35
Filler	2	950	$6.27\cdot10^{12}$	220	0.135	0	0.15	3.0	2000	35
Metal	4	3042	-	-	-	-	10.0	8.5	-	-
Char	1	385	-	-	-	-	0.4	1.5	-	-

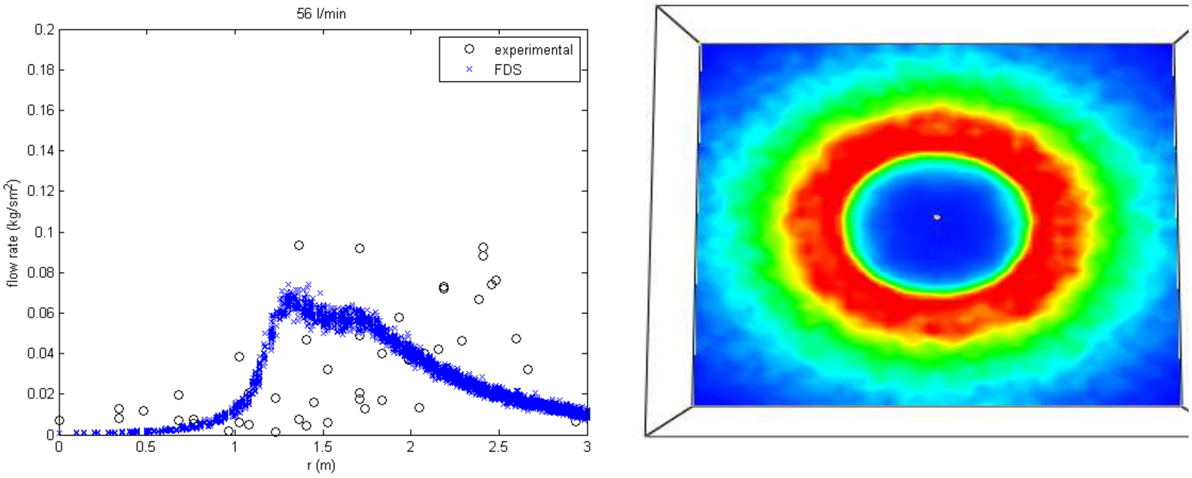

Figure 2 FDS model of the nozzle; left: flow rate as function of distances, right: accumulated water in the floor

Table 3 Sprinkler model parameters

	Spray angle [º]	Droplet velocity [m/s]	Flow rate at 5 bar	Droplet median diameter [µm]	Offset
Nozzle	20 % 40 – 50 80 % 50 - 75	40	56	700	0.1
Master nozzle	60-80	14	56	700	0.1

Smoke Alarm

Fire detection is based on OMNI-type smoke detectors using ion (smoke), optic and temperature criteria. They give the alarm if at least one of the criteria is fulfilled. There was no information available about the parameters, so the parameters and threshold values are set to typical values, and listed in Table 4.

Table 4 Properties of the smoke detectors in the FDS simulations

	Quantity	Threshold value	Parameters
Smoke	chamber obscuration	3.28 %/m	length = 1.8 m
Beam	path obscuration	33 %	-
Heat	link temperature	68 °C	RTI = 150 $(ms)^{1/2}$

Ignition Source

According to the fire scenario, the ignition source is a burning power cable. That is implemented as a burner that is located on one of the power cable trays. The behaviour of a burning power cable is adapted from full scale cable fire test with horizontal cables [4]. The measured heat release rate increases very slowly during the first 13 min. Then it shows a rapid increase, with the maximum value (500 kW) reached after 20 min. After that it starts to decay first slowly, then faster until after 30 minutes the fire is out. In Monte Carlo simulations, the maximum heat release rate and the time of the maximum are random numbers around these results.

MONTE CARLO SIMULATIONS

The Monte Carlo (MC) simulations were performed with and without the sprinkler system. In both cases one hundred Latin hypercube (LHC) [5] samples were used. The random variables and their distributions are listed in Table 5. In the simulations without sprinkler system, x, TRI and T_a were not used as random variables. The parameters of distributions were chosen mainly according literature values. The thicknesses of the layers of power cable are varying 50 % of the original power cable model. Table 6 shows different sets of thermal properties for concrete, [3], [6], [7]. In the MC simulations, the concrete properties were chosen from uniform distributions covering the range of values found from the literature.

