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Failure Distribution in Instrumental Cables in Fire

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ABSTRACT

The fire-induced response of a four-conductor automation cable connected to a pressure transmitter has been investigated. Two series of fire experiments with two different cable types exposed to flames from a propane gas burner have been carried out. Times to first disturbance in transmitter voltage supply and transmitter current output was determined as well as times to first disturbance in insulation resistance between pairs of conductors in a non-energised open circuit cable. Probability distributions have been fitted to the observed cumulative frequencies of time to first disturbance. The function of the system was also studied without fire exposure considering the effects of conductor breaks, different short circuit resistances and voltage supply. The dependence of current output on short circuit resistance and voltage supply has been expressed mathematically.

KEYWORDS

Fire, instrumental cable, pressure transmitter, failure distribution, insulation resistance, short circuit, transmitter voltage, current output

INTRODUCTION

Fire-induced changes in automation cable signals may cause critical malfunction in plant control functions as shown in a pioneering paper by Hasegawa et al. [1]. In the present study, a four-conductor automation cable connected to a pressure transmitter was chosen as a simple example of a real process control system. From this work carried out in 1998 a conference report has been published earlier [2]. Since then also other, much wider studies have appeared [3-5]. Here we concentrate to present in depth the behaviour of a pressure transmitter with a four-conductor cable connecting to control room. The cable is suddenly exposed to flame temperatures, and failure modes of the transmitter are recorded.

SPECIMEN AND FAILURE MODES

Two types of polyvinyl chloride jacketed and insulated four-conductor automation cable were used in the fire experiments, commercial notations MHMS-SI and NOMAK-E, with nominal conductor cross-section 0.5 mm^2, jacket thickness 1.0 mm and insulation thickness 0.35 mm. A cross-section of the four-conductor cable is presented in figure 1. The insulated conductors 1 to 4 were twisted in pairs surrounded by a plastic tape in both types of cable. The conductors in both cable types were shielded with a plastic faced aluminium tape immediately under the jacket. An earthing conductor V without insulation was under the plastic faced aluminium tape.

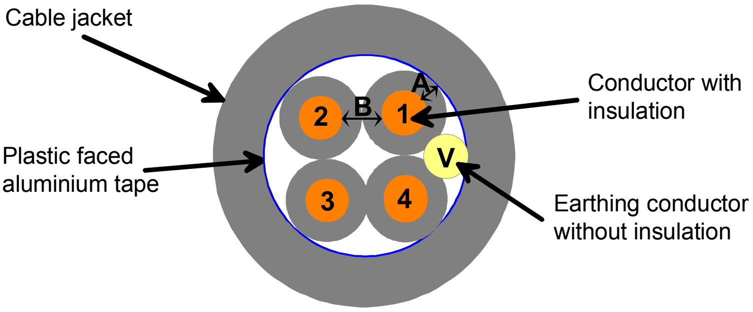
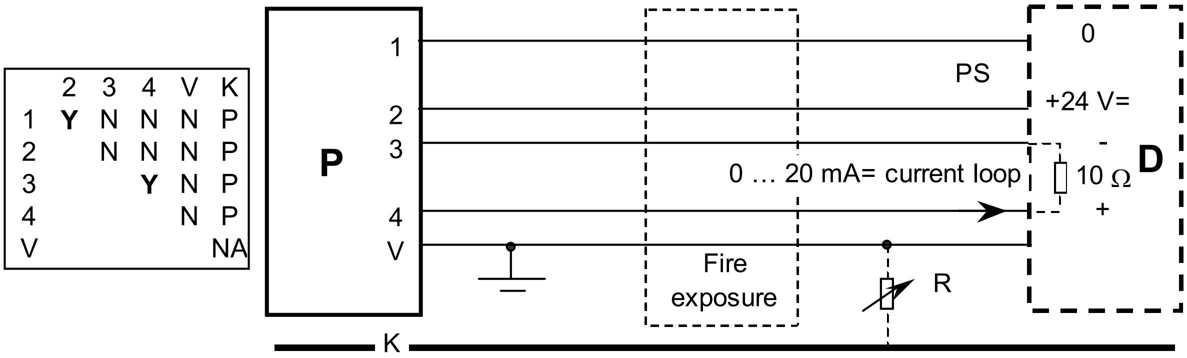


Figure 1. Cross-section of four-conductor automation cable. Possible paths of decreased insulation resistance indicated: A between pair conductor-aluminium shield, B between pair conductor-conductor. The plastic tape surrounding pairs of conductors is not shown.

