

Adherent dust particles

Dust sticks to everything and everyone and critically affects stringent requirements for manufacturing today's sensitive electronic products.

Abstract: *Dust particles are an important factor in the manufacture and use of electronic products. Strongly adherent particles are especially troublesome. We have investigated the mechanism of dust adhesion and found that it often involves water-soluble materials. Excursions of the relative humidity above and below a critical value can trigger a cementing effect that we believe leads to most of the damage caused by dust particles.*

Dust is such an ordinary part of daily life that we rarely notice it. Occasionally, a sunbeam at just the right angle or the sight of a laser beam in a darkened room reminds us of the multitude of particles that are always there in the air around us. Many of these particles are so small that they remain suspended in the air for days, but a single one of them, landing on an electronic device during manufacture, can cause its malfunction. Modern electronics—exemplified by marvelously ingenious integrated circuits, kinescopes, and the VideoDisc—has come to depend more and more on large arrays of very small elements. Malfunction of one or a small number of these elements can render a whole system useless. Large systems can also be damaged by airborne

particles. Outdoor solar-cell arrays many square meters in area become coated with dust that obscures incident light with a serious loss of efficiency.

Though the problem of dealing effectively with particles in manufacturing is formidable, there are some general principles that apply. These help us to understand what is happening and may help us to control the important conditions. Not all particles are the same. Some stick to surfaces more strongly than others, and these cause most of the trouble. We have investigated the nature of dust particles and the physical processes that lead to strong particle adhesion on surfaces. In what follows we will describe some of the things we have learned.

The role of electrostatic charge

Many dust particles are charged. They are attracted to neutral surfaces by electrostatic image forces. Conversely, the surface of an insulator can acquire an electrostatic charge and attract neutral dust particles to it by the same mechanism. Either way, more particles land on a surface when electrostatic charges are acting. In this sense electrostatic effects aggravate the dust problem. However, charged particles that reach a surface are not very much more firmly bound than neutral particles. By measurements that we will describe below, we have found an effect, due to water soluble salt crystals, that causes some particles to be

very much more firmly bound than others. To get an overall perspective, we first describe the particles normally found in the atmosphere.

The properties of atmospheric dust particles

*Time which antiquates antiquities, hath an art to make dust of all things.*²

—Sir Thomas Browne

Atmospheric particles range from 0.002 to 100 μm in diameter. Particles at the lower limit are generally unstable, since small solid particles coagulate to form larger particles, and small liquid droplets tend to evaporate rapidly. Particles at the larger limit sediment quickly under the influence of gravity. Solid particles are usually irregular in shape and often consist of aggregates. In general, small particles greatly outnumber large ones. Figure 1 shows typical particle-size distributions that have been measured in ordinary rooms and in various clean-room environments.³ Within RCA we carry out many processes in Class 100 installations. These provide an environment in which the number of particles per cubic foot that have diameters greater than 0.5 μm is 100 or less.⁴

The rate at which a particle falls in quiet air is a strong function of its diameter. Table I shows the time required for particles of various sizes to fall one foot. A 3.0- μm particle, for example, falls 0.006 ft/s. A moving stream of air can carry such particles along for great distances.

There are many sources of airborne particles. Each source contributes its own type of material with a characteristic particle-size distribution. Table II shows examples. It has been estimated that a total of about 4.3×10^7 tons of particles fall on the U.S. each year. About 72 percent of the material derives from natural

