Electrostatic Discharge

Understand, Simulate, and Fix ESD Problems

Third Edition

Michel Mardiguian

IEEE

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Preface to the First Edition

Static electricity is the most ancient form of electricity known to humans. More than 2000 years ago, the Greeks recognized the attraction between certain materials when they were rubbed together; indeed, the word *electricity* comes from the Greek *elektron*, which means amber. During the seventeenth and eighteenth centuries, several key experiments were conducted to understand and measure static electricity. But the discovery of electromagnetism and its formidable breakthrough has rapidly outgrown interest in static electricity. Even today, where the industrial applications of static electricity are not insignificant, they cannot compare with those of electromagnetism and electrodynamics.

Ironically, as much as static electricity was relegated to the attic of scientific evolution, she continuously occupied (I say "she" because electricity, in French, is feminine—don't ask me why) the headlines with her undesirable effects. If we consider the thousands of lightning strikes hitting the terrestrial atmosphere every minute, we have to realize that our planet with its surrounding clouds is nothing more than a huge electrostatic machine constantly charging and discharging on itself. For decades, people have been learning the hard way that statics can cause explosions of fuels and ammunitions. In 1937, the German flying boat *Hindenburg* arriving in Lakehurst, New Jersey, caught fire while anchoring at its landing mast. What could have been a severe incident became a tragedy: Due to international tension, the United States had put an embargo on helium sales to Germany and the vessel was inflated with hydrogen instead. The resulting fire caused the death of 37 of its hundred or so passengers. Although the causes have not been completely understood, electrostatic discharge (ESD) is at the top of the list.

More recently, during the 1970s in the United States, a spacecraft lauching rocket exploded during the fueling operation, killing three engineers. The cause was, beyond any doubt, identified as ESD. Satellites have paid a heavy toll because of ESD, from minor anomalies to severe malfunctions, as in the European Space Agency (ESA) MARECS satellite. In January 1985, during the assembly of a Pershing missile near Heilbronn, Germany, the motor case, made of Kevlar, was repeatedly rubbed against the cushioning in its container. The ensuing ESD caused the 4 tons of highly flammable propellant to catch fire and the motor exploded, blowing parts 125 meters away, killing three people and injuring nine.

Although such catastrophes are terrible and spectacular, they are quite rare; but a more insidious aspect of ESD bloomed in the early 1970s, with the massive arrival of integrated microelectronics. The plants producing integrated circuits (ICs) started to experience disappointing percentage yields. Once thoroughly investigated, the problem was found to be largely due to ESD during all fabrication steps and handling. Although the problem has been fully explained and drastic solutions adopted, ESD is still costing millions of dollars a year of pure losses. Considering the astronomical quantities of ICs manufactured each year, the mere fact that 3 to 30% of them die in infancy because of ESD represents an impressive amount of money. To quote G. C. Quinn, technical editor of *Electronics Test Magazine* (April 1984): "The volume range of ESD sensitive components is rising faster than the development and usage of ESD protections . . . Estimating costs of ESD failures not caught at manufacturing inspection is far more difficult. Many of the degraded, walking-wounded devices may not show up until after termination of the manufacturer's guarantee." Around 1980, Lockheed Corporation reported a one-year cost savings of $1.8 million through static protection measures, which reduced ESD-related failures by a 16 to 1 ratio. Arithmethic, then, tells us that Lockheed had endured losses of $1.92 million the previous year. Even with severe protection measures, some manufacturers still confess that ESD is causing 39 to 48% of their IC rejects. The only hope that the plague will ever be dominated is a progressive awareness of people and the growing use of robots on manufacturing lines.

But the worst was yet to come: With the proliferation of microelectronics in all possible applications, an even bigger number of complaints flourished about ESD-related erratic bugs, transient malfunctions, erased memories, and the like. Although the economic losses resulting from erroneous transactions and corrupted data of all kinds are difficult to evaluate, it is probably an even larger figure than the one for chip damage during fabrication. It seems ironic that a physical fact, known for 2500 years as doing nothing but nasty things to us, has continued to defy electronics engineers. Solving the problem of transient errors induced by ESD has not been given the same concerted effort as the manufacturing aspect. Most early research was performed by isolated pioneers fighting with their own weapons. Initiating the research themselves, seldom supported by vast budgets, these men used their sagacity and all the resources they could find to investigate a problem for which no measuring techniques existed. They had to invent the tools they needed, and they had to be statisticians, chemists, and radio-frequency (RF) designers all at once. The names of Ted Madzy, W. Byrne, Michael King, Ralph Calcavecchio, Richard Simonic, and many others that I don't know of are the people to whom all of us who followed are indebted. By mentioning their work, this book will try to render a piece of the recognition they deserve: They paved the road for bringing the understanding of ESD from black magic up to an analytic method. We hope this book will demystify ESD and give a step-by-step strategy for predicting, testing, and reducing its effects on electronic equipment.

Gainesville, Virginia
June 1985

MICHEL MARDIGUIAN

Preface to the Third Edition

The two previous editions of this book had a very favorable reception from the EMC community. However, the first and second editions, published by the EMC consulting firm Interference Control Technologies, had a rather limited distribution and have been out of print since the year 2000. A new edition was sorely needed, incorporating current technological advances with the needs of the engineering community.

Since the first edition of this book 22 years ago, the electrostatic discharge (ESD) phenomenon has continued to plague the electronic industry. In spite of undisputable progress in ESD awareness and protection measures, which are inforced by regular audits and accreditations, the "sleeping sentinel" syndrome takes its toll. Inspections often reveal that in an assumed static-free manufacturing chain, all but one of the workstations or handling/packing posts are adequately protected. This single defective link is enough to compromise the entire ESD line of defense. Sometimes it was the very apparatus intended to eliminate human influence, for example, automatic handling by robots, that created a new ESD problem, sometimes worse than the one it was supposed to cure.

Once these pernicious problems are fixed, the return on investment of a flawless ESD control program is often spectacular, not forgetting that this is a constant battle because today's problem is frequently the consequence of some unanticipated effect of yesterday's solution.

