Acute Effects of Smoke from Fires on Performance of Control Electronics in NPPs

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Abstract

Acute effects of smoke on control electronics used in programmable automation circuitry in NPPs were studied experimentally and theoretically. Relevant physical parameters of smoke, and electrical performance of circuitry were measured online for a period of an hour. It was noticed insulation resistance decreased three orders of magnitude due to soot deposits on surfaces on uncoated circuitry. A quantitative model for smoke exposure and deposition on surfaces was proposed based on existing physical models of aerosols. A consistent picture of the relevant processes was found, and an easy calculation method for smoke hazard estimation for PSA-work is proposed for insulation resistance deterioration. This model allows also estimation of the required performance of protective coatings to prevent parasitic leakage currents between different parts of circuitry. For real commercial circuits, coated by a protective lacquer layer, no electrical changes were observed.

INTRODUCTION

Disturbances of control electronics by acute effects of smoke have been a matter of concern for a while. At Sandia National Laboratory a series of experiments has been carried out recently [1 - 5]. Utilizing their experience we designed experiments around a standard smoke exposure chamber [6]. The main goal was to quantify the effects observed in Sandia if practicable. Descriptions of the preliminary results of this study has been given earlier [7 - 8].

For characterising changes on electronic circuits microscopic properties of soot are needed. Smoke is understood as the visible part of fire effluent. It is an aerosol, where small particles of solid or liquid are suspended in air. The main element of the particles (soot) is carbon. Single smoke particles are usually conglomerates of smaller spherules about 30 nm in diameter forming complicated space structures [9]. The effective diameter extends from tens of nanometers to tens of micrometers, sometimes even higher. A typical value of the geometric mean volume diameter falls in the interval 0.3 ... 3 μm. Soot smoke deposits on surfaces form an electrically (semi)conducting film, which could deteriorate sensitive electronics.

Particle sizes from PVC smoke have been determined under different conditions [10]. The size distribution is roughly logarithmically normal [9] with a mean of 0.6 μm for smouldering PVC. For flaming combustion particle size distribution has a maximum at 0.2 μm. The size distribution is not constant but varies somewhat with time. This temporal behaviour is understood in terms of smoke particle coagulation and settling. Settling removes larger particles more efficiently than small particles. Coagulation is a phenomenon where two colliding particles stick together after collision.

In our experiments polychromatic light extinction was measured. The intensity I_0 of the pencil of a light ray attenuates after transmitting through a pathlength L of the smoke to intensity I as

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$$\frac{I}{I_o} = \exp(-kL) \tag{1}$$

The mass concentration of smoke c_m is obtained from direct optical measurements as

$$c_m = \frac{1}{\sigma_{ext}} \frac{1}{L} \ln\left(\frac{I_0}{I}\right) \tag{2}$$

where σ_{ext} is the specific extinction coefficient. σ_{ext} varies slightly with wavelength from about 9.5 m^2/g at 450 nm to about 5 m^2/g at 1000 nm. The value $\sigma_{ext} \approx 8.5\ m^2/g$ at 550 nm was used in this study.

There are in principle several different physical mechanisms, which deposit smoke aerosol particles suspended in air on the solid surface at different conditions and rates. Particles are driven by external forces like gravitation and electric fields. Charging of soot particles is caused by field and diffusion charging mechanisms. Furthermore, thermophoresis causes soot particles to settle on surfaces. All these processes act simultaneously leading to a complicated dynamic behaviour of smoke particles close to solid surfaces like PCBs.

THEORETICAL MODELS

Coagulation Model

Smoke particles have a continuous distribution of sizes as discussed above. There is continuous change in the number of particles during the experiment. A dynamic model of smoke particle settling in the chamber including coagulation is proposed for explaining at least qualitatively the temporal behaviour of smoke density during the experiments. Curve fitting on this model was tried leading to a fair agreement as shown in Fig. 1.

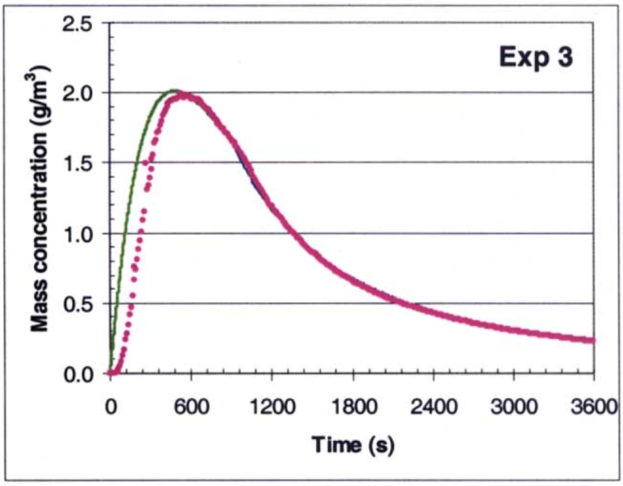


Figure 1. Curve fit (solid) of experiment 3 (dots) to the mass concentration using a simple dynamic model.