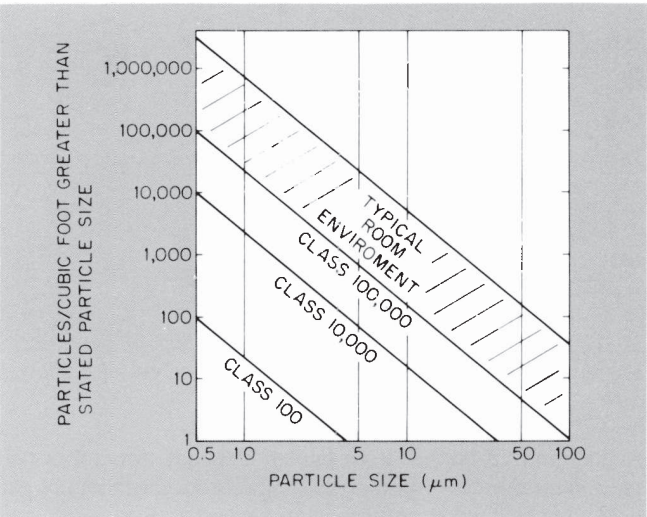
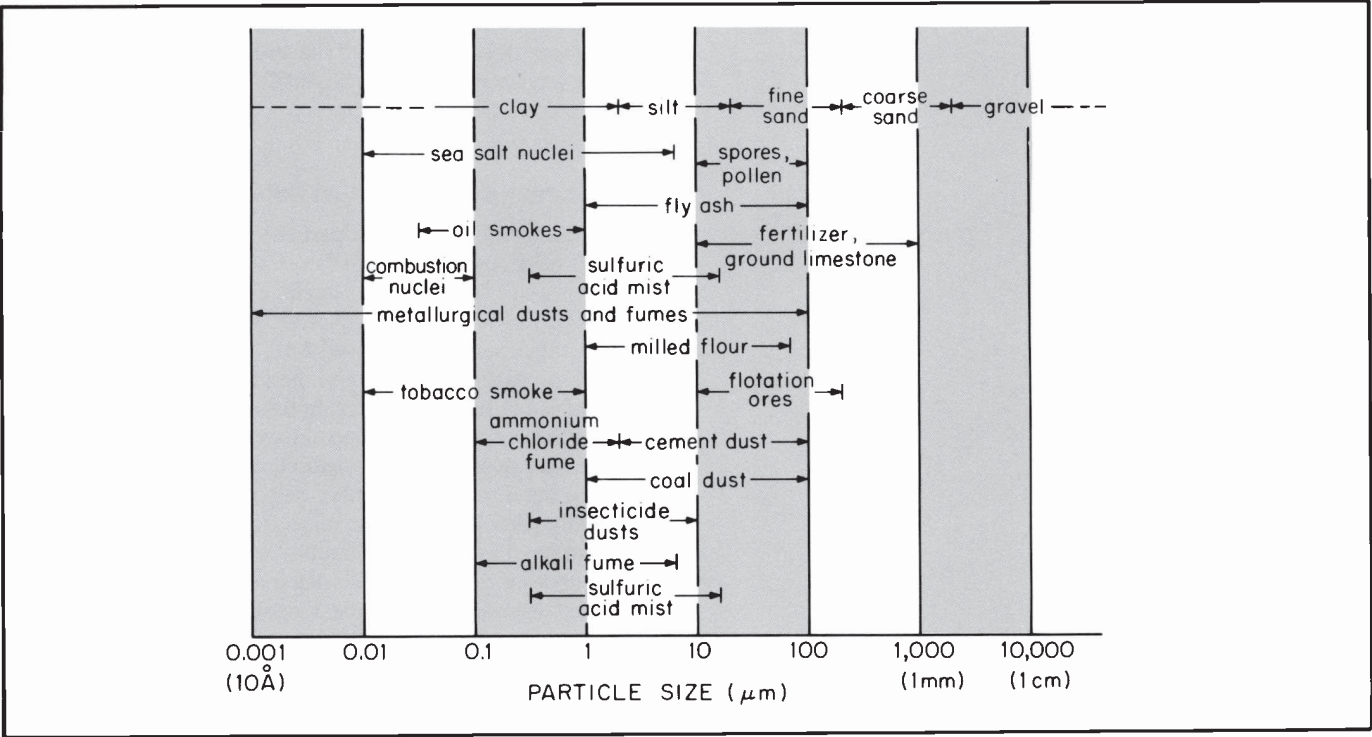


Fig. 1. Approximate distribution of particle sizes in a typical room atmosphere, and in three classes of filtered, clean environments as defined by Federal Standard Number 209a.³

Table I. Time needed for a particle to fall one foot in still air.

Size of particle in μm	Time needed to fall 1 ft
0.25	10 hr
0.5	3 hr
1	1 hr
2	15 min
3	3 min

Table II. Approximate size distribution of a variety of airborne particulate contaminants. Data from *Chemical Engineer's Handbook*, 5th Edition, Ed. R.H. Perry and C.H. Chilton, McGraw-Hill Book Company, New York, pp. 20-79.



