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# Hygroscopic Fine Mode Particle Deposition on Electronic Circuits and Resulting Degradation of Circuit Performance: An Experimental Study

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## ABSTRACT

A portion of electronic equipment failures is a consequence of particle deposition on electronic circuits in normal indoor environments. Deposited hygroscopic particles reduce the electrical isolation (EI) between conductors. In laboratory experiments, we investigated the mechanisms, locations, and effects of particle deposition on electronic circuits with surface mounted chips (SMCs) and also on small television sets. One set of electronics was exposed for 281 hours to an unusually high concentration of artificially-generated ammonium sulfate particles while a second set (experimental controls) was exposed to normal indoor particles. The particle mass concentration in the high-exposure chamber was 500 times higher than normal. Television reliability was observed and the changes in EI between adjacent legs of SMCs were measured. The experiments demonstrate the strong influence of electrostatic forces on the locations and rates of particle deposition. Although televisions did not fail after exposure to concentrated aerosols, the EI between adjacent legs of the SMCs was, in many cases, greatly diminished. Relative humidity had a very strong influence on the magnitude of EI. A qualitative explanation of the mechanisms of particle deposition and circuit degradation is proposed, including the role of fibers. Finally, a potential method to reduce particle deposition on electronic components is discussed.

Key Words: electronics, experiments, deposition, failures, indoor air, particles

# INTRODUCTION

## Background

An estimated $1 billion is spent annually to repair failed electronic circuits in U.S. telephone switching offices and approximately 20% of these failures (worth $200 million) are thought to be caused by indoor air pollutants [1, 2]. Given the widespread use of electronic equipment in the U.S. economy, the total U.S. cost of electronic equipment failures caused by indoor air pollution must be many times larger. Protection of electronic circuits against indoor air pollutants represents an important issue for industrial economies which rely on increasingly smaller electronic devices for communication and information processing. In the future, as electronic components, circuits, and spacing between adjacent conductors continues to get smaller[1]; degradation of circuit reliability from indoor particle deposition may assume even more importance.

## Indoor particles

Airborne particles commonly have a bimodal mass distribution. The coarse-mode particles (diameter range approximately 2 μm to 20 μm) are typically generated as a result of the mechanical wear of materials. They can derive from mineral and biological sources and include fibers. Coarse mode particles are usually removed from the indoor air at a moderate to high efficiency with the filters in building air handling systems. Fine mode particles have diameters smaller than approximately two micrometers and are typically generated as a result of combustion and photo-chemical gas-to-particle conversion. Fine-mode particles may be generated indoors but many of these particles enter buildings with outdoor air. Fine-mode particles are not efficiently removed by the filters used most commonly in building air handling systems.

Fine mode particles may cause greater hazard to indoor electronics than coarse particles. They more difficult to filter from the air and they are often hygroscopic as discussed subsequently, Also, fine particles can deposit equally well on vertical and horizontal surfaces. Voltages applied to electronics can produce strong electric fields dramatically enhancing fine particle deposition (for example, it is common to find enhanced deposits of fine-mode particles on top of power supply lines on a circuit board).

Major mechanisms affecting coarse mode particle deposition onto electronic circuit features include gravitational settling and inertial impaction. The major forces affecting fine mode deposition include diffusional deposition, and deposition caused by thermophoretic and electrostatic forces.

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[1] For example, in some new electronic devices with "fine-pitch" spacing, the spacing between pins is approximately 0.25 mm. Such devices may have 300 pins in one side of an integated circuit chip and more than 1000 total pins. .

Hygroscopic particles, both coarse and fine mode, can absorb moisture from the environment and change their diameter (and mass), and thus their major deposition mechanism. Once deposited, the increase in their conductivity with increasing water content can also increase their impact on circuit performance. Such hygroscopic particles can easily represent as much as half of the total mass of fine particles in a building; most of these hygroscopic particles are ammonium sulfate salts [3]. When the environment reaches a critical relative humidity (CRH), these salts deliquesce and become electrically conductive. Depending on their composition, fine particles tend to deliquesce above 50-65% relative humidity (CRH is 81% for pure ammonium sulfate).

## Contamination effects on electronic equipment

In the microelectronics manufacturing environment, sensitive electronic features on the integrated circuit (IC) chip are directly exposed to indoor air. Deposited airborne particles can substantially degrade device yield by causing failures on exposed electronic components [4]. Therefore, extremely low airborne particle concentrations are maintained in manufacturing environments (e.g., clean rooms). Furthermore, IC chips are encapsulated in the final stages of the manufacturing process. Thus, when electronic components are operated in the workplace environment, many of their critical and sensitive features are isolated from the ambient air. However some features still remain directly exposed to ambient air including the "legs" of surface mounted chips (SMCs) that provide the electrical connection between the SMCs and the electrical traces on the circuit board. Particles can accumulate on a circuit over the years and create bridges of agglomerated particles between adjacent non-protected conductors. The reliability of contaminated electronics may not be immediately affected when such accumulation occurs. For example, circuit boards contaminated with hygroscopic salts may function normally at low humidity (below the CRH) but fail during a high humidity episode (above the CRH) when the deposited hygroscopic particles permit leakage currents and electrical shorts. Failures of circuit boards in the telecommunications industry due to hygroscopic dust have been documented [5, 6]. A cost-benefit study suggests that, in many telephone switching offices, the costs of more efficient building filters and continuous fan operation are more than offset by the savings from reduced electronic circuit failures [7].

Particle-induced degradation of electronic circuits depends on several factors including the layout of the circuit, the characteristics of the particles, the location and magnitude of deposition, and the degree of threat to circuit performance from reduced electrical isolation of adjacent conductors. Compared to the substantial body of literature related to the prevention of deposition of fine particles on semiconductor surfaces during the manufacturing process, relatively few studies of electronics circuit degradation from particle deposition in the workplace environment have been published.

