Deposition of aerosol (‘‘hygroscopic dust’’)
on electronics – Mechanism and risk

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Abstract

In this paper the risk associated with deposition of aerosol (‘‘hygroscopic dust’’) on printed circuit boards is assessed for different equipment designs and deployment. The amount of deposited dust is related to (1) the total dust availability in a given type of equipment and (2) to the rate of deposition of dust due to different mechanisms. Of these, the Brownian diffusion, gravitational settling, thermophoresis and electrophoresis are of different relative importance depending on such design factors as air flow in the enclosure, temperature gradients between boards and walls and presence of electric fields. The expressions for electric fields in the vicinity of printed circuit boards relevant to electrophoretic deposition are derived. It is shown that not only the sealed Absolute Humidity Control Modules but also the breathing Relative Humidity Control Modules should not present a hygroscopic dust risk for either indoor or outdoor applications. Direct air cooled system with forced convection present a definite dust reliability risk both for indoor and outdoor applications while open natural convection cooled systems present a borderline case where each design has to be considered separately.

1. Introduction

Electronic equipment, especially in the telecommunication field, is known to be prone to failure at elevated humidity due to deposition of hygroscopic dust on printed circuit boards [1]. It is known that the presence of water soluble impurities leads to surface resistance degradation at high relative humidity [2]. It is also known that hygroscopic dust is always present in the atmospheric air but is particularly plentiful in industrialized urban environment [3]. Its particle size centers around 0.5 \( \mu \text{m} \) [4] and thus filters in central office buildings have only limited success in the removal of this type of particulate matter [5]. Sensitivity of functional printed circuit boards to surface resistance degradation varies and is thus a subject to a qualification procedure [6]. Making sure that such sensitivity is low is one way of alleviating the hygroscopic dust problem. This could be achieved through a careful selection of components, isolation of particularly sensitive ones and/or conformal coating of boards. Yet another approach is to control the relative humidity at critical surfaces [7]. The most direct way of preventing the dust problem is to limit the amount of deposited hygroscopic dust through design. This requires a thorough understanding of the factors governing the availability of the dust and the deposition rates.

In this paper the physical basis of the dust ingress into enclosures and deposition mechanism on printed circuit boards is addressed with the view to derive a predictive methodology for assessment of the dust risk for a given type of equipment design. The Brownian diffusion for both dust ingress and deposition process will be discussed along with deposition through gravitational settling, thermophoresis and electrophoresis. A detailed treatment of aerosol physical chemistry is given in monographs [8–10]. The basis of surface resistance degradation and the related critical contamination values will be also discussed. The derived predictive methodology will be demonstrated on a set of...
design examples and generalizations on applicability of these designs will be drawn.

2. Mechanism of dust deposition

2.1. The notion of deposition velocity

Typically, mass transfer of a substance is described in terms of flux density \( J \), i.e., in the case of surface deposition the amount of the substance deposited per area per time is given by

\[
J = \frac{1}{A} \frac{dN}{dt}
\]

with customary units of \([\mu g/cm^2 s]\). Since the mass transfer is usually assumed to be proportional to concentration of the substance, it is natural to define the properties of the substance as the ratio of \( J \) to the dust concentration in air \( c \).

\[
v_d = J/c = \left( 1/4c \right) \frac{dN}{dt}
\]

If the concentration is measured in \( \mu g/cm^3 \), the defined value \( v_d \) has a dimension of \([cm/s]\) and is thus called “deposition velocity” [9,11]. Generally, it should be understood as the proportionality coefficient between the average flux and concentration although it could be interpreted also as the average physical velocity of a set of particles arriving at the surface \( A \) (see Fig. 1).

Literature data concerning dust deposition rates and airborne concentrations frequently refer to a given ion (sulfate, chloride, sodium, etc.) while the “magic number” refers to the total mass of deposited particles. One has to be careful when doing this type of estimations since different ions are frequently shown to have different deposition velocities. This means that they are associated with particles of different size and origin.

2.2. Depletion of dust in a closed module

In a closed container (no exchange with the environment), the concentration of a species is related to its mass \( m \) as \( c = m/V \) and thus the rate of change of the dust concentration in air due to deposition can be described as

\[
\frac{dc}{dt} = -\frac{(dm/dt)}{V}
\]

where the variable are defined in the caption of Fig. 1. Since \( (dm/dt) = AV_v c \) (\( A \) is here the total surface of the walls and printed circuit boards in the module) we have

\[
\frac{dc}{dt} = -cAV_v /V
\]

This can be solved for the initial conditions of \( t = 0 \) and \( c = c_0 \) giving

\[
c = c_0 \exp(-t/\tau)
\]

where \( \tau = V/A V_d \) is the time constant for dust deposition. The surface contamination of the deposited dust after time \( t \) will be equal to

\[
\mu = \mu_{max} \left[ 1 - \exp(-t/\tau) \right]
\]

where \( \mu_{max} = (Vc_0/A) \) is the maximum surface contamination for closed systems which will occur when all the available dust is deposited, and is the limiting contamination value for many enclosure designs in which air exchange is slow. Eqs. (5) and (6) were derived without any reference to the actual mechanism of dust deposition which would help us estimate the values for the deposition velocity \( v_d \).