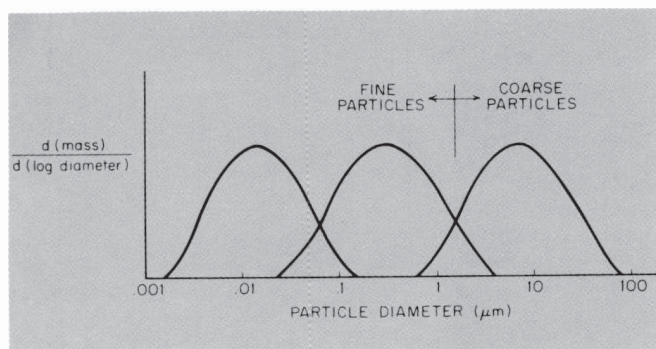


Fig. 2. Typical mass distribution of particles as a function of size.

sources and 28 percent from human activities. Around heavily industrialized areas or primary natural sources, the fallout of particles may be hundreds of times the average.

The largest natural sources are blowing soil, ocean spray, forest fires, and volcanic activity. Blowing soil is most important in arid regions, such as the U.S. Southwest, that have little natural vegetation, although it is a very important source everywhere. Ocean salt spray dries in the air, leaving behind salt crystals that make up a large source of dust particles, worldwide. Concentrations are high near the seashore but, in some areas such as California, onshore winds carry particles inland for hundreds of miles. Volcanic activity is usually a minor source, but an occasional major eruption can produce a dust cloud that encircles the earth and produces vast amounts of sedimentation for a year or more. Forest fires account for about 7 percent of the total. Plant pollen and spores contribute about 3 percent, and, at certain times of the year, may be the dominant particle source. Table III shows the sources of particulate material due to human activity.

Table III. Breakdown of airborne particulate contamination due to human activity (from Reference 5).

Activity	Percent of total mass
Transportation	5.6
Fuel combustion in stationary sources	54.5
coal (incl. coal refuse burning)	(39.8)
fuel oil	(1.3)
natural gas	(0.9)
wood & plant matter (incl. structural fires)	(12.5)
Industrial processes	39.9
iron & steel	(9.3)
other metals	(0.8)
cement	(4.1)
stone, sand, rock, etc.	(4.1)
coal cleaning	(0.9)
phosphate rock	(0.9)
lime	(2.1)
asphalt batching	(2.5)
other mineral products	(0.8)
oil refineries	(0.5)
other chemical industries	(0.4)
grain handling & storage	(3.7)
pulp & paper	(3.3)
flour & feed milling	(1.4)
solid-waste disposal	(5.1)
Total	100.0

Table III does not include occasional human sources, such as salt crystals of sodium chloride and calcium chloride. These are put on highways to melt snow and ice. The resulting solutions are later sprayed into the air by moving traffic and end up as atmospheric particles.

Recent studies⁶ show that there can be three distinct peaks in the size distribution of atmospheric particles, as shown in Fig. 2. Coarse particles have a mean diameter of about 9 μm and they derive from fly ash, mechanical and industrial processes, larger sea-spray particles, wind-blown dust, volcanoes, and plant particles. They leave the atmosphere primarily by sedimentation. There is also, typically, a peak in the distribution for diameters around 0.02 μm . These particles are the primary nuclei from combustion and have enormous concentrations near combustion sources. With time they grow by condensation and coagulation to a mean diameter of about 0.3 μm . Smaller sea-spray particles and wind-blown dust also contribute to the 0.3- μm peak. Many of these fine particles are at least partly liquid. They are removed from the atmosphere primarily by rain. On a mass basis, there is relatively little coagulation of fine particles with coarse particles.

The above description applies to the particles found in an outdoor environment. Indoors, there are additional things to consider. First of all, how do particles make their way from the outside to the inside? Particles will enter via an air exchange if the air speed at the points of entry is high enough (Table I) to keep the particles in suspension. This is especially important during the heating season when there is a high rate of air exchange. Many particles are carried in by people. We inevitably accumulate and redistribute particulate material. In addition to this transfer process, particles are also generated indoors in great abundance. Home cooking exhausts, mists, smoke, and industrial fumes, along with the inevitable human emissions, all contribute.

