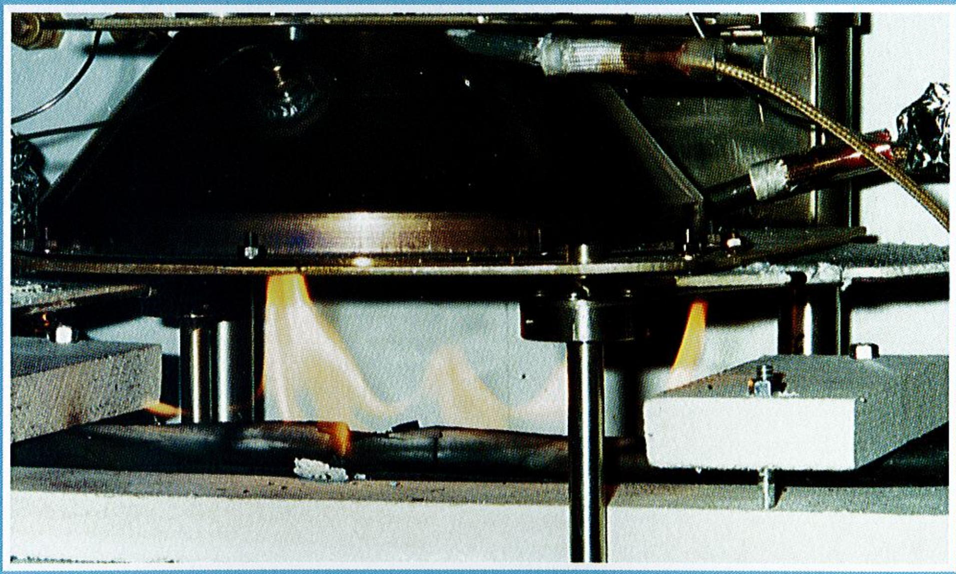
Petra Andersson
Patrick Van Hees

Performance of Cables Subject to Thermal Radiation

Brandforsk Project 612-991



SP Swedish National Testing and Research Institute
SP Fire Technology
SP REPORT 2000:24

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Abstract

Cables are in many cases part of safety systems and hence knowledge of their functional performance is vital. In this project the performance of cables subject to thermal radiation has been investigated. Four different cables were investigated, two data cables and two low voltage cables. The cables were irradiated in the cone calorimeter and the time to short circuit was measured. In addition a case study was made on optical cables subject to thermal radiation and on one data cable subject to an elevated temperature.

Key words: Damage criteria, Cables, Thermal radiation

Sökord: Skadekriteria, kablar, strålningspåverkan

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Preface

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Sammanfattning

Inom de flesta typer av anläggningar och konstruktioner överförs kraft och kontrollsignaler via någon typ av kablar. Störningar på ett system vid onormal påverkan inträffar ofta på kablar då de har en mycket stor geografisk sträckning i förhållande till komponenter. Komponenter är också betydligt lättare att skydda beroende på sin geografiska kompakthet. Att skydda kablar med olika anordningar är möjligt men blir då mycket kostnadskrävande.

För att kunna optimera skyddsåtgärder vid brand måste skyddsföremålens skadekriterier kunna fastställas bättre. Vid riskanalyser överdimensioneras ofta skyddsåtgärder på grund av allt för konservativa antaganden. Då det är möjligt att förutsäga brandens fysiska förutsättningar bör också effekterna av brand kunna bedömas realistiskt. Kablars nuvarande klassning ger litet underlag för denna bedömning. Framtagandet av en metod för att kunna bedöma kablars skadekriterier bedöms viktigt då kablar ofta har en stor geografisk utsträckning och har stor risk att utsättas för brand. Branddata på alla kablar från leverantören vore en önskvärd situation.

I detta projekt har tid till skada på kablar mätts beroende på infallande termisk strålning. Kortslutning är kriteriet på skada. Två olika signalkablar med metalledare och två olika lågspänningskablar testades i konkalorimetern. Ett fåtal försök gjordes även på optiska kablar samt på elektrisk kabel utsatt för en viss omgivningstemperatur.

1 Introduction

Cables are in many cases part of safety systems and hence knowledge of their functional performance is vital. In places where large amount of cables are placed it is essential to know, for example, how many back up systems should be provided and what type of active or passive protection should be used.

An example can be given of a power plant. In a large cable gallery different cable trays are quite often present. When a local fire occurs on one side of the gallery the company exploiting the power plant needs to know what type of passive or active fire protection has to be used to limit the danger the fire can cause. One can use calculation methods to predict a variety of characteristics such as, the thermal radiation on the cables remote from the fire. However, information on how much "electrical" damage occurs at certain levels of thermal radiation and after certain exposure times is lacking. Thus, the fire protection has to use high safety factors resulting in larger investments. Moreover, the situation can be even more difficult for already existing power plants. In such cases new requirements can result in costly investments if no fire engineering calculations can be used.

Hence, the problem of defining the failure time of a cable subject to thermal radiation is important input data in fire safety assessments of power plants. In this respect essentially two conditions can occur. The cable is under load (specific for power cables) or at limited load (more applicable for instrumentation and data cables). The latter type of cable is divided into cables with metallic and non-metallic (optical) core.

The thermal stability of the insulation material of cables is normally tested but not the functionality of the cables. Also the ignitability and fire performance of cables is quite often tested with test methods such as IEC 332-1, IEC 332-2 and IEC 332-3. For the functionality the IEC 331 test standard is applicable but this test uses a flame source in which the cable is positioned. Hence little information is available from this test to establish failure times at lower thermal radiation levels and under non-flaming conditions.

Some investigations, mainly full-scale, have been made. Cline, Riesemann and Chavez[1] conducted full-scale tests with one IEEE-383 qualified and one unqualified cable. The cables were unprotected, protected with a ceramic fibre and sheet metal cover, and protected with a fire protective coating. The unqualified cable short circuited in all tests, the qualified cable only when unprotected. Chung, Siu and Apostolakis[2] made an attempt to model these test assuming that damage occurred at a certain surface temperature with the computer code COMPBRN, however the result was not very convincing. Wheelis[3] made additional full scale tests which showed that parameters such as whether the cable was terminated in the fire room, geometry and convective heat transfer were important. Frank and Moieni[4] based their calculation of a probability distribution for time to damage of cables on Lee's[5] findings that there is a critical thermal radiation below which no damage will occur and that the critical energy level needed for damage is the product of the imposed thermal radiation and the time to damage. These results were later criticized[6] since the results were extrapolated from high exposure levels and short exposure times. Nowlen[7] also found that the short circuit of energized cables usually results in a fire consuming all insulation material in the vicinity of the fault and that whether the cables were aged did not decrease the time to damage. Nowlen and Jacobus[8] concluded that the results from aging degradation tests using steam could be used for fire damage threshold calculations. In addition they observed leakage currents of 10-15 mA sometimes under extended periods before the short circuit.

In this report the time to damage for 4 different cables subject to different thermal radiation levels is presented. The cables were both loaded and non-loaded. In addition the same result is presented for three optical cables. The results for one cable subject to a certain gas temperature are also presented.

2 Cost Benefit Analysis

Cables are used in many areas for power and signal transportation. Disturbances in many processes can occur due to signal failure and/or power disturbances. Such failures can occur due to mechanical or other abnormal impact of the cables. The cables are especially vulnerable due to their distribution in the building. This is different with other crucial components which are usually situated in a confined area. A variety of cable protection is available but protecting all cables is expensive.

When conducting probabilistic safety analyses the probability of different scenarios is evaluated. Together with a performance based way of thinking the fuel load, ventilation, geometry, component and cables location and damage criteria can provide the basis for such an estimate. For instance within nuclear power plants certain acceptable levels of risk exist. If realistic damage criteria are missing then conservative values must be used. Today all cables are assumed to fail immediately when the gas temperature exceeds 200 °C regardless of type of cable. These conservative values could result in costly investments.

In some cases where redundant systems are needed, lack of information on damage criteria could result in the fact that the cables must be placed in different fire compartments. Constructing new fire compartments can amount to more than 10 million SEK for a plant. The cost – benefit ratio considerations was hence a strong argument to conduct this project.

If methods were available to test cables ability to function during a fire then it could be a valuable extra sales argument for cable manufacturers. It would be useful for industrial cable users if the electrical performance of the cable during harsh conditions was classified in the same manner as the cables contribution to a fire.

3 Damage Criteria

An immediate problem when discussing time to failure is how to define the damage criteria. Initially in this project the resistance between two conductors in the cable was measured. The resistance was found to decrease continuously during the test and therefore the problem of defining a damage criteria in form of a resistance level remained unsolved. In addition measuring the resistance using direct current(DC) does not necessarily say anything about the cable performance when alternating current(AC) is used. Therefore a standard insulation test procedure with a Megger (DC source) to decide when the cables were damaged was rejected. Instead a short circuit was chosen as damage criteria. The same damage criterion has been used by other investigators.

4 Experiments

Three different types of experiments were conducted. The main part of the practical work was focussed on electrical cables subject to thermal radiation in the cone calorimeter (ISO 5660). In addition a case study with an electrical cable subject to a gas temperature in a tubular furnace was conducted as well as a case study with optical cables subject to thermal radiation in the cone calorimeter. All experiments conducted are listed in Annex B.

4.1 Experimental Set-up – Electrical Cables

An electrical switchboard was constructed for the experiments. The switchboard is shown schematically in figure 1 for unloaded cables and figure 2 for loaded cables. The AC-voltage in each phase was measured for each experiment by means of a voltage divider together with a DC-level that indicates whether the fuse was working or not. In addition the current through one of the conductors was measured using a current clamp. The current clamp had three different ranges i.e. with a maximum of 1, 10 or 100 A. The output from the clamp was 1 V at full range. Measurements were made every second.

