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BEHAVIOUR OF FRENCH ELECTRICAL CABLES UNDER FIRE CONDITIONS

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ABSTRACT

A Fire Probabilistic Safety Assessment - called the Fire PSA - is being carried out by the French Institute of Nuclear Safety and Protection (IPSN) to be used in the framework of the safety assessment of operating 900 MWe PWRs. The aim of this study is to evaluate the core damage conditional probability which could result from a fire. A fire can induce unavailability of safety equipment, notably damaging electrical cables introducing a significant risk contributor. The purpose of this paper is to present the electrical cable fire tests carried out by IPSN to identify the failure modes and to determine the cable damage criteria. The impact of each kind of cable failure mode and the methodology used to estimate the conditional probability of a failure mode when cable damage occurred is also discussed.

INTRODUCTION

One of the objectives of a Fire Probabilistic Safety Assessment (Fire PSA) is the study of the potential impact on electrical cables of fires that could occur within a plant. The primary questions are:

- What are the threshold criteria (temperature, heat flux, etc.) beyond which the cable is damaged?
- What is the failure mode of cables?
- How do cable failures impact plant equipment operation and plant operation?

This paper presents the studies performed by the Institute of Protection and Nuclear Safety (IPSN), within the framework of Blayais 1 Fire PSA[4] to determine the behaviour of France's electrical cables under fire conditions. More specifically, it serves in:

- the identification of possible cable failure modes and the impact of each kind of failure on the operation of plant equipment.
- the IPSN fire tests performed to identify the dominant failure modes and to determine the cable damage criteria.
- the quantification of the conditional probability of a failure mode when cable damage has occurred.

Electrical cables of French NPP

In a Nuclear Power Plant (NPP), the electrical cables are classified according to the following three categories:

- power cables that carry alternating current (6.6 kV and 380 V) and direct current 125 V and 48 V with high intensity.
- control cables that use low voltage 48 V.
- instrumentation cables also of low voltage 30 V and 24 V.

All cables are composed of one or several conductors (2, 3, 7, 16….). Each conductor is electrically isolated by a layer of electrical insulation (PVC layer). Cables also have an integral PVC protective over-jacket and most cables also have a shield below this jacket that serves as metallic protection. Figure 1 illustrates an electrical cable consisting of 7 conductors.

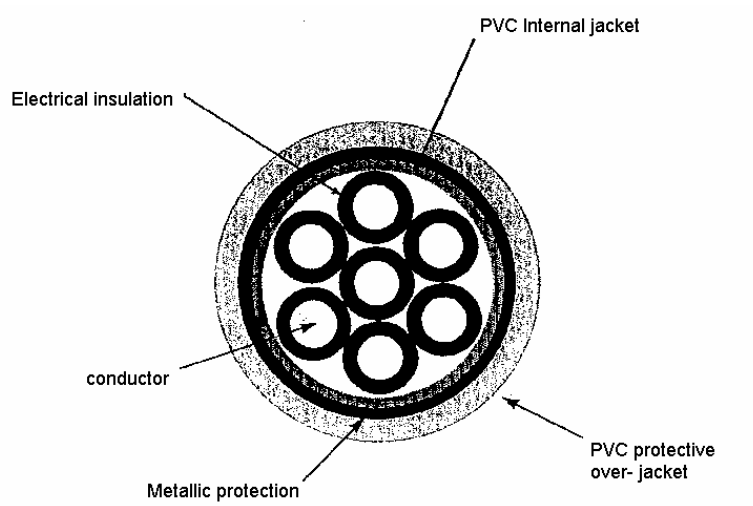

Figure 1: An electrical cable consisting of 7 conductors.

Electric cable failure modes

The heating of an electrical cable can provoke the loss of insulation resistance (in this case a leakage current is induced between 2 conductors), and/or the melting of the insulation (2 or more conductors can come into contact). Failure induced by fire on an electrical cable can result in one of the following electrical failure modes:

- open circuit: the conductor is broken. Due to the loss of its electrical conductivity, the power signal does not reach its destination.

- shorts to ground: one or several conductors comes into electrical contact with a grounded conducting material like a grounded race way. This contact diverts current from a circuit (for alternating current a protection intervenes to cut the current).

