# Development of fire PRA methodologies for the analysis of typical Italian NPP designs

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## 1 INTRODUCTION

In the perspective of the application of PRA for external events to typical Italian PWR power stations, a prototype fire risk analysis was performed.

Fire PRA's have been performed for a number of american nuclear power stations (e.g. Zion, Indian Point, Limerick, etc.). To this aim a large amount of studies have been developed to set up a methodology for the analysis (a review of such studies up to 1982 is presented in Chapter 11 of /1/, while more recent developments are presented in /2/, /3/, /4/, /5/ and /6/, among others).

The aim of the prototype application was to verify the applicability of such methodology for the analysis of typical Italian PWR power stations, taking into account some specific features, such as:

- Safety standards required by the Italian Control Authority;
- High separation of safety devices typical of the Italian PWR design;
- Differences in fire frequencies between Italian and American plants.

The application was performed for a vault of the Emergency Auxiliary Building, which contains one of the redundant divisions of safety and support systems.

The analysis was subdivided into three main steps:

- Fire hazard analysis;
- Propagation analysis;
- Plant system analysis.

The fire hazard analysis and the propagation analysis are described in Sections 2 and 3, respectively. The plant system analysis is based on the PRA already developed for internal events /7/. In Section 4 numerical results of the study are summarized and conclusions are presented.

## 2 HAZARD ANALYSIS

This step of the study was divided into a screening procedure, which identifies critical plant locations, and a fire-occurrence frequency evaluation.

The screening was based on a bounding approach, which led to investigate for each area additional features until either it was proved that the plant location under consideration gave a negligible contribution to the Core Melt frequency, or a complete fire risk analysis was found necessary and a detailed model of the area was set up.

A graphical sketch of the screening procedure is shown in Figure 1. The screening analysis was characterized by the following specific features:

- Reference was made to a "plant area" instead of to a "fire area", as in previous studies, to account for possible interactions among different areas in terms of both fire propagation and fire suppression induced flood;

- An area was kept for subsequent analyses if the failures of all equipments and cables in the area led to any Initiating Event, even if no safety system required after the Initiating Event was damaged. This was done in order to be able to compute small Core Melt probabilities due to fire, in accordance to the Italian regulatory requirements.

The frequency of fire in the Emergency Auxiliary Building of the PWR Italian plants was obtained by means of a Bayesian update of the frequency computed for American plants /2/, using specific data collected from European reactors.

Subsequently, the fire occurrence frequency in a given region of a given area was obtained by multiplying the previously computed frequency by appropriate reduction factors. These reduction factors were determined on the basis of expert opinion, considering types and quantities of combustibles, types of equipment present, frequency of accesses for control and maintenance.

In view of the prototype nature of the analysis the entire computation was performed only for one area, which was subsequently considered in the propagation analysis (Figure 2). For Region 2 in this area an average fire frequency of $4.3 \times 10^{-5}$ event/year was obtained, with lower and upper five percentiles equal to $3.4 \times 10^{-6}$ and $4.4 \times 10^{-4}$ event/year, respectively.

## 3 PROPAGATION ANALYSIS

The propagation analysis was performed incorporating all types of uncertainties on an overall basis. Specific attention was devoted to the development of the stochastic model for the variables affecting the fire propagation and to the calculation of fire propagation probabilities.

The propagation analysis has been subdivided into three steps:

- Sensitivity analysis, to identify the most significant variables controlling fire propagation;

- o Response surface analysis, to correlate the time of fire propagation to critical equipment to the previously selected variables;

- o Probabilistic analysis to compute the probability that the fire can damage critical equipment, whereby the previously selected variables are considered as uncertain.

In the prototype application the propagation analysis was limited to one of the areas selected after the screening procedure. The layout of the area is shown in Figure 2, where two regions are indicated as critical for fire propagation. Criticality was identified as the possibility that both electrical groups A and C of the first redundant electrical division are damaged; this event requires shutdown of the plant.