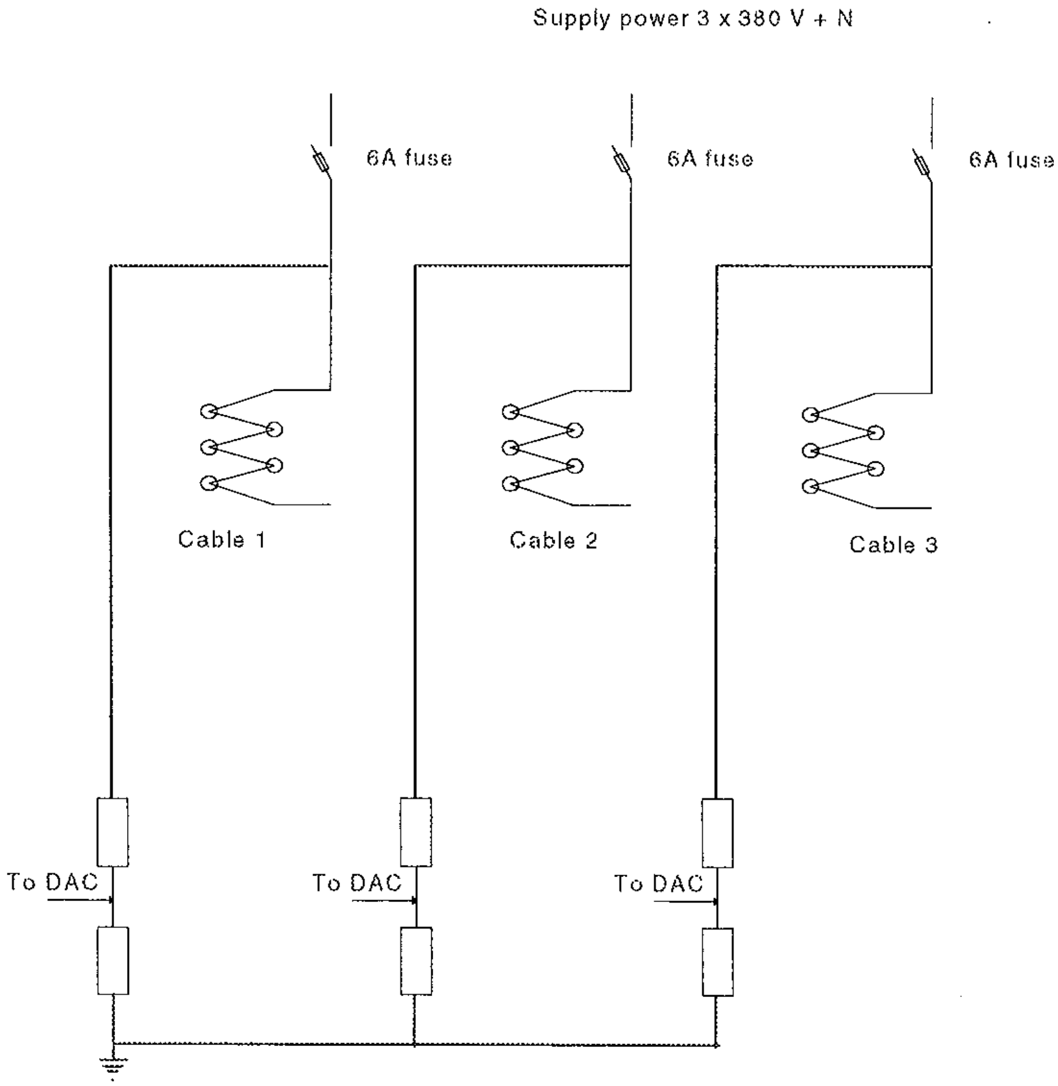

Figure 1. Schematic of experimental set-up for unloaded cables.

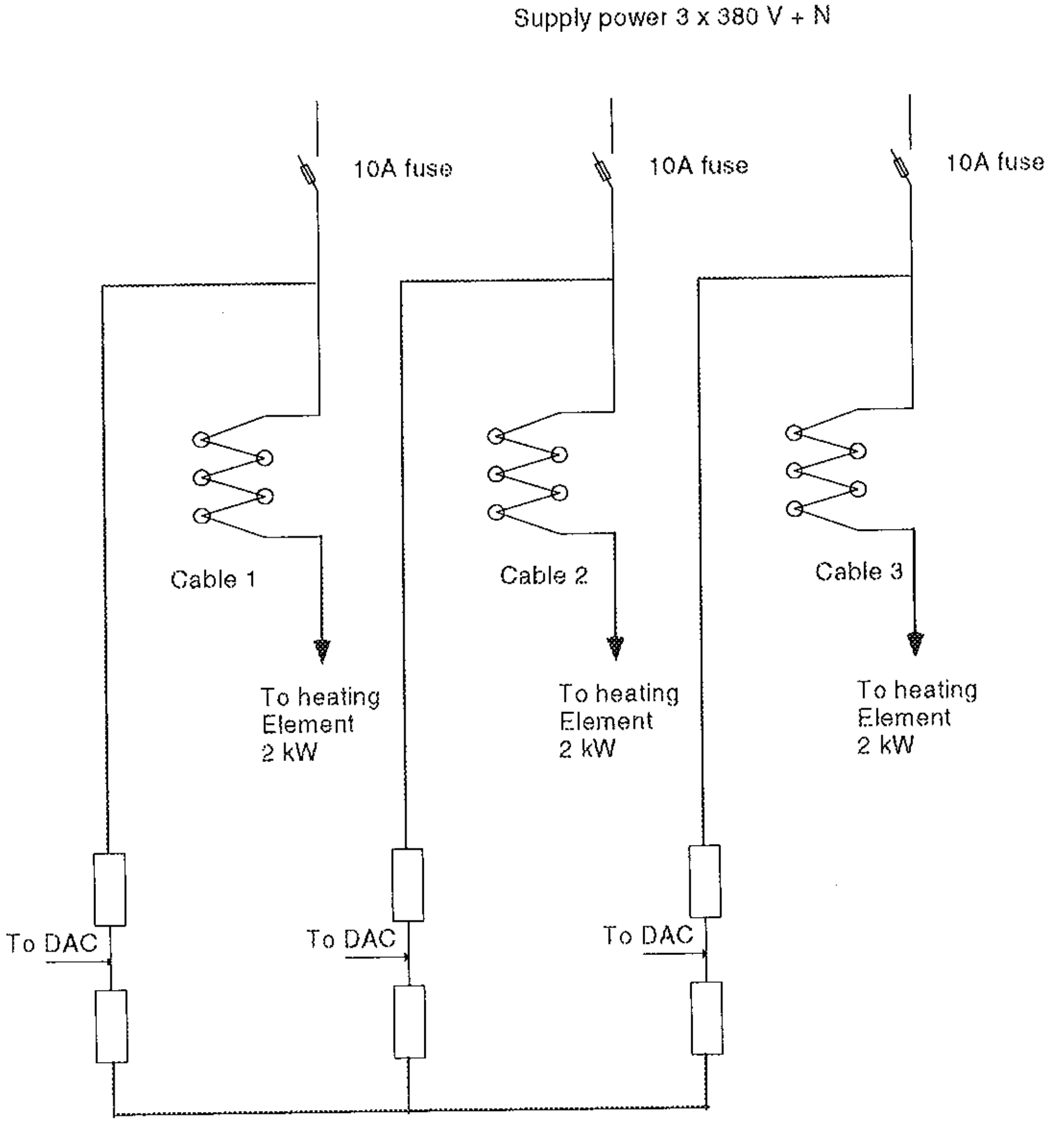

Figure 2. Schematic of experimental set-up for loaded cables.

4.2 Cone Calorimeter Experiments

The experiments conducted on electrical cables in the cone are listed in Annex B. Two different data cables were tested, one 12x2x0.5mm² called F24 and one 8x2x0.5mm² called F25 and two different low voltage cables, one 7x2.5mm² called F22 and one 5x1.5mm² called Ekk. More information on the F22, F24 and F25 cables are provided in Annex A[9].

Some of the low voltage cable tests were conducted with the cable loaded by means of three 2 kW heating elements. Two different mounting configurations were used, one with the cable mounted straight with a non-combustible board in direct contact with the cable and one with the cable bent according to installation recommendations with a 6 mm distance to the non-combustible board. In addition, 4 tests were made on aged cables.

Both sheathing and insulation was PVC in the F24 cable. The F25 cable was flame retarded since the sheathing material was an enhanced PVC material. The F22 cable insulation material was XLPE with a zero halogen Polyolefin sheathing material is. The Ekk cable had both sheathing and insulation made of PVC. For the F24 cable the time to ignition according to ISO 5660 was 6 s at 75 kW/m^2, 20 s at 35 kW/m^2, 150 s at 20 kW/m^2 and 509 at 12 kW/m^2. For the F25 cable the time to ignition was 6 s at 75 kW/m^2, 37 s at 35 kW/m^2, 263 s at 20 kW/m^2 and 1111 at 12 kW/m^2. For the F 22 cable the time to ignition was 23 s at 75 kW/m^2, 98 s at 35 kW/m^2 and 507 s at 20 kW/m^2.

The aged cables provided by the industry had been used in real applications. The cable specified as "old 14-conductor" was a 14x1 data-cable from 1979. The cable specified as "old 32-conductor" was a 32x0.5 cable from 1986. The "old cable" was a 4x1.5 low voltage cable from 1986.

The cables were placed in the cone as indicated in figure 3. The cables were connected to the electrical switchboard and mounted on the non-combustible board. The board was mounted in the cone while an insulating plate shielded the cable from the thermal radiation. The power to the cables was switched on and the measurement started, after 2 minutes the insulating plate was removed so that the cables were irradiated. The experiment continued until the fuses were blown. If nothing happened after 30-60 minutes the experiment was broken.

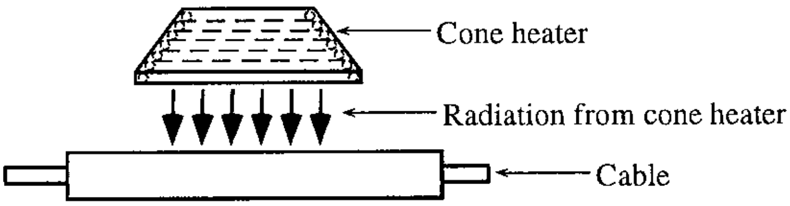

Figure 3. Schematic figure of electrical cable in cone calorimeter.

