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

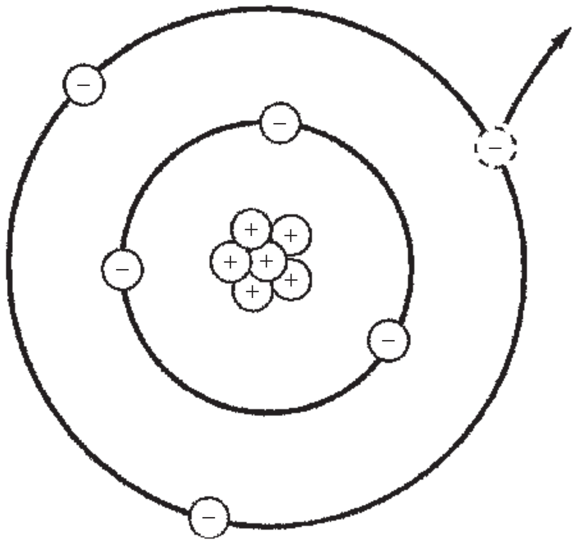


Figure 1.1 If by heating, rubbing, and the like, one electron is leaving the orbit, the material is left with six protons and only five electrons.

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.

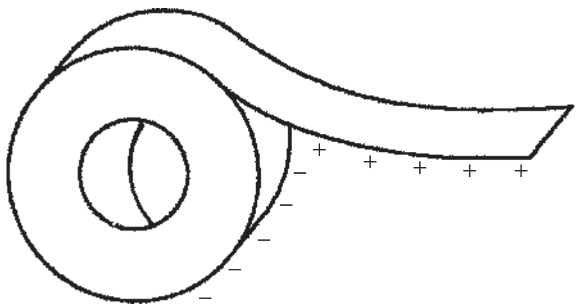


Figure 1.2 Stripped end of acetate tape is attracted by the surface of the tape reel.

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

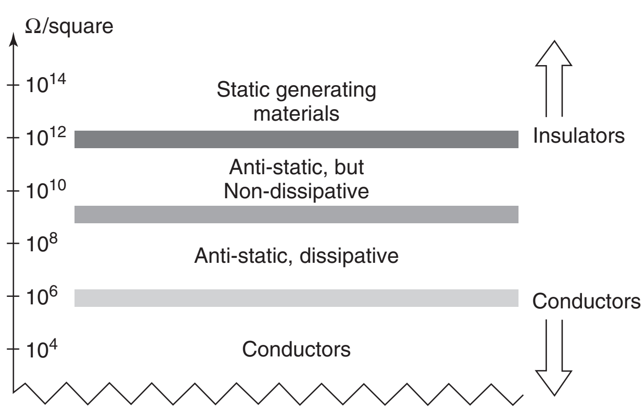


Figure 1.3 Propensity of materials to create ESD problems, based on surface resistance in ohms/square.

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 $\varepsilon_{r1}, \varepsilon_{r2}$ 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

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

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.

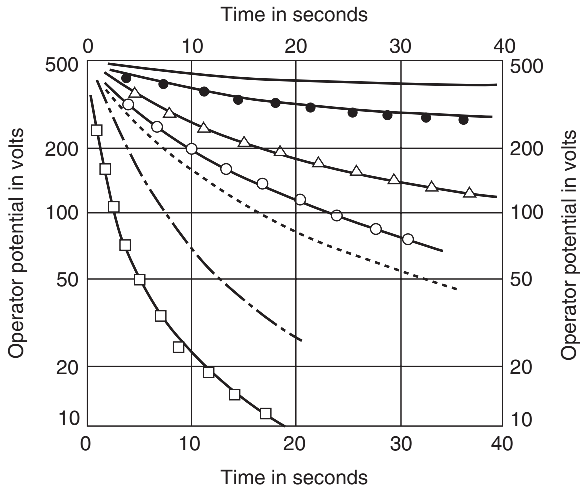
Many evaluations have been made of the electrostatic voltages reached by a person walking on several types of floors. Generally, these tests are made using a kind of "standard walking procedure." The person walks a given number of steps with a given type of shoes; then his (her) charging voltage is immediately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