Table 5 Variables in the MC simulations

	Distribution	**Parameters**	**Comments**
Burner			
X	uniform	0, 1.75	distance from sprinkler ([m]
z	discrete		power cable trays, p = 0.2 each
Q_{max}	triangular	500, 300, 700	max HRR [kW]
t_{max}	triangular	1200, 900, 1500	time of the peak [s]
Sprinkler			
RTI	triangular	150, 120, 180	$[(ms)^{1/2}]$
T_a	triangular	68, 61, 75	activation temperature [ºC]
Concrete wall			
k	uniform	1.4, 1.8	[W/m·K]
c_p	uniform	0.6, 1.0	[kJ/kg·K]
ρ	uniform	2100, 2500	[kg/m^3]
Power cable			
k (sheath)	triangular	0.05, 0.01, 0.3	[W/m·K]
d (sheath 1)	uniform	0.625, 1.875	thickness of the layer [mm]
d (insulation)	uniform	3.0, 9.0	thickness of the layer [mm]
d (sheath 2)	uniform	1.25, 3.75	thickness of the layer [mm]

Table 6 Thermal properties of concrete in the literature

Property	**in [6]**	**in [7]**	**in [3]**
ρ [kg/m^3]	2323	2150 - 2450	2100
k [W/m·K]	1.64	1.37, 1.4 - 2.5	1
c_p [W/m·K]	0.84	0.88, 0.6 - 0.85	0.88

RESULTS

The results of both MC simulations are presented here. Rank-order correlation coefficients are calculated between the input variables and results. The confidence levels mean the confidence that the correlations are non-zero.

The total heat release rates in the cable tunnel with sprinklers were about 10 % of the heat release rates when sprinklers were not operating. The heat release rates and the correlation coefficients with variables are shown in Figure 3. The most significant variable with 0.99 confidence level in both cases is the z-coordinate of the initial burner. Other relevant variables were the maximum heat release rate of the initial burner, the specific heat capacity of the concrete wall and the thickness of the first sheath layer of the power cable. In case with no sprinklers, also the thickness of the filler and insulation layer had some effect. With sprinklers, the density of the concrete was significant. All these variables had at least 0.9 of confidence level. It is interesting to notice, that in case with sprinklers, the correlation coefficients of concrete density and specific heat have different signs. As these variables are only used as a product, the nature of these correlations may be spurious.