Research is needed to better understand the mechanisms involved in the deposition of indoor particles on electronic components and circuit surfaces during operation. An improved understanding is also needed of the impacts of particle deposition on electronic circuit reliability. Such knowledge will assist in the development of analytical tools for predicting electronic failure rates as a function of various ventilation and particle filtration scenarios and also facilitate the selection of cost-effective HVAC systems capable of reducing electronic failure rates induced by indoor particles.

### Objectives

The primary objective of this work was to assess the impact of hygroscopic particle deposition on the electrical functioning of exposed electronics. We aimed to experimentally demonstrate that particle deposition on electronic surfaces results in a decrease in electrical isolation and/or premature electronic equipment failures. Related objectives were to study the influence of electric field strength on particle deposition and to quantify the influence of relative humidity on the electrical isolation of exposed electronics.

## METHODS

### Overview

In an earlier experimental study, researchers developed a submicron particle exposure chamber where the rate of deposition throughout the chamber was accelerated by maintaining a high velocity field within the chamber [6]. In contrast, we designed and built a sub-micron particle exposure chamber where deposition is accelerated by increasing the particle concentration. The particle deposition rate on indoor surfaces is usually represented as a first order process such that the deposition rate scale linearly with the particle concentration away from the walls, in the "core" of the room [8].

Experiments were conducted to study the deposition of fine-mode polydisperse particles on electronics placed in an exposure chamber. As a control experiment, we exposed identical electronic circuits to normal ambient laboratory air in a second exposure chamber.

In the first experimental phase, electronic equipment was exposed for 281 hours simultaneously in the two exposure chambers. The elevated particle concentration in the experimental chamber was approximately 500 times greater than the reference particle mass concentration of 30 $\mu g/m^3$ from a study of 38 commercial buildings [9]. Thus, particle deposition quantities in the first exposure chamber were expected to be equivalent to a 16 year exposure to a normal indoor particle concentration. The control exposure chamber had a normal indoor particle concentration.

In the second experimental phase, the electronic equipment was visually and microscopically inspected. The performance of the televisions was assessed by visual observation of the displays during operation for a range of relative humidities. The electrical isolation of adjacent legs of the SMCs was also measured over a range of relative humidities.

## Electronics

Several identical television sets (Radio Shack Portavision, model number 16-121A) were purchased from a local retailer. These were selected to represent typical electronic devices in office buildings such as computers and video display terminals that have integrated digital electronic circuits as well as high voltage video circuits with strong electrical fields. During the experiment, the television sets were connected to a video display pattern generator (LEADER, model LCG-395A).

Standardized SMC circuits were specially manufactured for our research project and are shown in Figure 1. They comprise a 1 cm square dummy surface-mounted chip whose 52 legs (spaced 0.65 mm center-to-center) are connected to the surface trace conductors on the circuit board. The surface trace conductors extend over a 9 cm by 7 cm circuit board, and terminate in a 22-pin edge connector. Thirteen legs emerge from each of the four sides of the square dummy chip. From each set of 13 legs, five consecutive legs were individually connected to the edge connector via five individual surface trace conductors. The remaining 32 legs of the chip were connected in a "parallel" configuration; every alternate leg was connected to the same surface trace conductor, forming two sets of 16 legs in parallel. Legs were classified in two categories: type I, for the individually connected legs and type II for the parallel-connected legs.

## Exposure chambers

The experimental system is illustrated diagrammatically in Figure 2 and the physical conditions during experiments are summarized in Table 1. Ten television sets and 20 SMC circuit boards were exposed to a high concentration of particles in the experimental exposure chamber (EC1). Fourteen circuit boards were oriented vertically and six were horizontal (with the chips facing up). Among the vertically-oriented circuit boards, type II legs on five were electrically grounded, legs on another five were at a 10 VDC-differential voltage (low voltage) and legs on the remaining four were at a 240 VDC-differential voltage (high voltage). All legs on the horizontally oriented circuit boards and all type I legs, regardless of board orientation, were electrically grounded.

As a control, four television sets and two vertically oriented SMC circuit boards with all legs grounded were exposed to normal laboratory air in a second exposure chamber (EC2).

The dimensions of EC1 and EC2 were respectively 0.43m x 0.66m x 1.24m and 0.6m x 0.44m x 0.76m. Both chambers had aluminum walls, floor and ceiling. One wall in EC1 was of plexiglass, allowing visual observation of the television screen displays. EC2 had a front that was open to the laboratory air.

EC1 was sealed carefully and maintained slightly depressurized to prevent the laboratory air and EC2 from being contaminated by the generated particles. The relative humidity in EC1 was controlled by injection of dry or humid clean air into the chamber. Humidified air was created by pumping the air through bubblers.

Temperature and relative humidity sensors were located in EC2 and in the laboratory. In order to avoid contamination from the high concentration of particles, temperature and humidity sensors for EC1 were located in a 3.8 liter aluminum box supplied with filtered air from EC1. The solid-state temperature sensors (AD-590-KH, Newark Electronics) were calibrated at multiple temperatures using a precision mercury thermometer in a temperature-controlled water bath. The relative humidity sensors (General Eastern Model RH-3) were calibrated at five reference relative humidities created with saturated salt solutions. The estimated uncertainties in the temperature and relative humidity measurements were ± 0.3 °C and ± 3% RH, respectively.

In EC1, an internal mixing fan was installed adjacent to the location where the stream of concentrated particles entered the chamber. The mixing fan forced air perpendicular to the incoming particle stream. A test was performed, using a sulfur hexafluoride ($SF_6$) tracer gas, to check the mixing within EC1. $SF_6$ was injected into the inlet air stream that normally contained a high concentration of particles and $SF_6$ concentrations were measured versus time at three locations inside EC1. The $SF_6$ concentrations varied less than 1.8% from the average concentration.