Nonetheless, once marketed and sold, some modern equipment, although it has undergone a compete EMC test program that includes ESD, is still experiencing malfunctions, a tangible share of which is traceable to ESD. Consider a recent example: This author, among other consultants, was asked to solve a problem on a certain model of car. Five percent of owners were experiencing a very unpleasant dashboard failure: During operation some displays would freeze up, eventually becoming totally dark without a possibility of reset, even after a stop-and-start action. The problem was a peculiar ESD configuration that had escaped the standard test program.

In order to cope with such omnipresent threats, intensive research has continued worldwide, using instrumentation that is much more elaborate than that available in the 1970s and 1980s to the pioneers of ESD studies. Recent studies have covered arc formation, initial spike with the hand/metal scenario, fields radiated in the vicinity of the discharge, and the like. Among the engineers who investigated these facets of ESD, one of the most prolific has certainly been D. Pommerenke of Missouri University. In the first few chapters of this new edition, we give an overview of these recent studies.

The problem of poor repeatability has always also plagued ESD testing, as with many EMC tests in general. But, while other tests have gained significant improvements in accuracy and credibility, ESD remains the black sheep of the herd, raising sarcastic jokes among EMC practicioners and lab technicians, who are struggling constantly with these "ESD guns that don't shoot right" or "ESD tests that make failing products pass and good products fail." Therefore, a substantial share of the R&D effort has been aimed at reducing the uncertainty attached to ESD generators and test procedures.

However, we have some reservations: While a tremendous amount of activity has been deployed toward ESD generator modeling, calibration, and error analysis that is basically "simulating the simulators," it seems that the EMC community has lost sight of the actual fact we are trying to counteract: the real, everyday electrostatic discharge. To our knowledge, no organized, wide ranging statistical survey of ESD events has been conducted since the last outstanding work done by R. Simonic around 1973–1974. Things have changed: People's habits are different: interior decoration, furniture, and clothing are different. Instrumentation that could capture and record ESD is now more accurate, with much greater bandwidth than in the early 1970s. As a result there is a danger that we may very well be trying to reproduce perfectly, with today's advanced simulators, events as they were recorded 35 years ago.

St. Remy les Chevreuse, France — Michel Mardiguian
May 2009

Acknowledgments

After writing the word *end*, my gratitude goes to to those who provided their timely assistance and information: Etienne Sicard and Alain Charoy who gave me valuable details on IC protection, David Pommerenke who shed some light on his very specific series of measurements and modeling, Diethard Mohr and William Rhoades for bringing me up to date on some current ESD documents status. My thanks go also to Joel Raimbourg and Sebastien Bazzoli who provided invaluable support for some practical experiments. Last, but not the least, I am grateful to Mark Montrose and Michael King—the latter being a living memory of the pionneering era of ESD—who expressed their encouragement for the making of this third edition.

Many thanks also to Jeanne Audino and Steve Welch of the IEEE Press team, for their very professionnal assistance that gave life to my crude manuscript, and again to Mark Montrose who did the technical review, adding some precious remarks. Very special thanks go to the editorial team at Wiley: Lisa Van Horn, Ernestine Franco, and Dean Gonzalez, respectively, senior production editor, copy editor, and illustration manager, who performed a meticulous editing and turned my crude sketches into fine drawings. I also thank my wife Corinne for her patience, not to mention that she has been the one who typed some of the chapters, as it is often the case with we engineers, who pretend to become writers.

M. M.

Chapter 1

The Electrostatic Discharge Phenomenon

Although a thorough description of the electrostatic phenomenon is beyond the scope of this book and has been covered by several authors (1–4), it might be useful to start by reviewing briefly how static electricity takes place, what are the contributing parameters, and why, eventually, it ends abruptly in its threatening consequence: the electrostatic discharge (ESD).

The following section is an extremely simplified view of the electrostatic charging mechanisms. While clearly not a treatise on static electricity, it illustrate the physics involved, in a simple manner. Readers with a good basic knowledge of electrostatics can probably skip this preliminary portion.

1.1. PHYSICS INVOLVED

Any material is made of atoms. Unless submitted to certain external influences (heating, rubbing, electrical stress, etc.), the atom is at equilibrum; that is, the amount of negative charges represented by the electrons orbiting around the nucleus is exactly balanced by an equal number of positive charges or protons aggregated in the nucleus. Therefore, the net electric charge seen from the ouside is zero.

In good conductors, the mobility of electrons is such that the conditions of equilibrium will always exist; that is, no significant static field will exist between different zones of the same piece of metal. With nonconductive materials, however, the lesser mobility of electrons does not provide such a rapid recombination of charge unbalance. If heated, or rubbed strongly (which also creates heat), a nonconductor will free up electrons.

Depending on the nature of its outer valence orbit, a nonconductive material may be likely to give up electrons or to capture wandering electrons.

Electrostatic Discharge, *Third Edition*, by Michel Mardiguian

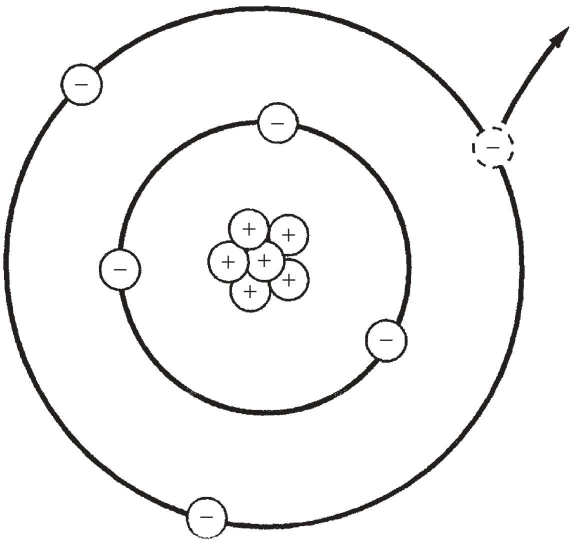


Figure 1.1 If by heating, rubbing, and the like, one electron is leaving the orbit, the material is left with six protons and only five electrons.