In figures 4-7 examples of the outcome of the measurements are presented. The time in the figures is the time from start of measurement, the time for start of radiation is 120 s. In most tests no influence on the AC voltage or the current through one of the conductors was seen until the fuse was blown. In some tests it was possible to see the current peak just before the fuse was blown as in figure 6. In many cases the current peak was missed since measurements were only recorded once per second and the short circuit phenomenon is very fast. In some experiments the cable ignited when short circuit occurred. Photos taken during the experiments are presented in Annex C.

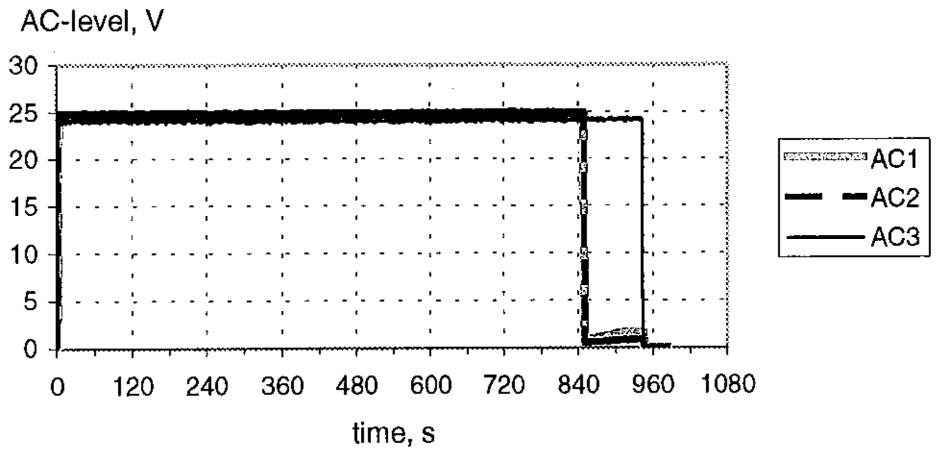

Figure 4. Example of AC-level output for each phase for the F25 cable, test 2 as defined in Annex B.

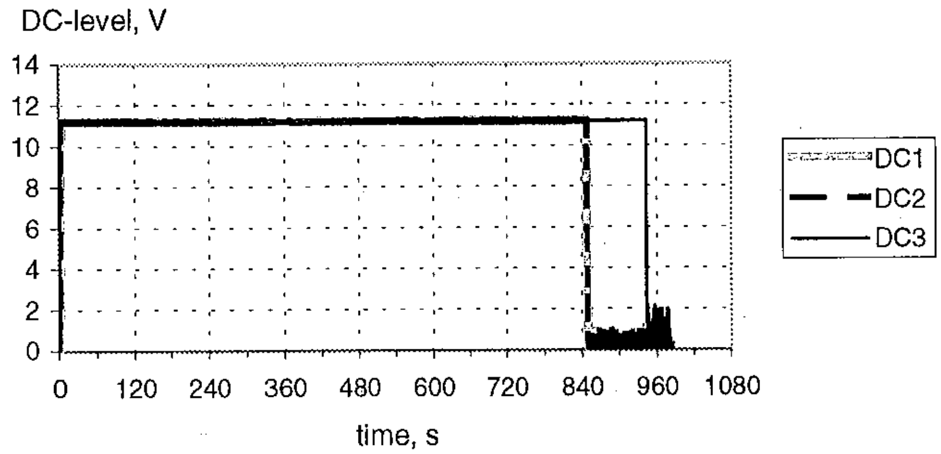

Figure 5. DC-level of each phase for same experiment as in figure 4.

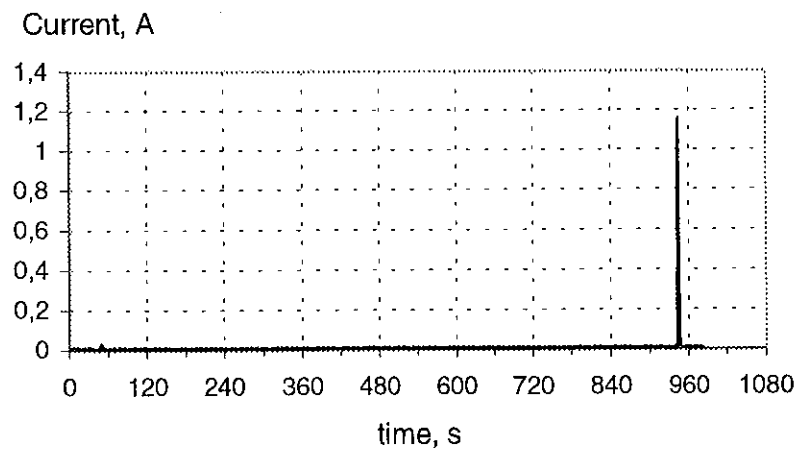

Figure 6. Current through neutral conductor for the same experiment as in figures 4 and 5.

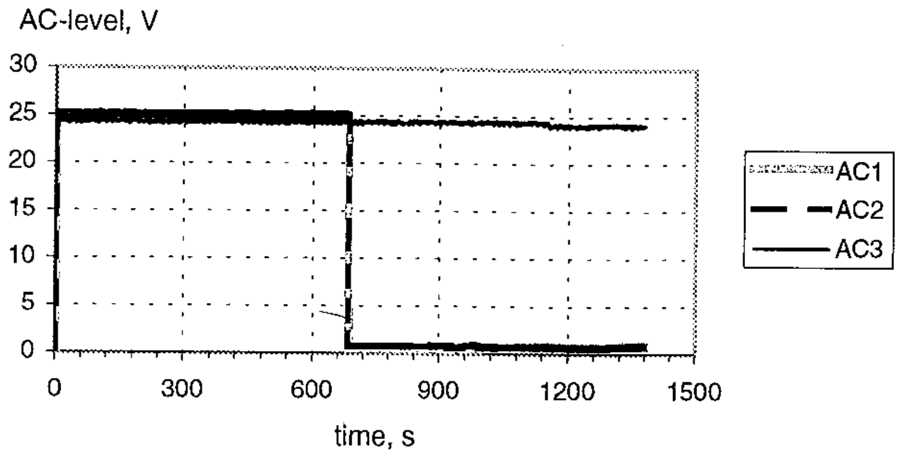

Figure 7. AC-level of each phase for another experiment.

4.3 Gas Temperature

A case study was conducted with the cables subject to a certain gas temperature. The experiments were conducted on a 4 conductor cable, one of the conductors was coupled to phase 1 and another one to neutral. A schematic test set-up is shown in figure 8.

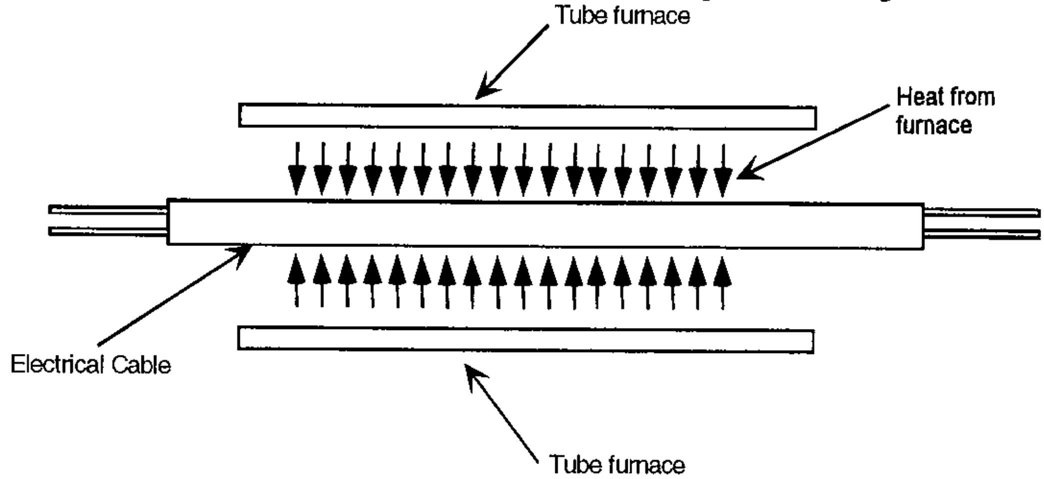

Figure 8. Schematic of experimental set up, cables subject to a constant temperature.

Two similar experiments were conducted at 400 °C. A short circuit occurred after 2.5 minutes and 1 minute and 45 seconds respectively. No further investigation of the performance at other temperatures was made since this was not within the scope of this project.

4.4 Optical Cables

A case study was conducted on optical cables subject to thermal radiation in the cone calorimeter. A schematic of the experimental set up is shown in figure 9. The experiment was conducted using laser light of 850 nm. Three different cables were tested, one 16x62.5/125 indoor/outdoor, one 4x62.5/125 indoor/outdoor and one 2x62.5/125 indoor, all were multimode fibre cables.

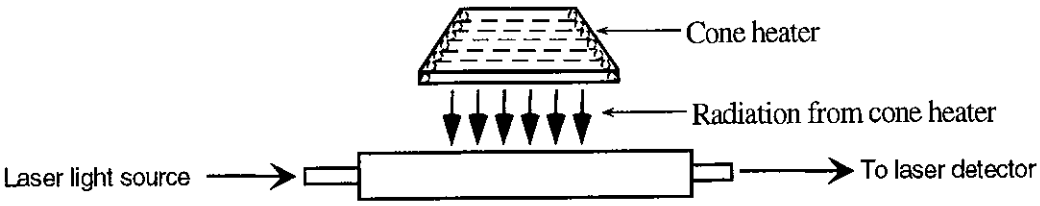

Figure 9. Schematic of test set up for optical cables.

For the 16 fibre cable one of the fibres was chosen for the measurement. A 15 kW/m² thermal radiation was applied after 1 minute pre-measuring time. Approximately 30 minutes later the thermal radiation was increased to ~18 kW/m². Approximately 15 minutes later the thermal radiation was increased to 20 kW/m² and after a further 15 minutes the thermal radiation was increased to 29 kW/m². The cable failed after 73 minutes (see figure 10). As seen in figure 10 nothing happened to the signal until complete interruption of the signal. Small changes in the signal level are most likely due to the cable moving.