Besides, in some circumstances, especially with electrophoretic deposition \( v_d \) may be influenced by deposition of conductive or non-conductive material and, therefore, not constant.

2.3. Deposition by diffusion or Brownian motion

(a) Stagnant air. Let us consider an infinitely large volume of air with the dust concentration \( c \). If there is absolutely no movement of air, the kinetics of dust deposition can be obtained [12] from a solution of the Fick’s second law equation

\[
\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2}
\]

where \( D \) is the diffusion (or Brownian motion) coefficient of dust. Solving (7) for the case of one-dimensional diffusion and with the conditions of (1) \( c = c_0 \) at \( t = 0 \) and \( x > 0 \) and (2) \( c = 0 \) at \( x = 0 \) and \( t > 0 \) the distribution of dust concentration in air is as in Fig. 2 and the amount of dust deposited on the wall can be approximated [9,10,12] for short time (or, equivalently, for large stagnant volumes) by

\[
N(t) = 2c_0 A \sqrt{Dt/\pi}
\]

(b) Stirred air. Completely stagnant air does not exist except for very small containers. Air always moves through convective forces and/or through imposed fan action. In this situation the mathematically easiest approach is to assume that the air movement averages the dust concentration everywhere except for a thin boundary layer close to
the surface. In this model the diffusion has a steady state character with a linear concentration gradient as in Fig. 3

\[ J = \left( \frac{D}{d} \right) c_0 \]  

Comparing Eqs. (9) and (2) we can see that in this situation the deposition velocity is related to the diffusion constant as

\[ v_d = \frac{D}{\delta} \] (boundary layer)

Thus, in order to be able to estimate dust deposition on a board we have to be able to estimate the diffusion constant \( D \) and the boundary layer thickness \( \delta \).

2.3.1. Estimating diffusion coefficients for the Brownian motion of dust

According to Einstein [13], the diffusion coefficient of a particle undergoing Brownian motion in gas can be described as

\[ D = \frac{k_B T}{f} \] (11)

where \( k_B \) is the Boltzmann’s constant and \( f \) is the so called friction factor. When Brownian motion of aerosol particles are considered, we encounter two extreme cases: (1) **Particles very large**, i.e., the particle diameter much larger than the free mean path of air \( (d_p \gg \lambda) \). For these particles the friction coefficient can be calculated [8,9] from the Stokes expression characterizing the motion of bodies in fluids, (2) **Particles very small**, \( (d_p \ll \lambda) \). For these particles the friction coefficient can be calculated from an expression of the kinetic theory of gasses which is used to calculate diffusion coefficients of molecules in gas phase. For the (3) intermediate cases where the values of \( d_p \) are comparable with \( \lambda \) there is no theory and an empirical interpolation is applied. When combining all the three regions, it is customary to use a Stokes type equation for the friction factor

\[ f = \frac{3\pi \eta d_p}{S_C} \] and \[ D = \frac{k_B T}{3\pi \eta d_p S_C} \] (12)

where \( \eta \) is air viscosity and a correction coefficient, the so called Cunningham’s slip factor \( S_C \) was introduced which is given empirically [9] as

\[ S_C = 1 + \frac{1}{d_p} \left[ 2.514 + 0.800 \exp \left( -0.55 \frac{d_p}{\lambda} \right) \right] \] (13)

The shape of the expression (13) for the slip factor is such that the friction coefficient reduces to the Stokes equation for \( d_p \gg \lambda \) and approaches the molecular theory equation for \( d_p \ll \lambda \). Slip correction factors range from 1 for particles with \( d_p > 2 \text{ } \mu \text{m} \) to 216 for \( d_p = 1 \text{ } \mu \text{m} \). Thus calculated diffusion coefficients for different particle sizes are shown in Fig. 4.