A nonconductive material that gives up an electron, as shown in Figure 1.1, will become positively charged. Such unbalanced atoms with a lack of electrons are called *positive ions*. A nonconductive material that takes extra electrons will become negatively charged, and its atoms with excess electrons are called *negative ions*.

Charges with like sign repel while charges with opposite sign attract. Therefore, it seems that nature will rapidly take care of the unbalance by recombining the charges. Unfortunately, while this recombination is instantaneous in metals (i.e., indeed, how a current flows), the high resistance of nonconductive materials makes it unlikely to happen, until such a high gradient of field is reached that either an arc or a mechanical attraction will occur. Besides rubbing or heating, which is the common generation mechanism, an object can become charged by *contact* with another previously charged object.

This ability of nonconductive materials to acquire electrostatic charges is known as triboelectricity. Once a nonconductive material has been subject to triboelectric charging, the charges trapped on its dielectric surface are not easily removed. Grounding the piece of material will do nothing since, on insulators, charges have no mobility. Only a flow of ionized air, hot steam, or conductive liquid can remove the charge unbalance.

Static charging ability is frequently shown on triboelectric scale, such as the one in Table 1.1 Materials labeled “positive” will take on a positive charge every time they are frictionned against a material lower on the scale. Although this kind of scale is true overall, the precise ranking of each material within the scale should not be definitely relied upon in real-life situations. Many authors and practicians in the ESD community, such as A. Testone (3), have shown how deceptive such triboelectric tables can be.

Table 1.1 Triboelectric Series

More (+)	Dry air
	Plexiglass
	Bakelite
	Cellulose acetate
	Silicon wax
	Glass, mica
	Nylon
	Wool
	Human hair
	Silk
	Paper, cotton, wood
	Amber, resins (natural or synthetic)
	Styrofoam, polyurethane
	Polyethylene
	Rubber
	Rayon, Dacron, Orlon
	PVC
	Silicon
More (−)	Teflon

For example, let us take a reel of ordinary office adhesive tape. If we quickly unwind some length of tape, everyone knows that this segment becomes charged and can attract small particles of dust, hairs etc and the like. But since both sides of the tape are the same material, they rank the same (e.g., positive for acetate) on the table, and this piece of film could not develop an electric field against itself.

However, after unwinding this short segment (Fig. 1.2), we notice that it is strongly attracted by the rest of the reel, which indicates that *there has been a charge transfer*, whereas one side of the tape has acquired electrons that the other side has lost. How can the same material be at the same time a "taker" and a "giver" of electrons, thus contradicting the triboelectric scale? Furthermore, if we cut this piece of tape (using insulating gloves and scissors to prevent our conductive body from influencing the results), and approach it to the reel, some areas of the tape are attracted, while others may be repelled.

The mechanisms coming into play in this apparently simple experiment are multiple and complex. For one, the materials involved are not just acetate against acetate; there is the adhesive layer and also the air itself, which is on the top (+) side of the scale. Then, the tape surfaces have changed their radii as they were separated, such as the "run-away" electrons do not face exactly the same region as when the contact was tight.

Therefore, even two insulating materials of the same nature can eventually develop opposite charges if sufficient friction, shear, or bending is applied. This happens hundreds times a day in a photocopier when foil is slipped over the paper stack.

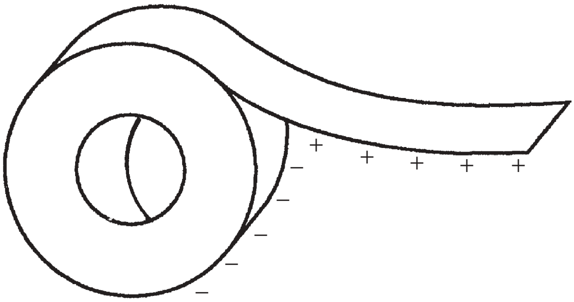


Figure 1.2 Stripped end of acetate tape is attracted by the surface of the tape reel.

Thus, although triboelectric scale is a fair indication of the polarity of the charge acquired by materials, we must stay away from peremptory statements when facing an electrostatic charging situation. Static field meters are good instruments to get a true measure of the static voltage acquired by various materials.

Now consider the classical example of a person walking on a synthetic carpet, rubbing his body on an insulated chair pad, or moving his nylon shirt sleeve over a polyvinyl chloride (PVC) surface: the farther apart the two materials are on the triboelectric scale and the faster the relative motion of the person, the more electrons will be freed by the givers and captured by the takers. This creates a charge unbalance—hence a latent electric field.

Figure 1.3 suggests a scale of merit for the propensity of materials to create more or less ESD problems. It is based on the surface resistance in ohms per square (i.e., the resistance of a sample square, whether it is 1 cm^2 or 1 m^2, yields the same results).

Material with more than 10^9 Ω/square are likely to develop electrostatic potentials that will not bleed-off by themselves due to the high insulation of

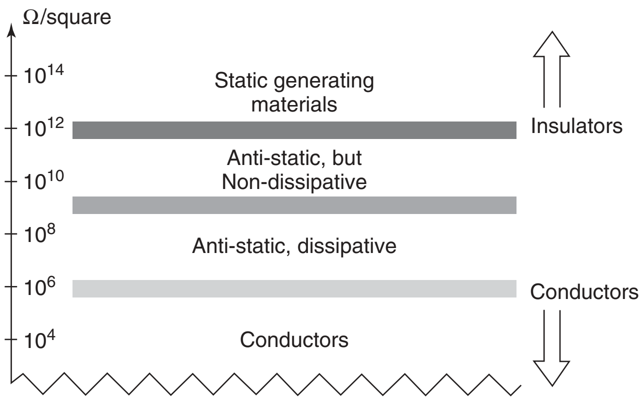


Figure 1.3 Propensity of materials to create ESD problems, based on surface resistance in ohms/square.

the material. Materials with less than 10^9 Ω/square, even if not real conductors, will not keep the charge unbalance very long because recombination will occur through the material itself.