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

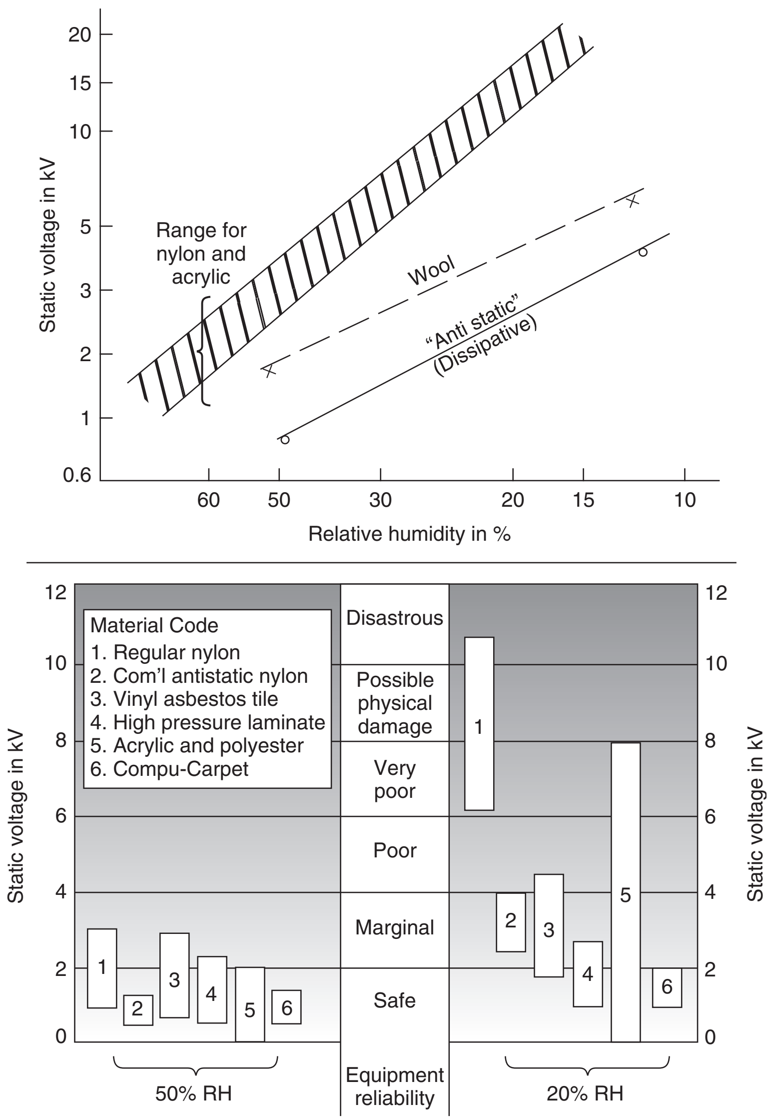


Figure 1.5 Typical range of static voltages generated by walking on common floor covering materials (adapted from Ref. 8).

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

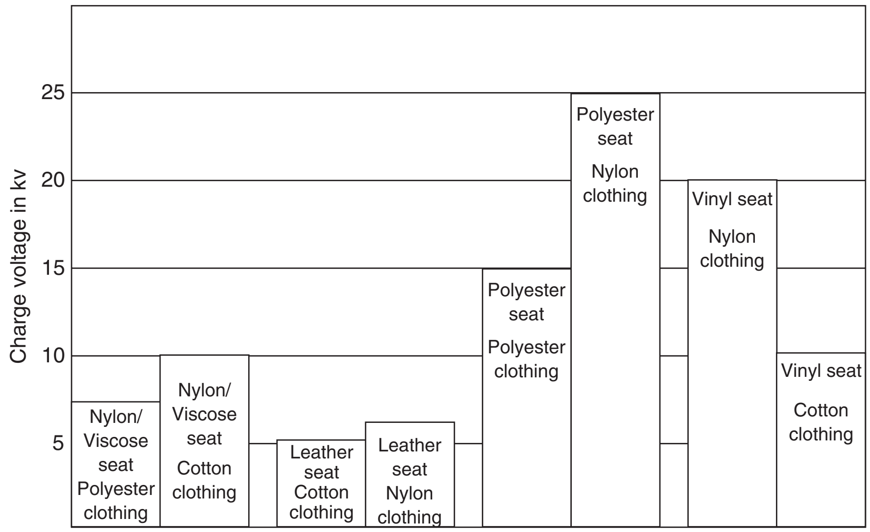


Figure 1.6 Electrostatic charging voltages for various car driver/car seat combinations (9).