2.3.2. Dust ingress into enclosure through openings

It is obvious that in the case of most interest to us \( (i.e., 0.1-1.0 \text{ } \mu \text{m} \text{ size}) \) dust diffusion coefficients are many orders of magnitude smaller than coefficients for particles of molecular size such as water in air which is 0.24 \( \text{cm}^2/\text{s} \) [14]. Thus the ingress of dust into a module will be much
slower. For example, a crack or an opening with 1 hr time constant for moisture ingress will have a 4 years (!) time constant for 0.1 μm aerosol. If this is the only route of dust ingress, one should not expect any dust related reliability problems. However, in outdoor condition there may be also dust ingress driven by “breathing” or atmospheric pumping caused by daily temperature variations. For daily variations between (absolute) temperatures \( T_0 \) and \( T_1 \) it can be easily shown that the concentration of dust inside the container after \( N \) daily cycles \( c_{iN} = c_a[1 - (T_0/T_1)^N] \) where \( c_a \) is the ambient dust concentration. The shape of this equation does not allow one to define a time constant in the usual sense. However, purely for comparative sense we define the initial “time constant” \( \tau_0 \) as time in which the inside dust concentration \( c_{iN} \) assume 1−1/e of the ambient value, we get \( \tau_0 = [\ln(T_1/T_0)]^{-1} \). For diurnal temperature variations of 20 °C, \( T_1/T_0 = 1.067 \) and \( \tau_0 = 15 \) days. Therefore, breathing may be much more important route of aerosol ingress than diffusion. However, the modern Relative Humidity Control Modules for outdoor applications involve porous diffusion plugs which allow movement of water vapour but stop particulate matter [7].

2.3.3. Estimating the boundary layer thickness for dust (laminar flow)

When considering the boundary layer the proper meaning of this notion should be clarified [11]. The boundary layer which is used in fluid mechanics is the momentum boundary layer and it depends on the momentum diffusivity of the fluid, which is 0.15 cm²/s for air. In heat transfer the thermal boundary layer is related to the thermal diffusivity of air equal to 0.24 cm²/s. Since these two diffusivities have similar values, their respective boundary layers are practically of the same thickness. With the diffusion of small particles like gas molecules the boundary layer thickness is still very similar to the momentum and thermal ones because the diffusivities (diffusion coefficients) are very similar. E.g., water in air has \( D = 0.24 \text{ cm}^2/\text{s} \). Thus, when considering surface deposition of small MW impurities like water, ozone or nitrogen oxides, the boundary layer values from fluid mechanics can be applied. However, this is not the case for aerosol deposition. Their diffusion coefficients being much smaller, the related diffusion boundary layers are much thinner than with momentum transfer. The thicknesses of the respective layers are related [15] through the scaling relation \( \delta_{\text{mom}}/\delta_{\text{conc}} = (v/D)^{1/3} \) where the ratio of kinematic viscosity to the diffusion coefficient, \( v/D \), is known as the Schmidt number, \( S_c \). It is worth stressing that a thinner boundary layer does not necessarily mean faster deposition because \( \nu_{d} = D/\delta_{\text{conc}} \) and \( D \) scales stronger than \( \delta \).

Actual expressions for \( \delta \) as a function of air velocity are also a function of the distance \( x \) from the air inlet and are thus different for different positions on the board surface [8].

\[
\delta_{\text{mom}} = 1.72 \sqrt{\frac{v}{x h}} \quad (14)
\]

Expressions for values averaged over surface areas are available in literature [11,15] but from our point of view they are of limited utility as we are interested in dust concentration in a given area of the board. For the purpose of this paper it is sufficient to know that the appropriate scaling property for \( \delta \) is [16]

\[
\delta \propto \frac{1}{\sqrt{u_{\infty}}} \quad (15)
\]

where \( u_{\infty} \) is the air speed and that, because \( \nu_{d} = D/\delta \), the deposition velocity scales as

\[
\nu_{d} \propto \sqrt{u_{\infty}} \quad (16)
\]

This enables one to estimate \( \delta \) and \( \nu_{d} \) for different \( u_{\infty} \) values from \( \delta \) and \( \nu_{d} \) values determined experimentally for one particular condition. For instance, although a rather wide distribution of deposition velocities is observed, for the average air speed near the wall of ca. 5 cm/s [1], the deposition velocity for the dust in central offices with the size centered around 0.5 μm [1,4] may conservatively chosen to be ca. 0.005 cm/s [1,3]. As far as the effect of particle size is concerned, values of \( \delta \) scale as \( D^{1/3} \). Since \( \nu_{d} = D/\delta \), the deposition velocity scales as

\[
\nu_{d} \propto D^{2/3} \quad (17)
\]

Thus estimated deposition velocities are shown in Fig. 5. The approximate character of such predictions is sufficient for risk assessment.

2.4. Gravitational settling

Gravitational settling is relatively unimportant with very small particles but it increases proportionally to the particle size. The terminal (steady state) settling velocity is

\[
\nu_{t} = \frac{\rho d^2 g}{18 \eta} S_c \quad (18)
\]

![Fig. 5. Deposition velocity as a function of air flow for different sizes of particles.](image-url)
where \( \rho \) is the particle density and \( S_C \) is, again, the slip correction factor which is only important for small aerosols. Fig. 6 shows the relative importance of this mode of particle deposition for the vertical particle motion. When compared with Brownian deposition from flowing air movement at the typical 5 cm/s, the relative importance of gravitational settling is rather small. On the other hand, gravitational settling becomes relatively more important if the air is flowing very slowly (\( \lesssim 0.5 \text{ cm/s} \)) or is stagnant. This means that we should expect more deposition on horizontal surfaces than on vertical ones and this is, indeed the case [1].

