# FIRE INDUCED DAMAGE TO ELECTRICAL CABLES AND FIRE GROWTH ON CABLES

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**Abstract:** Cable fires are statistically significant initiators of high-risk developments in NPPs. Statistical, analytical, numerical simulation, as well as experimental work in three countries is reviewed. Despite fair progress some areas for new research are still found to be necessary.

## 1. BACKGROUND

The international experience of nuclear power plants (NPP) shows that fire induced cable failure play a significant role for nuclear safety. In this context, several severe safety related, reportable events from all over the world, well known in the expert community, have to be mentioned, which are listed in table 1. Even smaller fire events including cables could be precursors to more serious development. Therefore, studies on cable fires at all scales are desirable. In this paper, a short summary of recent efforts at different fronts in three countries is surveyed.

**Table 1:** Internationally well known severe fire incidents involving cables

| Affected Plant Unit | Incident Date | Fire Type |
|---|---|---|
| San Onofre, unit1 (USA) | 12.03.1968 | Self ignited cable fire resulting from changes in cable layout (size) |
| Browns Ferry, units 1 and 2 (USA) | 22.03.1975 | Safety significant fire in cable spreading room (reactor building) resulting in regulatory changes by USNRC |
| Greifswald, unit 1 (Germany, DDR) | 07.12. 1975 | Large switchgear and cable fire |
| Beloyarsk, unit 2 (Russia, USSR) | 31.12.1978 | Large cable fire in turbine hall propagating to other plant areas resulting in severe damage of redundant instrumentation |
| South Ukraine, unit 2 (Ukraine, USSR) | 14.12.1984 | Cable fire inside containment propagating to various plant areas |
| Zaporoshye, unit 1 (Ukraine, USSR) | 27.01.1984 | Large cable fire of long duration (18 h) causing damage of different plant areas |
| Kalinin, unit 1 (Russia, USSR) | 18.12.1984 | Large turbine hall fire with several pilot fires at a power cable |
| Ignalina, unit 2 (Lithuania, USSR) | 05.09.1988 | Large cable fire by self-ignition causing damage of various cables |
| Waterford, unit 3 (USA) | 10.06.1995 | Switchgear fire propagating via vertical cables and a fire barrier to horizontal cable trays |

# 2. SMALLER FIRE EVENTS INVOLVING ELECTRIC CABLES

## 2.1 Experience from nuclear power plants in Germany

The operating experience of nuclear power plants (NPP) in Germany indicates that nearly 50 % of the reportable fire events at NPP involve electric equipment, in particular cables (see [1]). In this context, the worldwide well known large switchgear and cable fire event at the VVER 230-440 type NPP Greifswald, unit 1 in December 1975 has to be mentioned at first, since it affected equipment of different redundant trains in different plant areas and buildings and would have been categorized as a level 3 incident on the international INES reporting scale [2], if the respective reporting criteria had been in effect at that time.

Other fires involving electrical cables occurred at different German NPPs, such as two hydrogen fires at the hydrogen generator (occurring in 1988 and 1990) affecting generator control and support equipment including cables, or one more significant hydrogen fire in the reactor annulus of a pressurized water reactor type plant (in 1991) where cables of the hydrogen pressure decrease equipment were degraded (see [1]). Two further events to be mentioned in this context are a short circuit in a 220 kV / 380 kV high voltage system resulting in a cable and lubrication oil fire and a cable fire, where due to mechanical load by a metallic frame a short circuit caused a fire of a 220 V support cable inside the cabinet of a body sound check system (see [1]). None of these fires degraded the nuclear safety seriously, but several of them could have been safety significant under different boundary conditions.

Last not least a lubrication oil fire at a German PWR type reactor has to be mentioned, which occurred in 2000 during restart after the annual outage. Leaking lubrication oil perforated into insulation material of a main coolant pump and self-ignited (autoxidation) at the hot component affecting also a higher amount of cables. Due to the plant state the significance of the event was low (see [1]), but it could have the potential to affect electric I& C equipment of more than one redundant train under different plant conditions (plant states).

## 2.2 Experience from electrical fires in Finland

Recently, there have not been particular electrical fire events at Finnish NPPs. Instead we report generally on Finnish electrical fires [3] indicated as electrically induced from statistics on large fire accidents during 1980-1993 based on unpublished material from the Federation of Finnish Insurance Companies. A fire accident was recorded as large, if the value of the material loss exceeded 100 ... 250 k€ in prices of the year 2000 (the limit defining a large accident varied within this interval during the period due to inflation and changed definitions). Ignition mechanism as well as failed component was used without distinction in these statistics to express fire cause. The cumulative loss distributions are presented in figure 1 for cables, switchboards, and other power line faults. In comparison to large loss fires in general all of these are slightly smaller than large loss fires in general as indicated in table 2. The median value of a cable fire is 0.22 M€ as compared to 0.32 M€ of all large loss fires. Average losses are respectively 0.34 M€, and 9.71 M€. Cumulative distribution of losses is generally skewed, and roughly logarithmically normal.