Aguet (5) relates the propensity to electrostatic charge to the dielectric constant of the materials that are rubbed. He indicates the surface charge density σ_s:

$$\sigma_s = 15 \times 10^{-6}(\varepsilon_{r1} - \varepsilon_{r2}) \text{ Coulomb/m}^2 \tag{1.1}$$

where ε_{r1}, ε_{r2} are the relative permittivity of the two materials.

For instance, if one looks at a rubber shoe sole ($\varepsilon_{r1} = 2.5$) representing 250 cm^2 and a nylon carpet ($\varepsilon_r = 5$), the maximum total charge Q that can be acquired is

$$\begin{aligned} Q &= 15 \times 10^{-6}(5\text{–}2.5)250 \times 10^{-4} \text{ m}^2 \\ &= 0.93 \times 10^{-6} \text{ Coulomb} \end{aligned}$$

If the corresponding foot-to-ground capacitance C is about 100 pF, the static voltage is derived from

$$Q = CV \tag{1.2}$$

Hence,

$$V = \frac{Q}{C} = 9300 \text{ V}$$

It might seem, therefore, that there is practically no upper limit to what voltage a person can attain. Why not 50 kV 100 kV? Richman, in his very illustrative pamphlet on ESD (6), explains that, hopefully, personnel electrostatic voltage cannot exceed 30 kV in the most extreme cases because:

1. The capacitance of the human body, no matter what we do, cannot drop below 30–40 pF, a value that Richman calls our "capacitance to infinity."
2. Above approximately 25 kV, the corona will start to self-limit our voltage by bleeding off the charge, that is, the assumption of constant charge Q is no longer valid.

So, in most practical situations, the upper range of human body static voltage is 20–25 kV.

Summarizing this short description of electrostatic charging, we can say that static electrification is a complex phenomenon that one cannot solely characterize by any single parameter, such as the ranking of the material on a triboelectric scale, its surface resistivity, or dielectric constant. To the contrary, static dissipation can be dependably related to resistivity.

1.2. INFLUENCING PARAMETERS

Once the type of materials present is known, the most important parameter is relative humidity. It is well known that, during winter and spring seasons, all integrated circuit manufacturers have recorded an increased rate of "infant mortality" in their chips, and field engineers report an increasing number of service calls for computer failures.

Several things happen when relative humidity is low:

- Normally, the moisture content in the air tends to decrease the surface resistance of floors, carpets, table mats, and the like by letting wet particles create a vaguely conductive (or say, less than 10^9 Ω/square) film over an otherwise insulating surface. If the relative humidity decreases, this favorable phenomenon disappears.
- The air itself, being dry becomes a part of the electrostactic buildup mechanism every time there is an airflow (wind, air conditioning, blower) passing over an insulated surface.

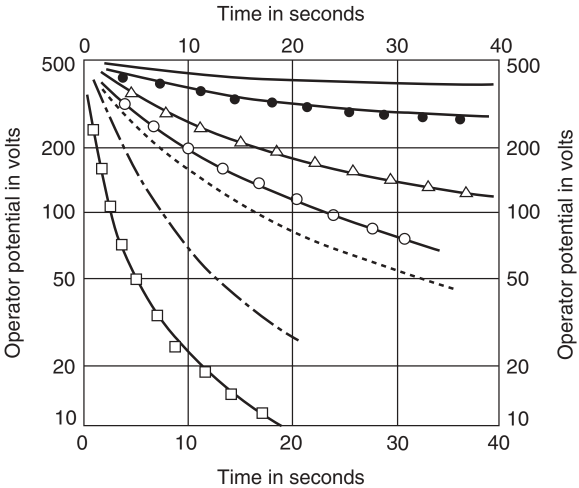
Many evaluations have been made of the electrostatic voltages reached by a person walking on several types of floors. Generally, these tests are made using a kind of "standard walking procedure." The person walks a given number of steps with a given type of shoes; then his (her) charging voltage is immediately measured with an electrostatic voltmeter having a quasi-infinite input impedance.

The importance of measuring the voltage immediately after charging, and preferably having this same short time for all experiments, is seen in Figure 1.4. If the time elapsed between the end of the charging phase and the instant of the measurement is not kept constant, comparisons between materials, clothes, shoes, and the like become inaccurate.

Figure 1.5 shows the range of acquired electrostatic voltages for several floor types and two values of the relative humidity (RH). On the left side, the voltages are shown for an RH of 50%. Even with a notoriously bad type of carpet such as nylon, the voltage stays within 1–3 kV. Note that this is already enough to kill some integrated circuits if the person touches directly a module or a printed circuit board (PCB). But the scale in the middle merely suggests the likely consequences when the charged person touches a typical electronic cabinet, *without direct contact* to a module or connector pin. What is shown as "likely consequences" assumes that the stressed equipment is of an ordinary design, not especially hardened against ESD. (Chapter 5 will explain how a system can be made reasonably immune to ESD.)

The right side of the chart shows what happens with the same kind of floor coverings when RH goes down to 20%. Nylon jumps to 6–11 kV, and some other synthetic carpets cause people to charge up to 8 kV.

The diagram in Figure 1.5 is restricted to the most current types of floors. With some specific materials, things can go even worse. The worst floor ever is probably a silicon waxed wooden floor where human ESD voltages over 20 kV



Legend

	Shoe sole	Floor	RH
———	Composition or leather	Vinyl	4%
—●—	Leather	Conductive (0.27 MΩ)	5%
—△—	Composition	Conductive (0.95 MΩ)	4%
—○—	Leather	Conductive (0.27 MΩ)	45%
- - - - - -	Composition	Conductive (0.27 MΩ)	5%
—·—	Composition	Conductive (0.27 Ω)	45%
—□—	Conductive	Conductive	

Figure 1.4 Electrostatic-generated voltages will decay at a rate that is dependent on relative humidity, floor covering, and type of clothing worn by personnel. Decay times can take several minutes to reach safe levels (7).

have been commonly reported. A well-known, and often painful, static environment is that of an automobile interior (Fig. 1.6), since a car is a metallic envelope isolated by its tires and replete with plastic and synthetic textiles.