Failure modes in cable connected to pressure transmitter

Automation cable MHMS-SI from data acquisition system D to a Siemens Teleperm pressure transmitter P (figure 2) was investigated first without fire exposure. The following failure modes were considered [5]:

Open circuit	when any of the leads 1 - 4 are broken to cut galvanic contact over the damaged site
Internal hot short	when any two of the leads 1 - 4 are in galvanic contact
Ground short	when any of the leads 1 - 4 is in galvanic contact with V
External hot short	when any two of the leads 1 - 4 is in galvanic contact with K (if potential V ≠ K)



	2	3	4	V	K
1	**Y**	N	N	N	P
2		N	N	N	P
3			**Y**	N	P
4				N	P
V					NA

Figure 2. Numbering of conductors of automation cable connecting pressure transducer P to data acquisition system D: power supply PS, 1 and 2, current loop, 3 and 4, earth V, indeterminate potential difference with conducting cable tray K. On left a matrix of cold experiments on shorts between different pairs of leads: influence (Y), no influence (N), possible influence (P) on pressure indication current, not studied (NA).

Consequences from breaks in and short circuits between conductors

As cold experiments permanent influences of disturbances in cable were measured, but not transient effects. The consequence from a break (open circuit) in any one of the conductors 1...4 is interruption of transmitter current output. Results of binary contacts (mainly internal hot shorts) between the conductors is shown also as a matrix on the left hand side of figure 2. Only hot shorts between pairs of conductors 1-2 and 3-4 were found to have consequences (Y) for the transmitter current output, while all other conductor-conductor hot short combinations were found to have no influence (N) on transmitter function or 0…20 mA current output. Hot shorts between conductors 1-2 causes interruption of transmitter current output. For hot shorts between conductors 3-4, the transmitter 0…20 mA current output depends very strongly on the short circuit resistance (Figure 3). If a multiple short circuit contains short 1-2, transmitter current output is interrupted. If the multiple short circuit is 1-3-4 or 2-3-4, transmitter current output is interrupted. Ground shorts with the earthing-conductor V do not change the current output. External hot short of any of the leads with conducting cable tray K might have an influence, if there is a marked potential difference between K and V. Combination K-V was not studied (NA).

Pressure transmitter current output with different short circuit resistances

Pressure transmitter current output was measured with pressures p = 0, 3, 6 and 10 bar. Short circuit resistances R between conductors were ∞, 0.3, 1, 10, 100, 1000, 10k, and 100 kΩ. Only two short circuit pair combinations have an effect on current output, 1-2 interrupting the current output and 3-4 with current output depending very strongly on the short circuit resistance. The consequences of short circuits between a pair of conductors do not change if the pair is in contact with the earthing-conductor or the plastic faced aluminium tape.

The results concerning short circuit between conductors 3-4 are presented in figure 3, where the short circuit current output i at different pressures is divided with the corresponding open circuit current i_∞ (infinite resistance). These normalised currents are almost coincident for the different pressure values making simple curve fitting possible. The inverse tangent function with fitting parameter $R_0 = 6\ \Omega$ gave a satisfactory fit to the measured values (figure 3). It appears that changes in the current output do not occur until short circuit resistances drop below some hundred ohms.

Transmitter current output as a function of voltage supply

Transmitter current output was measured as a function of voltage supply u and was found to be steady at these pressures down to supply 12 V, in accordance with the transmitter specification which guarantees performance down to 12 V voltage supply. The current output as a function of voltage supply can thus be described by a step function

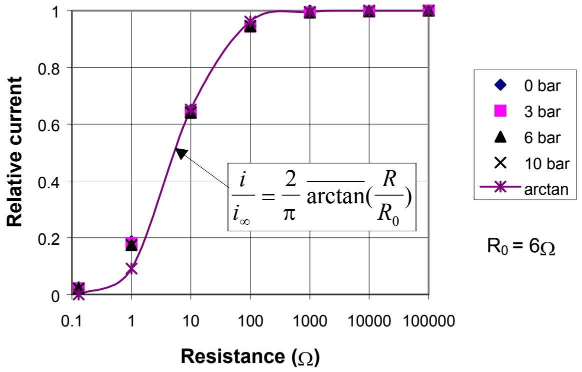


Figure 3. Pressure transmitter relative current output i/i_∞ versus short circuit resistance between conductors 3-4, measured values at different pressures and fitted inverse tangent function.