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

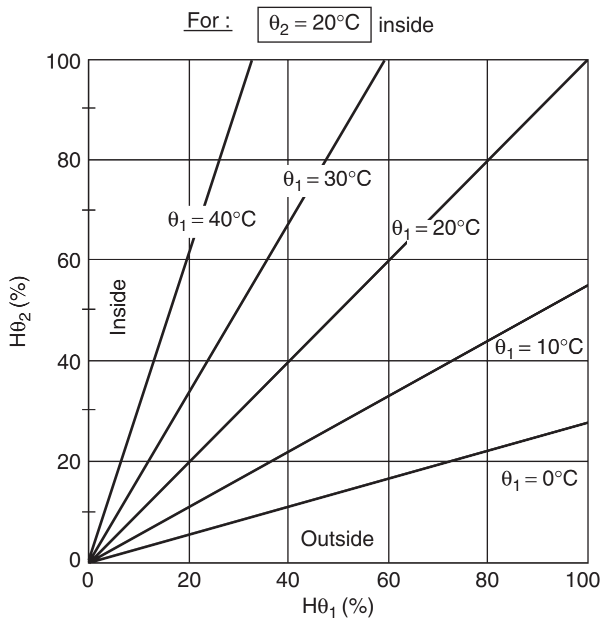
Although an infinity of ESD cases have been reported, the ones that are plaguing the electronic industry belong to either the human body discharge or the charged object discharge. (9) So far, we have emphasized the electrostatic charges generated by human beings, as shown in the most common scenarios 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	66
	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	46	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	76	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	76	62	83	59	82	56	86	60	78	62	80	60
	St. Louis	19	83	66	82	59	83	56	86	57	91	69	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	78	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	86	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	56
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)

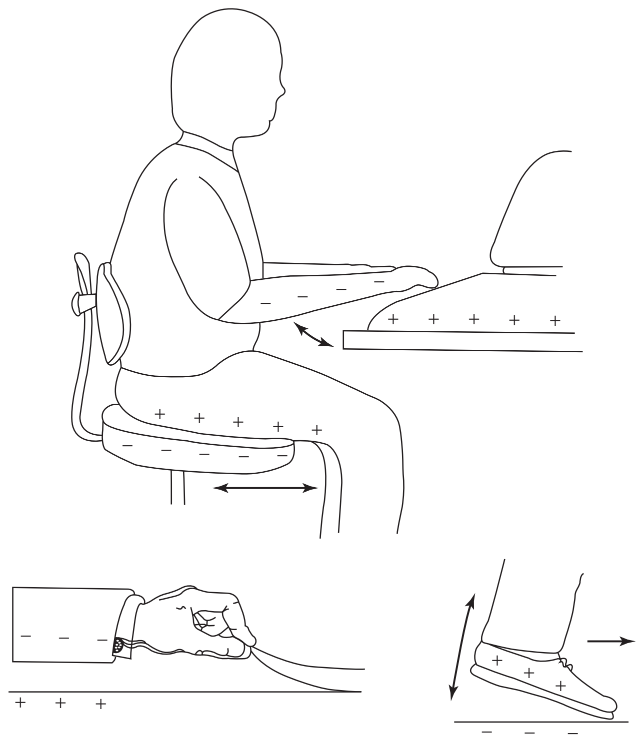


Figure 1.8 Some of the classical ways a human can accumulate static charges.

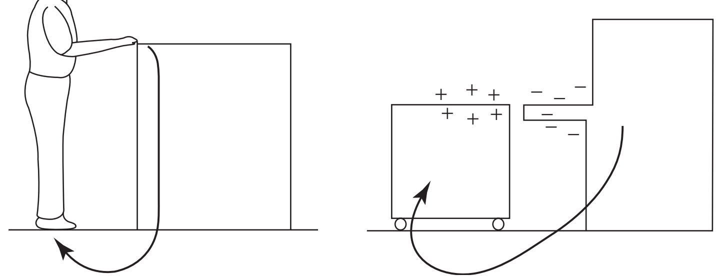


Figure 1.9 ESD with or without a human body involved.