Soot Resistivity Model

For understanding temporal behaviour of insulation resistance (Fig. 5) a simple theoretical model is proposed. Soot deposit is presumed to be a (semi)conducting layer. The deterioration of insulation resistance is caused by ohmic bulk conduction through deposited soot between the copper strips of the comb figure on the board (Fig. 2).

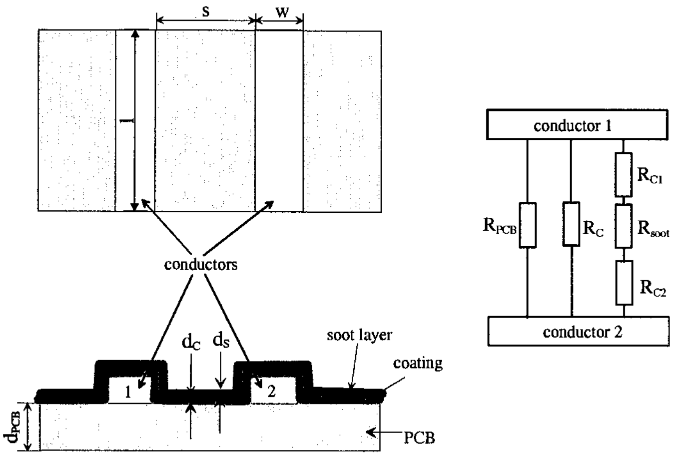


Figure 2. Electrical conduction on a circuit board (PCB) with soot and coating (left) and equivalent circuit (right) with resistances in parallel.

The measured insulation resistance R of the comb figures is the clean printed circuit board insulation resistance R_{PCB} and the soot resistance R_S in parallel. The ratio between soot deposition thickness $d_s(t)$and specific resisitivity ρ_s of soot is then

$$\frac{d_s}{\rho_s} = \frac{s}{nl}\left(\frac{1}{R} - \frac{1}{R_{PCB}}\right) \tag{3}$$

where l is the length of the conductors, s is the constant distance between the conductors and n is the number of soot strips between the conductors.

Considering a situation with two parallel conductors protected with a thin coating (Fig. 2) the possible paths of conduction and corresponding resistances are

- through the circuit board material, R_{PCB}
- through the layer of coating between the conductors, R_C
- through the coating layer on conductor 1, the soot layer and the coating layer on conductor 2 in series, $R_{C1} + R_S + R_{C2}$

The measured resistance R is then these resistances in parallel

$$\frac{1}{R} = \frac{1}{R_{PCB}} + \frac{1}{R_C} + \frac{1}{R_{C1} + R_s + R_{C2}} = \frac{l d_{PCB}}{s\rho_{PCB}} + \frac{l d_C}{s\rho_C} + \frac{1}{2\rho_C \frac{d_C}{l w} + \rho_s \frac{s}{l d_s}} \tag{4}$$

where ρ_{PCB} and ρ_C are the resistivities of printed circuit board and coating, d_{PCB} and d_C are thickness of printed circuit board and coating and w is the conductor width. To obtain a general view on the behaviour of conductivity as expressed by Eq. (4) as compared with conductivity of a clean board we calculate the ratio of these conductances denoting it by γ:

$$\gamma = 1 + \frac{\rho_{PCB}}{\rho_C}\left\{\frac{d_C}{d_{PCB}} + \frac{1}{\frac{2 d_C d_{PCB}}{ws} + \frac{\rho_s}{\rho_C}\frac{d_{PCB}}{d_s}}\right\} \tag{5}$$

where all variables are arranged to form nondimensional ratios of two similar quantities. Plotting γ as a function of coating thickness using soot thickness as a parameter for given PCB-cards, effect of soot in coated cards can be easily estimated.

EXPERIMENTAL

Experiments were performed, with a mockup printed circuit board containing four comb figures and one experiment with a real ABB DSAI 130 circuit board The circuit board was placed in vertical position in the centre of the smoke chamber and exposed to smoke from a smouldering PVC cable jacket. The cable jacket sample was exposed to thermal radiation from a radiator cone at an irradiance level of 25 kW/m^2 in the absence of a pilot flame. The duration of radiation was 15 min and smoke deposition was allowed in the chamber for the next 45 min, after which the smoke chamber was vented. Recovering of the circuits was monitored for 24 hours after venting.