In order to minimize the temperature increase in EC1 due to the heat dissipation from the television sets, three external fans directed laboratory air at a high velocity toward the exterior surfaces of EC1. With these fans operating, the temperature in EC1 was approximately 2.5 °C higher than the surrounding room temperature. The spatial variation in temperature within EC1 was approximately 2 °C.

## Particle generation

Particles were generated by atomizing an aqueous solution of ammonium sulfate (10 g $L^{-1}$) with 1% of uranin[2] (sodium salt of fluorescein) using a constant output atomizer (TSI Model 3076) and compressed filtered dry air. The resulting particle stream was dried by passing it through two diffusion dryers mounted in series. The particle stream passed through the 25.3 liter settling chamber where large particles were removed by settling. The particles were neutralized with a

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[2] The uranin was added to permit quantification of the amount of particle deposition on the circuits. These results will be provided in a subsequent paper.

Kr-85 source, which brought the particle charge distribution to a Boltzmann equilibrium. Finally, the particle stream entered EC1 at 3 liters per minute, through a 1.25 cm ID copper tubing.

## Particle measurements

Due to the limitations of the particle instrumentation, the high concentration of particles in EC1 was not analyzed directly. Instead, a volume of particle-laden air from EC1 was mixed with a larger volume of HEPA-filtered air in a dilution chamber. Samples from the dilution chamber were then analyzed with the particle instrumentation.

Particle size distributions in the range [0.1-2 μm] were measured in eight size bins with an optical particle counter (OPC) [PMS Model LASAIR 1003]. A differential mobility analyzer (DMA) consisting in an electrostatic classifier (TSI Model 3071) coupled to an ultrafine condensation particle counter (TSI Model 3025) measured the particle size distribution in the range [0.01-0.34 μm]. The generated polydisperse particle had a mass median diameter of 0.48 μm, with a geometric standard deviation of 1.8 . The particle mass concentration in EC1 was found to be approximately 15 $mg/m^3$.

## Electronics reliability tests

All SMC circuit surfaces were cleaned with a methanol bath and cotton swabs and dried with compressed HEPA-filtered air before the controlled exposure to particles. For reference, the electrical isolation between the legs of the clean SMCs was measured as a function of relative humidity. Electrical isolation was then measured after the controlled exposure of the SMCs to particles. Before these post-exposure measurements of electrical isolation (phase 2), the exposed surface trace conductors on the circuit boards were cleaned one more time, since the location of interest on circuits were the legs of the chips and the gaps between these legs. Thus, the measurements of electrical isolation were not affected by particle deposition between and on the electrical traces of the circuit boards. (In modern electronics, these traces on circuit boards are normally protected from indoor air contaminants). Electrical isolation measurements took place with the SMCs located inside EC1 at a controlled humidity.

For the electrical isolation measurements, a 200 VDC differential voltage was applied between the 2 terminals connecting the adjacent legs of type II on 12 exposed SMCs. All were vertically oriented circuits: four at high voltage (circuits 1 to 4), four at low voltage (circuits 5 to 8) and four grounded (circuits 10 to 13). A multimeter electrometer (Keithley Model 619) measured the leakage current through the edge connector and, therefore, between the adjacent legs of the chip. The equivalent resistance between the parallel legs was calculated, as the quotient between the differential voltage and the leakage current. For every circuit, measurements were performed under different stable relative humidities from 30% RH to 90% RH (measurements at lower RH preceded measurements at higher RH). For circuit 1, a series of measurements of EI was subsequently made at approximately 60% RH, after deliquescence of ammonium sulfate aggregates on the legs of the SMC.

The maximum electrical resistance detectable with the multimeter and 200 volt power supply was approximately 28.5 TΩ. To check multimeter performance, repeated measurements were made with several precision resistors in the range of $10^8$ to $10^{13}$ Ω. These same measurements were performed using another calibrated pico-ammeter (Keithley Model 674). The differences in measurements of electrical resistance were less than 3%. Measurement precision was also assessed using a SMC circuit. In successive measurements between type II legs of a clean SMC as a function of relative humidity, the relative standard deviation of the measured resistance was ~ 20%.

Television set reliability was assessed by visual observations of screen displays while televisions received the signal from the video display pattern generator.

Electronic circuit features were observed with an optical microscope (Micromaster EL). The microscope had a total magnification of 40.

## RESULTS

### Observations

Television screen displays were periodically monitored during the 281 hour exposure test. Relative humidity was 25-52% during the test. Subsequently, television sets were exposed in EC1 for 20 hours without high concentrations of particles, to a relative humidity varying from 70% RH to 90% RH. No malfunctions were observed even with relative humidity above ammonium sulfate CRH (81% RH).

Exposed television sets were inspected. Particle aggregates were observed both inside and outside the devices on various surfaces such as the screen displays and interior electronics. Particle deposition was spatially very uneven. During the approximately 12-day experiment, dendritic accumulations of particles up to a few millimeters in length were observed to grow from the televisions' external surfaces. Particle aggregates formed several bridges (a few millimeters long) between the television sets and the rack supporting them. Particle accumulations appeared to be influenced by the electrostatic field created by the televisions; for example, the aggregates were perpendicular to the television walls when the televisions were on and directed downwards, when the television was turned off.

The legs of SMCs were visually inspected. The highest levels of particle accumulation were observed between adjacent type II legs with a differential voltage (see Figure 3). Locations of high particle deposition included the sharp edges and especially at the sharp bends of the legs of the SMCs. However, particle accumulation was also observed between legs that were grounded (legs of type I).