Fire propagation analyses were based on simulations by means of the code COMPBRN III (/4/), which represented the deterministic reference model for the study.

A preliminary analysis indicated that for Region 1 the chance of a fire damaging both electrical groups is negligible, even under the most conservative assumptions. For Region 2 this event was verified to be possible and the reference scenario is presented in Figure 3, where the pilot fuel is constituted by oil, eventually left on the floor after maintenance.

Sensitivity analyses were performed to investigate which variables controlled fire propagation. These analyses indicated that oil density, cable density, oil specific heat, oil thermal conductivity and cable porosity have negligible to small influence on fire propagation.

The variables which resulted to control fire propagation are presented on Table 1 together with their stochastic models. They have been chosen on the basis of an extensive review of available data.

A response surface analysis was developed to set up relationships between the time the fire needs to propagate to electrical groups A and C (propagation time) and variables in Table 1. It was found more appropriate to develop this correlation assuming that an unlimited quantity of combustible is available and to introduce this constraint later, in the subsequent probabilistic analysis. Consequently, the response surface was limited to the first five variables in Table 1.

The response surface was based on the results of a set of simulated cases where the values of the variables were changed according to a factorial design augmented with star points /8/. The functional form of the response surface was originally chosen, similarly to Siu /9/, relating the propagation time to a single parameter, which is function of the selected variables and has its own physical meaning. However, such approach was found to lead to non-satisfactory fitting with the simulated results (multiple regression coefficient equal to 0.76). A different functional relationship was then chosen based on a multivariate regression /8/ of the propagation time versus the selected variables. This significantly improved the fit to a multiple correlation coefficient equal to 0.96.

Finally, the probabilistic analysis was aimed to compute the fire propagation probability, defined as:

$$P_f = P [ \tau_p \leq \tau_e \cap \tau_p \leq \tau_c ] \qquad (1)$$

where $\tau_p$ is the propagation time, $\tau_e$ is the time necessary to extinguish the fire and $\tau_c$ is the consumption time of the available combustible. $\tau_p$ is a function of random variables in Table 1, as previously discussed, as well as $\tau_c$, through a simple physical relationship. A stochastic model for $\tau_e$ was defined according to /5/. Note that an additional random correction was applied to $\tau_p$ to account for the uncertainty on the model used for fire propagation /10/.

Equation (1) was computed using First-Order Reliability Method for component /11/ and system analysis /12/. Numerical results indicated a probability of 0.158 for the propagation time being less than extinguish time and of 0.196 for the propagation time being less than consumption time. The fire propagation probability was 0.130, with high correlation between the two events. The sensitivity factors of such probability to the different uncertainty variables (defined according to /13/) are shown in Table 2.

## 4 RESULTS AND CONCLUSIONS

To compute fire induced Core Melt probability, the results of hazard and propagation analyses described in Section 2 and 3 were combined with the Core Melt frequency computed for the initiating event and the support state as determined by the fire considered. From the PRA for internal event, the average value of this frequency was found 2.5 x $10^{-3}$ event/year. Using the average fire frequency the resulting fire induced Core Melt frequency is 1.4 x $10^{-8}$ event/year.

It is noted that the range of variation of the fire occurrence frequency can affect this result by one order of magnitude. Additionally, this value is derived for a single area, and the contributions of all area shall be summed up to obtain the final value for the plant. It is expected that more critical areas will be detected in other buildings.

On such a basis it is concluded that, although high separation of safety systems is required in Italian PWR plants, the frequency of fire induced Core Melt can reach values not negligible with respect to Italian safety standards. For this reason, fire PRA studies for the entire plant are considered necessary and should be performed with appropriate modifications of the methods used for the American plants in order to be able to estimate lower fire induced Core Melt frequencies. These modifications mainly refer to the screening procedure, as previously discussed in this paper. Further upgrading of the fire propagation analysis is recommended, although its effects on final numerical results could be marginal. Special attention deserves the evaluation of the fire occurrence frequency, which can be uncertain and can affect final results by orders of magnitude.