**Table 2:** Large loss fires in Finland 1980-2000 - all and cable related

| | All Fires | Cables | Switchboard | Other Network |
|---|---|---|---|---|
| Number of fires | 1566 | 48 | 25 | 35 |
| Total loss [M€] | 1111 | 16 | 16 | 17 |
| Median loss [M€] | 0.32 | 0.22 | 0.29 | 0.23 |
| Average loss [M€] | 0.71 | 0.34 | 0.66 | 0.49 |

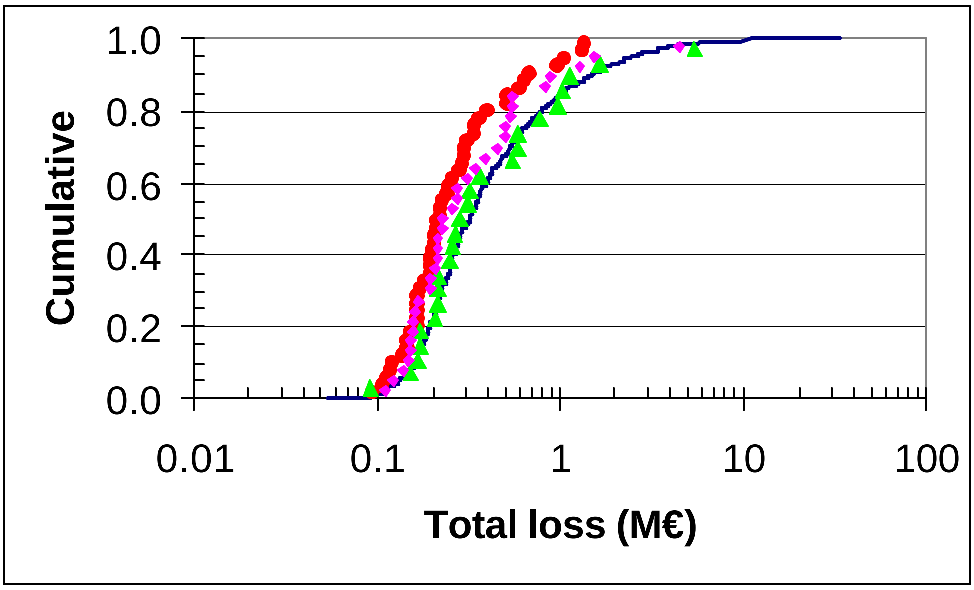

**Figure 1**: Distribution of losses in electrical fires in Finland 1980 - 2000: all large loss fires (full line), cables (dots), switchboard (triangles), and other power line (diamonds).

Electrical fire causes and the total number of all sizes of fires in Finland during 1994 and 1995 as recorded in the Finnish national accident data base ONTIKA (now renamed PRONTO) [4] are presented in table 3. The database ONTIKA contains information on accidents, which concern the fire and rescue authority. The fire officer in command at the fire scene is responsible for collecting information about the accident for ONTIKA. The fire cause recorded is often only a rough guess because the fire brigade does not perform fire investigations proper. This is especially true where the fire cause is not obvious, as in many fires of electrical origin.

**Table 3:** Fire causes in Finland in 1994 and 1995 according to Finnish national accident database ONTIKA [5]

| Fire Cause | 1994 | | 1995 | |
|---|---|---|---|---|
| **Electrical fires** | No. | % | No. | % |
| Short circuit or ground fault | 870 | 75 | 984 | 72 |
| Loose connection | 36 | 3 | 56 | 4 |
| Overheating | 54 | 5 | 73 | 5 |
| Improper installation | 17 | 1 | 11 | 1 |
| Other electrical faults | 186 | 16 | 236 | 17 |
| **Electrical faults, total** | **1163** | **100** | **1360** | **100** |
| **All fires** | | | | |
| Electrical faults, total | 1163 | 13 | 1360 | 13 |
| Lightning | 287 | 3 | 306 | 3 |
| Other known causes | 6229 | 70 | 6798 | 67 |
| Unknown | 1191 | 13 | 1580 | 16 |
| **Total** | **8870** | **100** | **10044** | **100** |

## 2.3 Experience from NPPs worldwide

Worldwide known cable fire events in NPPs were analysed [3] from AIRS [6] event reports at the status of the year 1997. The respective results are shown in table 4. The number of events is so small, that differentiation between various failure mechanisms is not pronounced, except for unknown causes. Table 5 lists damaged components showing cables to be the causes in 10 % of the cases. As an ignition source cable insulation (table 6) is twice as common or totally 21 % of the cases. Concluding it is seen, cables are not the most frequent cause of failures or ignitions, but still constitute a sizeable risk.

**Table 4:** Failure mechanism leading to ignition in fires originating from electrical faults as described in AIRS event reports (1997), [6]

| Failure Mechanism | No. of Events | % |
|---|---|---|
| Overheating | 5 | 13 |
| Short | 6 | 15 |
| Ground fault | 5 | 13 |
| Arcing | 7 | 18 |
| Loose connections | 3 | 8 |
| Unknown | 13 | 33 |
| **Total** | 39 | 100 |

**Table 5:** Failed component in fires originating from electrical faults as outlined in AIRS event reports (1997), [6]

| Failed Component | No. | % |
|---|---|---|
| Cable | 4 | 10 |
| Switch, breaker | 10 | 26 |
| Contact, splice, terminal | 6 | 15 |
| Relay | 2 | 5 |
| Transformer | 10 | 26 |
| Slip ring in turbogenerator | 1 | 3 |
| Unknown | 6 | 15 |
| **Total** | 39 | 100 |

**Table 6:** Ignited component or material and circuit voltage in fires originating from electrical faults as described in AIRS event reports (1997), [6]

| Ignited Component | No. | % | Voltage | | |
|---|---|---|---|---|---|
| | | | Power | Control | Not specified |
| Cable insulation | 8 | 21 | 7 | 1 | |
| Switch, breaker | 4 | 10 | 2 | | 2 |
| Contact, splice, terminal | 1 | 3 | 1 | | |
| Relay | 2 | 5 | | 2 | |
| Oil | 11 | 28 | 11 | | |
| Slip ring in turbogenerator | 1 | 3 | 1 | | |
| Unknown | 10 | 26 | 6 | | 4 |
| No fire*) | 2 | 5 | 2 | | |
| **Total** | 39 | 100 | 30 | 3 | 6 |

*) Two cases: (1) scorching of cable insulation and risk of fire, (2) the electrical fault was interrupted within a few seconds by the over-current protection.