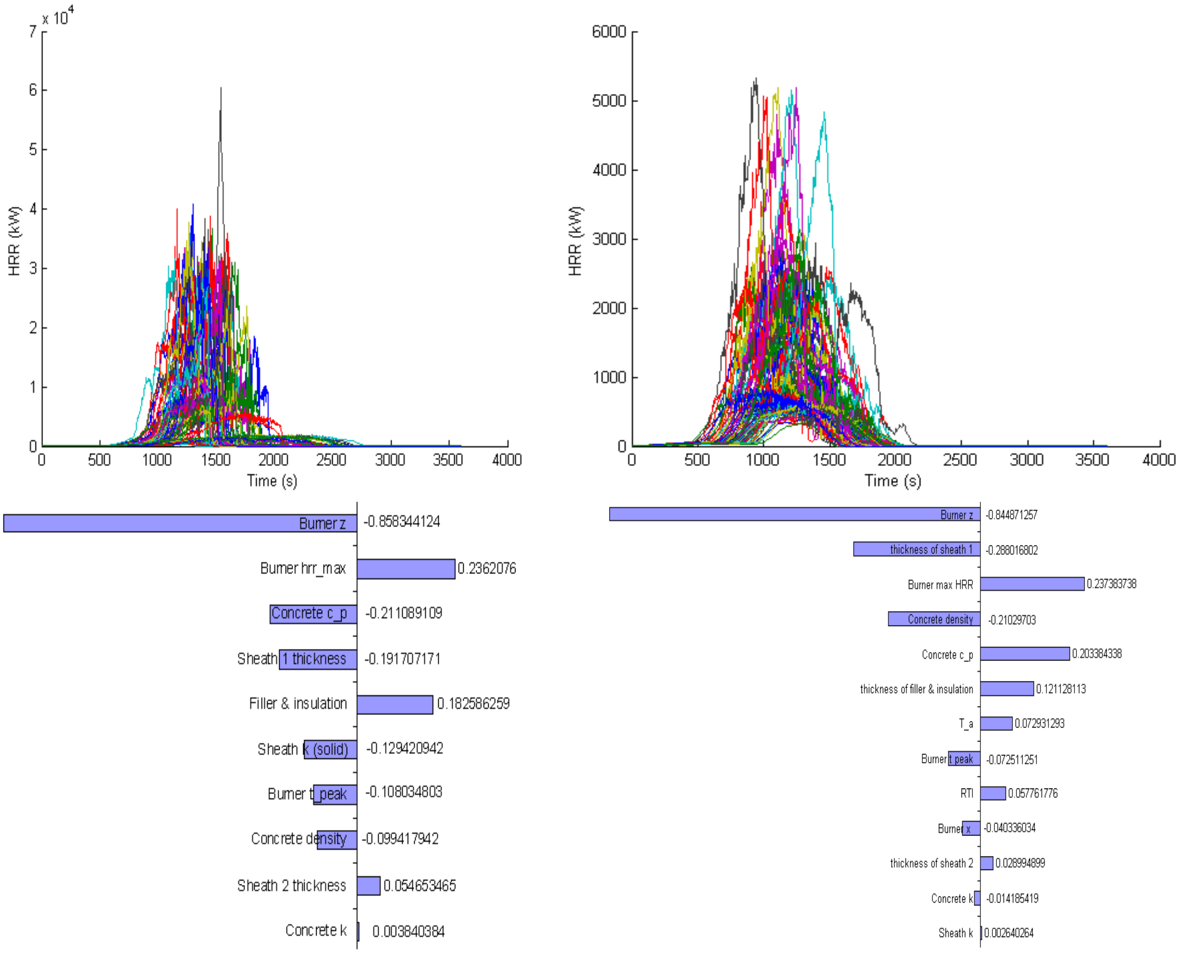

Figure 3 Upper part: heat release rates in the MC simulations; lower part: correlation between maximum heat release rate and the variables; left: without sprinklers, right: with sprinklers

The fire is assumed to begin from the power cable tray of one subsystem. The most important result of the simulations is the probability at which the cables of the other subsystem in the opposite side of the corridor would be damaged. A cable was assumed to be damaged, if the temperature in the insulation layer exceeded the predefined limit. In this work, two limits (180 ºC or 220 ºC) were considered. Without sprinklers, almost 100 % of the power cables of the other subsystem were damaged during the fire. The failures started to occur after 800 s. I&C cables were damaged in 60 % of the cases. The failures started after 1000 s. The time-dependent failure probabilities and the correlations of the failure time of the I&C cables are shown in Figure 4. The most significant correlations between cable failure time and the variables are from the z-coordinate of the initial burner, the peak time of the burner and the thermal conductivity of the sheath layer.

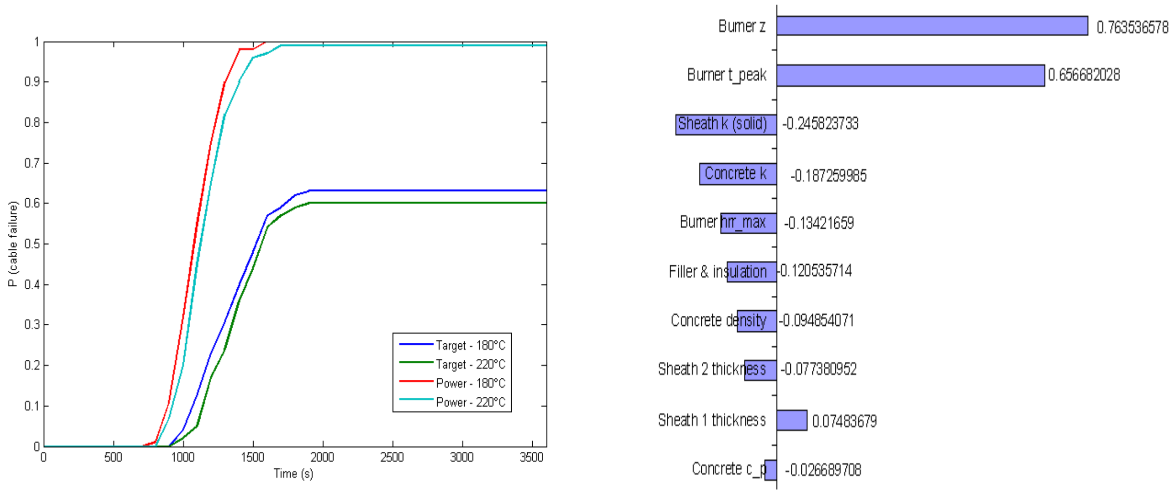

Figure 4 Cable failure time distributions and correlations without sprinklers (Target = I&C)

In the simulations with sprinkler system, cable damages did not occur at all. The distributions of the maximum temperatures of the cables and the correlations of the target cable maximum temperature are shown in Figure 5. The highest maximum temperatures of the power and I&C cables in the other subsystem were 120 ºC and 60 ºC, respectively. These temperatures are not even close to the limit temperatures. The most significant variables for the I&C cable temperatures were the z-coordinate of the initial burner, specific heat capacity of the concrete and thickness of the first sheath layer.