It is hard to overemphasize the role that people play as purveyors of dust. A person moving about transfers prodigious quantities of dust onto clothing by sitting, leaning and touching, then flings the particles hither and yon with sudden movements. In the home, particle counts increase by factors of ten to twenty when people are moving about. In the lower background of the clean room these effects stand out even more. The use of clean room overgarments is only marginally effective. Too little attention is paid to this human factor.

Experimental study of dust adhesion

We have found that the dust particles that settle on a surface are not all held equally strongly. Most are bound only by electrostatic or weak intermolecular forces, and can be easily moved by a jet of air or a probe. A few of the particles stick very tightly.⁷ Often, they cannot be removed from the surface without breaking off the particle or a piece of the substrate. Clearly a different mechanism of binding is acting in this case.

To measure adhesion properties we applied known quantities of standard dust samples by sedimenting the dust onto test surfaces, using a suitably dimensioned box with a timed shutter, so that only particles in the size range from 1 to 30 μm landed on the surface. Particle concentrations were determined by counts done under a microscope. To determine the degree of adhesion we used a modification of the VideoDisc system as a tool. The stylus can be used to scan a large area systematically so that it encounters nearly every particle on the surface. Immediately after dusting the surface, and for any time thereafter, as long as the relative humidity in the room had not risen above 80 per-

cent, the stylus traversed the grooves of the disc and pushed nearly all particles out of its way without incident. Almost none of the particles adhered strongly to the surface.

However, if the dusted surface was exposed to a humidity cycle in which the relative humidity rose above 80 percent for an hour or more and then returned to a lower value, the behavior of the particles was quite different. Some particles then adhered strongly and were literally cemented to the surface. When the stylus hit one of these particles, it was kicked out of its groove. By using a suitable circuit, these events were recorded and counted. In this way, we found that, after the humidity cycle, about 1 percent of the particles had become strongly adherent. Microscopic examination of the dusted surface at this point showed that some particles were surrounded by a stain. These were usually adherent particles. We had directly measured the force needed to move these particles. It was orders of magnitude higher than the force needed to move nonadherent particles and was often roughly equal to the mechanical yield strength of the substrate material. The particle had been glued to the surface by the action of the humidity cycle.

These results suggested to us that the adhesive effect triggered by the humidity cycle is due to the presence of water-soluble particles in the dust. These may be present alone or together with another particle as part of a composite particle. Since water-soluble particles make up only a small fraction of all dust particles, this would explain why only a few particles become strongly adherent after the humidity cycle. In a humid atmosphere, soluble particles adsorb water on the surface until part of the crystal dissolves. This process is called deliquescence and we will describe it more fully below.

We confirmed the idea that soluble salt particles are responsible for most of the strong dust adhesion by washing the dust in water before using it for the adhesion test. The dust was washed in pure water, then dried and used as in other tests. When this was done, we found almost no strongly adherent particles. This result confirms that water-soluble material present in natural dust is responsible for the strong dust adhesion.

Deliquescence

At high relative humidities the atmosphere has a high moisture content. When the relative humidity exceeds a certain critical value, the deliquescent salt takes up moisture to form a solution.