## 3. EXPERIMENTAL AND MODELLING ACTIVITIES ON CABLE FIRES

### 3.1 Loose contact and cold solder junction

For a loose contact or cold solder junction a finite point or surface resistance $R$ is created [3]. If a current $I$ is driven through this contact, a thermal power of $Q = I^2R$ is created over a very small volume of current carrying material. This will heat the material soon to high temperatures. We idealise the model to a wire carrying a current, and cooling into ambient from its bare metal surface. A loose connection is created in one cross section of the wire, where heat is produced at constant rate $Q$ in a plane. By using linear heat transfer theory [7], the temperature rise $\Delta T(t)$ of the heated cross section in the wire is given by

$$\Delta T(t) = \dot{q}''\sqrt{\frac{r}{2\pi kh}}\,\gamma\left(\tfrac{1}{2}, t/\tau\right) \tag{1}$$

where $\dot{q}''$ is the power density in the cold junction [W/m$^2$], $r$ the radius of the wire, $k$ thermal conductivity of copper, and $h$ effective heat transfer coefficient from the surface of the wire. To cover wide enough range we assume $h$ = 25 ... 100 W/m$^2$K. $\gamma$ is the incomplete gamma function [8], and time constant $\tau$ is given by

$$\tau = \frac{r}{2}\frac{\rho c}{h} \tag{2}$$

where $\rho$ is the density and $c$ the specific heat capacity of metal (copper). Asymptotically Equation (1) approaches a value

$$\lim_{t \to \infty} \Delta T(t) = \dot{q}''\sqrt{\frac{r}{2kh}} \tag{1'}$$

which is the maximum temperature for the given radius *r* and conductivity *k* of the metal of the wire, the effective heat transfer coefficient *h* and power density $\dot{q}$¢ in the cold junction.

In figure 2 two limiting curves are calculated using Equation (1) to demonstrate temporal behaviour of a cold junction of a 1 mm$^2$ copper wire. For a total temperature rise of 200 K (Equation (1')) 4.6 W is needed if *h* = 100 W/m$^2$K. The final state is reached in about 30 s. Only 2.3 W is needed for the same temperature rise, if *h* = 25 W/m$^2$K, but now more than a minute is needed to reach the final temperature. Generally only 1 ... 12 W is needed to heat a cold junction of a wire of 0.5 ... 4 mm$^2$ cross section used in electronics to a temperature able to ignite combustible material nearby. Time constants *t* were in the range 5 ... 160 s, respectively.

As shown from figure 2, the steady temperature is the real indicator of the potential ignition. Therefore, different boundary conditions, like cable insulation, do not change drastically the rate determining factors given in Equation (1'). For that reason no more complicated boundary conditions are attempted for this linear configuration. Two-dimensional configurations with analogue dissipating boundary conditions would be interesting, but they were not studied in this project. A loose joint between two layers of conductors on different sides of a printed circuit card, where the point like source is imbedded in resin, would be of special interest. Since this material of the printed card is combustible and conducts heat badly compared to metals, it might create a dangerous local hot spot, a potential ignition source. This is in principle the problem of constriction resistance treated widely in old electrotechnical literature.

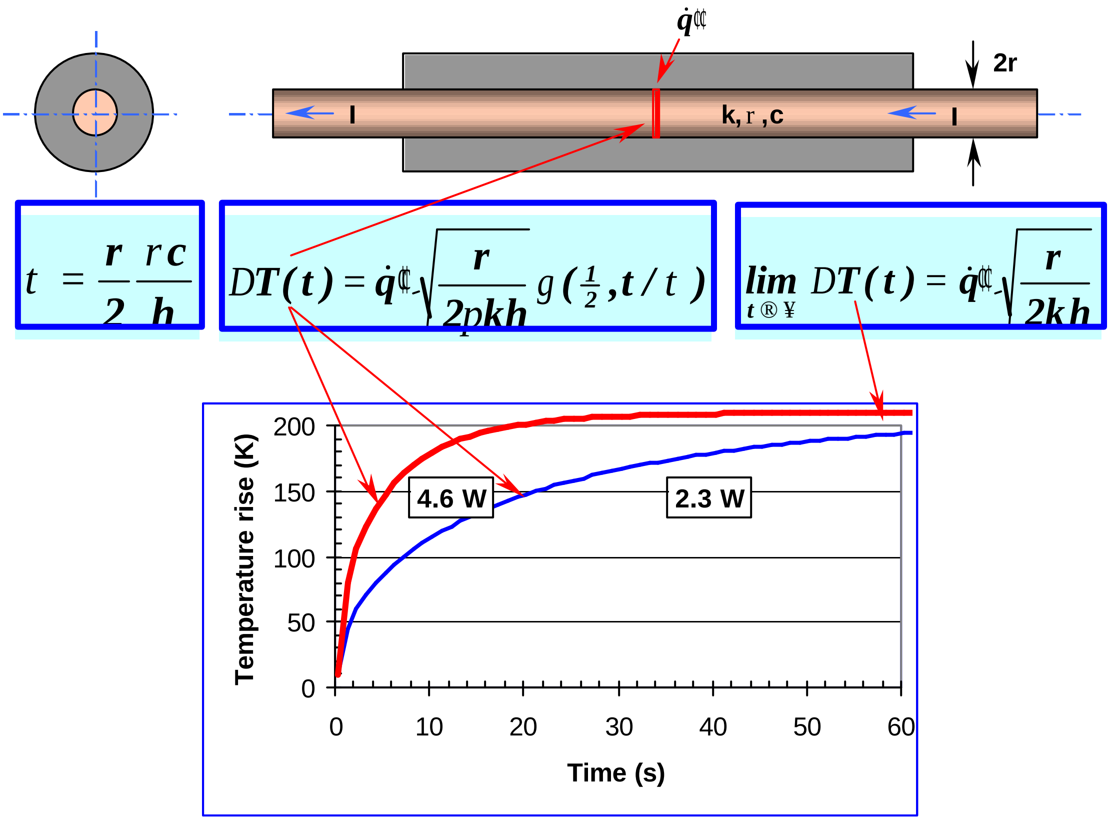

**Figure 2:** Heating of a cold junction in a 1 mm$^2$ copper wire

### 3.2 Heating from overloading

Consider an insulated cylindrical cable carrying a current in a metal conductor with geometry and notations as shown in figure 3. If the cable is carrying an overload of current, the final temperature $T_2$ is given by [3, 9]