- short circuit: direct electrical contact between 2 conductors with another conductor of the same cable. The short circuit either has the potential to energise the affected conductor (in this case, an inadvertent order can be induced, closure of a valve, for example) or to create contact between 2 conductors of opposite polarity (in this case, the current trip occurs).

- damage of insulation conductor resistance: this corresponds to a leakage current before the total loss of insulation resistance, which provokes contact between 2 conductors. This failure mode has to be considered, especially when several cables of the same busbar are located in the same compartment. In this case, the cable's current leakage could be insufficient for the intervention of the lowest level circuit protection, but the sum of the current leakages of all the cables could trip a higher level circuit protection and induce the loss of the electrical bus.

The consequences of cable damage depend on failure mode, type of cable and the design of instrumentation and control. For instance, for a 900 MWe PWR:

- <u>A short circuit</u>, in the case of multi-wire power cables, can result in inoperability of the corresponding actuator as a result of tripping of a circuit breaker or contactor. For control cables, the consequences of contact between conductors varies with the type of cable:

  - the contact between conductors of opposite polarity causes short-circuiting and, generally, disconnection of the affected control part,

  - contact between an energised and a de-energised conductor can generate a spurious signal.

- <u>A short to ground of single and multi-wire cables</u>, of alternating cable current causes tripping of the associated circuit breaker or contactor, and hence inoperability.

Moreover, the following events must also be considered:

- As a result of failure per demand protection for over-current, straightforward shorting as mentioned above can persist (non-tripping of the corresponding outgoing feeder cubicle). The consequences can be excessive heating of the conductors and/or tripping of the upstream switchboard.

- If a fire lasts long enough, the temperature will cause failure of the cable tray by slumping. The cable will no longer be supported and will break. It should be noted that in such cases the other failure modes (already mentioned) would have already occurred well before the cables broke.

Fire tests

To study the behaviour of electrical cable under fire conditions, IPSN carried out the following fire tests:

1. A full-scale fire test called PEPSI involving power cables (380 V alternating current and 125 V direct current), control cables (48 V) and instrument cables (24 V).

2. Analytical Tests which consisted in heating cables in an oven. These kinds of tests were performed under different temperatures for control cables (48 V direct current) and for power cables (380 V alternating current).

PEPSI Test

The experimental program consisted of exposing five cable trays to different thermal loads inside a ventilated room (5 volumes/h). Different thermal loads were achieved by the differing positions in relation to the fire, being an oil pool fire of 1 m^2. A cabinet was located near the fire (Figure 2).

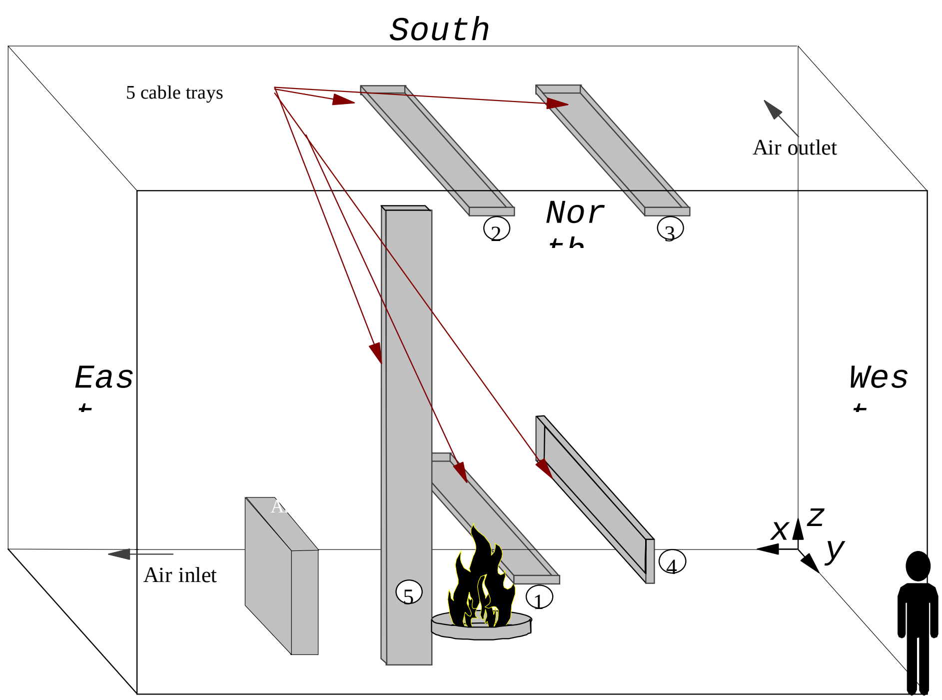

Figure 2: PEPSI 1 Test.