FIRE EXPERIMENTS

Two series of fire experiments were carried out under similar circumstances, one series of 9 experiments with cable type MHMS-SI and one series of 24 experiments with cable type NOMAK-E. The cables were exposed to direct flame contact from a propane gas burner in order to simulate a local fire-induced electrical fault in the cables.

The experimental configuration is presented in figure 4. Two cables were studied in each experiment, one energised cable C1 connected to the pressure transducer P and one non-energised open circuit cable C2 for monitoring short circuiting through insulation resistance measurements. The transducer was in a flowing potential in the fire experiments.

The cables were attached with steel wire to two adjacent rungs R of a steel ladder cable tray CT (figure 4b). The distance between the rungs was 250 mm and the inner width of the ladder was 370 mm. The experiments were carried out in nearly free space with the 170 mm x 170 mm gas burner B and the part of the cables exposed to fire surrounded on three sides by 15 mm thick mineral wool boards S guiding air flow in order to stabilise flames. The burner was ignited outside the cable set-up, the flame was stabilised to constant 12.4 kW power and the burner was located beneath the cables with flames rising through the centre of the free space between rungs R (figure 4a). The distance between the upper surface of the gas burner and the cables was chosen so short (85 mm) that the cables above the centre of the burner were in the persistent flame, thus ensuring identical fire exposure conditions during the test series.

The transmitter input was pressurised with compressed air from a cylinder to 6 bar gauge constant pressure corresponding to typical value for the investigated pressure transmitter. The supply voltage to and current output signal from the pressure transducer was monitored using data acquisition unit D. Times to hot shorts between pairs of conductors in cable C2 were monitored through direct insulation resistance measurements with a voltage divider circuit. With suitable voltage divider circuit parameters a resistance range of magnitude 100 Ω ... 1 MΩ could be studied.

Gas temperatures about 10 mm above the cables were monitored with 0.5 mm K-type thermocouples. Time for exposure to fire was determined from gas temperature measurements as time for distinct temperature rise.

Data were collected at 0.1 s interval in the experiments; later term simultaneously means within this time step. Each experiment was continued for a couple of minutes after the observation of specific changes in the electrical signals.

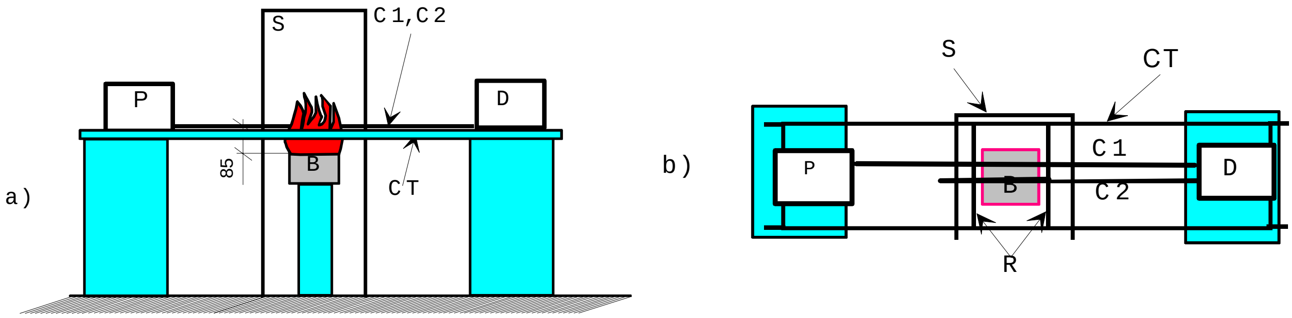


Figure 4. Configuration in instrumental cable fire experiments, a) side view, b) top view. Symbols are explained in the text. Dimensions in mm.