$$T_2 = T_0\left(\frac{1}{Bi} + ln\frac{b}{a}\right) \qquad (3)$$

where temperature $T_0$ is calculated from

$$T_0 = \frac{I^2}{2p^2 s\; k a^2} \qquad (4)$$

and the Biot number $Bi$ from

$$Bi = \frac{bh}{k} \qquad (5)$$

In contrast to cold junctions, rather high currents are needed to produce temperatures likely to lead to ignition of combustible insulation material as is shown in figure 3.

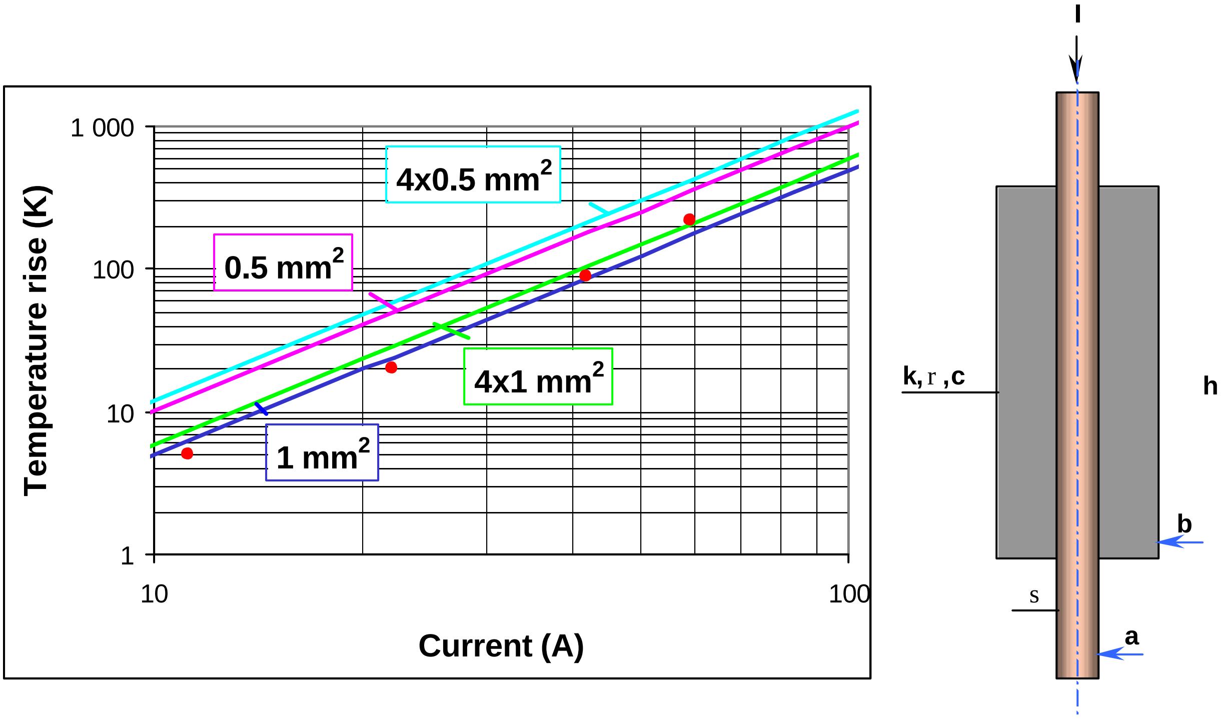

**Figure 3:** (right) Geometry and notations of an insulated cable heated by electrical current. a radius of conductor, b radius of cable, k thermal conductivity of cable insulation material, h effective heat transfer coefficient from the surface of cable, ρ density, c specific heat capacity, I electrical current and σ electrical conductivity
(left) Heating of cables from overcurrent. Full lines are theoretically calculated maximum temperatures for different types of cables, and the dots experimentally measured data from tests using a 4 x 1 mm$^2$ cable [3, 9]

Comparison of theoretical plots with measured points shows rather good agreement. The outcome from these series of experiments was that it is an unlikely mode of ignition. To produce an increase of temperature in excess of 200 K currents of the order of 60 ... 100 A are needed. Since most of the electrical instruments are protected for overcurrents using fuses, they are likely to trip before high enough heating is obtained.

## 3.3 Damage probability of the second target in a cable tunnel

For estimation of damage probability of second target a Monte Carlo platform was written [10] by using commercial programs: @Risk for sampling and statistics, and Excel for input data base. CFAST deterministic fire simulation program was used and a number of simple correlations was given to describe response of targets or barriers. The calculation platform, named PFS, was applied to a cable tunnel, where different redundancies were on opposite sides either without any physical barrier or separated by a partial screen (figure 4). Collecting realistic dimensions and cable data from Finnish NPPs, damage probability was estimated for PVC cables as shown in figure 4. The positive effect of the screen is clearly demonstrated. Calculation platform PFS is so general, that any fire model or simulation program can be used, and an arbitrary scenario can be assessed once relevant input distributions are available or are collected from real objects.