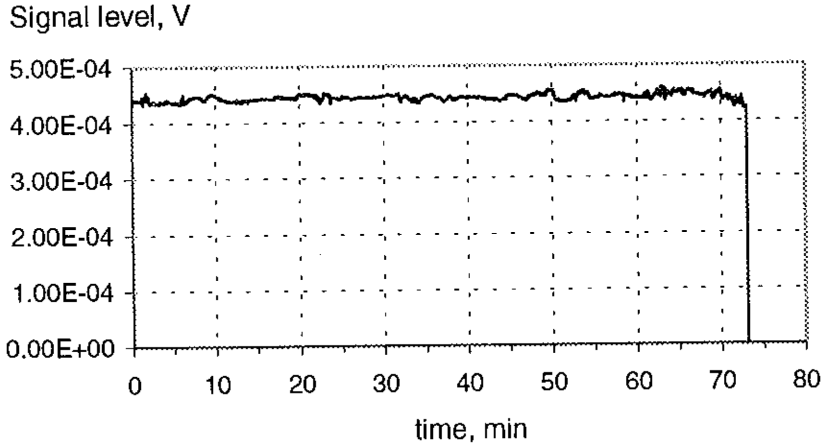

Figure 10. Signal level as a function of time for the 16 fibre cable.

For the 4 fibre cable all fibres were welded so that one long fibre, 4 times the cable length, was formed. The same thermal radiation levels were chosen as in the 16 fibre case. The cable failed after almost 73 minutes as seen in figure 11.

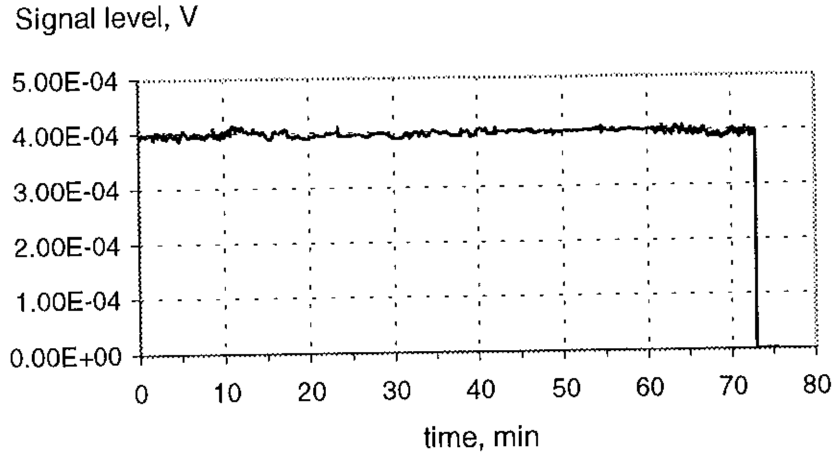

Figure 11. Signal level as a function of time for the 4 fibre cable.

For the 2 fibre cable the two fibres were welded together at one end so that the light passed through one fibre and returned through the other. The experimental procedure was similar to the 16 and 4 fibre case but since no failure had occurred after 1.5 h the thermal radiation was increased further to about 32 kW/m². Still no failure occurred and the experiment was interrupted after 2 hours. The cable still functioned after the experiment, despite the fact that all the insulating material had been burned away, it was even possible to remove the cable from the cone calorimeter without failure. A photo of the cable after the end of the thermal radiation test is shown in figure 12.

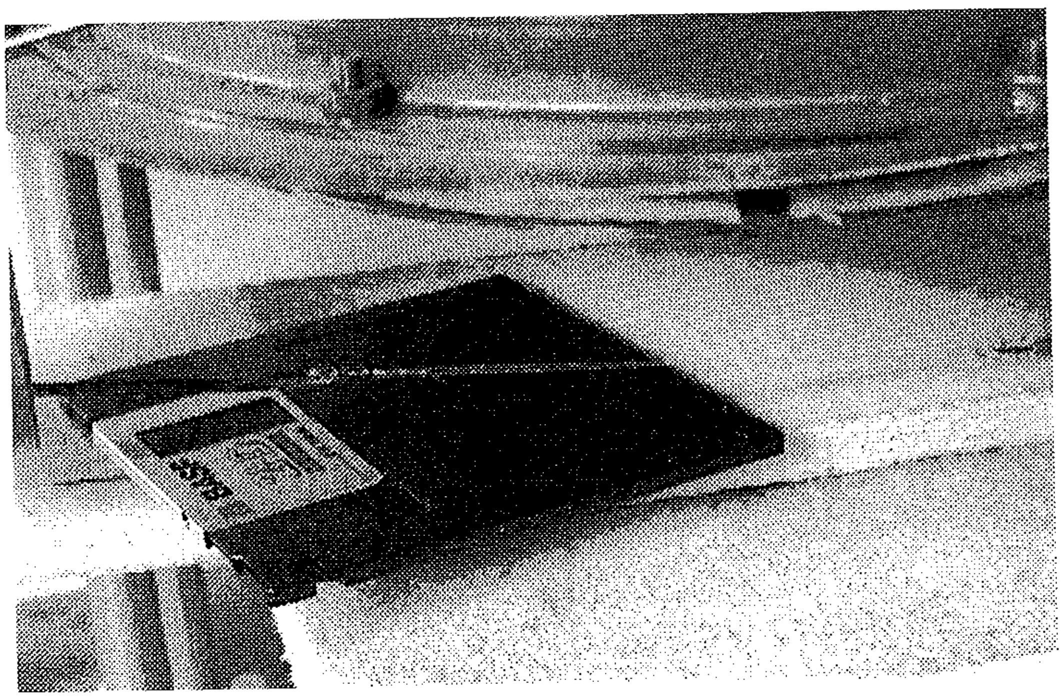

Figure 12. Photo of the 2 fibre cable after experiment.

5 Discussion and Interpretation of Test Results

5.1 Discussion

The results for the different cables are presented in figures 13-16 as thermal radiation applied as a function of time to short circuit. In Figure 17 a comparison between the two data cables is made.

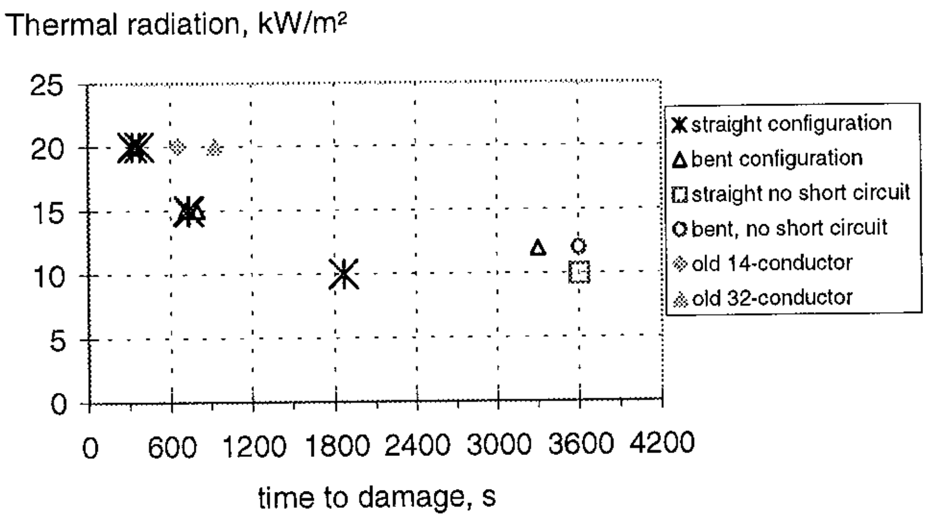

Figure 13. The results for the F25 cable together with the old 14 and 32 conductor cables.

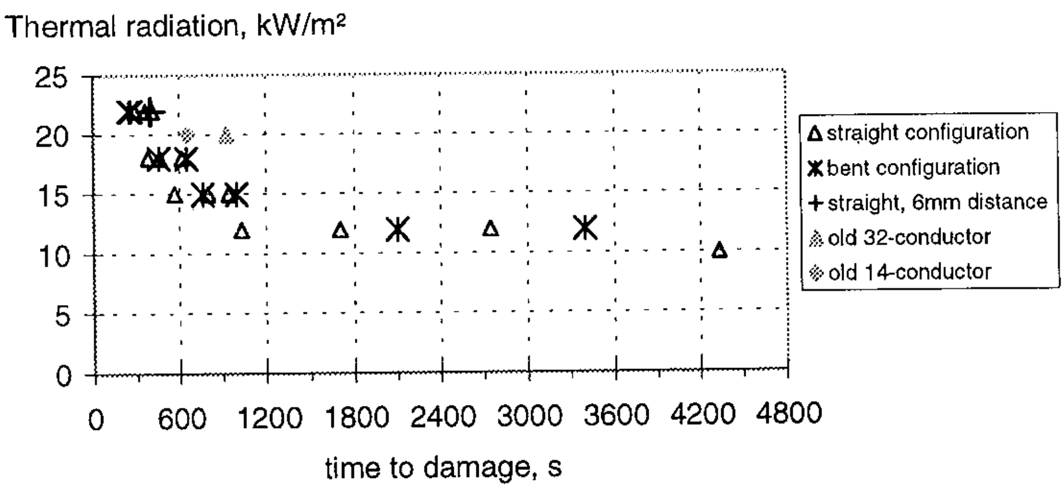

Figure 14. The results for the F24 cable together with the old 14 and 32 conductor cables.

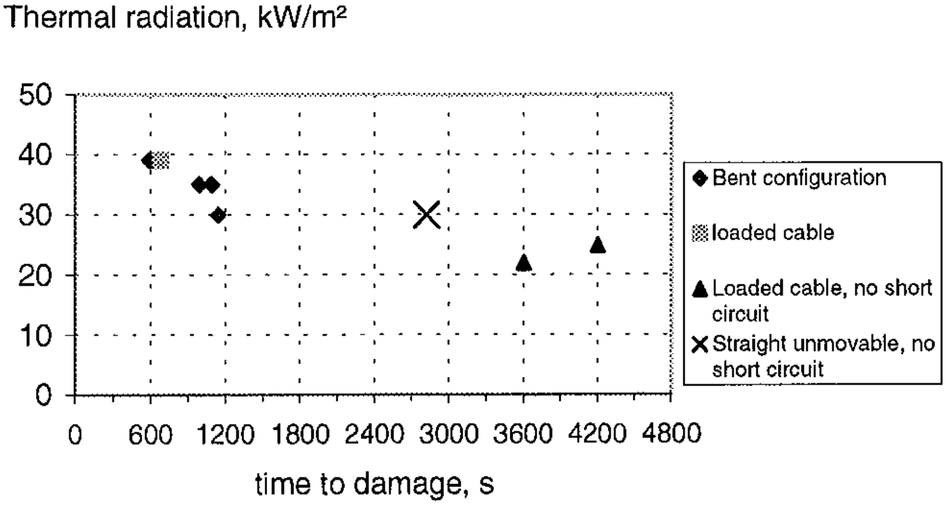

Figure 15. The results for the F22 cable.