Microscopic examinations revealed the presence of agglomerations of ammonium sulfate particles that occasionally bridged adjacent legs of SMCs. Bridges of particles were spatially non-uniform. They were not exclusively located between adjacent legs exposed to a high differential voltage -- we observed uneven particle accumulation between legs of both types, even on grounded legs. However, the accumulation of deposited mass was dramatically enhanced on legs exposed to a high differential voltage. Deposition patterns between the high voltage legs were bulky, whereas bridges of deposited particles were thinner for circuits with conductors at low voltage or ground. Moreover, we could observe the presence of fibers within some of the finer agglomerations of particles. Fibers could not be observed within heavier accumulations of particles, possibly because the deposited particles obscured the fibers. In the absence of fibers, finer agglomerations of particles were preferentially located at the sharp bends of the legs including bridges between adjacent bends in legs.

Figure 4 shows particle deposition patterns between legs of chips at various relative humidities. It was clearly observed that for higher relative humidities (above 81% RH), ammonium sulfate particle aggregates between adjacent legs of chips disappeared after deliquescence, whereas non-hygroscopic fibers persisted.

The surfaces of the circuit boards were also inspected and particle accumulation was observed at two distinctive recurrent locations on the circuit boards with a high differential voltage: a) between the pair of surface traces (on the circuit board) exposed to a high differential voltage; and b) on the thin edges of the circuit board, in the vicinity of the conducting traces exposed to high voltage.

## Electrical isolation measurements

EI between adjacent legs of SMCs was measured before and after the circuits' exposure to the highly concentrated particle mixture. Similarly, EI was measured before and after the control circuits were exposed to normal laboratory air in EC2. The circuits are respectively referred to as "clean", "exposed" and "control". As shown on Figure 5, the EI between adjacent legs of type II showed a large (approximately exponential) decrease with increasing relative humidity. The EI for SMC circuits exposed to a high differential voltage decreased by approximately 3 orders of magnitude (from approximately $10^{15}$ Ω to $10^{12}$ Ω) when RH increased from 35% RH to 65% RH.

The EI for circuits 1 to 4 (vertically oriented with high voltage) decreased by several orders of magnitude after exposure to the high concentration of particles. For these circuits, at 60% RH, the ratio between EI on exposed circuits to EI on clean circuits varied from 1:600 to 1:5,000. On the other hand, for circuits

5 to 8 (vertically oriented, low voltage) and 11 to 13 (vertically oriented, grounded), this ratio was smaller than 1:20, at 60% RH. (Circuit 10 had an elevated ratio of 1:1,000 due to the high EI of the clean circuits.) For the control circuits, the post-exposure values of EI were essentially unchanged from the pre-exposure values.

Figure 6 shows the range of the measured EI on clean and exposed circuits for the three differential voltages at a relative humidity of 60% RH. Low voltage and grounded circuits exposed to high concentrations of particles have EIs in the same order of magnitude compared to clean circuits[3]. Circuits exposed to a high differential voltage have EIs that are about a factor of 1000 lower (from TΩ to GΩ) after particle exposure. .

The influence of deliquescence of the deposited particles on EI was studied. EI, at approximately 60% RH, between adjacent legs of SMC circuit 1 were measured twice -- once, before deliquescence of deposited ammonium sulfate and once, after obtaining deliquescence by exposure to RH above 80%. EI was 20% lower after deliquescence, which is not a significant change given the measurement precision.

At 90% RH, EI on circuit 3 was initially approximately 3.2 MΩ. However, the EI on circuit 3 was not stable at 90% RH and dramatically decreased with time. Although EI continued decreasing, we stopped the electrical measurements at 8.93 kΩ to prevent equipment damage. Circuits 1 and 2 did not exhibit this instability at 90% RH. Subsequent microscopic observations of the surface of SMC circuit 3 revealed evidence of burns linking inter-trace conductors at the location where the legs of the chip extend to the surface of the circuit board.

## DISCUSSION

Tests with the television sets did not demonstrate that exposure to high concentrations of particles caused premature failures. The absence of television set failures was surprising. Two potential explanations follow. First, deliquescence of deposited particles in the television sets during experiments with high humidity may have been prevented by the elevated (but unmeasured) air temperatures inside the television sets, relative to air temperatures surrounding the televisions. Due to the higher temperatures inside the televisions, the relative humidity inside televisions may have been lower than the critical relative humidity of ammonium sulfate. Second, the spacing between electronic conductors in the television electronics was larger than that in the most modern electronics.

Experimental results showed that the electrical isolation of the SMC circuits was, in many cases, substantially decreased after particles deposited on

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[3] The EI range for clean grounded circuits on Figure 6 is affected by the unusually high EI of Circuit 10 prior to particle exposure.

the circuits. Also, electrical burns occurred on one SMC exposed to a high concentration of particles and to a high humidity.

The particle accumulation on the SMC circuits and the television sets was spatially very uneven. The locations of deposited particles indicated very clearly that electrostatic forces have a strong influence on particle deposition rates and locations.

The experiments indicate that particle accumulation on SMC circuits and episodes of high RH are two independent processes that can together cause considerable drops of EI between adjacent conductors of SMC circuits. EI decreased approximately exponentially with increasing RH, in some cases from $10^{12}\Omega$ at 30% RH to $10^{6}\Omega$ at 90% RH. These results corroborate previous findings where EI of circuits exposed to various dusts was measured as a function of relative humidity [5,6]. The EI ranges in electronics taken from field settings, measured at a similar relative humidity, are comparable to our results.