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TABLE 1
STOCHASTIC MODEL FOR VARIABLES
CONTROLLING FIRE PROPAGATION

| VARIABLE | UNITS | MINIMUM VALUE | MAXIMUM VALUE | TYPE | PARAMETERS | |
|---|---|---|---|---|---|---|
| | | | | | t | r |
| Cable Conductivity | W/m°K | 0.085 | 0.165 | Beta | 8 | 2 |
| Oil Combustion Heat | J/kg | $3.5 \times 10^7$ | $4.6 \times 10^7$ | Beta | 8 | 5 |
| Oil Burning Rate | $kg/m^2s$ | 0.032 | 0.075 | Beta | 4 | 2 |
| Oil Amount | kg | 0. | 8. | Beta | 14 | 2 |
| Oil Burning Area | $m^2$ | 0.01 | 0.1 | Uniform | - | - |
| Cable Damage Temp. | °K | 340. | 570. | Beta | 8 | 1 |

TABLE 2
SENSITIVITY FACTORS OF
FIRE PROPAGATION PROBABILITY

| VARIABLE | SENSITIVITY FACTOR |
|---|---|
| Cable Thermal Conductivity | 0.058 |
| Oil Combustion Heat | -0.102 |
| Oil Burning Rate | -0.255 |
| Oil Amount | 0.000 |
| Oil Burning Area | -0.680 |
| Damage Temperature | 0.551 |
| Extinghuish Time | -0.269 |
| Model Uncertainties | -0.279 |
| Response Surface Uncertainties | 0.066 |