Efforts were made to monitor all possible combinations between pairs of conductors. Difficulties occurred in isolating the combinations, probably due to ground loops through solid state relays of the data acquisition system. Thus only independent combinations could be studied. Pairs 1-2 and 3-4 were chosen in accordance with the conclusions that only hot shorts between these two pairs had consequences for the current output signal. For ground shorts the resistance between conductor 1 and the earthing conductor V was also monitored. It was noticed in preliminary experiments that temporally the resistance curve behaved in a different way than the resistance between 1-2 or 3-4, showing exponential damping.

RESULTS AND DISCUSSION

Voltage supply to cable C1

The usual behaviour of the voltage supply curve U_{supply} in both MHMS-SI and NOMAK-E series was constant voltage until sudden drop to zero voltage (figure 5). Time to first disturbance in U_{supply} corresponds thus to first zero voltage measurement. In one experiment no disturbance was detected during the 126.9 s long experiment.

The voltage supply cut off is probably due to functioning of the over-current protection of the voltage supply unit as a consequence of short circuiting in conductor pair 1-2. The consequence on I_{out} as presented above is that the transmitter current output is interrupted.

Current output signal from cable C1

Varying behaviour was noticed in first disturbance in current signal output I_{out} (figure 5) as presented below. The discussion is partly speculative, because we had not available the circuit diagrams of the commercial pressure transmitter. It has active compensation and stabilisation circuits, which cause transients (< 1 s) after hot shorts.

a) I_{out} dropped to zero or 2...3 mA below zero level, without changes in U_{supply} (3 cases in MHMS-SI series and 15 cases in NOMAK-E series, example in figure 5a). This can be interpreted as hot short between conductors 3-4.

b) I_{out} increased to maximum measurement range about 500 mA (3 cases in MHMS-SI series and 3 cases in NOMAK-E series, example in figure 5b) simultaneously with an 0.5...1.3 V drop in U_{supply}. In 4 cases the high I_{out} level dropped to zero simultaneously with supply voltage cut off, in one case I_{out} dropped to zero 0.1 s before voltage cut off and in one case the ordinary I_{out} level was recovered for 0.8 s before voltage cut off and I_{out} drop to zero. The outcome is interpreted as hot short between power supply conductor pair 1-2 causing interruption of transmitter current output, but the preceding current transient is not evidently interpreted.

c) simultaneously with U_{supply} drop to zero, I_{out} increased to 9...10 mA (4 cases in NOMAK-E series), example in figure 5c. The voltage supply cut off is due to a hot short between 1 and 2, followed by a current transient after which the current signal also goes to zero.

d) I_{out} dropped to zero or 2...3 mA below zero level, simultaneously with or immediately after U_{supply} drop to zero (3 cases in MHMS-SI series and 2 cases in NOMAK-E series, example in figure 5d). This is interpreted as a consequence of voltage supply cut off due to hot shorts between 1 and 2.

Additionally a drop of about 1 mA was noticed in I_{out} level before first disturbance in 3 NOMAK-E experiments, an example is marked with an arrow in figure 5d. These small drops in current output level were not noticed as first disturbances because the drop could not be unambiguously interpreted. They might be indications of small insulation resistance between conductors 3 and 4 in current loop. Using the curve of figure 3, it is observed that changes of this magnitude are induced if insulation resistance drops at 10 Ω level.

In some experiments a recovering of current output signal to normal level was noticed under condition of ordinary voltage supply. This is probably due to temporary opening of hot shorts.

Time to first failure

A comparison between times to first disturbance in current output signal I_{out} and voltage supply U_{supply} gives:

- in MHMS-SI series a disturbance occurred in I_{out} before disturbance in U_{supply} in 3 experiments out of 9, and in 6 experiments same disturbance time was recorded.
- in NOMAK-E series a disturbance occurred in I_{out} before U_{supply} in 14 experiments out of 24, in 9 experiments same disturbance time was recorded, and in one experiment U_{supply} went to zero 0.1 s before I_{out}.

Current output signal seems to have slightly shorter time to first disturbance than voltage supply for both cable types, the difference being about 2...4 s according to cumulative failure probabilities presented in figure 7. No specific correlation was noticed when comparing different types of first disturbance in I_{out} with times to first disturbance.