### 2.5. Thermophoretic deposition

A particle in a temperature gradient (e.g., between two boards of different temperature) will be subjected to a greater momentum transfer from air molecules on the hot side than on the cold side. This will result in a net force pushing the particles towards the colder surface. For particles small in comparison with the mean free path of air (\( d_p < \lambda \), in practice for \( d_p < 0.1 \mu m \)) the theoretically derived thermophoretic velocity [9] in air is independent of the particle size and is

\[
v_{th} = \frac{-0.55\eta}{\rho_{air} T} \nabla T (d_p < \lambda) \tag{19}\]

In standard conditions (20 °C, atmospheric pressure) the proportionality factor between the velocity and the temperature gradient in Eq. (19) amounts to \(-2.8 \times 10^{-4} \text{ cm}^2/\text{s K}\). With larger particles (\( d_p > \lambda \)) the velocity is weakly dependent on particle size through a coefficient \( H \approx (k_{air}/k_p + 4.4\lambda/d_p)/(1 + 6\lambda/d_p)(1 + 2k_{air}/k_p + 8.8\lambda/d_p) \) which depends on the temperature gradient inside the particle and is thus a function of the particle diameter and thermal conductivities of air \( k_{air} \) and of the particle material \( k_p \) [9] and the slip correction factor \( S_C \).

![Dust deposition velocity on printed circuit boards due to different deposition modes.](image)

Fig. 6. Dust deposition velocity on printed circuit boards due to different deposition modes.

The proportionality coefficient in Eq. (20) for the particle sizes of 0.1–1.0 \( \mu m \) ranges typically from \(-2.0 \times 10^{-4} \text{ cm}^2/\text{s K} \) to \(-1.0 \times 10^{-3} \text{ cm}^2/\text{s K} \).

The relative importance of this mode of dust deposition is compared in Fig. 6. We can see that the relative importance of thermophoresis (at the realistic gradient of 1 °C/cm encountered when, e.g., we have in a module two printed circuit boards 5 cm apart and one of them is 5 °C hotter than the other) and that of gravitational settling are similar for 0.1–1 \( \mu m \) range but the diffusional deposition out of air flow is at least an order of magnitude higher.

### 2.6. Electrophoretic deposition

#### 2.6.1. Charges on dust particles

Under normal atmospheric conditions, due to cosmic radiation and natural radioactivity there are about 1000 ions per every cm\(^3\) of air, of approx. equal amount of each charge. The consecutive processes of collisions, acquiring and losing charges eventually lead to establishing an equilibrium charge distribution in particles known as Boltzmann equilibrium. In Boltzmann equilibrium an approximation for the average charge (absolute value in \( e \) units) on particles of a given size is [9]

\[
\bar{n} = 2.37\sqrt{d_p} \tag{21}\]

with \( d_p \) in \( \mu m \). This approximation becomes numerically accurate for \( d_p > 0.1 \mu m \).

The electrophoretic deposition velocity (\textit{vide infra}) is linear with regards to the particle charge and the average deposition velocity will be thus function of the average charge of the particles. Average charges for atmospheric particles at Boltzmann equilibrium are given in Fig. 7. The particles can acquire a higher charge than due to Boltzmann equilibrium if very strong electric fields are present. This is the basis of the electrostatic dust removal. However, it only becomes significant at the kV/cm field level.

#### 2.6.2. Particle motion in the electric field

In an electric field of strength \( E \), a charged particle with \( n \) elementary charges will move with the terminal velocity

\[
v_w = \frac{neES_C}{3\pi\eta d_p} \tag{22}\]

which is analogous to the equation for gravitational settling [9]. The values calculated are shown in Fig. 6 for comparison with other deposition modes.

For the particle size range of 0.1–1.0 \( \mu m \) the charge is, on the average 1 or 2 elementary units. The electrostatic deposition rate becomes comparable with the gravitational settling at a field strength of 1.8 V/cm and, more interestingly, with the Brownian deposition from flowing air at 180 V/cm (see Fig. 6). With stagnant air the relative
importance of Brownian deposition is comparable with that of gravitational settling and thus electrodeposition would be relatively more important.