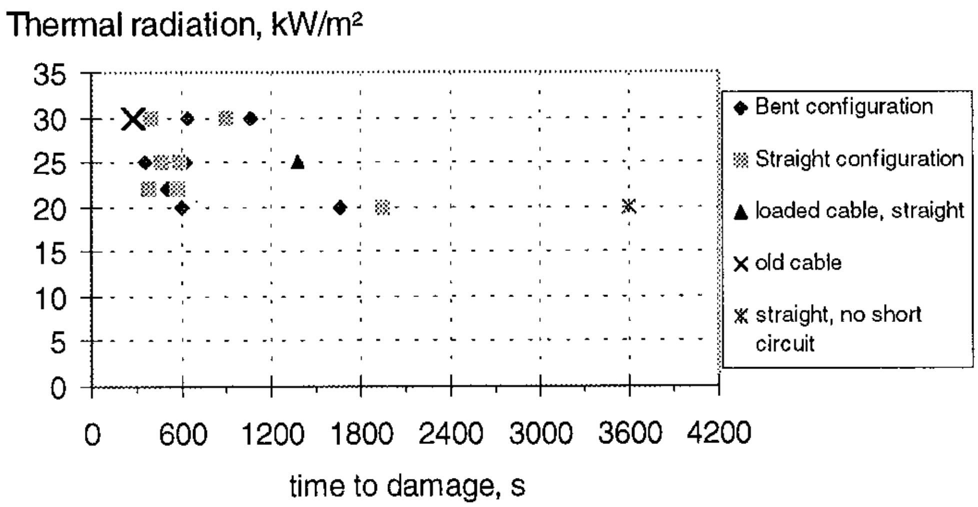

Figure 16. The results for the Ekk cable together with the old FKLK.

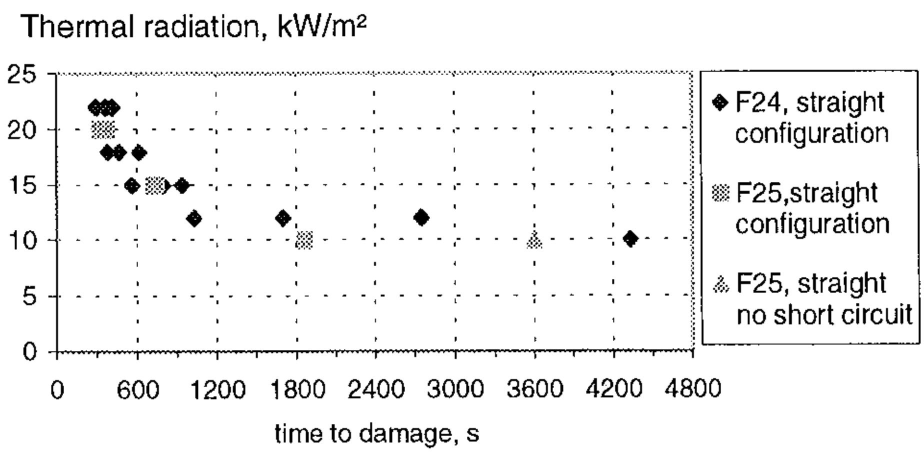

Figure 17. Comparison between F24 and F25 cable.

As previously mentioned in most cases no influence on the AC voltage or current was observed until the fuse was blown. However, in three of the Ekk tests a small current increase occurred under a prolonged time before the fuse was blown. These tests are presented in figures 18-20. These currents are small, of the order of 10 mA and are not very severe for low a voltage supply. No such phenomena were observed for the data cables where small currents could result in unwanted phenomenon. In some cases for the data cables a small current increase occurred in one of the phases after short circuit in another phase.

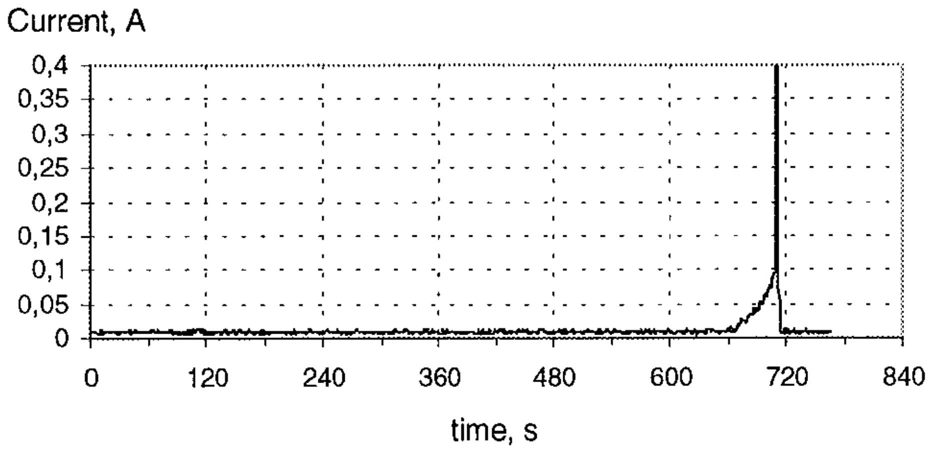

Figure 18. The current as a function of time for an Ekk test with a 1 minute current increase before the fuse was blown, straight configuration, 25 kW/m², test 46 in Annex B. Short circuit occurred at the current peak.

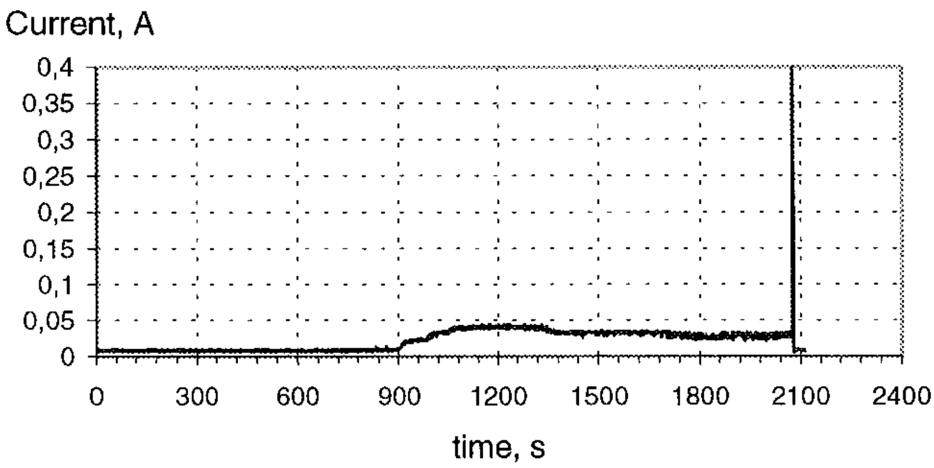

Figure 19. The current as a function of time for another of the Ekk tests with a current increase before the fuse was blown, straight configuration, 20 kW/m², test 48 in Annex B. The increase was about 30 mA for almost 20 minutes. Short circuit occurred at the current peak.

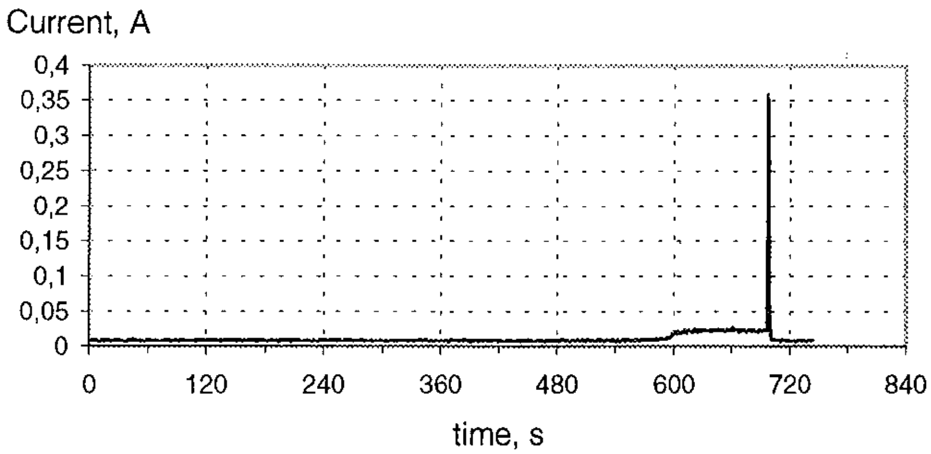

Figure 20. The current as a function of time for another of the Ekk tests with a current increase before the fuse was blown, straight configuration, 22 kW/m², test 56 in Annex B. The current increase was about 10 mA for about 90 s. Short circuit occurred at the current peak.

In most cases the failure occurred at a level where the cable was already significantly damaged. Hence it is insufficient to use only the short circuit criterion as the one to determine whether cables need to be replaced after a fire. Additional testing and criteria might be required. The only conclusion which can be drawn is the following. A cable subjected during a fire to levels close to the ones resulting in short circuit should be changed as the risk for fatal damage of the insulation is large, despite the fact that the cable might still work.

5.2 Interpretation of Test Results - Use of Critical Dose Concept

Frank and Moeini[4] have suggested a model for damage to cables subject to thermal radiation. This model implies that a critical radiation level $\dot{q}''_{cr}$ exists that the cable can withstand for an unlimited time. Above this level the time to damage t_d can be calculated from a critical dose, E_{cr}, using:

$$E_{cr} = t_d \cdot (\dot{q}'' - \dot{q}''_{cr}). \qquad (1)$$

Their work has however been subject to much criticism since the results were extrapolated from rather high radiation levels.