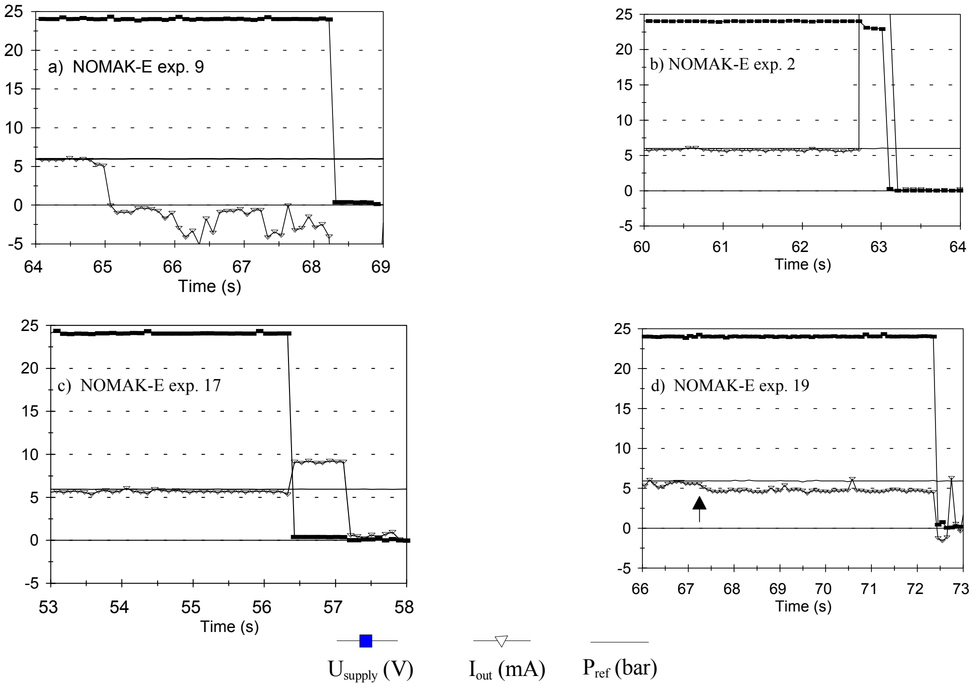


Figure 5. Voltage supply U_{supply}, different types of disturbance in current output I_{out} as explained in the text, and reference measurement of compressed air pressure.

Resistance measurements from cable C2

Only critical combinations 1-2 and 3-4 were studied and additionally 1-V. Times to first disturbance in other combinations of conductors remained thus unexplored. The first resistance drop was noted as first disturbance, without distinction between magnitude of resistance drop. The times to first disturbance are thus somewhat conservative, because it is possible that a noticed small drop in insulation resistance does not effect the function of the cable, cf. figure 3 where consequences on the current signal output occurs only for insulation resistance smaller than 1 kΩ.

The overall behaviour of the resistance curves in both MHMS-SI and NOMAK-E series can be described as:

a) Intermittent disturbances in periods of no disturbance (figure 6a).
b) Drop to total short of longer duration (figure 6b).
c) Subsequent disturbances with exponentially decreasing resistance leading to either total short (figure 6c) or recovering eventually followed by total short (figure 6d).

Types a) and b) or combinations of them were predominant for pairs 1-2 and 3-4 (figures 6a and 6b) with only 3 events showing exponentially decaying resistance before total short. All resistance curves for pair 1-V showed type c) shape, with examples in figure 6c and 6d.

The time to first disturbance in pair 1-V was clearly shorter than times to first disturbance in pairs 1-2 and 3-4 for both cable types. The reason for this is the structure of the cable (figure 1), which will be discussed more below.

Comparing times to first disturbance for conductor pair 1-2 and 3-4 shows that pair 3-4 has slightly shorter times to first failure than 1-2 for cable type MHMS-SI, while the times do not clearly differ for cable type NOMAK-E (figure 7). Speculatively current loop, which might create higher potential differences, might be an explanation; still definite conclusions are difficult especially for MHMS-SI series because of the small amount of experiments.