2.6.3. Electric fields near printed circuit boards

For the purpose of this study we will assume that traces on printed circuit boards can be approximated as charged wires. Let us consider two very long parallel traces with charges per unit length \(-\lambda\) and \(+\lambda\), respectively, separated by distance of \(d = 2a\) (see Fig. 8). Approximating traces as charged wires, the potential at any point is given [17,18] as

\[
V = \frac{\lambda}{2\pi\varepsilon_0} \ln \frac{r_1}{r_2} = \frac{\lambda}{2\pi\varepsilon_0} \ln \frac{(x + a)^2 + y^2}{(x - a)^2 + y^2}
\]  

The capacitance of the two trace system is [18,19]

\[
C = \frac{\pi\varepsilon_0 l_0}{\ln \left[ \frac{(d_w + 1) + \sqrt{(d_w + 1)^2 - 1}}{r_w} \right]}
\]  

(24)

Since \(\lambda = C\Delta V/l_0\) where \(l_0\) is the length of the trace, we have

\[
V = \frac{\Delta V}{2 \ln \left[ \frac{(d_w + 1) + \sqrt{(d_w + 1)^2 - 1}}{(x + a)^2 + y^2} \right]} \ln \frac{(x + a)^2 + y^2}{(x - a)^2 + y^2}
\]  

(25)

where \(w\) is the metal trace width. We are interested here in the electric field in the \(x\) direction in the plane \(x = 0\). At this plane the \(y\) direction field is zero. Differentiating Eq. (25) with the condition of \(x = 0\) we have

\[
(E_x)_{x=0} = \frac{\partial V}{\partial x}_{x=0} = \frac{\Delta V}{2 \ln \left[ \frac{(d_w + 1) + \sqrt{(d_w + 1)^2 - 1}}{(x + a)^2 + y^2} \right]} \left. \frac{a}{a^2 + y^2} \right|_{x=0}
\]  

(26a)

These considerations will be greatly simplified if we assume that for the commonly encountered geometries of the traces on boards the expression in the denominator in the above expression is unity (this will happen if \(a/r_w \ll 1.15\), i.e., when \(a\) and \(r_w\) are of the same order of magnitude). We have then

\[
(E_x)_{x=0} = \frac{\Delta V a}{a^2 + y^2}
\]  

(26b)

On the shortest path between the traces (on the surface of the board) \(y = 0\) and \(E_x = \Delta V/a\), which would be the electric fields inside a flat capacitor.

Assume that there are two copper traces on a line card, 1 mm (≈40 thou) apart with the typical telephony voltage of 48 V. The electric field as a function of the distance from the board is shown in Fig. 9. As mentioned above, for 0.5 \(\mu\)m dust particles in laminar air flow the electrostatic deposition is comparable to the Brownian one at and above 100 V/cm. Such field values extend up to 2 mm away from the board, i.e., well beyond the diffusional boundary layer which is ca. 0.12 mm for a rather quiescent air flow of 5 cm/s.

With lines of lower bias, e.g., 5 V, the fields strong enough to influence dust deposition do not extend beyond the boundary layer. Since dust inside the boundary layer will get deposited anyway, the role of the field will be only a change in the dust distribution pattern on the surface.
rather than a total increase in the amount of deposited dust. Since this effect favours deposition in the immediate vicinity of the lines and the area of a component solder attachment, it still can play a role in the circuit reliability.

2.7. Photophoresis

This is a particle motion mechanism in which the momentum transfer from light to the particle is the driving force. Interestingly, non-transparent particles will move away from the light source and transparent particles towards the source. Apparently, most of the momentum transfer happens at the back wall in the latter case. This is a relatively weak effect requiring strong light sources, e.g., lasers [9]. With no permanent light source inside the equipment this mechanism is not expected to play a significant role in electronics.

3. Surface resistance degradation by hygroscopic dust

3.1. Water condensation on impurities: the critical RH

Surface resistance degradation is the main mechanism of humidity related failures at all packaging levels [2,20,25]. If there is a deposit of a water soluble impurity on the surface, an additional mechanism of liquid water formation will be triggered [2,20]. Despite the common misconception, the impurity does not have to be ionic as long as it is water soluble and substances like sugar may be quite effective [20]. The real difference between the ionic and non-ionic impurities, however, will be in the conductivity of thus liquefied water. Also, ionic substances form two or more species upon dissolution.

When the relative humidity exceeds a critical value $\text{RH}_{\text{crit}}$, which corresponds to the water chemical potential of the saturated solution, water will condense until an equilibrium is established. In the context of hygroscopic dust we usually refer to this event as “deliquescence”. According to Robinson and Stokes [21] the relative humidity of vapour pressure of water over a solution of molality $c_m$ is (neglecting here the so called osmotic coefficient which is close to unity),

$$\text{RH}/100 = \frac{p(m)/p(0)}{\exp(-\beta c_m M_w/1000)}$$

where $\beta$ is the number of fragments formed through dissociation (e.g., $\beta = 3$ for $\text{NH}_4\text{HSO}_4$ and $\beta = 1$ for sucrose), $M_w = 18$ is the molecular weight of water. If the solubility of a given substance in water is $c_{\text{max}}$, the deliquescence point is given as

