Nuclear Engineering and Design 241 (2011) 5263–5274

Contents lists available at SciVerse ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Probabilistic simulation of cable performance and water based protection in cable tunnel fires

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ARTICLE INFO

Article history:
Received 19 January 2011
Received in revised form 29 August 2011
Accepted 11 September 2011

ABSTRACT

Nuclear power plants contain a significant amount of fire load in form of electrical cables. The performance of the cables is interesting both from the fire development and system failure viewpoints. In this work, cable tunnel fires are studied using numerical simulations, focusing on the fire spreading along power cables and the efficiency of the water suppression in preventing the cable failures. Probabilistic simulations are performed using Monte Carlo technique and the Fire Dynamics Simulator (FDS) as the deterministic fire model. The primary fire load, i.e. the power cables are modelled using the one-dimensional pyrolysis model, for which the material parameters are estimated from the experimental data. Two different water suppression systems are studied. The simulation results indicate that using either suppression system decreased the heat release rate in the tunnel to less than 10% of the non-suppressed case. Without water suppression, the cables of the second sub-system were damaged in almost all fires, but when either of the studied water suppression systems was used, the probability of the cable failures was decreased to less than 1%. This result indicates that in current scenario, the probability of losing both sub-systems is determined directly by the suppression system unavailability.

1. Introduction

The safety of nuclear power plants relies heavily on concepts such as defence-in-depth and redundancy. For fire safety, the defence-in-depth means that attempts are made both to prevent the ignition of fires and to prepare for their consequences. Fire may also challenge the redundancy if it can penetrate through the barriers between the redundant parts. Sometimes the components of two subsystems can be located in the same room. This can challenge the safety of the plant especially when dealing with cables placed in the cable spreading rooms and cable tunnels. If the cables belonging to the other subsystem catch fire, they can be assumed to have already failed electrically. From the viewpoint of Probabilistic Risk Assessment (PRA), the probability of the failure in the other subsystem is extremely interesting (Paté-Cronell and Dillon, 2006) and several different methods have been used for the computation of the failure probability. One of the methods is based on the use of a severity factor which is the likelihood of those heat release rates for a given fire source that can cause a failure of a given target. As mentioned in the guidance document by the U.S. Nuclear Regulatory Commission (NRC, 2005), the application of severity factors has been a point of debate in past PRA approaches because fire severity-likelihood relationships are heavily influenced by expert judgment. Additional difficulty comes from the fact that neither the fire sources nor the targets may be explicitly specified in spaces such as cable tunnels because both of them can exist anywhere in the space.

The risk of losing both subsystems can be reduced by several means, such as physical separation between the subsystems, choice of cable materials and the use of fire suppression systems. The requirement for the physical separation is typically 6.2 m (20 ft), as suggested by the U.S. NRC in 10 CFR 50.48 (Appendix A and R). If the minimum distance cannot be fulfilled, some barriers should be placed between the cable trays. In some installations, information and control (IC) cables are placed inside metal cable conduits, which act also as thermal barriers. The sufficiency of the 6.2 m separation distance between the polyvinyl chloride (PVC) cable trays was studied by Shen (2006) using Fire Dynamic Simulator (FDS) simulations. In this work, the separation distance is fixed according to the actual case from a Finnish nuclear power plant (NPP), and the focus is in the simulation of fire spreading and fire suppression.

The cable materials are a versatile group of different kinds of plastics. Although modern, flame-retardant and non-corrosive cable sheath materials are on the market, the cables of the existing

Abbreviations: CFD, Computational Fluid Dynamics; DSC, Differential Scanning Calorimetry; FDS, Fire Dynamics Simulator; GA, Genetic Algorithm; HCl, hydrochloric acid; HRR, heat release rate; IC, information and control (cable); LHC, Latin Hypercube (sampling); MC, Monte Carlo (simulation); MLR, mass loss rate; NPP, nuclear power plant; PFS, Probabilistic Fire Simulator; PMMA, polymethyl methacrylate; PRA, Probabilistic Risk Assessment; PVC, polyvinyl chloride; RTI, response time index; TGA, Thermogravimetric Analysis.