- 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 conscienciously 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

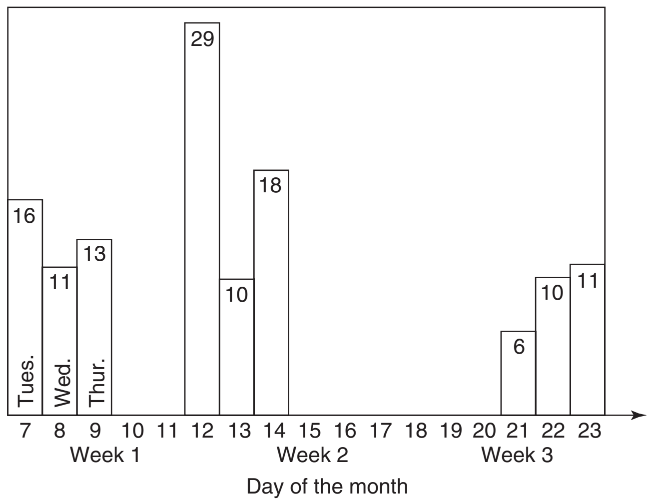


Figure 1.10 Number of discharges/day in a medium-size office area with copier, computer, word processor, telex, and mailing machine.

ESD events, not the eventual failures. It must be also noted that discharges of less than 1500–2000 V were generally not felt by a person and, therefore, were not recorded: They represent no risk for normal electronic equipment, but their absence in a sampling could skew the statistical analysis and produce overly pessimistic conclusions.

A much more intensive survey was done by Simonic (10, 11). During two surveys spread over several years, he has compiled with an impeccable rigor thousands of measurements of both human and furniture ESD in quasi-real-life conditions. His work represents such an outstanding contribution to the subject that it deserves a detailed analysis, as shown hereafter.

1.4.1. Personnel ESD Statistics

The first compilation made by Simonic covered personnel ESD events. The survey was run for 16 months, and its analysis allows one to predict, given a human contact discharge, the probability P of exceeding a peak discharge current I. The highlights of the analysis are the following:

- The rooms surveyed had a high human activity (terminal room with 16 operator-attended stations).
- The rooms had uncontrolled (or poorly controlled) RH and wool carpet.
- The purpose of the survey was to record the number of *discharges, not the number of machine failures*, which would have restricted the scope of the study.

Therefore, to be sure that what was measured was the ESD current caused by people (and not furniture ESD), and to provide every person with the same calibrated discharge path, a special monitoring setup was devised:

- I_{ESD} was measured by a current probe (current transformer) placed on a specially equipped metal doorknob.
- Only the interior side of the door handle was equipped, so only personnel ESD from inside the room was recorded.
- The current probe was connected to a recorder with 9 separate channels, set to specific threshold levels. The probe had a 100-MHz bandwidth, but accounting for the whole instrumentation chain, the final 3-dB bandwidth was 30 MHz.
- Each channel was recording the number of occurrences its own threshold was exceeded [therefore it can be directly translated in a $P(I > 1x)$ statistic].
- The RH was constantly monitored.

The study collected data from 498 eight-hour shifts, with an average of 120 discharges per shift. Thus, about 60,000 ESD events were logged and arranged in 3800 data entries. Using sound statistical practices, a regression analysis weighted to the number of human contacts was performed. Over a more limited period, one type of antistatic carpet was also surveyed. Since some people had finger rings, wrist straps, and the like, it is likely that a certain percentage of human/metal discharge is included in the collected data.

The 30-MHz bandwidth seems insufficient to measure ESD pulses with 1-ns rise time (which would need at the very least a 350-MHz bandwidth). But the system was calibrated by a reference ESD pulser delivering a waveform with a 2-ns rise time, 320-ns time constant, and a source impedance of 2000 Ω (behaving like a current source). Thus, the correlation between the 30-MHz limited bandwidth and the actual pulse bandwidth was taken care of by the calibration.

The analysis reveals, of course, a strong correlation between the RH and the peak currents reached. A convenient equation for predicting the current I, given a probability P , was derived from the analysis:

$$I \geq 10^{A} P^{B} (\mathrm{RH})^{C} \tag{1.5}$$

with

$$A = 4.12 \qquad B = -0.645 \qquad C = -3.39$$

within the following range:

0.95 confidence

RH% comprised between 15 and 55

Probability $P(I) = 0.001 < P < 1$

Table 1.3 Peak Current (in Amperes) Having a Probability $P(I)$ of Being Exceeded by Personnel ESD

RH Percent		$P(I)$			
		1	0.5	0.1	0.01
15 <	< 20	0.22	0.80	2.4	8.7
20 <	< 25	0.14	0.73	1.9	7.1
25 <	< 30	0.11	0.35	1.1	3.5
30 <	< 35	0.072	0.20	0.80	2.2
35 <	< 40	0.059	0.11	0.40	1.3
40 <	< 45	0.052	0.075	0.17	0.56
45 <	< 50	0.042	0.055	0.10	0.25
50 <	< 55			0.072	0.15