Combustion lasted roughly 1 hour, with the temperature of the gases in the room reaching 90 to 210°C. Apart from tray 4, which seemed intact, the others were all damaged over differing lengths. The east face of the cabinet was slightly deformed. The time at which the damage appeared varied between 4 min (tray 1) and 40 min (tray 3). The temperatures recorded on contact with the cables which were damaged were between 210°C and 350°C. Table 1 gives the gas temperature near the raceway and the corresponding failure time for each kind of cable.

Table 1: Temperature and damage time of electrical cables.

Damage time and temperature	**Raceway 1**	**Raceway 2**	**Raceway 3**	**Raceway 4**
Mean temperature	350°C	220°C	210°C	130°C
Mean flux	-	5400 W/m^2	5300 W/m^2	5700 W/m^2
380 V (3X16mm^2)	6 min / 370°C	38 min / 250°C	36 min / 215°C	No failure
380 V (3X6mm^2)	4 min / 460°C	19 min / 230°C	24 min / 215°C	No failure -
125 V (2X35mm^2)	13 min / 420°C	33 min / 250°C	42 min / 215°C	No failure
48 V (7X1.5mm^2)	7 min / 420°C	29 min / 240°C	24 min / 215°C	No failure -
24 V (2X0,5mm^2)	3 min / 390°C	32 min / 250°C	28 min / 225°C	No failure

Analytical fire test of electrical cable damage:

The objectives of these analytical tests were:

- to get data to develop a model for FLAMME-S code permitting an estimation of the electrical damage time, taking into account the inertia of the cable.
- to confirm the cable damage temperature deduced from the PEPSI test.
- to get further information on cable failure modes.

These tests were carried out in an oven where two cables were simultaneously introduced. The first one was equipped with thermocouples (internal and external temperature measures), the second one received current in order to detect the moment when contact between internal conductors or between internal conductors and the metallic protection occurred. The tests have been performed for different initial oven temperatures (between 200°C and 400°C). The results showed that the first failure mode that occurred was a short circuit (contact between internal conductor) and that this failure occurred when the internal temperature of the cable reached about 220°C. Table 2 shows the mean temperatures obtained for different temperatures of the oven.

Table 2: Cable temperature at damage time.

Oven temperature (°C)	**Cable temperature at first short-circuit (°C)**	
	Wall temperature	Internal temperature
250	209	201
300	242	220
400	268	223

Insights gained from fire tests

The loss of functionality in electrical cables is a complex phenomenon that depends on the cable materials and dimensions, the electric and mechanical loads on the cables, as well as on the magnitude of the heat flux and its time of exposure, among other factors.

The PEPSI test revealed that the first damage that appeared was the softening of the insulation material (PVC internal jacket). This softening began when it reached 220°C and induced, over time, the dispersion of insulation material from around the conductors, with respect to mechanical tension exerted on the cable. It provoked contact between internal conductors of the cable. This phenomenon occurred when the gas temperature was not too high (in general below 350°C) before the damage of PVC protective over-jacket.

The analytical tests confirmed that the first failure mode that occurred was a short circuit provoked by contact between conductors. These tests showed that the softening of insulation material began when it reached 220°C. This temperature was identical for the 380 V power cable and 48 V control cable. Moreover, all conductors short circuited and the contact between a conductor and the metallic protections happened after contact between internal conductors. The inertia of cables was substantial. For instance, in an oven at 250°C, the cable damage time was about 20 min for 380 V power cables and 15 min for 48 V control cables. During tests in an oven at 400°C, the PVC protective over-jacket ignited before contact between internal conductors.

The PEPSI test and the analytical tests revealed that, prior to the short circuit, there was no leakage current between 2 conductors. Consequently, the damage of the insulation material was a phenomenon with quick kinetics.

Electrical cable damage in the framework of fire PSA

The aim of the IPSN Fire PSA is to evaluate the probability of core damage which could result from a fire in the 900 MWe PWRs.