The order of magnitude for short circuit transient time constant *RC* was estimated to 0.1 μs for two cases, short circuit between two conductors and between conductor and shield. This is much smaller than time scale for 1-V disturbances. The observed "exponential decay" in the 1-V resistance curves is thus probably due to heating and reduction of insulation resistance or influence from an outer circuit (data acquisition system) and is not a property of the investigated cable.

Distribution of time to first disturbance

Cumulative failure probabilities for the observed times to first disturbance were estimated using the median ranks suggested by McCormick [7] and are presented in figure 7. The observed cumulative frequencies reveal "tails" with higher times to first disturbance at higher cumulative frequencies, with exception for combination 1-V. This appears especially for NOMAK-E cable series and the voltage supply data.

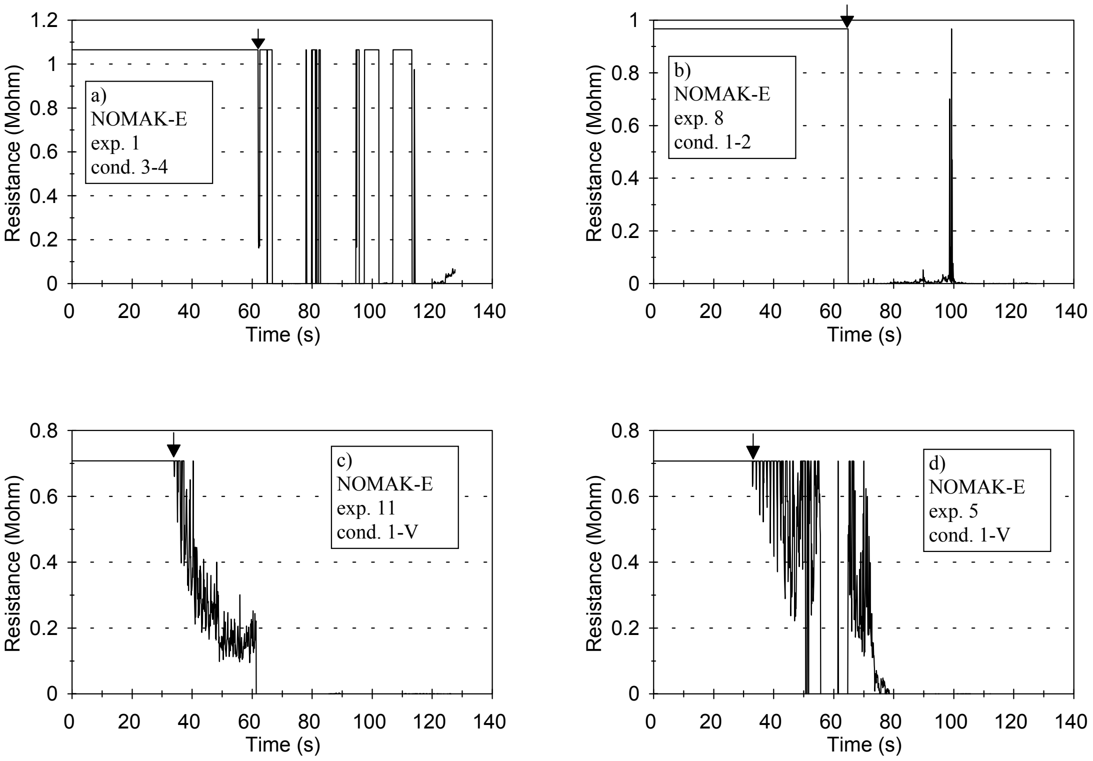


Figure 6. Examples of insulation resistances measured from cable C2. The first disturbance is indicated with an arrow.

Normal, lognormal, Weibull and Gumbel cumulative distributions *F(t)* [7, 8] could all be satisfactorily fitted visually to the observed data without time delay. A still better fit to the observed data was obtained by introducing a time delay to the Weibull distribution,

$$F(t) = 1 - \exp(-(\frac{t-\tau}{\beta})^{\alpha}) \tag{2}$$

where t is the observed time to first disturbance, α shape parameter, β scale parameter and τ time-delay parameter.