$$\text{RH}_{\text{crit}}/100 = \exp(-\beta c_{\text{max}}/55.5)$$

For droplet formation, surface tension should be also taken into account for accurate assessment of $\text{RH}_{\text{crit}}$ [2]. The values for $\text{RH}_{\text{crit}}$ are tabulated in literature for many substances. For ammonium hydrogen sulfate, $\text{NH}_4\text{HSO}_4$, the main ingredient of hygroscopic dust [5], $\text{RH}_{\text{crit}} = 39\%$ [24]. Thus, the presence of hygroscopic dust may cause leakage current and/or corrosion at humidities lower than $\text{RH} = 60\%$ normally expected as the failure trigger point with clean surfaces [7]. Most dusts deliquesce in the 30–80% RH range, i.e., within the operating range for most electronics [6]. The composition of dust changes with the geographical location and will be different in large cities, rural areas, over the land and over the sea. For instance, in the large metropolitan areas of the north-eastern US there is a higher probability of encountering the low deliquescing ammonium hydrogen sulfate in the dust caused by interaction between tropospheric sulfuric acid (which originates mostly from fossil fuels) and ammonia (mostly of agricultural origin).

3.2. Bridging: the critical dust accumulation

Deliquescence is only one of the two necessary conditions for a significant resistance degradation of the printed circuit board surface. The other one is connectivity [2,5]. In order to ensure an uninterrupted conductivity path a continuous bridge from particle to particle must be formed. From the percolation theory [22] it follows that the probability of connectivity is 90% when 53% of possible dust adherence sites are occupied. The conductivity due to percolation is a very sharp function of surface coverage by dust particles and is basically a catastrophic, “all or nothing” dependence where surface coverage at the onset of conductivity is practically the same as that of 100% probability. Such “all or nothing” dependence is know in practice with conductively filled composite materials where the conductive filler concentration must exceed some critical value below which the composite is non-conductive. This change from an insulator to a conductor over a narrow range of filler concentration is due to the formation of a network among the filler particles [26]. Assuming a median mass
diameter to be 0.52 \mu m and that their density is that of ammonium hydrogen sulfate, the main dust ingredient (1.78 g/cm\(^3\)). Weschler [5] estimated that the bridging will occur at the concentration of 1.85 \times 10^8 \text{particles/cm}^2 which is equivalent to the mass surface concentration of 24.2 \mu g/cm\(^2\). It was later shown that at high humidity the critical surface concentration in such systems is independent of the average particle size or the particle size distribution [2]. Weschler’s estimation [5] was based on dry concentration of particles, however, and the diameter of deliquescent particles will be somewhat larger [2,23]. Thus, it can be seen from Eq. (27) that at the deliquescence point (RH = 39%), the particle will absorb 1 g of water per each 2.5 g of dry NH\(_4\)HSO\(_4\) increasing the volume by a factor of 1.74. The particle diameter which scales with the volume as \(V^{1/3}\) will increase by the factor of ca. 1.2 and its cross-section area scaling as \(V^{2/3}\) by the factor of ca. 1.45. Additionally, taking into account that the particles were shown [3] to contain a significant amount of insoluble material (e.g., silica) besides salts it will be prudent to use 15 \mu g/cm\(^2\) as the “magic number” in our generic study when estimating time to failure of the electronic equipment, even though the actual value may vary somewhat according to the geographical region and the related type of dust.\(^1\)

Dividing the value by the deposition rate estimated for a given type of equipment and geographical conditions, the expected time to failure, or rather time to proneness to failure at an increased humidity can be estimated.

4. Design risk assessment

4.1. Dust property values for predictive methodology

In order to be able to assess the risk due to dust for a given module equipment design, we need to assume reasonable but skewed towards safety values for hygroscopic dust from the available data, as discussed in the preceding sections. It is proposed here that the typical values characterizing hygroscopic dust be used for the generic design considerations. The proposed values which are listed in Table 1 are on the conservative side of the available literature data [1,3] which suggest ca. 80% efficiency of air filtration in telephone offices. From this set of values we will be able to estimate critical dust accumulation for a given design. These values should be replaced with actual data for a given location if available.

| Particle size | 0.52 \mu m |
| Concentration | Indoor (CO) 6.0 \mu g/m\(^3\) |
| | Outdoor 30.0 \mu g/m\(^3\) |
| Deposition velocity | 0.005 cm/s |
| At air speed | 5 cm/s |
| Critical dust accumulation | 15 \mu g/cm\(^2\) |

Table 1

Selected dust property values for predictive methodology based on more conservative of the literature data

availability and if there is enough dust available, how long it would take to reach the deliquescence corrected “magic number” of 15 \mu g/cm\(^2\). Thus the following steps will be followed.

A. Assessing dust availability. (1) Identify routes of ingress, (2) estimate rates of ingress, (3) calculate the total amount of hygroscopic particulates, (4) estimate internal surface area, (5) assuming 100% deposition calculate surface concentration.