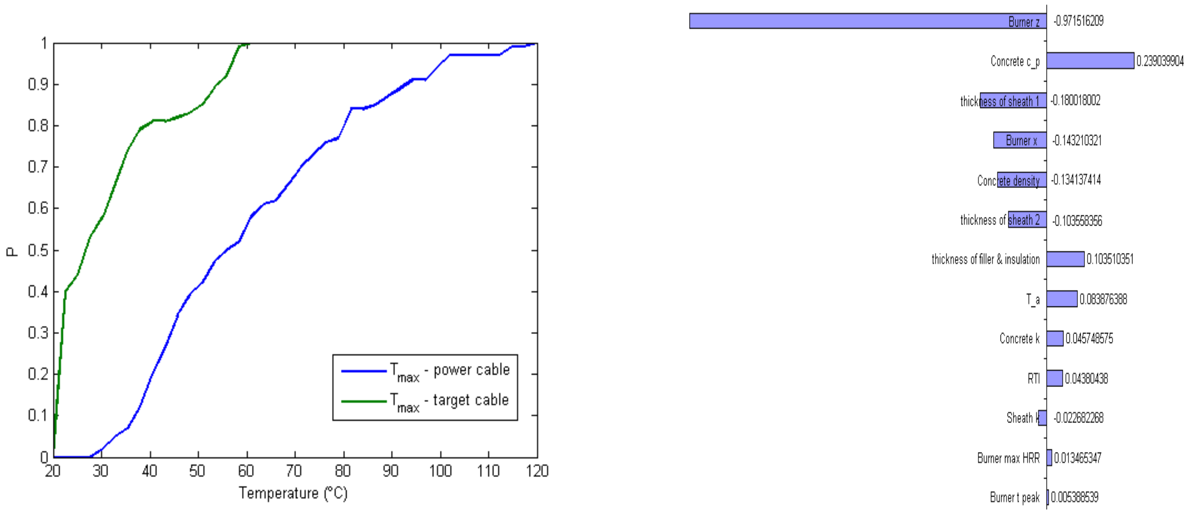

Figure 5 Distributions of maximum cable temperatures and the correlations for I&C (target) cables

The simulations did not take into account the operation of the fire fighters. However, the operating conditions were monitored at 7.5 m distance from the fire ignition point. The measurement points were placed in the middle of the corridor at three different heights, 0.5 m, 1.0 m and 1.5 m. Tolerable conditions were defined to be T (temperature) < 100 ºC, V (visibility) > 1 m and Q (radiative heat flux) < 10 kW/m^2. If the sprinkler system was not operating, the probabilities for temperature exceeding 100 ºC were 0.5, 0.3 and 0.02 at heights 1.5 m, 1.0 m and 0.5 m, respectively. Other conditions remained tolerable. If sprinklers were in use, the visibility was the only condition becoming intolerable. The visibility vanished every time between 900 and 1600 s. The probabilities are provided in Figure 6.