It may seem that a relative humidity of 20% is a rather low. Indeed, as shown in Table 1.2 for relative humidity over the year in major U.S. cities, only a few locations have an RH less than 20%. But in absolute numbers, cities such as Albuquerque, Tucson, and Phoenix are industrial/business areas representing millions of people with hundreds of thousands of electronic devices installed, which must function correctly, even during the winter/spring months.

In fact, the problem is more critical than Table 1.2 would have us believe: The recorded RH values are those found outdoors by the weather bureau. A significant difference may exist between the RH outdoors and its actual value in a heated building. This is due to the fact that, given the same quantity of water, warm air has a greater ability to absorb moisture; therefore, its relative humidity (compared to saturation) is lower.

Equation (1.3) shows that in a restricted space whose temperature is T_2, the relative humidity is

$$\mathrm{RH}_{2(T_2)} = \mathrm{RH}_{1(T_1)} \frac{T_2}{T_1} e^{C(1/T_2 - 1/T_1)} \tag{1.3}$$

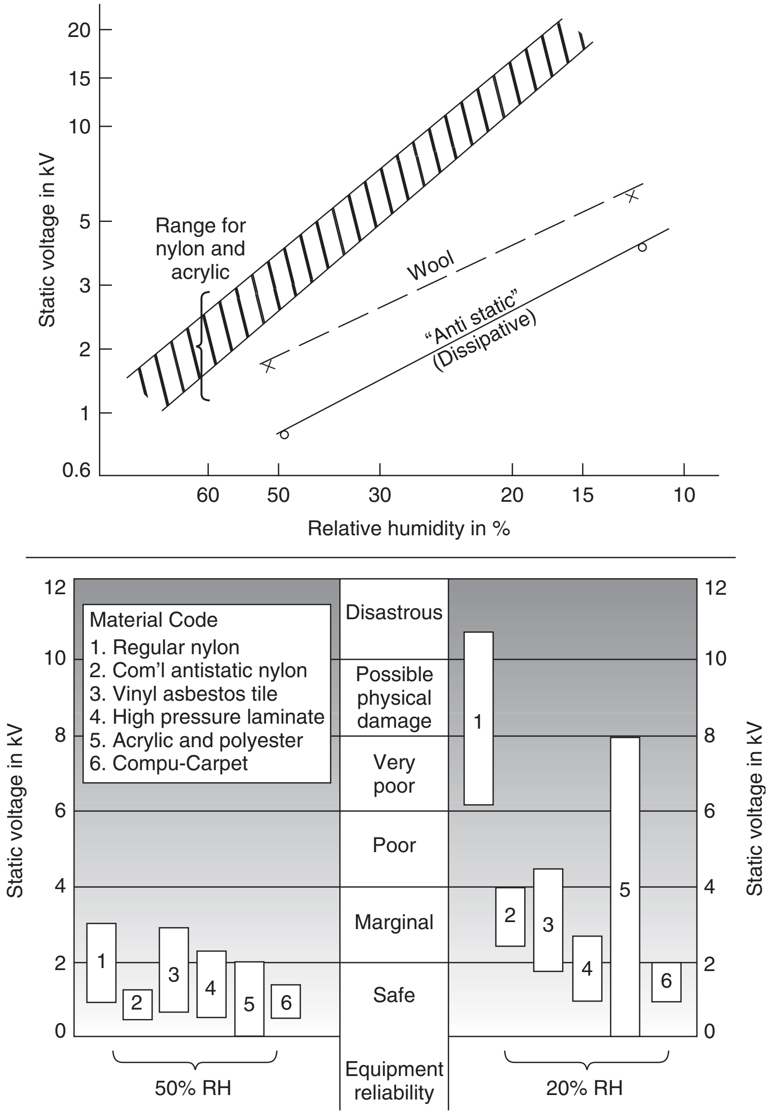


Figure 1.5 Typical range of static voltages generated by walking on common floor covering materials (adapted from Ref. 8).

where RH_1 is the relative humidity of the outer ambient, at temperature T_1, and C a constant equal to 5370 between -20°C and $+70^\circ$C; T_1 and T_2 in the formula are given in kelvins.

The equation has been plotted in Figure 1.7 for a few typical situations. For instance, on a winter day where the outside temperature is 0°C (273°K) and the

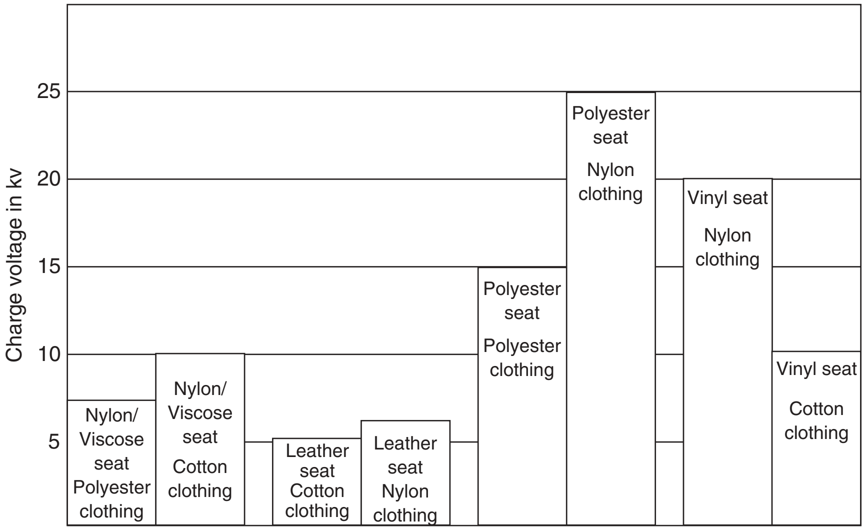


Figure 1.6 Electrostatic charging voltages for various car driver/car seat combinations (9).