In our experiments, only one SMC circuit showed an extreme decrease of EI at high RH (circuit 3). This decrease resulted in surface trace conductor deterioration <u>on</u> the circuit-board (where the legs of the SMC connect to the surface trace conductors), whereas particle accumulation occurred primarily between the legs of the chips, i.e., <u>above</u> the circuit-board. The previous research also found that the EI decreased dramatically as RH increased and that the decrease in EI was more pronounced as the RH reached the CRHs of dusts [5].

The failure threshold for digital and analog circuits as dust contamination becomes more conductive was assessed previously [5]. Based on a model, complete functional failure was predicted to occur when the parasitic resistance between adjacent leads of conductors drops to approximately 1 MΩ. Based on this criterion, some of the EI decreases in our study are significant enough to affect electronics reliability.

Ammonium sulfate particles bridging between adjacent legs of the SMCs was frequently observed in conjunction with the presence of fibers. It appears that the fibers between adjacent legs of SMC circuits provide a substrate for bridging by particles. In addition, we observed that particle accumulations bridging adjacent legs systematically disappeared after deliquescence of the hygroscopic matter, whereas non-hygroscopic fibers still persisted (as shown on Figure 4). Hence, by providing fine particles with a substrate for deposition and a pathway between adjacent conductors, fiber deposition appears to be a potentially important factor for the reliability of electronic equipment.

In the light of these observations, we suggest the following understanding of the contamination process. First, hygroscopic particles accumulated between adjacent legs of the SMC to form a bridge, sometimes depositing on fibers already present between legs, under the influence of the electric field. Then, when the RH reached the CRH the deposited matter deliquesced and flowed over the legs (due to capillarity and/or gravity), occasionally reaching the circuit-board surface. Finally, during high humidity episodes, deliquesced matter sometimes formed a new bridge between surface-trace adjacent conductors at their junction with the legs of the SMC. This theory is consistent with: (a) the low EI measured on circuit 1 at 60% RH, after deliquescence, even in the absence of visible bridge between adjacent legs; and (b) the degradation of the circuit board observed for circuit 3.

The source of the fibers observed on the SMC boards is uncertain. Presumably some fibers deposited from laboratory air before the SMCs and televisions were sealed in the exposure chambers. Also, some fibers may have been from the cotton swabs used to clean the SMC circuits before they were installed in the exposure chambers. Since fibers and large particles are present in normal indoor air, fiber and large particle deposition on circuits would be a normal occurrence. The SMCs had a very limited period of exposure to normal airborne fibers (a few days) but the exposed SMCs and televisions had the equivalent to ~ 16 years of exposure to fine particles.

Efficient air filters have been used to reduce electronics failure rates caused by indoor air pollution [2, 7]. Our experimental results point to another option -- a modification of the geometry of the legs of the SMC circuits. We found that particles tended to deposit preferentially at the sharp bends in the legs of the SMCs presumably because of the strong electric field created by these sharp bends. Smoothing or eliminating the bends in the legs, i.e., increasing their radius of curvature, would reduce the particle deposition at these locations.. Hence, smoothing or eliminating the sharp bends in the legs of SMCs could be an innovative method to reduce failure rates in electronics.

## SUMMARY AND CONCLUSIONS

We have shown that particle deposition results in significant drops in EI between adjacent legs of chips of electronic components, although we did not prove that deposition of hygroscopic particles causes premature failure of a typical electronic device (television). Moreover, we found that EI decreased by several orders of magnitude with increased relative humidity below the CRH of the particles deposited on the circuit board. Fine particle accumulation on electronic circuit features was found to be spatially very uneven. Based on the locations of heavy particle deposition, it is evident that electrostatic forces substantially enhance particle deposition at certain locations within circuits.

This research suggests a possible scenario for hygroscopic fine mode particle contamination of electronic components, that reveals the importance of fibers during the deposition mechanism. Hence, future experimental research would be more realistic if the air surrounding the electronic equipment contains both fine particles and coarser particles and especially fibers. Lastly, this paper suggests that the failure rates of electronic equipment may be decreased by smoothing or eliminating the sharp bends in the legs of surface mounted chips.

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## REFERENCE

1. Weschler, C. (1994) Personal communication, Dr. Charles Weschler, Distinguished Member of the Professional Staff, Bellcore, Red Bank, NJ.
2. Weschler, C.J.; Shields, H.C. "The impact of ventilation and indoor air quality on electronic equipment" *ASHRAE Transactions*, vol. 97, 1991, pp. 455-463.
3. Sinclair, J.D.; Psota-Kelty, L.A.; Weschler, C.J.; Shields, H.C. "Measurement and modeling of airborne concentrations and indoor surface accumulation rates of ionic substances at Neenah, Wisconsin" *Atmospheric Environment*, vol 24A, No. 3, 1990, pp. 627-638.
4. Cooper, D.W. "Particulate contamination and microelectronics manufacturing: an introduction", Particle *Science and Technology*, vol 5, 1986, pp. 287-299.
5. Burnett, W.H.; Sandroff, F.S.; D'Egidio, S.M. "Circuit failure due to fine mode particulate air pollution", Proceedings *of the ISTFA '92*, Los Angeles, CA, October 1992, pp. 329-333.
6. Frankenthal, R.P.; Siconolfi, D.J.; Sinclair, J.D. "Accelerated life testing of electronic devices by atmospheric particles: why and how" *Journal of Electrochemical Society*, vol 140, No. 11, November 1993, pp. 3129-3134.
7. Weschler, C.J. "Predictions of benefits and costs derived from improving indoor air quality in telephone switching offices" *Indoor Air*, 1991, vol 1, pp. 65-78.
8. Nazaroff, W.W.; Gadgil, A.J.; Weschler, C.J. "Critique of the use of deposition velocity in modeling indoor air quality" *American Society for Testing and Materials*, N.L. Nagda, Philadelphia, 1993, pp. 81-104.
9. Turk B.H.; Grimsrud, D.T.; Brown, J.T.; Geisling-Sobatka, K.; Harrison, J.; and Prill, R.J. (1989). "Commercial building ventilation rates and particle concentrations", *ASHRAE Transactions*, vol. 95, Part 1, pp. 422-433

Table 1. Experimental parameters during the Phase 1 exposure test.