The combinations 1-2 and 3-4 in NOMAK-E cable series show three points at exceptionally small times in two successive experiments, 3.7 s for 1-2 and 22.3 s for 3-4 in the same experiment and 22.8 s for 1-2 in the next experiment. The reason for these three disturbances is not clear, but the fact that in the former experiment a disturbance was noticed in pair 1-2 even before the propane burner was placed beneath the cables may indicate that these exceptionally early disturbances are not due to heating of cables. If these three possibly spurious disturbances are ignored, there seems to exist threshold values for the distributions. This is reasonable as the burning and consumption of the cable jacket and conductor insulation introduce a delay before insulation resistance has decreased enough for short circuiting to occur. According to this argumentation Weibull distributions with time constant were fitted to observed cumulative distributions giving fairly good results as presented for NOMAK-E cable in figure 8.

The threshold values τ from Weibull distributions give thus an estimate of the shortest time to first disturbance in the examined automation cables (Table 1). The threshold times for power supply U_{supply} and current output I_{out} in the energised cable C1 and conductor combinations 1-2 and 3-4 in the non-energised cable C2 are in the interval 39.3 ... 42.5 s for MHMH-SI and 36.7 ... 38.0 s for NOMAK-E cable.

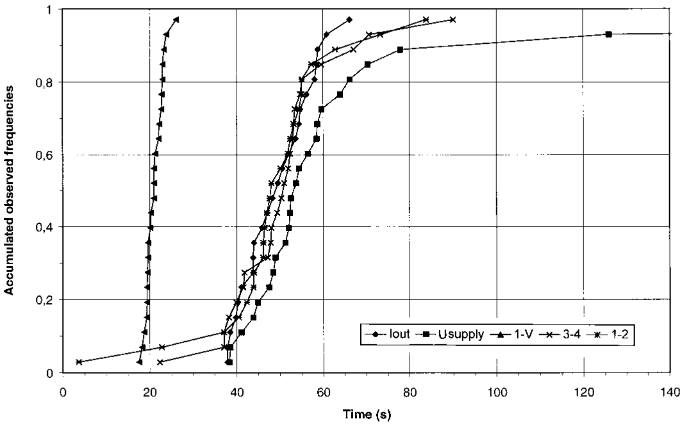
The physical interpretation for τ comes by applying linearized heat conduction theory on an infinite cylinder with a symmetric metal core. A closed form analytical solution is obtained in terms of an infinite function series consisting of an orthonormal set of space eigenfunctions in form of linear combination of Bessel functions [9]. As the first rough estimate two terms of the series are sufficient to order of magnitude calculations leading to a simple formula for τ

$$\tau = -\tau_1 \ln(1 - \Delta T_d / \Delta T_a) \tag{3}$$

where heating time constant τ_1 is calculated from the lowest eigenvalue of Helmholtz equation i.e. the first positive root of a determinant consisting of Bessel functions. Damage temperature rise ΔT_d is roughly the melting temperature of

PVC ($\approx$ 180 K) and ambient temperature change ΔT_a the flame temperature ($\approx$ 1000 K in these experiments). Details of derivation of equation (3) will be given in an extended paper. Calculating by this model for a copper wire 0.8 mm in diameter surrounded by 1.35 mm PVC insulation, a value of $\tau_1 \approx 42$ s was obtained resulting to $\tau \approx 12$ s as the damage time. As the geometry of real cable differs a lot from this symmetrical model the result is remarkable good as compared with experimental values of times to ground fault as seen from curve fittings where 13 s and 17 s were obtained for MHMS-SI and NOMAK-E cables respectively. Damage times of approximately 40 s for hot shorts are explained qualitatively by the same model as the melting has to take place deeper in the cable, but it will be discussed only in an extended paper.