RH about 40%, the actual RH in a room heated at 22°C will be only 9%! Unless the heating, ventilation, or air-conditionning system (if there is one) compensates for this lack of water vapor, which it generally does rather poorly, or a humidifier is installed, the ESD risk is very high.

Besides the type of material and the relative humidity, other factors play a role in the severity of the human electrostatic charge:

Type of clothing and shoes

Speed and manner of walking

Sex and size of the person

Body capacitance

Body resistance

The two last factors will be discussed in the next section because they strongly influence the dynamic characteristics of the discharge.

1.3. VARIOUS TYPES OF ELECTROSTATIC CHARGING WITH HUMANS AND OBJECTS

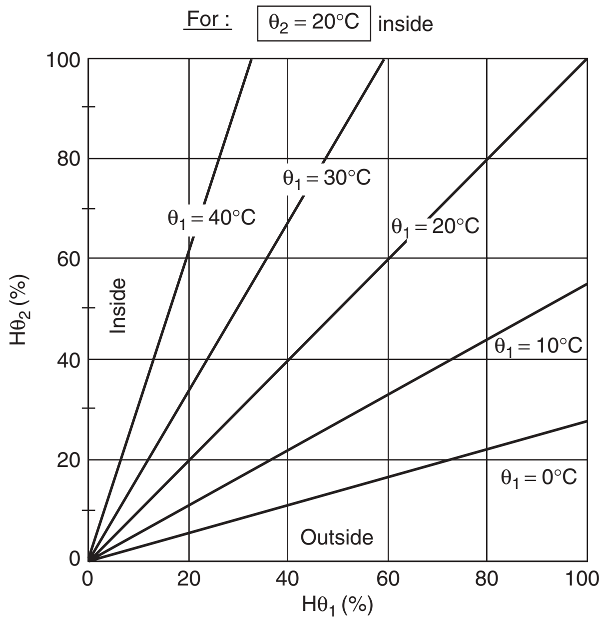
Although an infinity of ESD cases have been reported, the ones that are plaguing the electronic industry belong to either the human body discharge or the charged object discharge. (9) So far, we have emphasized the electrostatic charges generated by human beings, as shown in the most common scenarios of Figure 1.8.