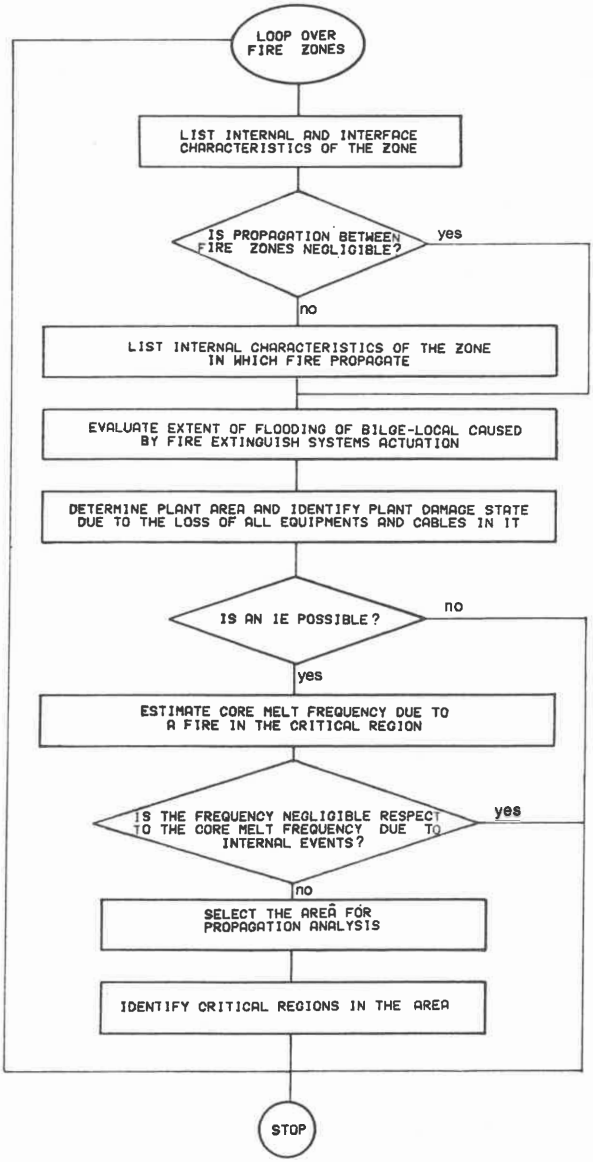


FIGURE 1

FLOW-CHART OF SCREENING PROCEDURE

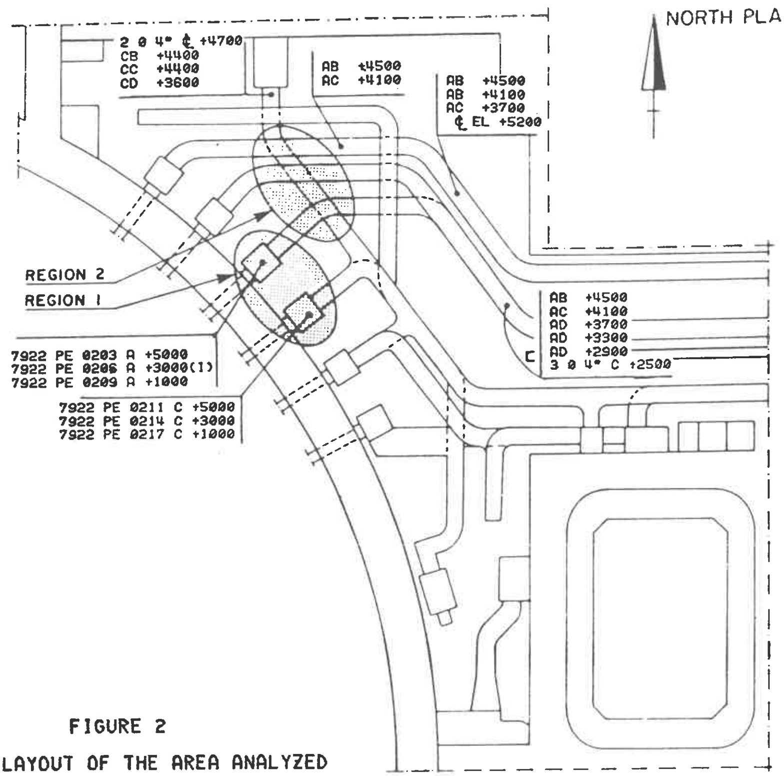


FIGURE 2

SKETCH LAYOUT OF THE AREA ANALYZED

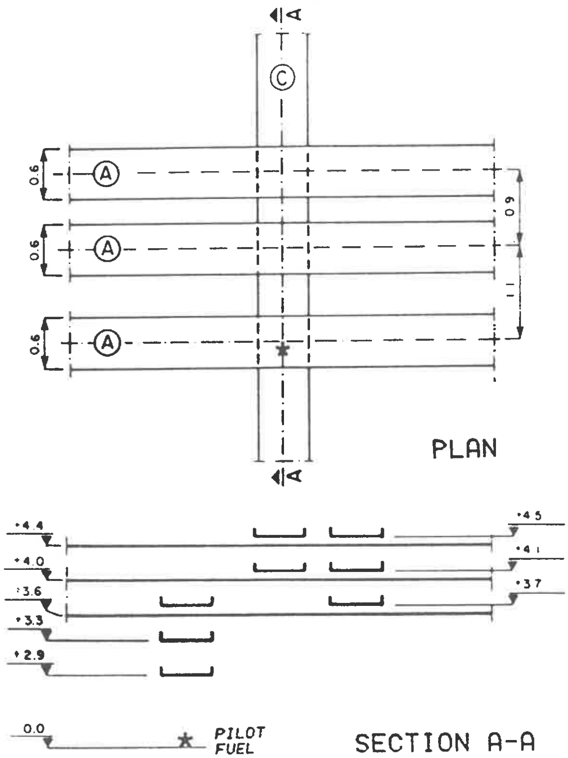


FIGURE 3

FIRE PROPAGATION MODEL REGION 2