From figures 13, 14 and 17 it is seen that a critical level below which no short circuit occurs for the data cables would be about 9 kW/m². However it is difficult to make a good estimate of this level from these experiments, more experiments using thermal radiation levels about 9 kW/m² are needed. The value of 9 kW/m² is in rather good agreement with 8 kW/m² as is reported for IEEE unqualified cables in the literature[6]. The thermal radiation is 9 kW/m², 7 meters from a 1 m² heptane pool fire.

For the F25 cable the mean time to damage was 810 s at 15 kW/m², this results in a critical dose of 4860 kJ/m² using equation (1) and assuming that the critical thermal radiation level was 9 kW/m². At 22 kW/m² the mean time to damage was 316, this results in a critical dose of 4108 kJ/m². However, by using 810 s at 15 kW/m² and 316 s at 22 kW/m² to calculate a critical radiation level from equation 1 one obtains 10.5 kW/m². For the F24 cable the mean time to damage was 744s at 15 kW/m², this gives a critical dose of 4464 kJ/m² assuming that the critical thermal radiation is 9 kW/m² and at 20 kW/m² the time was 344 which results in a critical dose of 3780 kJ/m². By using 744 s at 15 kW/m² and 344 s at 20 kW/m² to calculate a critical radiation level from equation 1 one obtains 10.7 kW/m².

Another approach is to assume that the radiation is not included linearly in the critical dose but to a certain power. This is often the case for toxicity doses and burns of humans. In this case the critical dose is calculated by

$$E_{cr} = t_d \cdot (\dot{q}'' - \dot{q}''_{cr})^n \qquad (2)$$

When applied to the results above assuming that the critical thermal radiation level is 9 kW/m², n = 1.3 for the F24 cable and n = 1.2 for the F25 cable. However, for F25 this means that the critical dose is 7175 but using 1.2 at the 18 kW/m² level results in 7444 so adding the exponent n to the formula improves the model somewhat. On the other hand, the most important parameter is probably $\dot{q}''_{cr}$ since whether the cable short circuits after 500 or 520 s is not that crucial for the overall safety analysis.

For F22 and the Ekk cable it is not possible to extrapolate any model from the results which raise some questions on how generally applicable the model is. However, it seems that no damage occurs at thermal radiation levels below 18 kW/m² for the Ekk cable or below 25 kW/m² for the F22 cable.

6 Conclusions

Despite the limited number of tests some conclusions can be drawn.

- In all tests the cables were severely damaged on the outside before any short circuit occurred. For Ekk and especially F22 all sheathing and insulation material melted away but the cables still functioned. The cables could continue to function for a long time if they were not touched so that the conductors almost came in contact with each other.

- No change in current or voltage is observed until just before the fuse is blown for the data cables. In three of the Ekk test a small current increase was observed during a prolonged time before the fuse was blown.

- For all cables the time to damage varied considerably between similar tests for the lower thermal radiation levels.

- The cable was often ignited when it short circuited.

- No significant difference between time to damage for the bent and straight configuration was observed for the data cables and the Ekk cable. However for F22 it was crucial whether the cable was bent or not. The bend of the cable in the bent configuration was according to installation recommendations. It was not possible to detect any difference depending on whether the cable was in contact with the non-flammable board or not as seen in figure 14. However, it was important whether the cable moved during the test.

- The F25 cable had flame retarded sheathing material while the F24 cable did not. This did not influence the time to damage severely. No correlation with the time to ignition was observed in this case.

- For the data cables there seems to be a critical level of about 9 kW/m^2 below which no short circuit occurs. To make a good estimate of this level several experiments at this level would be needed. For the Ekk cable and F22 it is even more difficult to estimate this level due to insufficient data. For the Ekk cable, however, this level is about 18 kW/m^2 and for the F22 cable about 25 kW/m^2.

- The aged cables tested were not exactly the same cables as the new ones. Therefore it is not possible to draw any conclusion concerning whether aged cables are more sensitive or not.

- The time to loss of signal for the optical data cables was surprisingly long.

- It seems that the approach used in this project in finding critical thermal radiation levels is useful but more experiments are needed in order to make more precise statements.

The project clearly demonstrated that functional performance of cables under thermal radiation and temperature exposure can be measured. This research area is important for use in, for example, risk analyses which is one of the important possible applications of this project.

7 Suggestions for Future Work

In most Fire Hazard Analyses one of the results is gas temperatures based on fire scenarios. In order to evaluate whether the cables in the room still works in that environment, a damage criteria depending on the temperature is needed. Therefore it would be useful to do a more thorough analysis where the cables are subject to an elevated temperature.

In addition it would be useful to investigate time to damage under more arduous conditions e.g. dropping something on the cable or have the cables hanging in themselves. It is important to find a standardised way to create realistic mechanic impact on the cables. More work needs to be done on the modelling of the critical dose and how to calculate time to damage when the surrounding temperature or thermal radiation is varying.

Cables are often classified according to heat release rate and time to ignition. It would be interesting to investigate whether the same classification could be useful for deciding cables performance in a fire environment or whether other cable performance data is necessary.

Optical cables are becoming more and more popular but in some industries they are not allowed due to safety reasons. This investigation implies that the optical cables are as safe but more work needs to be done in this area.

Another aspect where large amounts of money can be saved in the industry is to determine whether all cables have to be replaced after a fire. In order to determine this more work is necessary. The criteria used now i.e. short circuit is not sufficiently enough. There is no immediate solution to foresee how long a cable will continue to function if it only is damaged little. One approach could be to use data from ageing tests used for the insulation properties.

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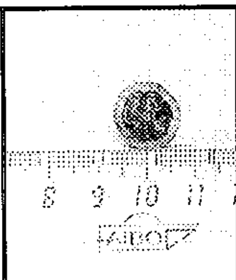
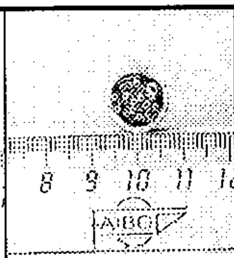
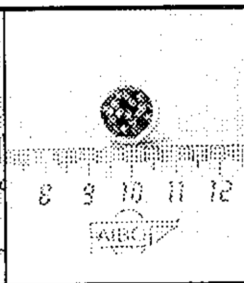
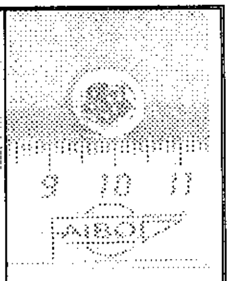
Annex A

Description of F Cables and Major Test Results in Fire Tests

A.1 Description F22, F24 and F25 cable[9]

Table A1.1 Description of cables used in the project

				
Cable number	22	24	25	Ekk
Cable type	Low Voltage 0.6/1 kV	Data Cable	Data Cable	Low Voltage 0.6/1 kV
Conductor size	7×2.5 mm^2	12×2×0.5 mm^2	8×2×0.5 mm^2	5x1.5mm^2
Screen	None	None	None	None
Armour	None	None	None	None
Conductor	Copper	Copper	Copper	Copper
Insulation	XLPE	PVC	PVC	PVC
Filler Mass	None	None	None	None
Sheath	ZHPolyolefin	PVC	RPPVC	PVC
Combustible Vol.	0.101 l /m	0.071 l/m	0.076 l/m	

A.2 Results according to IEC 60332.3 with heat and smoke release rate measurement (FIPEC procedures)[9]

Table A1.2 Full-scale database test results for FIPEC Scenario 1 and 2

Cable	Scen	Time to ignition (s)	Peak HRR (kW)	THR (MJ)	Peak SPR (m^2/s)	TSP (m^2)	FIGRA (kW/s)	SMOGRA (cm^2/s^2)	Damaged length (m)	Vol. of comb. material (l/m ladder)
22	1	58	566	129.0	1.65	267	0.555	13.3	4	1.2
24	1	36	250	32.8	2.82	439	1.298	120.4	4	0.7
25	1	54	28	7.6	1.23	269	0.086	61.1	1	1.0
25	2	63	59	19.1	2.72	536	0.229	95.9	1.72	1.0

A.3 Results of cone calorimeter tests[9]

Table A1.3 Summary of Cone Calorimeter results for cables at 35 kW/m²

Cable	t_{ig} (s)	Peak HRR (kW/m²)	THR (MJm²)	FIGRA1 (kW/m²s)	FIGRA2 (kW/m²s)	Peak SPR (m²/s)	TSP (m²)	SMOGRA1 (cm²/s²)	SMOGRA2 (cm²/s²)
22	103	164	202.2	0.09	0.76	0.019	11.35	0.10	0.11
24	21	171	80.2	0.46	2.86	0.094	27.30	20.24	21.82
25	32	169	105.0	0.36	1.44	0.061	30.26	7.80	8.17

Table A1.4 Summary of Cone Calorimeter results for cables at 50 kW/m²

Cable	t_{ig} (s)	Peak HRR (kW/m²)	THR (MJm²)	FIGRA1 (kW/m²s)	FIGRA2 (kW/m²s)	Peak SPR (m²/s)	TSP (m²)	SMOGRA1 (cm²/s²)	SMOGRA2 (cm²/s²)
22	48	217	202.1	0.17	1.90	0.036	19.50	0.29	1.29
24	10	198	79.4	0.62	4.66	0.125	31.83	35.96	45.11
25	11	187	111.6	0.47	3.22	0.095	41.36	21.91	25.42

Table A1.5 Summary of Cone Calorimeter results for cables at 75 kW/m²

Cable	t_{ig} (s)	Peak HRR (kW/m²)	THR (MJm²)	FIGRA1 (kW/m²s)	FIGRA2 (kW/m²s)	Peak SPR (m²/s)	TSP (m²)	SMOGRA1 (cm²/s²)	SMOGRA2 (cm²/s²)
22	23	440	243.0	0.44	5.90	0.068	25.23	0.66	4.04
24	5	254	76.4	1.20	6.73	0.184	38.04	59.10	101.53
25	4	219	98.4	0.68	4.58	0.135	45.23	4.37	74.07

Annex B

Overview of Test Results

Table 1. Tests conducted in project.