Table 1.2

Relative Humidity
in Selected U.S. Cities

STATE	STATION	Length of record (yr.)	Jan.		Mar.		May		July		Sept.		Nov.		Annual	
			7:00 a.m.	1:00 p.m.	7:00 a.m.	1:00 p.m.	7:00 a.m.	1:00 p.m.	7:00 a.m.	1:00 p.m.	7:00 a.m.	1:00 p.m.	7:00 a.m.	1:00 p.m.	7:00 a.m.	1:00 p.m.
Ala	Mobile	17	81	62	83	56	86	54	89	61	88	61	85	56	85	57
Alaska	Juneau	36	79	76	79	69	74	62	81	70	87	77	85	81	81	73
Ariz	Phoenix	19	45	32	33	23	18	13	28	20	31	23	37	28	32	22
Ark	Little Rock	19	80	62	78	56	86	57	87	58	89	59	82	57	83	57
Calif	Los Angeles	20	56	60	62	65	66	66	69	68	66	67	57	63	62	65
	Sacramento	19	85	70	68	52	50	36	47	28	50	31	75	59	63	46
	San Francisco	20	79	67	70	63	64	60	66	60	65	59	73	64	69	62
Colo	Denver	19	45	48	42	40	39	37	35	35	38	34	45	50	40	40
Conn	Hartford	20	72	57	72	53	73	47	79	51	87	56	80	57	77	53
Del	Wilmington	32	75	60	74	53	76	53	80	54	85	56	80	56	78	55
D.C	Washington	19	68	54	68	49	72	51	76	53	80	56	74	53	73	52
Fla	Jacksonville	43	87	57	85	49	84	50	88	58	91	62	89	55	87	55
	Miami	15	84	60	82	56	82	61	85	64	89	68	85	61	84	62
Ga	Atlanta	19	78	60	78	51	83	55	90	63	90	61	82	54	83	57
Hawaii	Honolulu	10	80	63	73	58	67	55	66	51	66	52	74	59	71	56
Idaho	Boise	40	73	70	55	44	45	34	33	21	39	30	65	60	52	44
Ill	Chicago	21	76	68	79	62	76	54	81	57	84	57	80	64	79	60
	Peoria	20	77	68	81	64	81	57	85	58	88	58	83	66	82	61
Ind	Indianapolis	20	81	70	80	63	82	57	87	60	91	59	85	67	84	62
Iowa	Des Moines	18	76	68	78	63	78	55	81	57	84	59	79	64	80	61
Kans	Wichita	26	79	63	76	54	83	55	78	49	82	55	79	57	79	55
Ky	Louisville	19	77	65	76	59	83	56	86	59	89	60	79	61	81	59
La	New Orleans	31	85	67	85	61	89	60	91	66	89	66	86	61	88	63
Maine	Portland	39	77	62	75	59	75	58	80	60	86	61	84	63	80	60
Md	Baltimore	26	71	58	71	51	77	53	82	53	85	56	77	55	77	54
Mass	Boston	15	68	58	68	57	71	58	73	56	79	61	75	61	72	58
Mich	Detroit	45	78	69	77	60	71	51	74	51	82	55	79	64	77	58
	Sault Ste. Marie	38	82	76	83	68	80	56	89	62	92	67	87	76	85	67
Minn	Duluth	18	74	68	77	63	76	54	83	58	86	63	80	69	80	63
	Minneapolis-St. Paul	20	72	66	76	63	76	52	81	54	86	60	80	66	79	60
Miss	Jackson	16	87	66	88	57	92	56	93	60	94	61	91	58	91	59
Mo	Kansas City	7	74	65	78	62	83	59	82	56	86	60	78	62	80	60
	St. Louis	19	83	66	82	59	83	56	86	57	91	59	85	63	84	60
Mont	Great Falls	18	63	62	53	48	46	40	38	29	45	36	55	54	50	45
Nebr	Omaha	15	76	65	76	57	79	55	83	56	87	61	80	62	80	59
Nev	Reno	16	68	50	47	33	33	25	28	19	34	21	56	41	44	31
N.H	Concord	14	74	60	78	56	79	48	86	52	91	57	85	61	82	55
N.J	Atlantic City	15	75	58	76	55	79	57	84	58	86	59	82	57	80	57
N. Mex	Albuquerque	19	50	39	32	23	24	17	35	27	40	31	42	35	37	28
N.Y	Albany	14	79	64	74	54	76	52	80	54	88	59	81	63	79	57
	Buffalo	19	80	74	80	67	76	56	79	55	83	60	82	70	80	63
	New York	58	68	60	67	55	71	53	75	55	79	57	73	59	72	56
N.C	Charlotte	19	78	56	80	51	84	54	88	59	90	58	84	53	83	54
	Raleigh	15	79	55	80	49	87	56	90	59	93	60	85	51	85	54
N. Dak	Bismarck	20	72	66	78	62	79	49	83	47	82	49	79	62	79	56
Ohio	Cincinnati	17	79	68	77	60	80	54	85	57	88	59	80	63	81	60
	Cleveland	19	77	70	78	65	77	58	82	58	84	61	79	66	79	63
	Columbus	20	76	68	73	58	79	55	84	56	88	59	81	64	80	59
Okla	Oklahoma City	14	79	61	75	52	83	58	81	50	84	56	78	54	80	54
Oreg	Portland	39	82	76	72	60	66	53	61	45	67	49	82	74	72	60
Pa	Philadelphia	20	73	59	71	53	75	53	79	55	83	57	77	56	76	55
	Pittsburgh	19	76	66	74	58	76	51	82	53	86	57	79	63	78	57
R.I	Providence	16	72	58	70	54	72	52	77	57	82	57	78	59	75	55
S.C	Columbia	13	82	55	83	48	87	51	89	56	93	58	88	49	87	52
S. Dak	Sioux Falls	16	74	67	80	63	80	53	81	52	85	57	82	64	80	59
Tenn	Memphis	40	78	63	76	56	82	55	85	57	86	56	79	55	81	57
	Nashville	14	80	65	78	54	87	56	91	59	92	61	81	59	85	58
Tex	Dallas-Fort Worth	16	80	61	80	57	88	61	81	50	87	59	81	56	82	57
	El Paso	19	44	34	28	20	22	15	39	29	44	34	38	32	35	27
	Houston	10	88	66	89	60	94	60	94	59	95	65	91	60	92	60
Utah	Salt Lake City	20	70	68	52	45	37	31	26	20	34	27	57	58	46	42
Vt	Burlington	14	70	64	73	59	75	51	80	54	87	64	79	69	78	60
Va	Norfolk	31	75	59	74	54	78	57	82	60	84	62	79	56	78	58
	Richmond	45	81	57	78	49	79	51	85	57	90	57	85	50	83	53
Wash	Seattle-Tacoma	20	78	74	74	62	67	54	65	48	74	59	80	74	73	62
	Spokane	20	82	77	67	54	52	40	39	25	50	34	81	74	62	51
W. Va	Charleston	32	77	63	74	53	82	50	90	61	91	56	80	56	82	56
Wis	Milwaukee	19	75	68	79	66	79	61	82	61	87	63	81	67	81	65
Wyo	Cheyenne	20	45	48	44	45	39	41	34	37	35	36	42	47	40	42
P.R	San Juan	24	80	64	77	60	77	65	78	66	79	67	81	66	79	64

Please note: These figures, given in percentages, represent the averages for the period of record through 1979. Eastern Standard Times are indicated.



$$H\theta_2 = H\theta_{1K} \cdot \frac{\theta_{2K}}{\theta_{1K}} \cdot e^{5400\left(\frac{1}{\theta_{1K}} - \frac{1}{\theta_{2K}}\right)}$$

H_θ : Relative humidity at temperature θ

θ : Temperature in K (formula valid for –20 to + 60°C)

Figure 1.7 Actual vs. apparent relative humidity.

Notice that depending on the nature of the two materials being rubbed together, the person can exhibit positive or negative charging.

Although humans tend to treat themselves as very special, physics does not care and treats us as a mere conglomerate of materials, vaguely conductive. There are thousands of occasions where the human body is not the electrostatic generator, but simply the carrier, or even is not involved at all (Fig. 1.9).

An example of a human as a carrier occurs when a person gets out from a car after a ride on a bright, cold, and windy winter day. The moment he puts his foot on the ground while his hand is touching the door handle, he often feels a violent ESD zap. The body was not the electrostatic generator in this case, the car was.There have been reports of highway toll gate attendants who could not stand their job because of too many ESD zaps when drivers where handling them the money!

Following is a list of some nonhuman ESD sources:

- Wheelchairs, carts, rolling furniture
- Rubber or textile belts and conveyors and their pulleys/rollers
- Cooling fans with plastic rotor blades
- Helicopter rotor blades (generally made of composite material)

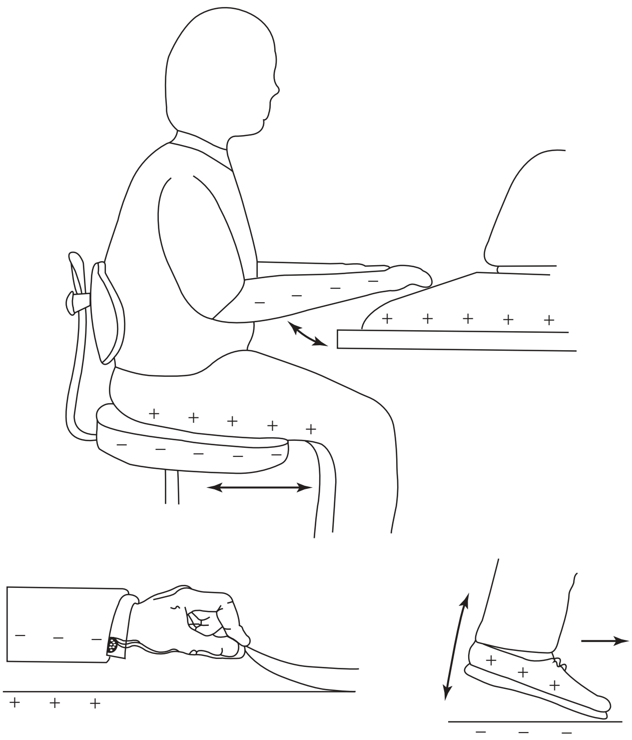


Figure 1.8 Some of the classical ways a human can accumulate static charges.