B. Checkpoint. Does the accumulation exceed or is, at least, the same order of magnitude as the “magic number”? If no, PASS. If yes, go to C.

C. Assessing dust deposition. (1) Establish speed of air motion, (2) establish relative importance of temperature gradients and electric fields, (3) estimate deposition velocity, (4) using the amount of particulates calculated in A calculate the amount of dust deposited over the expected life of the equipment.

D. Checkpoint. If the amount calculated in C is significantly lower (by an order of magnitude) the expected life of the equipment, PASS, otherwise mitigation strategy has to be devised (e.g., redesign, conformal coating, washing schedule, etc.)

4.3. Definitions of enclosure types

Enclosure type definitions are given in Table 2 in order to avoid any misunderstanding about the meaning of used terms.

4.4. Design examples

Hermetic and sealed enclosures (e.g., Absolute Humidity Control Modules [7]) will not be considered as they present no risk (Table 2). In all the examples the risk is estimated for 20 years life. In case where the risk is significant, time to reach the magic number for dust deposition is also calculated. We assume that the electrophoretic and thermophoretic deposition is negligible unless there are indications to the contrary.

Example 1. A semi-sealed outdoor unit 30 cm \times 20 cm \times 15 cm incorporates 4 boards 10 cm \times 10 cm. It contains a diffusion plug with the effective cross-section of 0.5 cm\(^2\) and thickness of 0.01 cm. In the unit (called Relative Humidity

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\(^1\) However, for circuits with high voltages (e.g., telephone circuits) preferential growth of aerosol particles into whiskers along lines of electric field was observed, in agreement with the above discussion of the electric field effects. The suggested approach in such case is to further reduce the magic number by a factor of 10.
Table 2

<table>
<thead>
<tr>
<th>Enclosure type</th>
<th>Moisture ingress</th>
<th>Time constant</th>
<th>Dust deposition (0.1–1 μm)</th>
<th>Time to bridging</th>
<th>Practical examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hermetic</td>
<td>Theoretically none</td>
<td>∞</td>
<td>None</td>
<td>∞</td>
<td>Microelectronic and optoelectronic packages</td>
</tr>
<tr>
<td>Sealed</td>
<td>Diffusion (walls and gaskets)</td>
<td>Days to months</td>
<td>None</td>
<td>∞</td>
<td>Gasketted metal container</td>
</tr>
<tr>
<td>Semi-sealed</td>
<td>Diffusion (plugs) and breathing</td>
<td>Minutes to hours</td>
<td>Plug limited Brownian diffusion and breathing</td>
<td>1000s of years</td>
<td>Plastic box with a Gore-Tex diffusion plug [7]</td>
</tr>
<tr>
<td>Vented and open</td>
<td>Air exchange (vents)</td>
<td>Seconds</td>
<td>Deposition rate limited</td>
<td>Years</td>
<td>Fan cooled CO type equipment, outdoor breathers</td>
</tr>
</tbody>
</table>

* These enclosure type definitions resulted from the author’s discussions with Dr. John Moss of Ottawa, Ont.

Control Module [7], we have: module volume $V = 9000 \text{ cm}^3$, total internal surface area (walls + boards) 3500 \text{ cm}^2. Dust availability: Brownian diffusion of dust through the diffusion plug. Assuming that any dust which gets into the enclosure is adsorbed irreversibly on the internal surfaces we have a steady state situation and the amount of dust collected over 20 years can be calculated [14] as $N = D A c t / L$. For outdoor conditions we assume the dust concentration $c = 30.0 \mu \text{g/cm}^3 = 3 \times 10^{-11} \text{ g/cm}^3$, the dust diffusion coefficient $D = 6.3 \times 10^{-7} \text{ cm}^2/\text{s}$ (see Fig. 4 and Eq. (14)), $L = 0.01 \text{ cm}$, $t = 630,720,000 \text{ s}$. Thus $N = 2.34 \times 10^{-9} \text{ g}$. Dividing by the total surface we have the resulting surface contamination of $6.675 \times 10^{-7} \text{ g/cm}^2$. This is many orders of magnitudes lower than the “magic number” of 15 μg/cm². Dust ingress through breathing. Assuming daily temperature variations of 30 °C, we will have 10% of the containers air exchanged every day. This will carry with it the proportional amount of the ambient dust. Thus everyday, assuming that all the dust settles on the surfaces, there will be $0.1 \times 9000 \times 3 \times 10^{-11} \text{ g} = 2.7 \times 10^{-8} \text{ g}$ of dust brought into the container. Over 20 years the breathing process will bring $2 \times 10^{-4} \text{ g}$ dust. This divided by the total surface will give $5.6 \times 10^{-2} \text{ μg/cm}^2$ surface contamination. This is, although much larger than the number from Brownian diffusion, still two order of magnitudes lower than the “magic number”. Thus, it is safe to assume that semi-sealed modules present no dust danger due to negligible availability of dust. There is no point of calculating deposition rates in this situation.