These functional analyses was performed, in the framework of this PSA, to establish the consequences of cable damage. Damage to cables can either cause a plant transient or lead to the unavailability of a safety-related item of equipment. Therefore the response of the actuators in the event of cable fire damage had to be analysed. Moreover, the probability of cable damage by a fire scenario needs to be known, to estimate the probability of safety equipment breakdown.

Consequences of cable damage

In the study of the consequences of cable damage, it is assumed that the internal contact between conductors occurs before short to ground of multi-wire cables by contact between conductors and cable trays connected to earth. Given these assumptions, the consequences for each kind of cable are the following:

a) power cable damage leads, in most cases, to the opening of the circuit-breaker by differential protection or over-current.

b) for the multi-wire control cables, the main failure modes taken into consideration are the following:

- if the two polarities, positive and negative, are present in the same cable: by a short circuit between positive and negative, the fire triggers the breaker module, which affects several actuators. This is particularly the case for control cables from the turn-push-light switches and from the controlling solenoid valves.

- if only one polarity is present in the same cable: in most cases, the isolation damage leads to the grounding of the conductor which causes, depending on the cable type, either the lack of a command or an inadvertent order.

c) for the instrument cables, fire leads to a voltage decrease towards a zero value for the control cables of pneumatic control valves, or an increase to a maximum value for cables originating from instrument sensors.

In the framework of the 900 MWe PWR, IPSN analysed safety related systems cables one by one. The consequences of damage to each cable was included in a data base[2], containing the following information:

- For power cables: the item of equipment is unavailable, the contactor affected, and for rooms with sufficient cables connected to the same switchboard, the loss of this switchboard by lack of selectivity is due to isolation defects. Moreover, the user has the list of items of equipment connected to each switchboard at his disposal.

- For control cables: the state of the actuator affected, the inadvertent command triggered, the breaker module lost and the consequences of this loss, the possibility of operating the actuator from the control room or the circuit breaker compartment.

Probability of a cable failure mode

To estimate the unavailability of a safety-related item of equipment, the probability of a fire scenario that damages electrical cable and the conditional probability of a cable failure mode when cable damage occurs must be known.

The damage probability of an electrical cable is estimated by means of an event tree that allows an inventory of the fire scenarios that can heat it to a temperature higher than 220°C. This event tree takes into account the different phases expressing the development of a fire up to the moment it is extinguished. These phases are the following:

- the ignition which corresponds to the appearance of a fire location[1].
- the local fire detection and confirmation by personnel.
- the fire extinguishing, when there is total control of the fire.

To identify the fire scenarios that damage an electrical cable, the development of the fire is simulated by the IPSN computer code FLAMME-S[3]. This code allows an evaluation of the damage time of the targets located in a compartment. That time is then compared to the time needed to extinguish the fire.

The conditional probability of a failure mode, given that cable damage occurred, was :

- in the first stage, conservatively taken to be equal to 1.
- in the second stage, estimated for dominant sequences of Fire PSA, especially when a spurious order can occur before the current trip.

The probability of having an inadvertent order before the trip of the 48 V was estimated for the control cable of 7 conductors connected to turn-push-light switches. This estimation was based on the following assumptions:

- the first short circuit that occurs is contact between conductors.
- all the contacts between conductors will take place.
- contact between a conductor of polarity + with the 'start-up' conductor (respectively 'shutdown') induces the start (respectively 'shutdown') of the item of equipment.
- if the conductor 'start-up' (respectively 'shutdown') is already in contact with the conductor of polarity – and enters into contact with a conductor of polarity +, the trip of the 48 V occurs before the spurious order (start or shutdown of the item of equipment).
- if the conductors 'start-up' and 'shutdown' are already in contact and enter into contact with a conductor of polarity +, the probability of start or shutdown of the item of equipment is 0.5.

Given these assumptions and a Monte-Carlo process, the probability of having a spurious order (start-up or shutdown of an item of equipment) before the 48 V trip, was estimated as 0.29.

CONCLUSIONS

Research and development in the field of fire risk assessment in Nuclear Power Plants, the Fire PSA revealed that additional work must be carried out to reduce the uncertainties related to damage criteria of electrical cables and to confirm the cable failure mode assumptions with a significant impact on the results of the Fire PSA. In performing Fire PEPSI Test and Analytical Tests, IPSN succeeded in gaining a better understanding of the behavior of electrical cables exposed to fire conditions

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