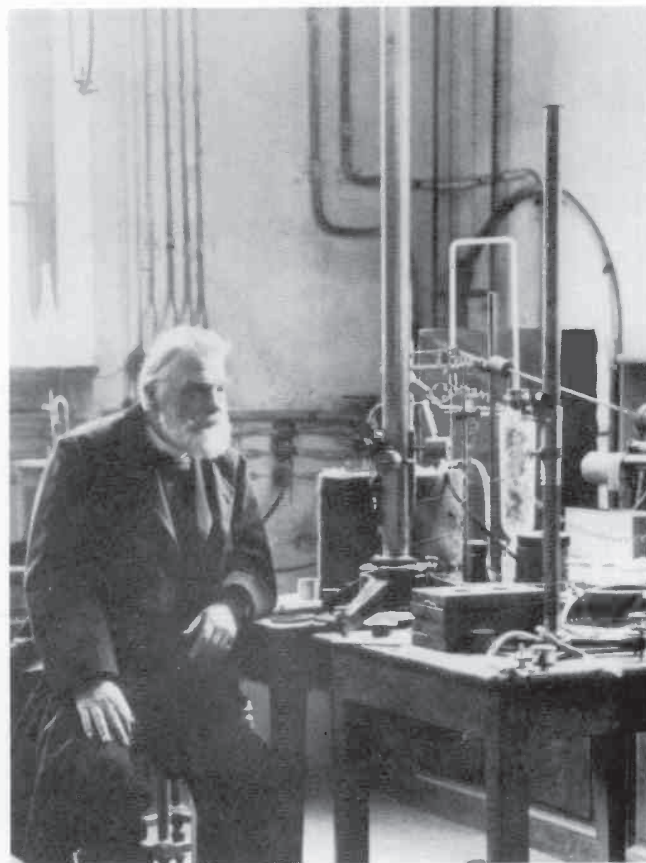


Fig. 3. François Marie Raoult (1830-1901) in his laboratory at the University of Grenoble, France. His theory of solutions, known as Raoult's Law, describes how the vapor pressure and other properties of a solvent change with the amount of dissolved material. It explains a wide variety of everyday phenomena, ranging from deliquescence to the behavior of antifreeze solutions. (Photograph provided by the Edgar Fahs Smith Collection, University of Pennsylvania.)

The solution continues to absorb moisture until its vapor pressure is equal to that of the water vapor in the atmosphere. If the relative humidity now falls below the critical value, the solution will lose water until the salt crystallizes again. The critical value of relative humidity varies from one material to another. The

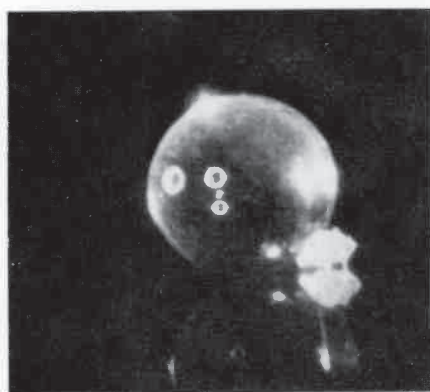


Fig. 4. A glass ball, 2.5 mm in diameter, rests on a glass substrate. A sodium carbonate particle, mass 300 times less than the ball, lies next to the ball. In (a), the humidity is below 78 percent and the particle is dry. In (b), the humidity has been raised to 90 percent and the sodium carbonate is

in water solution around the ball. In (c), the humidity has dropped below 78 percent and the sodium carbonate has redeposited around the ball, gluing it to the substrate. The force required to move the ball in (c) is 10^5 times greater than in (a).

Table IV. Critical values of relative humidity for some water-soluble salts that are found in the atmosphere. The critical humidity is defined in the text.

Soluble salt	Critical relative humidity (%)
LiCl	15
CaCl ₂	32
MgCl ₂	33
K ₂ CO ₃	44
NaCl	76
Na ₂ CO ₃	78
NH ₄ Cl	79
Na ₂ SO ₄	83
KCl	86
K ₂ SO ₄	97