*PHYSICAL PARAMETERS:*

EC1

Temperature : $T_{MIN}$ = 22.7 °C
$T_{MAX}$ = 28.7 °C
$T_{AVERAGE}$ = 25.7 °C (Standard deviation: 1.2 °C)
Relative Humidity: $RH_{MIN}$ = 25%
$RH_{MAX}$ = 51%

*PHYSICAL PARAMETERS:*

EC1

Temperature : $T_{min}$ = 22.7 °C
$T_{max}$ = 28.7 °C
$T_{average}$ = 25.7 °C (Standard deviation: 1.2 °C)
Relative Humidity: $RH_{min}$ = 25 %
$RH_{max}$ = 51%
$RH_{average}$ = 42% (Standard deviation: 6.3%)
Aerosol concentration : 15,300 $\mu g/cm^3$
Time of exposure : 281 hours

EC2

Temperature : $T_{min}$ = 22.2 °C
$T_{max}$ = 27.9 °C
$T_{average}$ =24.1 °C (Standard deviation: 0.9 °C)
Relative Humidity: $RH_{min}$ = 10 %
$RH_{max}$ = 48 %
$RH_{average}$ = 23% (Standard deviation: 7%)
Time of exposure : 281 hours

Ambient laboratory air

Temperature : $T_{min}$ = 21.3 °C
$T_{max}$ = 25.9 °C
$T_{average}$ =23.2 °C (Standard deviation: 0.6 °C)
Relative Humidity: $RH_{min}$ = 10 %
$RH_{max}$ = 53 %
$RH_{average}$ = 26 % (Standard deviation: 8 %)

*ELECTRONIC PARAMETERS:*

EC1

Circuits 1-4 : Voltage = 240 VDC Orientation = vertical
Circuits 5-9 : Voltage = 10 VDC Orientation = vertical
Circuits10-14 : Voltage = GROUND Orientation = vertical
Circuits 15-20 : Voltage = GROUND Orientation = horizontal
Television sets 1-10.

EC2

Circuits A-B : Voltage = GROUND Orientation = vertical
Television sets A-B-C-D.

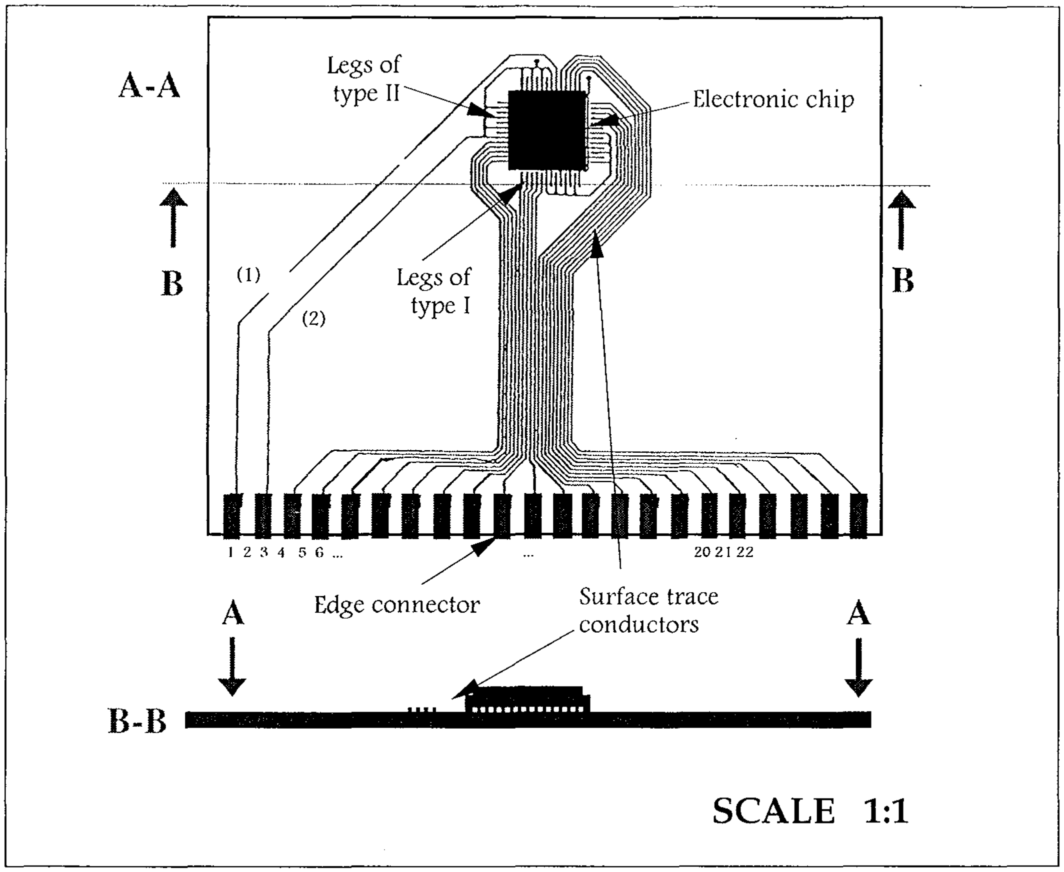


Figure 1. Layout of surface trace conductors and surface mounted chip circuit. A differential DC voltage was applied to type II legs via connectors 1 and 2.