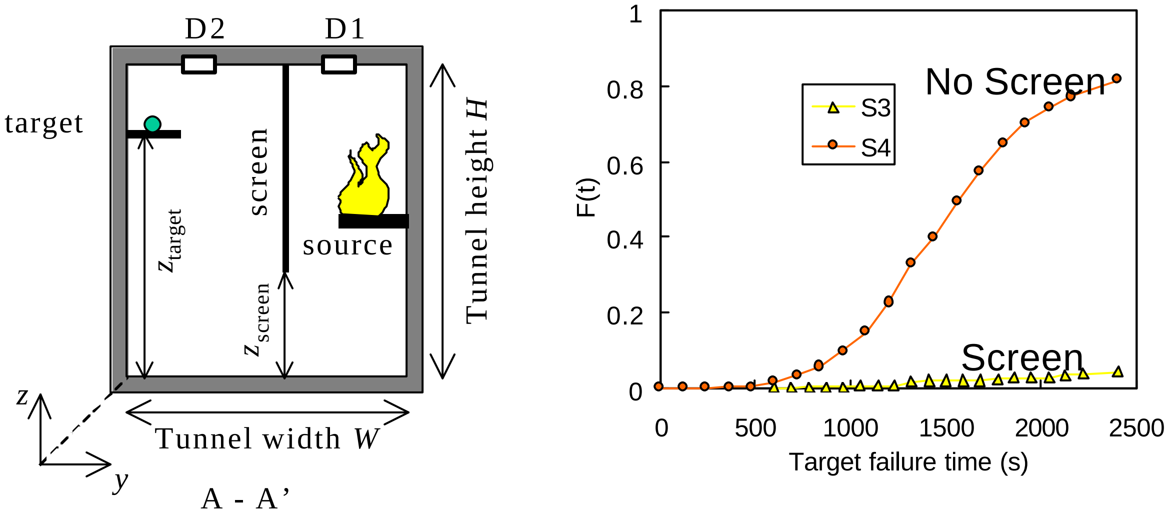

**Figure 4:** Effect of screen on damage of the second target assessed using PFS Monte Carlo platform, [10]

## 3.4 Insights gained from IRSN cable fire tests

The Institute of Radioprotection and Nuclear Safety (IRSN) conducted fire tests (PEPSI Test and analytical tests) within the framework of Blayais 1 fire PSA [11] in order to determine the behaviour of France's electrical cables under fire conditions. The objective of these tests (see [12]) is the identification of the dominant failure modes and the determination of cable damage criteria.

### *3.4.1 PEPSI test*

The experimental program consisted of exposing five cable trays to different thermal loads inside a ventilated room (5 volumes/h). Each cable tray is made of 20 cables whose characteristics are shown in table 7:

**Table 7:** Characteristics of cables selected to experiments

| Number | Type | Section | Voltage | Armored |
|---|---|---|---|---|
| 4 cables | Power | 3 * 16 mm$^2$ | 380 V | Yes |
| 4 cables | Power | 3 * 6 mm$^2$ | 380 V | Yes |
| 4 cables | Control | 2 * 35 mm$^2$ | 125 V | Yes |
| 4 cables | Control | 7 * 1.5 mm$^2$ | 48 V | Yes |
| 4 cables | Measurements | 2 * 0.5 mm$^2$ | 24 V | No |

Different thermal loads were achieved by the differing positions in relation to the fire, being an oil pool fire of 1 $m^2$. Four cable trays, each 5.5 m long, were set horizontally and were oriented on a South-North axis (figure 5). They were located in the following manner within the compartment:

- The cable tray 1 run crossed the plume of the blaze at a level where the flame will not reach it, 1.8 m above the initial level of the fuel.
- The cable tray 2, located vertically above the cable tray 1, crossed the plume of the blaze 0.35 m below the ceiling.
- The cable tray 3 was located out of the plume, high in the compartment (0.35 m under the ceiling); its East side was 1.5 m from the generatrice of the blaze.
- The cable tray 4 was located out of reach of the plume, near the blaze, 1 m from the edge of the combustion container, in an area where the thermal radiation is important.

One fifth cable tray 5, 7.4 m long, was attached vertically, North-East from the blaze. The distance from the central cable to the edge of the combustion container was 1 m.

The cables of the trays 1, 2, 3 and 4 were under voltage at the beginning of the PEPSI test. In this test, only the failure of cables was studied, thus only C1 cables (not flame propagator according to the NFC 32 070 standards) were chosen. These cables were the same as those used for the French PWR 900 $MW_e$.

An electrical cabinet was set near the fire. It was 1.2 m high, 1 m wide and 0.3 m deep and its faces are parallel to the sides of the compartment. The cabinet was exposed to heat flux from the flame (direct radiation).

The instruments set in the experimental chamber were:

- thermocouples to measure the temperature of the gases, walls, flame zone, plume and fuel,
- thermal fluxmeter to identify heat transfers at the walls, in the fuel container and along the cable,
- pressure transmitters,
- scales to monitor the mass loss of the fuel (vaporisation rate) and of the cable tray 1,
- gas analysers to continuously find the various gas concentrations,
- gas collecting jars to complete the other measurements,
- aerosol collecting devices to characterise their behaviour,
- PITOT tubes and MCCAFFREY sensors to measure the gases velocity in the flame of the blaze, in its plume and in the hot sub-layer below the ceiling,
- ANNUBAR to measure the flows in the various ducts of the ventilation network in the experimental chamber,
- interface modules associated with the tested electric cables to measure voltage or stray currents in order to detect the damage time,
- differential circuit-breakers coupled to tripping sensors to find the exact time of tripping.