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doi:10.1016/j.nucengdes.2011.09.014

Nomenclature

A	pre-exponential factor (s^{-1})
c_p	specific heat capacity (kJ/(kg K))
C	C-factor of sprinkler
E	activation energy (kJ/mol)
d	thickness (m)
ΔH	heat of reaction (kJ/kg)
ΔH_c	heat of combustion (MJ/kg)
k	thermal heat conductivity (W/(m K))
L	length characteristic of the smoke detector geometry
N	reaction order
q'''	source term in heat conductive equations
Q_{max}	maximum heat release rate of the initial burner (kW)
R	universal gas constant, 8.314510 J/(mol K)
RTI	RTI value of the sprinkler detector ($(ms)^{1/2}$)
T_a	activation temperature of the sprinkler detector (°C)
t_{peak}	time of the maximum heat release rate of the burner (s)
u	the free stream velocity (in sprinkler and smoke detector)
x	co-ordinate along the tunnel (m)
y	horizontal co-ordinate across the tunnel. Residue yield (kg/kg)
Y_c	mass fraction of smoke in the sensing chamber of the detector
Y_e	Mass fraction in the external free stream (of smoke detector)
z	vertical co-ordinate (m)
x_b, z_b	horizontal and vertical co-ordinates of the initial burner

Greek letters

β	volume fraction of water in the gas stream
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant, 5.67051×10^{-8} W/(m^2K^4)

power plants are often made of conventional plastics, such as PVC. Loss of the hydrochloride acid (HCl) gas from heated PVC acts as “in-built” flame-retardant, thus reducing the burning rate as compared to many other non-flame retardant polymers. However, burning PVC produces lots of smoke and toxic gases. Quite recently, Ferng and Liu (2011) used the FDS code to investigate the burning characteristics of the electrical cables in cone calorimeter experiments. In their article, they compared several gas phase measurements of cable and polymethyl methacrylate (PMMA) samples, but did not report how the cables were described in the simulations. In this work, the thermal decomposition of PVC cables is modelled using the pyrolysis model of the FDS code. The model parameters are estimated from small scale experiments (Matala et al., 2008). The occurrence of electrical failures in the target subsystem is predicted using temperature criteria, as demonstrated by Andersson and Van Hees (2005). This method was recently validated in Dreisbach and McGrattan (2008) and Dreisbach et al. (2010).

The suppression systems may be designed either to suppress the fire or to protect the subsystems from each other, or both. In fire-PRA, it is important to consider that the reliability of the active systems is not perfect. The sprinkler system, for instance, may suffer from system or component failures. The water suppression system of the room may fail to activate or problems may appear in individual nozzles or valves. The efficiency of the system also depends on the details of the design, such as nozzle placement, nozzle characteristics, sensitivity of the activating components or water flow rate. Chien et al. (2006) used FDS to study the effects of shielding and sprinkler spacing and pressure on the fire development in a NPP cable room.

In this work, we propose a probabilistic method of numerical simulation that gives the conditional probability of second subsystem failure, in case of *any* ignition in the cables of the tunnel. Monte Carlo (MC) simulations are performed using Probabilistic Fire Simulator – PFS (Hostikka and Keski-Rahkonen, 2003) for the statistical operations and FDS (McGrattan et al., 2007, 2010) as the deterministic fire model. The most important boundary conditions of the fire simulations are treated as random variables and the deterministic simulations are repeated many times with different input parameters. The statistical distributions of the random variables are based on the geometrical properties of the cable tunnel under consideration or expert opinions. The work demonstrates how the state-of-the-art deterministic fire simulation can be used in the probabilistic framework. The goals of the work are

1. to evaluate the effectiveness of two different water based suppression systems in the protection of the second subsystem in case of power cable fire,
2. to find out the probabilities of cable failures in cases when the suppression system does or does not operate, and
3. to evaluate the conditions affecting the operation of fire fighters.

The numerical tools used in this work are shortly described in Section 2. The details of the cable tunnel under consideration and its features, including the fire source, suppression system and the fire detection are described in Section 3. This section also describes how these aspects are implemented as boundary conditions for numerical simulations. The selection of random variables is described in Section 4 and the results of the probabilistic simulations in Section 5. The conclusions are presented in Section 6.

2. Overview of the numerical methods

2.1. Fire Dynamics Simulator (FDS)

FDS is developed as a co-operation between NIST (National Institute of Standards and Technology) and VTT Technical Research Centre of Finland. It models fire-driven flows by solving numerically a low-Mach number form of the Navier–Stokes equations. The time dependent field of thermal radiation is solved using Finite Volume Method for radiation accompanied by the gray gas model for the gas phase emission, absorption and scattering. The governing equations are explained in detail in the Technical Reference Guide of FDS (McGrattan et al., 2007). Here we only provide a brief summary of the models used for computing the specific features of the simulation.

In the current simulations, the fire development is predicted by the code itself – not prescribed by the user. In terms of Computational Fluid Dynamics (CFD) boundary conditions, this means that the inflow rate of fuel gas at cable surfaces is computed using a pyrolysis model. The heat conduction inside the solid materials is solved using the one-dimensional heat conduction equation

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x} k_s \frac{\partial T_s}{\partial x} + q_s''', \qquad (1)$$

where x is the internal distance from the material surface, $T_s(x, t)$ is the solid phase temperature and ρ_s, c_s and k_s are material properties. Source term q_s^m consists of heats of reaction due to the thermal decomposition reactions. Each solid surface can consist of multiple layers, and each can consist of a mixture of multiple material