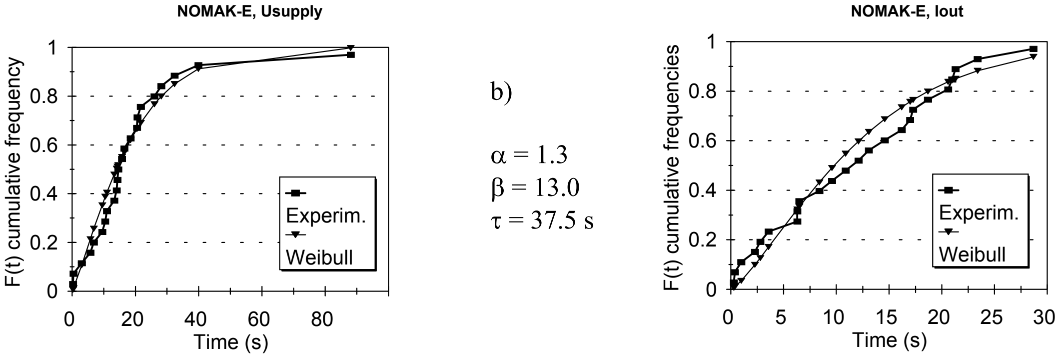
The Weibull distribution of damage times is explained qualitatively by needed movement of wires within softened or melted insulation to establish shorting contact. It requires some time especially here, where no external stress or bending was applied on the cables.



a)

b)

Figure 7. Cumulative failure probabilities for the observed times to first disturbance in a) MHMS-SI and b) NOMAK-E cable fire series. In one NOMAK-E case no U_{supply} failure was observed during the 126.9 s long experiment.



a)

$\alpha = 1.2$
$\beta = 19.0$
$\tau = 38.0$ s

b)

$\alpha = 1.3$
$\beta = 13.0$
$\tau = 37.5$ s

Figure 8. Weibull distribution (Eq. 2) fitted to observed cumulative frequencies of time to first disturbance.

Table 1. Parameters for Weibull distribution (Eq. 2) fitted to observed cumulative frequencies of times to first disturbance in cable fire experiments.

	MHMS-SI cable			NOMAK-E cable		
	α	β (s)	τ (s)	α	β (s)	τ (s)
U_{supply}	1.2	8.0	41.5	1.2	19.0	38.0
I_{out}	1.3	5.5	41.5	1.3	13.0	37.5
1-2	1.0	9.5	42.5	1.3	16.0	36.8
3-4	1.0	11.5	39.3	1.3	15.0	36.7
1-V	1.1	2.4	12.8	1.6	4.3	17.3

CONCLUSIONS

The present fire experiments give information on times to first disturbance in and the behaviour of the electrical function of a four-conductor instrumental cable connected to a pressure transmitter. Probability functions of disturbance times have been fitted to the observed cumulative frequencies. A simplified heat transfer model was made to explain the time delay of the occurrence of the first ground short, which is in good agreement with observations. The same model explains also time to the first hot shorts. The deterministic heat transfer model predicts the necessary minimum time to ground short. Sufficient time could not be modelled but is understood qualitatively and expressed experimentally as Weibull distribution.

The amount of experiments is so small, that no final conclusions on the distributions can be made. Despite that, on rough theoretical grounds Weibull distributions seem preferable, which is not in contradiction with sparsely available experimental information.

The parameters of the distributions have been fitted only visually in this work. There are also computational methods for estimating parameters, but they are not worthwhile here because of the small amount of observations in the present experimental series.

Both the fire experiments and the failure mode investigation without fire exposure indicate that the transmitter current output signal is not very sensitive to disturbances. Disturbances seem to occur only when the insulation resistance is less than an order of some hundred ohms, which can be considered equal to metal to metal contact. Accordingly, the experiments show an ON/OFF situation in most of the cases: stable current signal output until sudden drop to zero. In 6 cases out of 33 the current output exceeded the maximum measurement range 500 mA for a short duration, maximum 9.2 s, after which the output dropped to zero due to voltage supply cut-off. In three cases a current output level drop of about one mA to 4.6 mA level was noticed. The duration of these level drops were 1.4...12 s.

The experiments were carried out with a gas burner located 85 mm beneath the centre of the free space between two adjacent cable ladder rungs. They correspond thus to a situation without obstacles such as cable ladder rungs and cable ties, which should be investigated separately.

The present results correspond to a situation with cables in flame contact and are not directly applicable on cable signal behaviour in moderate fire environments. The results can, however, be used as a conservative estimate. Based on present experimental results fairly reliable estimates of times to first disturbance can be obtained using existing time dependent heat transfer models, and appropriate models for fire exposure other than a direct flame contact.

The results of this study should be considered as merely indicative because of the small amount of experiments in the series.

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