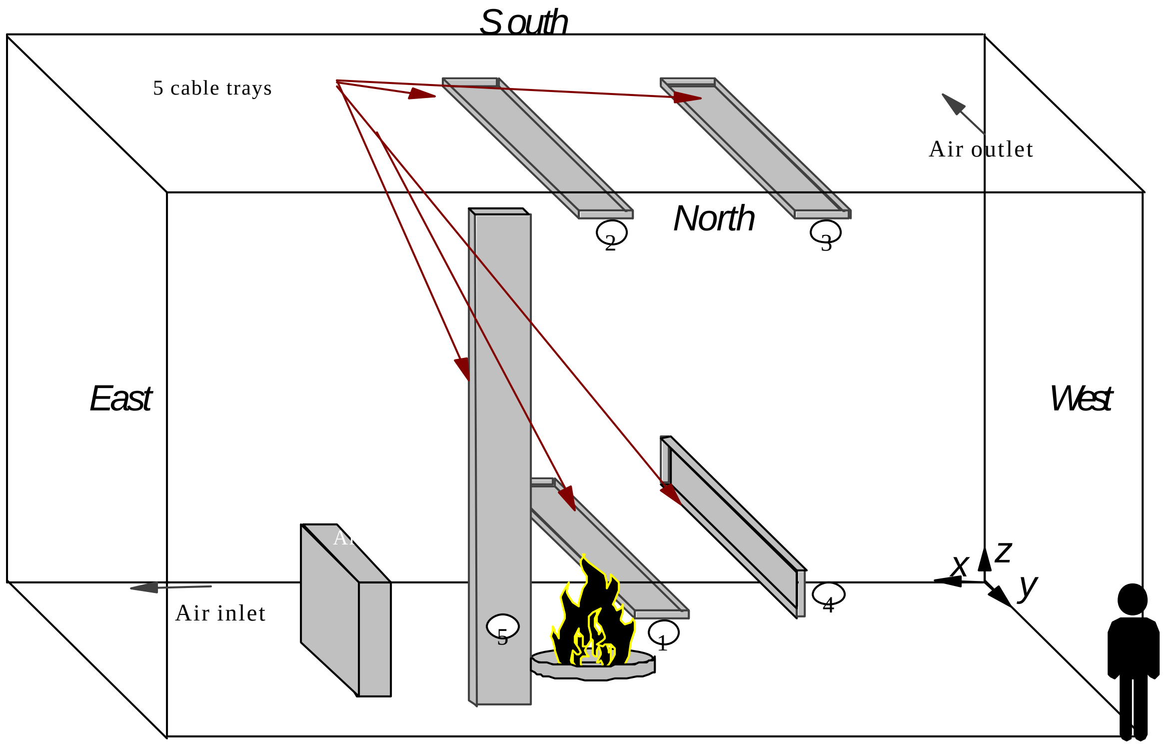

**Figure 5:** PEPSI 1 Test.

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 8 gives the gas temperature near the raceway and the corresponding failure time for each kind of cable.

**Table 8:** Temperature and damage time of electrical cables

| Damage Time and Temperature | Raceway 1 | Raceway 2 | Raceway 3 | Raceway 4 |
|---|---|---|---|---|
| **Mean temperature [°C]** | 350 | 220 | 210 | 130 |
| **Mean flux [W/m$^2$]** | - | 5400 | 5300 | 5700 |
| 380 V (3 x 16 mm$^2$) [min] / [°C] | 6 / 370 | 38 / 250 | 36 / 215 | No failure |
| 380 V (3 x 6 mm$^2$) [min] / [°C] | 4 / 460 | 19 / 230 | 24 / 215 | No failure |
| 125 V (2 x 35 mm$^2$) [min] / [°C] | 13 / 420 | 33 / 250 | 42 / 215 | No failure |
| 48 V (7 x 1.5 mm$^2$) [min] / [°C] | 7 / 420 | 29 / 240 | 24 / 215 | No failure |
| 24 V (2 x 0.5 mm$^2$) [min] / [°C] | 3 / 390 | 32 / 250 | 28 / 225 | No failure |

### *3.4.2 Analytical fire test of electrical cable damage*

The objectives of these analytical tests were:

- to get data to develop a model for the FLAMME-S fire simulation code permitting an estimation of the electrical damage time (see [13]), 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 9 shows the mean temperatures obtained for different temperatures of the oven.

**Table 9:** 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 |

### *3.4.3 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.

### 3.5 Cable fire tests in Germany

Due to the fact that cable fires, particularly in rooms with a high amount of safety related cables from different redundant trains are recognized to be safety significant by the German authorities, various analytical studies on the burning behaviour of cables and potential consequences of cables fires in nuclear installations have been performed within the last years.

In this context, real scale cable fire experiments with vertically as well as horizontally installed PVC cables with and without protective coatings have to be mentioned. These experiments carried out on behalf of the BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit) revealed the result that a rapid fire spreading is possible on cables, especially on vertical cable trays, if the cables are not protected by qualified intumescent or ablative coatings (see [14]). Coatings, however, provide a suitable protection measure for preventing fire spreading. Credit can be taken from this measure for a limited time period of approx. 15 min before the cable insulation material will participate in the fire giving the possibility of starting fire extinguishing within this time period. However, protective coatings do not represent fire barriers with a defined fire rating of 30 or more minutes.

The German licensees also recognized the significance of cable fires. Due to the fact that different types of insulation materials are installed in German nuclear power plants (NPP), depending mainly on the materials available at the time of the plant design, a large test series of cable fire experiments has been performed by iBMB (Institut für Baustoffe, Massivbau und Brandschutz) of TU (Technical University) Braunschweig.