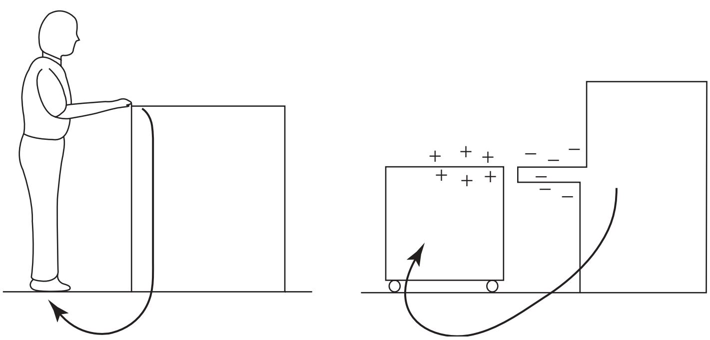


Figure 1.9 ESD with or without a human body involved.

- Paper movement (printers, copiers)
- Rapid flow or friction of gas, liquid, or granule against an insulating material or unground conductor such as:
  - Cleaning with airgun
  - PVC "skin-packing" with hot air blast
  - Cleaning with solvent
  - Fuel lines (including filling-in or draining-off a fuel tank)
  - Loading or dumping grains in silos
  - Rocket exhaust nozzle
  - Radomes, fiberglass hoods, and tips
  - Thermal blankets (spacecrafts)
- Device-manipulating robots on manufacturing lines
- Electrostatic painting process (the spray nozzle being charged around 80–100 kV)

Also, we must remember that a nonconductive object can become charged by contact with another, previously charged, object. This static-contaminated object will, in turn, be a potential hazard for electronics.

In all cases, whether a person is involved or not, the charged object will "seek" the first opportunity to recombine the unbalanced charges: This may occur smoothly by a progressive bleed of charges through a moderately conductive path, or may occur abruptly and generally accompanied by an arc.

In the case of a "self"-recombination, a small amount of current will flow during a certain time, and the result will be generally harmless. To the contrary, with an abrupt recombination, the discharge will occur during a very short time due to the high-voltage gradients involved, and the corresponding current will be high. Since its average value is

$$I(\mathrm{A}) = \frac{Q(\mathrm{Coulomb})}{t(\mathrm{s})} \tag{1.4}$$

when a discharge of microcoulombs takes place within tens of nanoseconds, the average current amounts to several amperes, with peak values that can reach up to hundreds of amperes.

1.4. STATISTICS OF VOLTAGES AND CURRENTS REACHED DURING ESD

Although the ESD phenomenon has been experienced and fought against for decades by electrical and electronics industries, it is only around the early 1970s that thorough studies were carried on its dynamic parameters. Measurements have been published of voltages and/or currents encountered during real or re-created ESD situations, sampled over a certain period of time or among a certain number of individuals. The statistics that have been gathered, to the knowledge of this author, can be classified as follows:

- Measured voltages of human ESD, depending on the materials involved (garments, type of shoes, type of floor covering)
- Measured voltages of human ESD, depending of the relative humidity (correlated or not with the time of the year)
- Measured voltage of objects and furniture ESD, against the type of objects and sometimes the type of environment (humidity and floor covering)
- Measured currents with furniture ESD, against type of environment and time of the year

Although they are more spectacular and seem to relate the most obviously with the severity of the discharge, the data collected on ESD voltages are not the most meaningful, neither are they the most crucial when trying to develop representative specifications for ESD simulation.

The voltages at which the persons were charged during the measurement campaign can be an ambiguous or inaccurate database. Was the voltage measured at its peak, right after a static buildup? Or was it recorded at the moment of an actual discharge? What were the mean value and standard deviation of the voltage decay between its peak value (as generated) and its value at the exact moment of the discharge? Were the people in the study aware that ESD voltages were gathered?

Every statistician knows that people in such surveys often tend to "sympathize" with the experimenter, *helping him to find what he likes to find* (in our case, for instance, by shuffling their shoes more consciencously on the carpet). Statistics is a discipline requiring specific precautions. In some of the often mentionned experiments, it is not clear that these precautions were taken or were feasible.

Doing a parallel between ESD and lightning, one could say that focusing on ESD voltages only is probably as irrelevant as would be concentrating on cloud-to-Earth voltages when studying lightning strikes: all sound statistics on lightning severity are based on lightning currents. Similarly, ESD statistics based on current seem the most dependable and usable. As for any transient, random events, statistical analysis is important for determining what is the risk that a certain value of electrostatic discharge will be reached (or the probability P that this value will be exceeded). Do we want to test the immunity of an electronic device or equipment to something that can happen once a day or once a year? How many failures per week or month do we risk by testing a machine only to a certain ESD level?

A rough example of recording the number of electrostatic discharges is shown in Figure 1.10. During a particularly cold and dry spring (early April 1982) in Virginia, the author had taken a limited survey of the number of discharges (as they were felt by people) in a set of offices where about 12 people were using one copier, a telex, a desk-top computer, a postage meter, and a word processor.

Discharges were recorded on Tuesdays, Wednesdays, and Thursdays for 3 weeks. These discharges did not necessarily cause equipment malfunction—in fact most of them did not—but the purpose of the survey was to count the