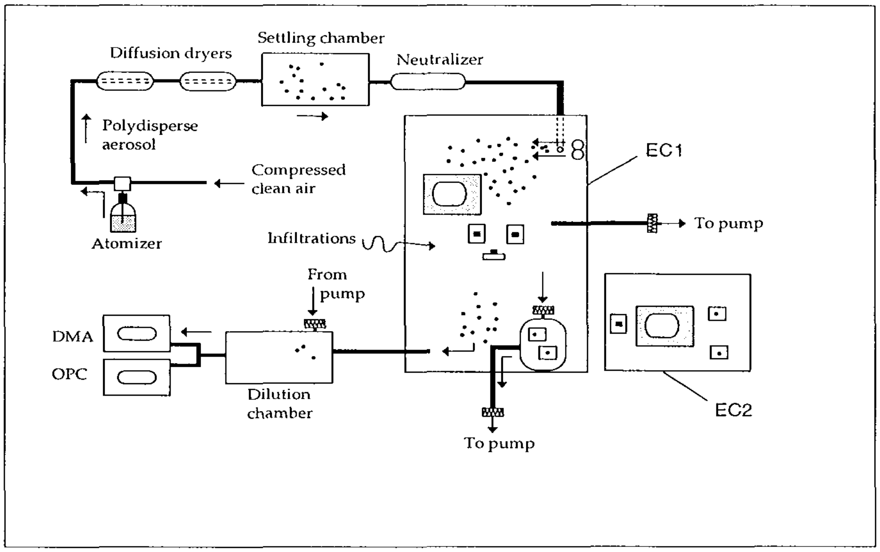
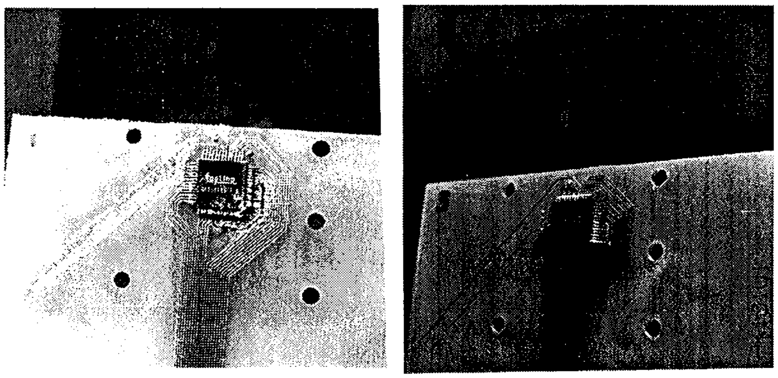
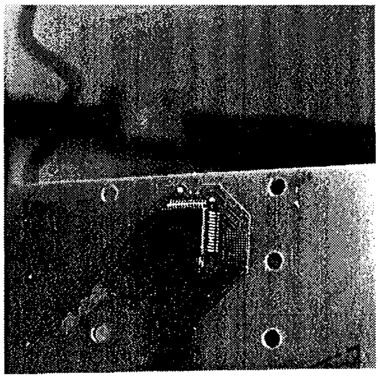


Figure 2. Diagram of primary experimental apparatus.

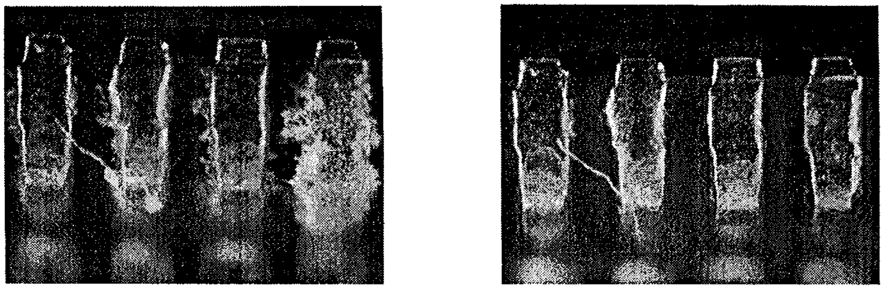


**High voltage** **Low voltage**



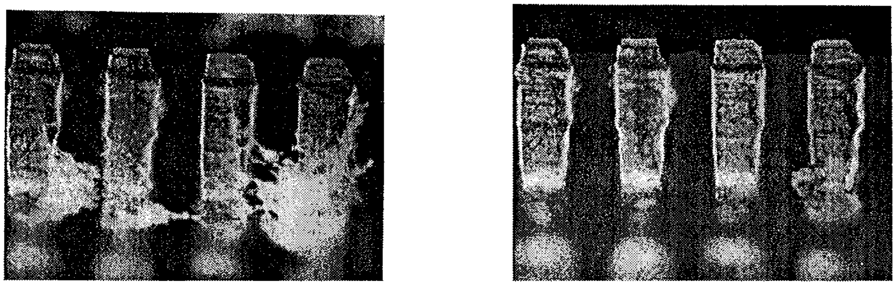
**Ground**

Figure 3. Ammonium sulfate agglomeration between adjacent legs of SMC circuits. Particles aggregates (white in color) deposited preferentially between legs of SMCs exposed to a differential voltage.



Low voltage, 60 %RH
[a]

Low voltage, > 85 %RH
[b]



High voltage, 65 %RH
[c]

High voltage, > 85 %RH
[d]

Scale 1:20

Figure 4. Particle deposition pattern between legs of SMCs exposed to high and low differential voltage before and after deliquescence. [a] and [b] show the same legs of SMC Number 5. [c] and [d] show the same legs of SMC Number 1.