These experiments gave first indications on the burning behaviour of cables with different types of cable insulation materials, halogenated ones, such as PVC (polyvinylchloride) as mainly used insulation material or PE (polyethylene), as well as materials without halogenic particles, such as silicone based insulations and highly improved fire retardant, non corrosive (FRNC) insulation materials, showing a significantly better behaviour under fire conditions for silicone or FRNC insulated cables (see heat release rates in figure 6, from [15])

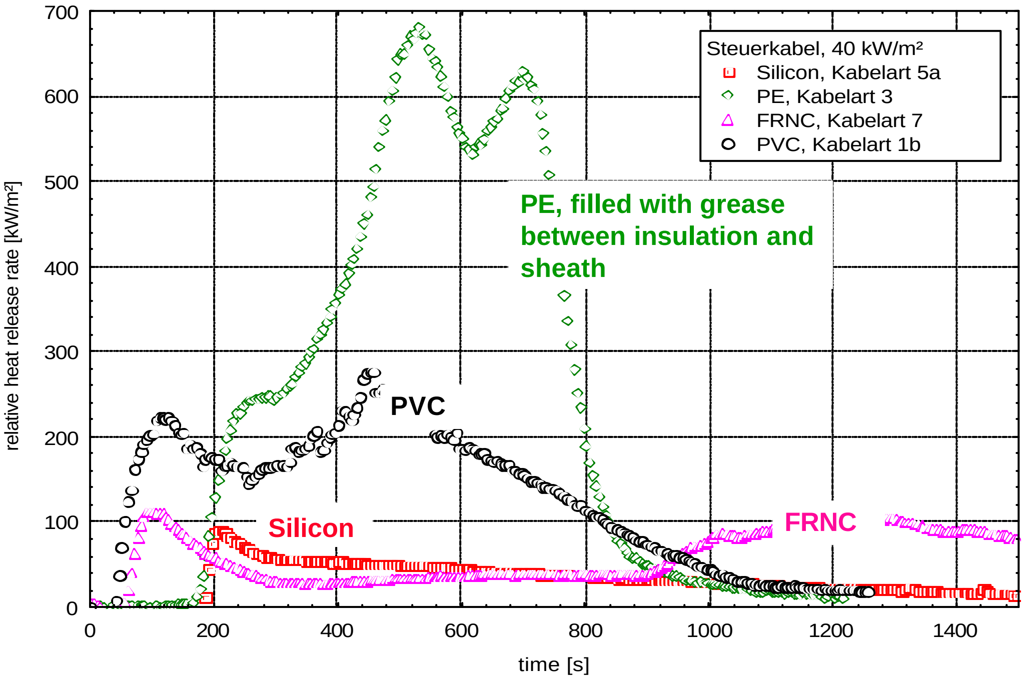

**Figure 6:** Cone calorimeter tests (from [15]) due to the standard ISO 5660 for control cables with different insulations as applied in German NPP

However, not all issues have been solved up to now by the tests in the past. In paricular, another important factor with respect to fire induced cable failures are the functional failures or potential circuit faults still representing an unresolved issue.

On behalf of the Federal German Auhority BMU, GRS intends to perform a series of real scale cable fire experiments in a fire compartment of approx. 13 m$^2$ floor area and 3.6 m up to 5.6 m height including functional loss tests considering the requirements of the international IEC standards as outlined in the following matrix (see table10) in 2003:

**Table 10:** Test matrix of cable fire tests including functional loss

| Room Fire Test Procedure | Test 1 | Test 2 | Test 3 | Test 4 |
|---|---|---|---|---|
| Material | PVC | PVC | FRNC | FRNC |
| Cable Type | power / control cables | power / control cables | power / control cables | power / control cables |
| Orientation | horizontal | vertical | horizontal | vertical |
| Heating system | gravel bed gas burner, 50 kW, no pre-heating | | | |
| Functional Loss Test * | yes | yes | yes | yes |

*) Based on German standard DIN 4102-12

The corresponding fire compartment layout equipped with horizontally mounted real configuration control cable trays is outlined in figures 3 and 4 (see also [15]).

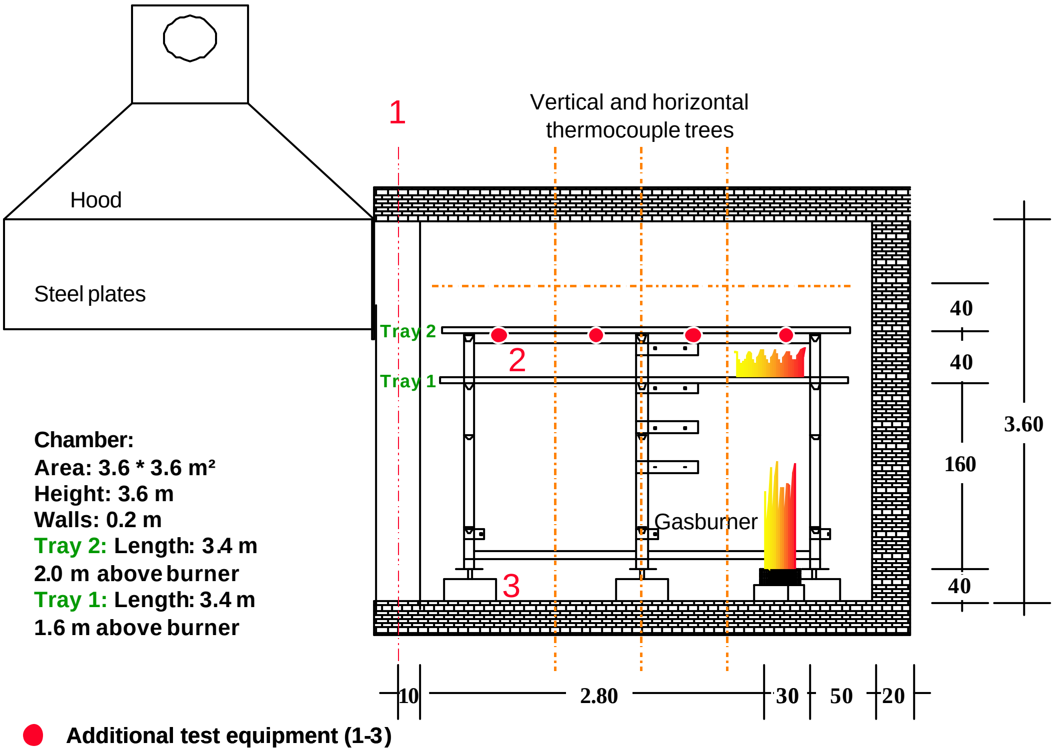

**Figure 7:** Layout of cable fire tests including functional failures foreseen in Germany – vertical section (from [15])