Insulation Resistance of Comb Patterns

The comb figures had 0.2/0.2 mm, 0.3/0.3 mm, 0.5/0.5 mm, 0.7/0.7 mm line widths and clearances (Fig. 3). The comb patterns were intentionally without protective coating.

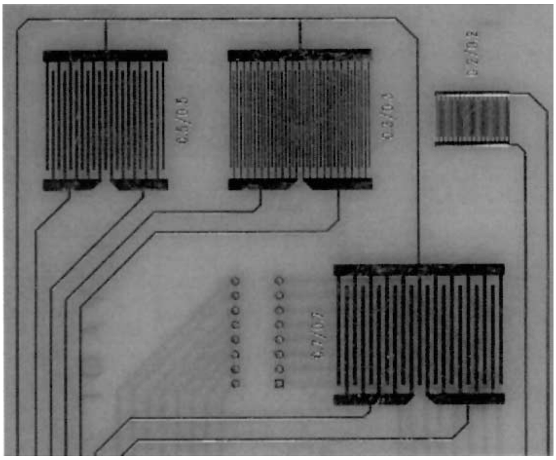


Figure 3. Comb patterns studied in smoke chamber.

Insulation Resistance of a Commercial Circuit Board

Insulation resistance was measured at three locations between conductive leads and ground. Distance between active and ground leads varied. The minimum distance in all locations was no more than 1 mm.

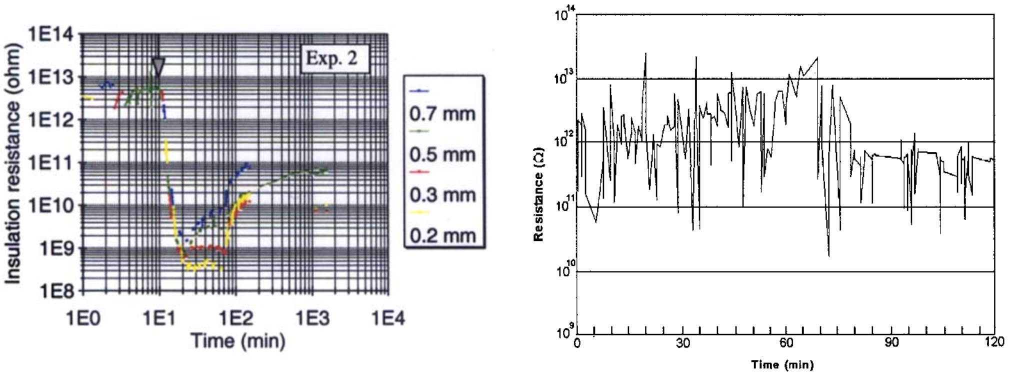
Other Measurements

In addition the following measurements were performed:

- Optical density of smoke by monitoring light transmittance through smoke
- Mass deposition of soot on a vertical and a horizontal thin aluminium foil
- Mass of the cable jacket sample
- Gas and surface temperatures
- O_2-, CO_2- and CO gas concentrations.
- Stability of analog input channels
- Time constants of digital electronics

RESULTS

Insulation resistance of comb patterns is presented in Fig. 5a and insulation resistance on the commercial circuit board is presented in Fig. 5b.



a) b)

Figure 5. a) Insulation resistances from comb figures. Start of radiation exposure is indicated with an arrow. b) Insulation resistance on the commercial circuit board. Irradiation of cable sample starts at 5 min.

d/ρ ratios from resistance measurements for the four comb patterns are presented in Fig. 6. The ***d/ρ*** -curves seem to saturate at $1 \cdot 10^{-12}$ S. The average soot deposition in the experiments was 1.0 g/m^2. Assuming a soot density of 1880 kg/m^3 [11] one obtains a soot deposition thickness of 0.53 μm and an effective soot resistivity of 10^6 Ωm.

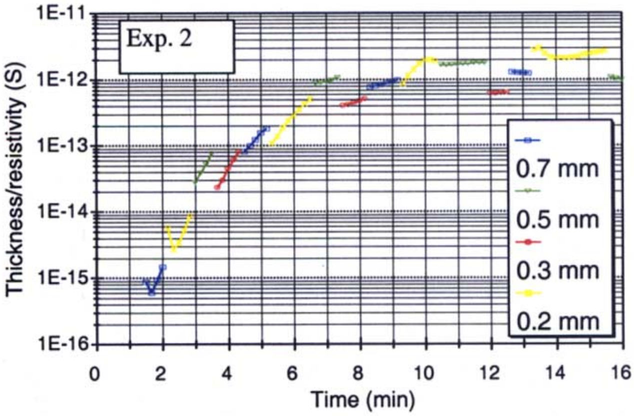


Figure 6. **d/ρ** ratios from resistance measurements for comb patterns.