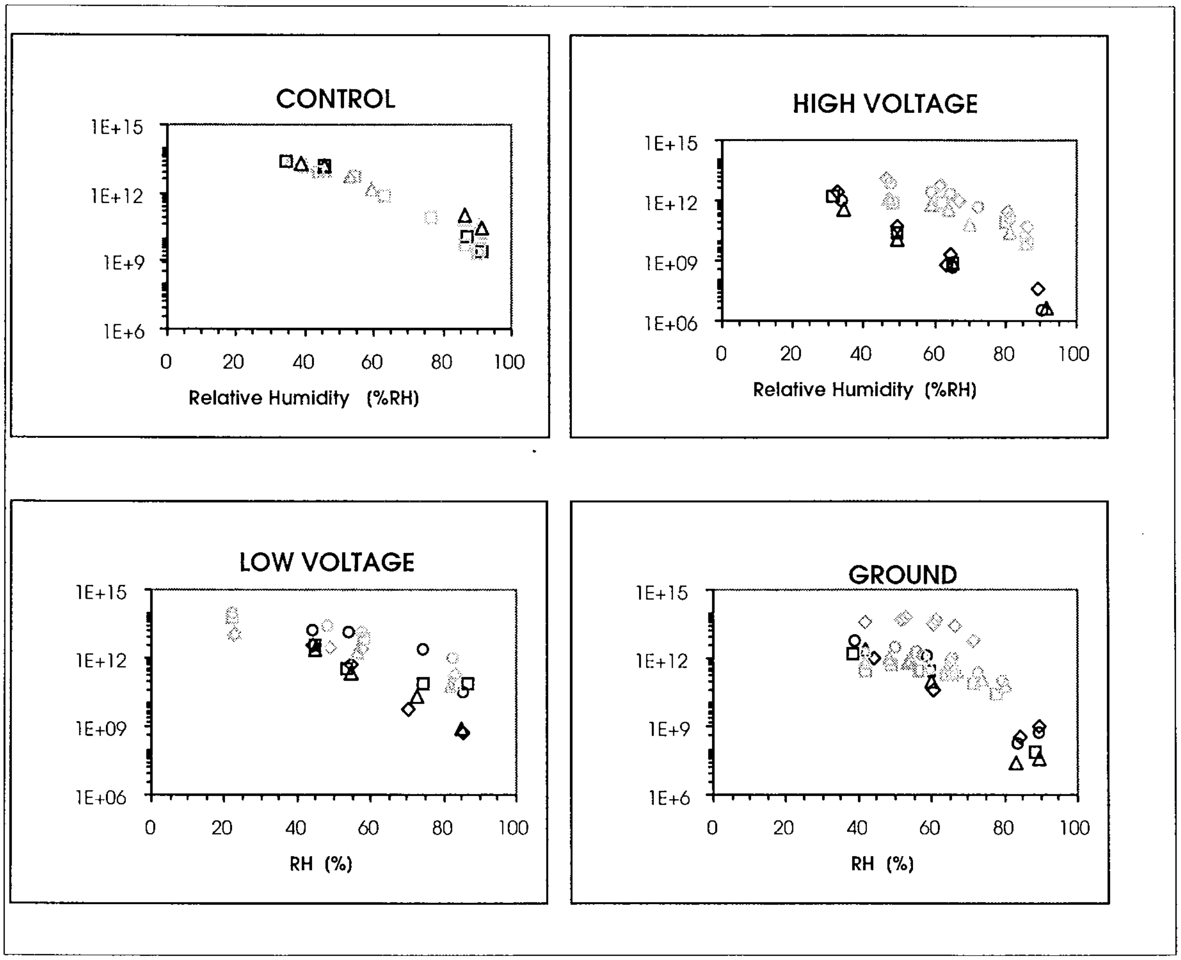


Figure 5. Electrical isolation as a function of relative humidity, showing exponential relationship. On each plot, a unique data point style represents a unique circuit. Dark data points are used for exposed circuits.

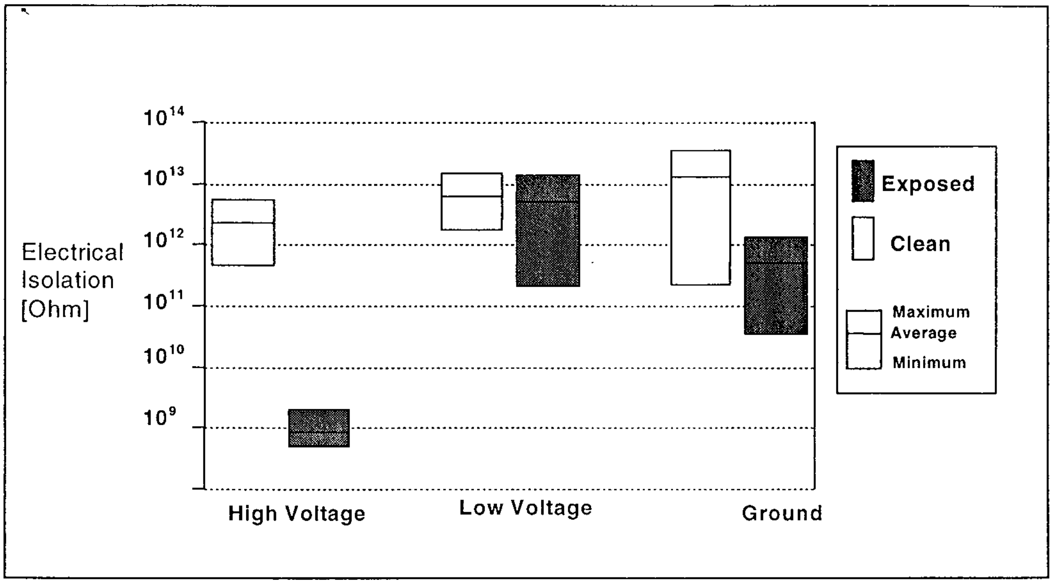


Figure 6 Range of electrical isolation at 60% RH on clean and exposed circuits for the three differential voltages.