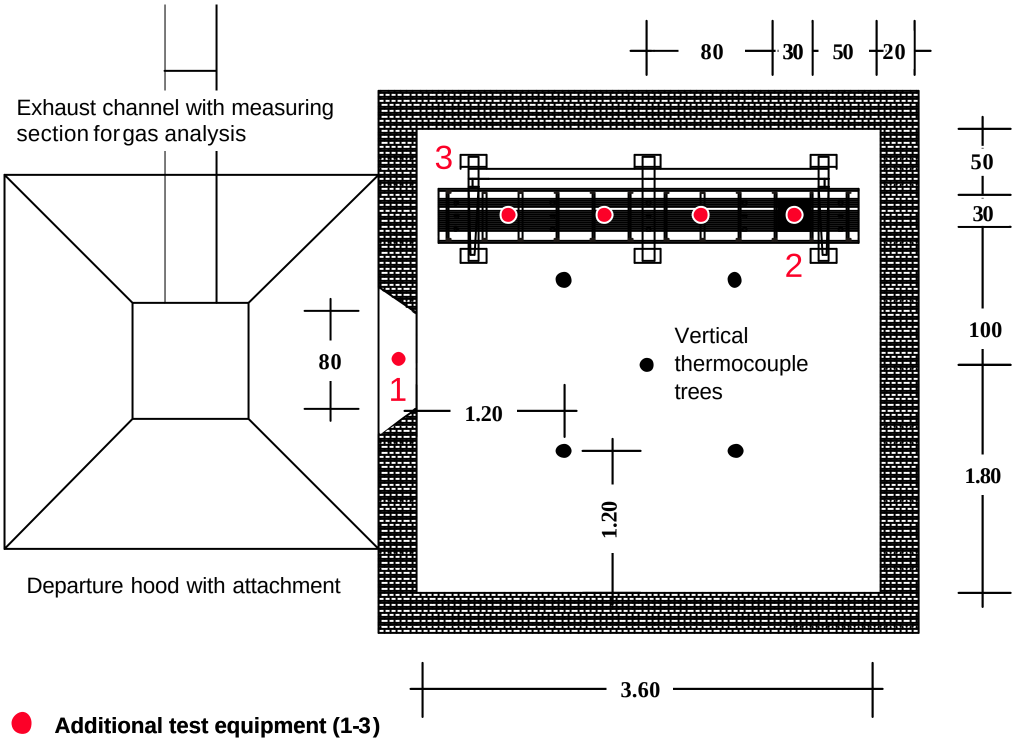

**Figure 8:** Layout of cable fire tests including functional failures foreseen in Germany – horizontal section (from [15])

Besides the gas temperatures of the cold gas layer, the hot gas layer, and the plume, cable surface temperatures as well as temperatures inside the cables will be measured. In addition, the heat release rate and the amounts of smoke and gases ($O_2$, CO, $CO_2$) will be analyzed. The experiments will be accompanied by individual measurements for functional loss by short circuit or interruption of the electric current as well as by measurements of changes in the cable insulation resistance.

## 4. SUMMARY AND CONCLUSIONS

A lot of research and development in the field of fire risk assessment for nuclear power plants has been performed in France. The fire PSA revealed that additional work has to 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 PEPSI Fire Tests and Analytical Tests, IRSN succeeded in gaining a better understanding with respect to the behaviour of electrical cables exposed to fire conditions.

In Finnish nuclear power plants cable fires have been recognized to be a major component for fire related initial events, because in certain areas there are not sufficient physical separation/partition between redundances. Consequently, various efforts were made to assess quantitatively the risk of cable fires by using statistical, modelling and experimental means at different levels of sophistication. Statistics from nuclear and non-nuclear sources show cable fires to be a significant component of large fire losses, although in the average material losses are only half of the average material losses of all large fires. This conclusion cannot be generalized to NPPs, because there cables have as nerves special function for safety not encountered in fires of many other built objects. In NPPs cable fires are not the most common cause of electrical ignitions but still a significant factor. There is a rough indication, power cables have 8 times higher ignition probability per plant, and 40 times higher probability per cable length than control cables.

In statistics root causes of electrical events are poorly know due to insufficient reporting, but also weak investigations. Therefore, physical models for ignitions were reviewed/made to facilitate fire investigations and risk assessment. For modelling an overheated cable a mathematical model was proposed, which compares favourable with a limited set of experimental data. An analytical model was made for cold joint or loose contact indicating that in a current loop very small level of electrical energy could lead to ignition of surrounding plastic materials.

A general Monte Carlo calculation tool was made to assess quantitatively damage probability for a given fire scenario. It was applied to a cable tunnel containing two redundant trains. Giving ignition of one train the probability of damage of the second train was successfully determined using deterministic fire simulation and relevant statistical input data for the scenario.

Fire PSA activities in Germany also indicated the significance of cables involved in fires at nuclear power plants. Still the functional electrical failure is an unresolved issue which has to be treated. Due to this, further experimental research will be carried out in the near future.

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