Resisitivities of metals are typically of order 10^{-8} Ωm, semiconductors 10^{2}...10^{4} Ωm and insulators 10^{10}...10^{18} Ωm in magnitude. Comparing the effective soot resistivity in the smoke experiments with these values indicates that the conductivity of the deposited soot is poorer than typical semiconductors but better than typical insulators.

The influence of coating is here considered on a level of magnitude study. Material parameters are presented in Table 1. Conductor width w = 0.1 mm, clearance between conductors s = 0.1 mm and conductor length l = 10 mm are used as typical dimensions. Calculating numerical values one obtains the different resistances presented in Table 1 (cf. Eq. (4)). It is noticed that the coating resistance effectively hinders leakage of current to the semiconducting soot layer.

Table 1. Typical values of resisitivity ρ and thickness d for PCB, coating (from literature) and soot (from measurements) and calculated resistances explained in text.

	ρ (Ωm)	d (m)	Resistance (Ω)
PCB	$10^{12}...10^{13}$	10^{-3}	$R_{PCB} \sim 10^{13}...10^{14}$
Coating	$10^{13}...10^{15}$	10^{-5}	$R_C \sim 10^{16}...10^{18}$ $R_{CI} \sim 10^{14}...10^{16}$
Soot	10^{6}	10^{-6}	$R_s \sim 10^{10}$

Using literature resistivity values for electronic component materials and our measured values for soot, the efficiency of protective coatings can be evaluated. In Fig. 7 γ according to Eq. (5) is plotted for the real PCB used in our experiments.

It is clearly noted that coating is very efficient to protect against soot deposition and that no effects on insulation resistance deterioration should occur for the real coated circuit studied electrically here. The left-hand parts of these plots are only academic, since the layer thicknesses in real dimensions would be subatomic in size. Even then they show that coating material as an excellent insulator is a very efficient way of protecting the circuits.

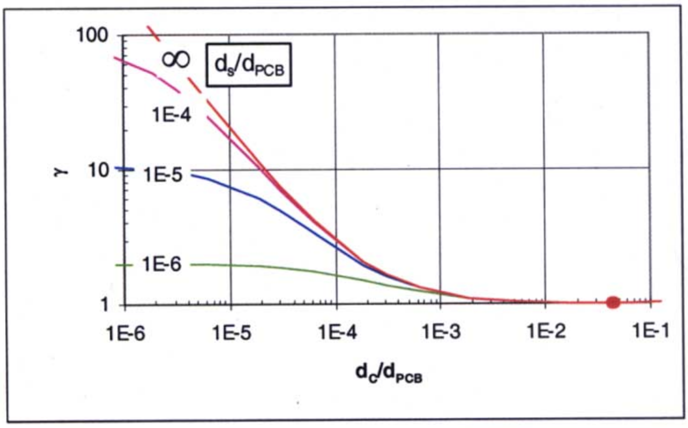


Figure 7. Effect of protective coating on the conductivity of a PCB laden with soot. Dimensions from the real PCB used for experiments. Typical coating thickness 10 μm corresponds to 0.006 on nondimensional horizontal scale.

CONCLUSIONS

Smoke exposure experiments on real and mock-up electronics circuitry has been carried out. Special attention was paid on fouling of insulation resistance due to soot layer accumulating from the smoky environment on the circuitry. The major component of soot is carbon. Deposits of soot particles are not expected to be electrically conductive like a graphite layer but rather likely semiconductive. Despite that, the conductance of a soot layer is high compared with conductance of good insulation materials, which are used as boards of printed circuits. Therefore, soot layer on an unprotected printed circuit board deteriorates insulation resistance between metallic electrical conductors.

The soot deposition effect on unprotected circuits is considerable: in the insulation resistance measurements of comb patterns the change is 3 ...4 orders of magnitude. After ventilation the worst case deviation from the original values was a factor of 10 ... 100 in insulation resistance.

As an example of modern electronics, components on the ABB DSAI 130 analog input board were studied. No significant change in insulation resistance was noticed during the smoke exposure because of protective coating of circuits.

In this paper such instrumentation was attached in a smoke exposure chamber, that dynamic behaviour of smoke emanating from a smouldering PVC source could be monitored continuously. The model for deterioration of insulation resistance allows a quantitative tool to estimate requirements for protection of electronic circuitry against soot by using various coatings. The model shows as expected, that modern electronics, like that used for today's programmable automation circuits, is in principle more vulnerable for smoke and soot than the conventional analog control circuitry used at the time our nuclear power plants were built. As for insulation resistance our experiments showed that use of protecting coatings could reduce the problem to a tolerable limit. There are still other electrical phenomena, which we did not study here. Therefore, our conclusions from this work are not an unlimited clearance for all smoke related problems on control electronics.

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