Test nr	cable	mounting	Load	Heat flux, kW/m²	coupling[a]	Time to failure, s			comments
						Phase 1	Phase 2	Phase 3	
1	F25	Straight in contact with board	No	15	C1 to phase1, the rest to neutral	740			
2	F25	Straight in contact with board	No	15	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral, current measured through neutral	780	780	726	
3	F25	Straight in contact with board	No	10	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral,		1743	1743	
4	F22	Straight in contact with board	Yes	15-25	C1-c2 to p1, c3-c4 to p2, c5-c6 to p3, current measured at p1	5200	5200		Ignited at short circuit
5	F24	Straight in contact with board	No	15	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	1068	795	10668	
6	F24	Straight in contact with board	No	15	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	562	562		
7	F24	Straight in contact with board	No	10-15	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	4330	4330		
8	F24	Straight in contact with board	No	22	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	364	364	427	Ignited at short circuit p3, burns about 1 minute
9	F24	Straight in contact with board	No	15	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	1143	939	939	
10	F24	Straight in contact with board	No	22	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	444	413	413	Ignited at short circuit p2 and p3 burns until 494 s.
11	F24	Straight in contact with board	No	12	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1		1700	1700	Interrupted after 1830 s
12	F24	Straight in contact with board	No	22	Cp1-cp3 to p1, cp4-cp6 to p2, cp7-cp9 to p3, cp10-cp12 to neutral	344	293	293	Ignited at short circuit p1
13	F24	Straight in contact with board	No	12	Cp1-cp3 to p1, cp4-cp6 to p2, cp7-cp9 to p3, cp10-cp12 to neutral	1028	1028		
14	F24	Straight in contact with board	No	12	Cp1-cp3 to p1, cp4-cp6 to p2, cp7-cp9 to p3, cp10-cp12 to neutral	2745		3035	
15	F24	Straight in contact with board	No	18	Cp1-cp3 to p1, cp4-cp6 to p2, cp7-cp9 to p3, cp10-cp12 to neutral	583	463	463	
16	F24	Straight in contact with board	No	18	Cp1-cp3 to p1, cp4-cp6 to p2, cp7-cp9 to p3, cp10-cp12 to neutral	658	658	616	

Test nr	cable	mounting	Load	Heat flux, kW/m²	coupling[a]	Time to failure, s			comments
						Phase 1	Phase 2	Phase 3	
17	F24	Straight in contact with board	No	18	Cp1-cp3 to p1, cp4-cp6 to p2, cp7-cp9 to p3, cp10-cp12 to neutral	639	382	382	
18	F22	Straight in contact with board	Yes, 1 kW/p	22	C1-c2 to p1, c3-c4 to p2, c5-c6 to p3, c7 to neutral, current measurement at p1				Experiment interrupted after 1 hour, no short circuit
19	F22	Straight in contact with board	Yes, 2 kW/p	>25	C1-c2 to p1, c3-c4 to p2, c5-c6 to p3, c7 to neutral, current measurement at p1				Experiment interrupted after 70 min, no short circuit
20	F22	Bent, 6 mm distance to board	Yes, 2 kW/p	39	C1-c2 to p1, c3-c4 to p2, c5-c6 to p3, c7 to neutral, current measurement at p1	679	679		Ignition at short circuit, burns rather good
21	F22	Bent, 6 mm distance to board	No	39	C1-c2 to p1, c3-c4 to p2, c5-c6 to p3, c7 to neutral, current measurement at p1	590	622	590	Ignition after 523 s
22	F22	Bent, 6 mm distance to board	No	35	C1-c2 to p1, c3-c4 to p2, c5-c6 to p3, c7 to neutral, current measurement at p1	992	992	992	Ignition after 909s
23	F22	Bent, 6 mm distance to board	No	35	C1-c2 to p1, c3-c4 to p2, c5-c6 to p3, c7 to neutral, current measurement at p1	1090	1090	1090	Ignition after 1105 s
24	F22	Bent, 6 mm distance to board	No	30	C1-c2 to p1, c3-c4 to p2, c5-c6 to p3, c7 to neutral, current measurement at p1	1142		1142	Ignition at short circuit
25	F22	Straight in contact with board	No	30	C1-c2 to p1, c3-c4 to p2, c5-c6 to p3, c7 to neutral, current measurement at p1				Experiment interrupted after 47 min. Cable mounted so that it could not move.
26	F25	Straight in contact with board	No	10	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral				Experiment interrupted after 1 hour, no short circuit
27	F24	Straight, 6 mm distance to board	No	22	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	395	395	459	
28	F24	Straight, 6 mm distance to board	No	22	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	405	405	510	
29	F25	Straight in contact with board	No	20	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral	373	602	460	
30	F25	Straight in contact with board	No	20	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral	500	414	321	
31	F25	Bent, 6 mm distance to board	No	12	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral				Interrupted after 1 hour, no short circuit
32	F25	Bent, 6 mm distance to board	No	12	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral	3300			Fuse before the switchboard was blown
33	F25	Bent, 6 mm distance to board	No	15	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral	1072	1099	710	Flashes at short circuit of p3

Test nr	cable	mounting	Load	Heat flux, kW/m²	coupling[a]	Time to failure, s			comments
						Phase 1	Phase 2	Phase 3	
34	F25	Bent, 6 mm distance to board	No	15	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral	800	800	1200	
35	F25	Bent, 6 mm distance to board	No	20	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral	346	473	346	Ignited at short circuit of p2
36	F25	Bent, 6 mm distance to board	No	20	C1-c4 to p1, c5-c8 to p2, c9-c12 to p3, c13-c16 to neutral	495	335	335	
37	F24	Bent, 6 mm distance to board	No	22	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	400	250	250	
38	F24	Bent, 6 mm distance to board	No	22	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	450	269	262	
39	F24	Bent, 6 mm distance to board	No	18	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	754	649	649	
40	F24	Bent, 6 mm distance to board	No	18	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	453	453	509	Ignited at short circuit of. p3
41	F24	Bent, 6 mm distance to board	No	15	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	765	765	765	Ignites at short circuit
42	F24	Bent, 6 mm distance to board	No	15	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	995	995		Interrupted after 900s
43	F24	Bent, 6 mm distance to board	No	12	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1	3397		3397	Current measurement not correct
44	F24	Bent, 6 mm distance to board	No	12	C1-c3 to p1, c4-c6 to p2, c7-c9 to p3, c10-c12 to neutral, current measured at p1		2099	2099	Ended after 2400
45	Ekk	Straight in contact with board	No	25	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral	470	1518	1518	
46	Ekk	Straight in contact with board	No	25	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	590	590	590	Ignites at short circuit
47	Ekk	Straight in contact with board	No	20	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1				Interrupted after 1 hour, no short circuit
48	Ekk	Straight in contact with board	No	20	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	1955	1955	1955	

Test nr	cable	mounting	Load	Heat flux, kW/m²	coupling[a]	Time to failure, s			comments
						Phase 1	Phase 2	Phase 3	
49	Ekk	Bent, 6 mm distance to board	No	20	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	1658	1658		Interrupted after 1980
50	Ekk	Bent, 6 mm distance to board	No	20	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	864	596	665	
51	Ekk	Bent, 6 mm distance to board	No	25	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	359		865	Interrupted after 1380
52	Ekk	Bent, 6 mm distance to board	No	25	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	623	892	892	
53	Ekk	Bent, 6 mm distance to board	No	22	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	506	706	706	
54	Ekk	Bent, 6 mm distance to board	No	22	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	765	512	550	
55	Ekk	Straight in contact with board	No	22	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	378	786	817	Ignited at short circuit p2
56	Ekk	Straight in contact with board	No	22	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral, current measured at p1	577	577	577	Ignites at short circuit, rather loud sound
57	Ekk	Straight in contact with board	No	30	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral	897	897	897	Ignited at short circuit
58	Ekk	Straight in contact with board	No	30	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral	391	1010	1010	
59	Ekk	Bent, 6 mm distance to board	No	30	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral	1063	1063	1063	Cable expands so it gets in contact with the board. Ignites at short circuit
60	Ekk	Bent, 6 mm distance to board	No	30	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral	642		642	Ignites at short circuit
61	Ekk	Straight in contact with board	Yes, 2 kW/p	25	Black to p1, Black/white to p2, Brown to p3, Blue and green/yellow to neutral	1375	1375	1375	Ignites at short circuit

Test nr	cable	mounting	Load	Heat flux, kW/m²	coupling[a]	Time to failure, s			comments
						Phase 1	Phase 2	Phase 3	
62	FKAR-8	Straight in contact with board	No	20	C1-c8 to p1, c9-c16 to p2, c17-c24 to p3, c25-c32 to neutral.	925	1198	925	
63	FKAR-G	Straight in contact with board	No	20	C1-c4 to p1, c5-c8 to p2, c9-c11 to p3, c12-c14 to neutral	978	537	696	
64	FKLK	Straight in contact with board	No	30	Black to p1, Black/White to p2, Brown to p3, Blue to neutral	284	280	280	
65	FKLK	Straight in contact with board	No	30	Black to p1, Black/White to p2, Brown to p3, Blue to neutral	269	269	269	Ignites at short circuit
66	16 fibre	Straight	NA	15-29	Light only through one of the fibres	4320			
67	4 fibre	Straight	NA	15-29	Light through all fibres	4314			
68	2 fibre	Straight	NA	15-32	Light through both fibres				Experiment interrupted after 2 hours, the fibres still functioned
69	Signal	Straight	No	400°C	One conductor to p1, one to neutral	250			
70	Signal	Straight	No	400°C	One conductor to p1, one to neutral	135			

NA Not Applicable

[a] C1 refers to conductor 1, p1 refers to phase 1, cp1 refers to conductor pair 1

Annex C

Photos from Experiments

Below is some photos taken during the experiments presented.