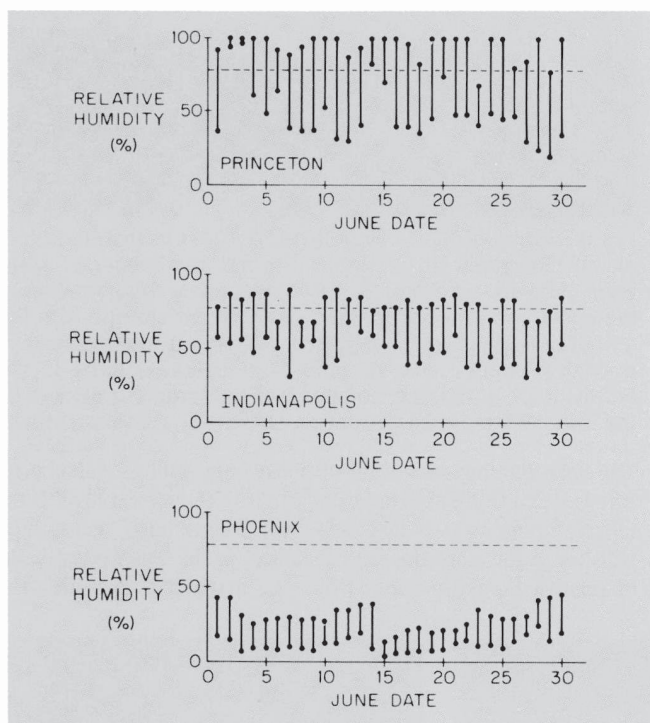


Fig. 5. High and low values of relative humidity for each day of June, 1981, for three locations: Princeton, New Jersey; Indianapolis, Indiana; and Phoenix, Arizona. The horizontal line at 76 percent is the critical relative humidity for deliquescence of sodium chloride. Princeton data were supplied by D.A. Kramer. The other data were supplied by the U.S. Department of Commerce. Such data can be obtained for any station for which data are recorded by calling Asheville, North Carolina, (704) 258-2850, extension 683, and requesting a Local Climatological Data Form.

more soluble the salt the lower the critical value (Fig. 3). In Table IV we list the critical values of relative humidity for several soluble salts that are found as particles in the atmosphere.

In Fig. 4 we show how deliquescence can cement a particle to a surface. In this case, we have used a small glass sphere on a



Fig. 6. Suppliers of table salt have found that the clogging of salt shakers, due to changes in relative humidity as described in the text, can be ameliorated by adding 0.5 percent of sodium aluminum silicate. This inert material coats the particles and reduces adherence. (Morton Salt trademark used with permission of Morton Salt Division of MortonNorwich.)

horizontal surface. The soluble salt is a particle of sodium carbonate, shown in Fig. 4a, touching both the sphere and the surface. Sodium carbonate particles are often found in the atmosphere and are emitted by the cooling stacks of power stations and industrial plants. Figure 4b and 4c show how, when the humidity cycles above and below the critical value of 78 percent, the salt dissolves, wets the sphere and the support surface, makes intimate contact, and then recrystallizes to form solid-solid bonds. This cements the sphere to the surface. At this stage, the force needed to dislodge the sphere from the surface is 27 grams, or 10^5 times the force needed to move it at the original stage shown in Fig. 4a. This sequence of flow and wetting, followed by solidification, is the normal way that an adhesive works. When the environmental conditions are right, any water-soluble salt can act as an adhesive.

The natural cycling of the relative humidity

Figure 5 shows high and low values of the outdoor relative humidity for each day in June of 1981 for three different locations: Princeton, New Jersey; Indianapolis, Indiana; and Phoenix, Arizona. As a reference point, the critical relative humidity value for the deliquescence of sodium chloride, 76 percent, is drawn in each graph as a horizontal line. The humidity cycle that we have described above takes place on those days that have one point above the critical line and one below it. In Princeton, the cycle took place on 25 days out of 30 in this month,

and in Indianapolis it took place on 19 days out of 30. In Phoenix it did not take place at all during this month.

Indoors, the humidity does not normally swing through as wide a cycle as it does outdoors. In one of the above locations, a well air-conditioned room might have a mean relative humidity of 50 percent with variations up and down of 10 to 15 percent. However, concern about energy usage has led to less air-conditioning. In June of 1981, for example, the indoor relative humidity in RCA Laboratories averaged about 70 percent. There were many days when the relative humidity went through the excursion that gives rise to sodium chloride particle adhesion. In winter the average relative humidity indoors will run much lower but there may still be excursions around the critical value for one of the materials in Table IV. When this happens, there can be adhesion due to soluble particles.

In addition to its effect on dust particle adhesion, the deliquescence effect also gives rise to a common irritant in daily life—the clogging of salt shakers. Excursions of relative humidity lead to solution and recrystallization of minute quantities of salt, causing the grains to stick to one another. Figure 6 and its caption show how one company has solved this problem and given us one of our most enduring advertising slogans—“When it rains, it pours.”

Acknowledgment

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