Example 2. An indoor (CO) piece of equipment has the same dimensions as the module discussed in Example 1, i.e., $30 \text{ cm} \times 20 \text{ cm} \times 15 \text{ cm}$ and also incorporates four $10 \text{ cm} \times 10 \text{ cm}$ boards. Due to convection cooling the inside air is being exchanged with the ambient at such a rate that one full exchange takes place on the average every 10 min. Dust availability. Assuming that all the dust which is brought in settles, we can estimate the total available dust as follows: The air is exchanged 6 times per hour or 144 times a day. The indoor dust concentration is assumed to be $6.0 \mu \text{g/cm}^3$ or $6 \times 10^{-12} \text{ g/cm}^3$. Each air exchange will thus carry dust in the amount of $5.4 \times 10^{-8} \text{ g}$. Over 20 years the total dust brought in will be $5.7 \times 10^{-2} \text{ g}$. This divided by total surface area gives 16.5 μg/cm². This value is practically the same as the magic number and therefore we should estimate deposition rates. Deposition rates. With the relatively fast exchange of air it will be prudent to simply assume that the dust concentration in air is the same as in the building, i.e., $6 \times 10^{-12} \text{ g/cm}^3$. Fluid mechanics and thermal considerations should determine the speed of air in the enclosure, but in the absence of fans we will assume that 15 cm/s is a reasonable conservative number. Therefore, the deposition velocity of a 0.5 μm particles is $0.0085 \text{ cm/s}$ (see Fig. 5). The resulting surface contamination can be calculated from the expression $\mu = \nu g t$ resulting in $\mu = 32.1 \mu \text{g/cm}^2$ exceeding here the critical value. Since our calculations have an approximate character, we have to assume that from the point of view of both the dust accessibility and deposition rates the natural convection module may present a hygroscopic dust risk. Thus either the design of the module should be reviewed or the boards should be made insensitive to the dust effect.

Example 3. The module of Example 2 is considered for outdoor use. Dust availability. In Example 2 for an identical module when used indoors we arrived at the possible contamination from the maximum dust availability of 16.5 μg/cm². The value for the outdoor conditions according to the higher dust content in the air (see Table 1) larger by a factor of 5. Thus we have the maximum possible contamination of 82.5 μg/cm². This exceeds the “magic number” several times. Deposition rates. The value of 32.1 μg/cm² obtained in the Example 2 should be also multiplied by the indoor/outdoor factor of 5. The resulting contamination is 190.5 μg/cm², much above the allowable limit. We can see that the design is definitely not suitable for the outdoor applications for long term reliability. As the limiting number is due to the dust availability, such a module should not be usable outdoors longer than 4–5 years.

Example 4. A central office module of the same dimensions as in the above examples is cooled by forced convection. The air flow along surfaces was found to be 50 cm/s. Dust availability. Does not have to be calculated. Due to the continuous air exchange with surroundings the dust concentration inside the module is always the same as in
the building. **Deposition rates** For 0.5 μm particles at the air flow of 50 cm/s the deposition velocity which scales as $\sqrt{u_{\infty}}$ is 0.016 cm/s (see also Fig. 5). The surface contamination resulting from 20 years of dust deposition will be $\mu = v_{dt} = 61 \mu g/cm^2$. This exceeds the "magic number" by a factor of 3. There is a definite dust risk factor associated with this design which may be further compounded by electrohydrodynamic and thermophoretic effect. The same module will, of course, be even worse in outdoor applications where the expected dust contamination would be ca. 220 μg/cm². As air flows along a surface, the laminar flow may eventually become turbulent, depending in the size of the wall or board thus increasing the risk even further. This is more likely to happen with faster flows where appropriate hydrodynamic analysis may be warranted for a given design. The consideration given here are for general assessment of design types only.

5. Conclusions

The above discussion and design examples lead us to the following generalizations.

- Sealed and semi-sealed (breathing) modules should not present a hygroscopic dust risk for either indoor or outdoor applications.
- Open natural convection cooled modules are a borderline case where details of the design have to be considered for each case. Some of them may be good enough for indoor but not for outdoor applications.
- Open forced convection cooled designs present a definite dust reliability risk both for indoor and outdoor applications.
- Thermophoretic and electrophoretic deposition do not change the general conclusions regarding risk but for some designs may influence the actual time to failure.

Acknowledgment

The paper originated when the author was with Nortel, Ottawa, Canada.

References


(b) Generic requirements for reliability qualification testing of printed wiring assemblies exposed to airborne hygroscopic dust. Technical Advisory TA-NWT-001274, Bellicore, October 1993.