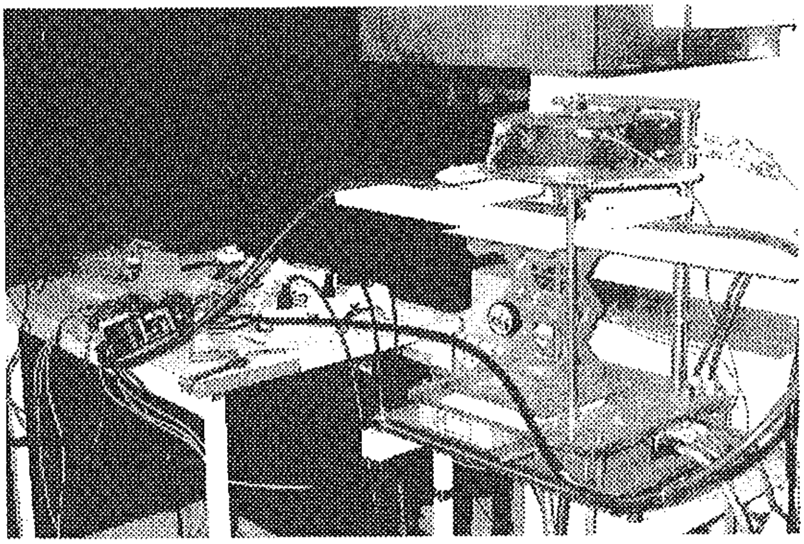


Figure 1. Experimental set-up. In the foreground the cone calorimeter with a F22 cable mounted in the straight configuration. The switchboard together the current clamp is seen in the background.

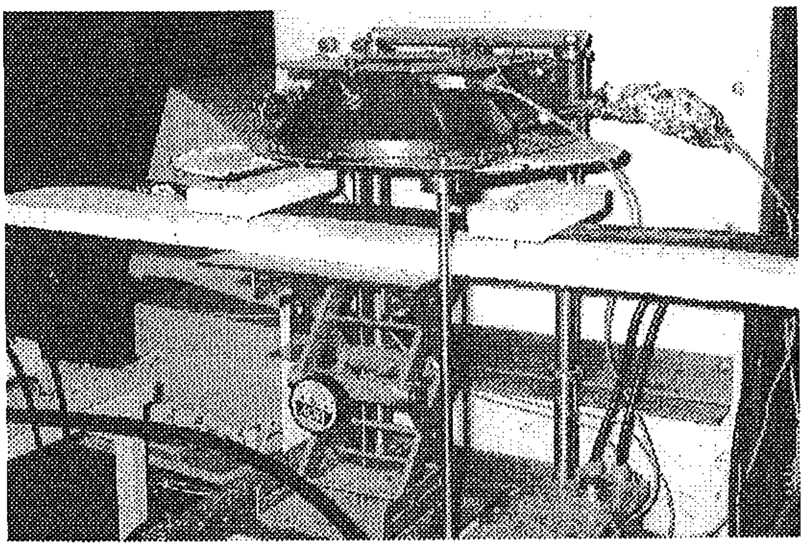


Figure 2. A closer look at the cone calorimeter.

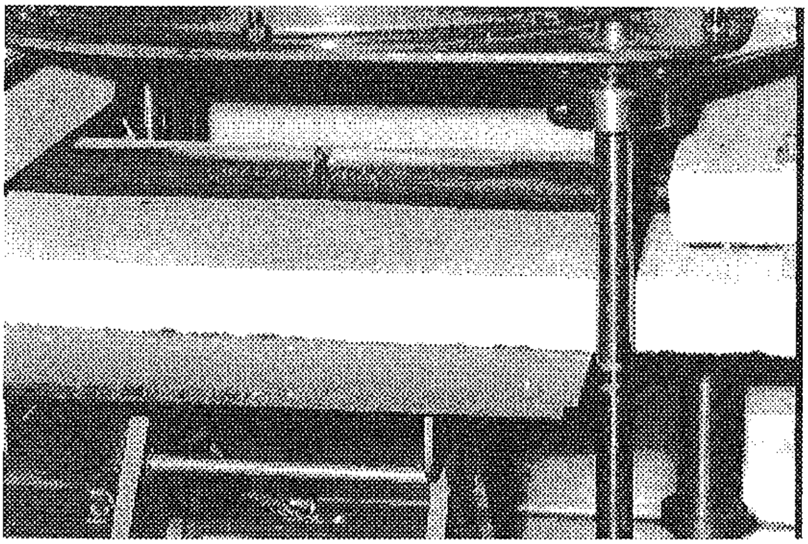


Figure 3. The cable cracks.

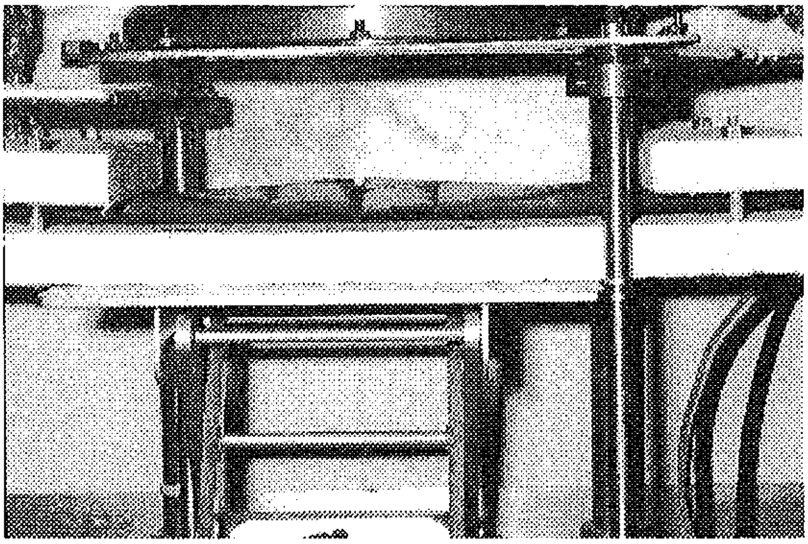


Figure 4. Smoke from the cable

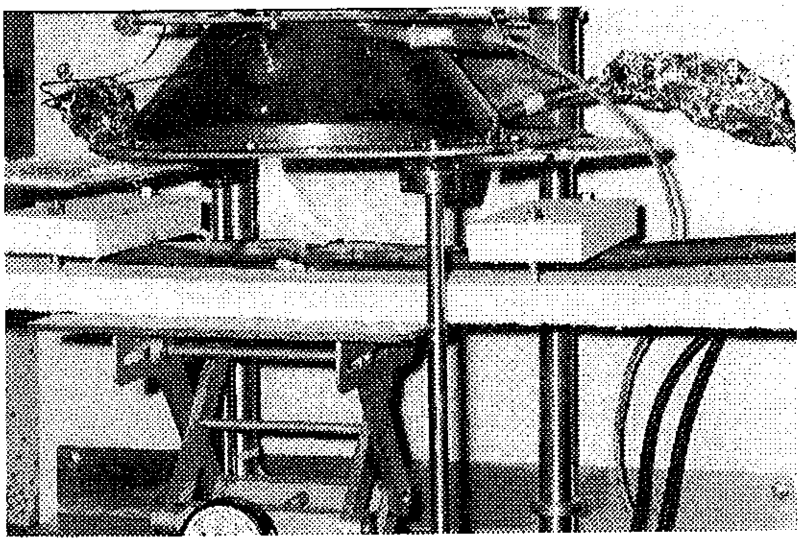


Figure 5. The cable ignites when short circuit occurs.

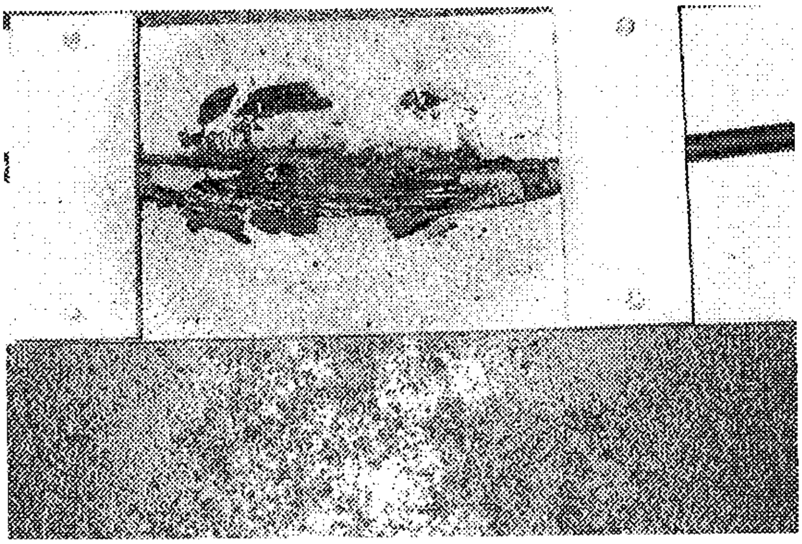


Figure 6. The F22 cable after the experiment.

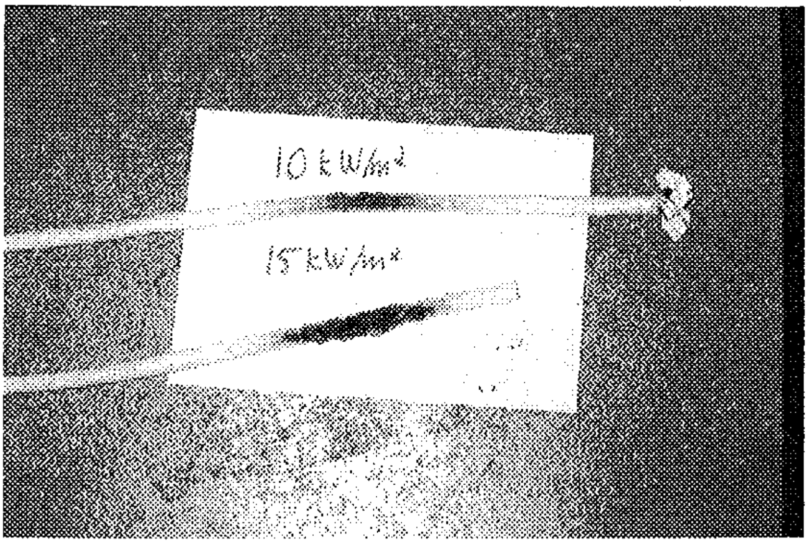


Figure 7. One of the data-cables after two different thermal radiation levels. The cable subject to 10 kW/m² thermal radiation was not as damaged on the outside when short circuit occurred as the one subject to 15 kW/m².

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