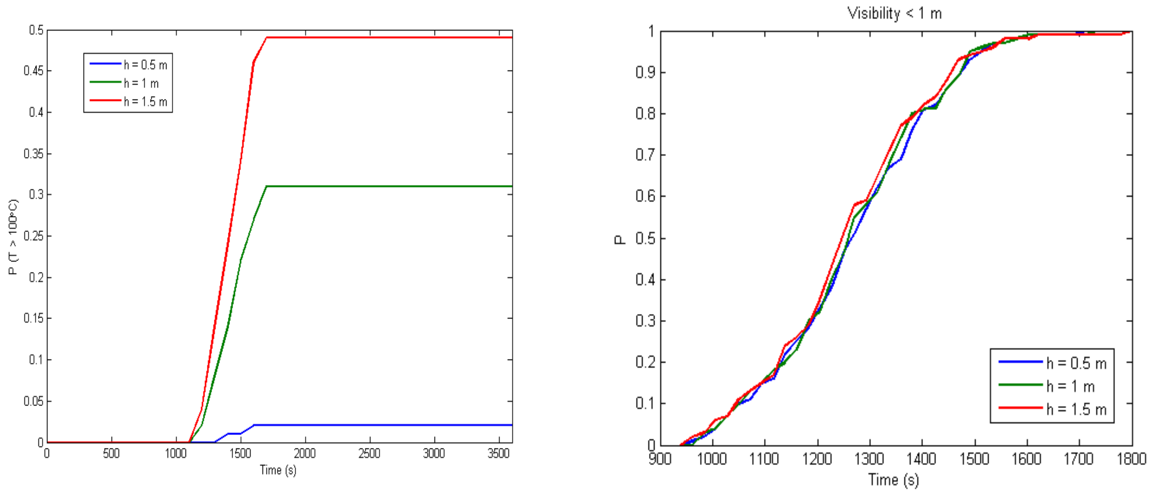

Figure 6 Distributions of times to reach intolerable conditions for a human; right: without sprinkler system, left: with sprinkler system

The capability of fire fighters to prevent the cable damages can be studied by monitoring the available time they have to reach the cable tunnel and to put out the fire. The first component in the chain of events is the alarm. In the simulations, the smoke alarm is actuated as soon as the first of the three criteria is fulfilled. The distributions of the activation times are shown in Figure 7. The smoke and the beam detectors are always actuated before the first 75 s, heat detector and sprinklers are much slower. In the simulations without sprinklers there were heat detectors that marked the time when a sprinkler would have been actuated. The difference between the times of actuation for heat detectors and sprinklers results from the different places where they are located.

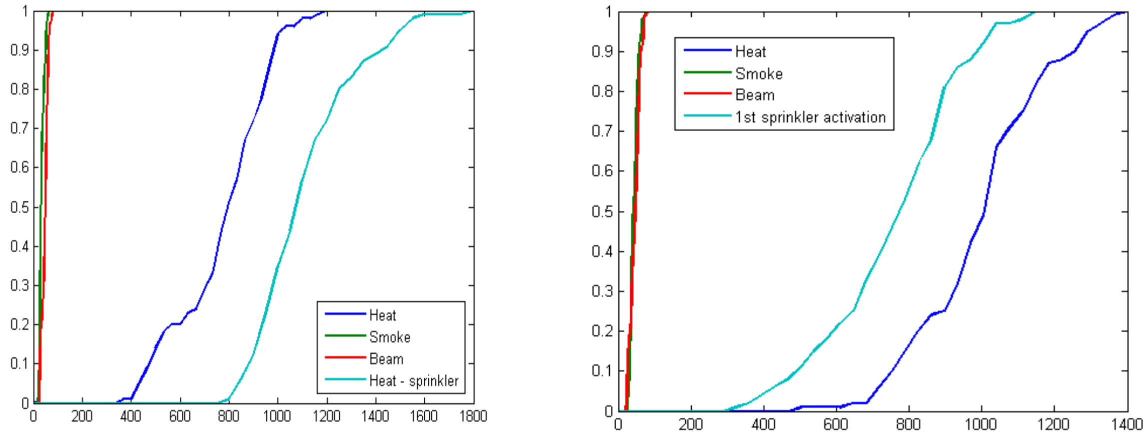

Figure 7 Alarm time distributions of the smoke detectors; left: without sprinklers, right: with sprinklers

CONCLUDING REMARKS

Fire in a cable tunnel was simulated using Monte Carlo technique and FDS, Version 5. One hundred Latin Hypercube samples were used with random variables associated with the placement of the ignition point, tunnel properties and cable properties. The model also considered the fire detection using the multi-criteria detectors. The most important results of the simulations were the failure time distribution and overall failure probabilities of the I&C and power cables of the other sub-system. The simulations were performed both with and without sprinkler system. In the case without sprinklers, the probability of at least one I& cable failure was 0.6. The time of this failure mainly depends on the height of the ignition point. For power cables, the failure probability was practically 1. The results with the sprinkler system indicated that the sprinklers provide highly efficient protection between the sub-systems. The probability of the cable failures was less than 1 %. This is a significant result as it suggests that in this kind of design the overall failure probability of the paired sub-system mainly depends on the reliability of the sprinkler system.

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