For example, what is the current that will be exceeded only 10% of the time, given a RH% of 20, with 95% confidence?

$$I \geq 10^{4.12}(0.1)^{-0.645}0.645.(20)^{-3.39}$$
$$I \geq 2.2 \text{ A}$$

Equation (1.5) has been arranged in a tabular form in Table 1.3, with the results of the survey plotted in Figure 1.11, where personnel ESD event curves give the current I having a probability $P(0.01 < P < 1)$ of being exceeded.

Table 1.3 shows the current increasing approximatively like the inverse cube of RH. Given a same probability (P), currents will be 20–40 times greater at

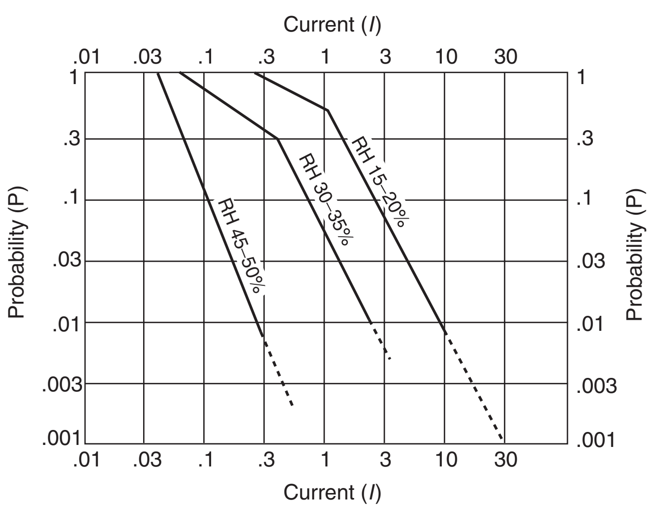


Figure 1.11 Simonic's personnel event curves.

RH = 15% than at RH = 45%. Also a given current I will be exceeded 100 times more often at RH 15% than at RH 45%.

Since the RH% has been recorded at intervals of 15–20, 20–25, and so on, the curves shown in Figure 1.11 are mean values of P in these intervals. Given the strong dependency of $P(I)$ on the relative humidity, even a 5% RH interval corresponds to large variations of P for a given I, around the mean value. For instance, for a 15–20 RH interval, assuming the average RH is 17.5%, a current of 5 A will have a 0.025 (or 2.5%) probability of being exceeded. However, for this interval and a same (P) the lower bound (RH = 15%) corresponds to 8.4 A, while the upper bound (RH = 20%), gives only 3.2 A.

To complicate the issue, the average value of RH in the interval does not correspond to the mean value of $P(I)$ in that interval. Therefore, the curves of Figure 1.11 are a good indication considering that, in reality, RH has daily fluctuations that often exceed 5%; if a more accurate prediction is needed, Eq. (1.5) should be used.

A reconstituted histogram of the personnel ESD events is shown on Figure 1.12. In addition to the current intervals, two voltages are also indicated on its lower scale:

- The voltage at which a 1-kΩ pulse generator should be charged to replicate the same event.
- The voltage at which an IEC-type simulator (see Section 3.2) should be charged to create the same currents. This takes into account the fact that above 8 kV, the IEC simulators switch from contact discharge (hand/metal) mode to air discharge.

Of course, this attempt of relating P to a number of events/shift is broadly indicative. While the probability P for a current I is a well-supported figure, the total number of events/shift in a room depends strongly on its size, occupancy, and activity. The rooms in this study could have exhibited from a few tens to several hundred events/shift. A gross estimate would give, for a low RH and carpeted room, an average total of 100 events per shift.

Also not shown, but reported in Simonic's study, is the fact that antistatic carpet (acrylic carpet incorporating conductive fibers) did show a 36 times reduction in ESD currents for the (15–20)% RH interval and 23 times reduction for the (30–35)% interval.

1.4.2. Furniture and Objects ESD Statistics

The second of Simonic studies covered furniture ESD events. The survey lasted several years, and addressed ESD voltages in both computer rooms and data processing offices. The statistics are not compiled in percent probability but in number of ESD events per shift.

Being a meticulous experimenter, Simonic had to select sites with significant probability of ESD occurrences. With ordinary offices, as was the case

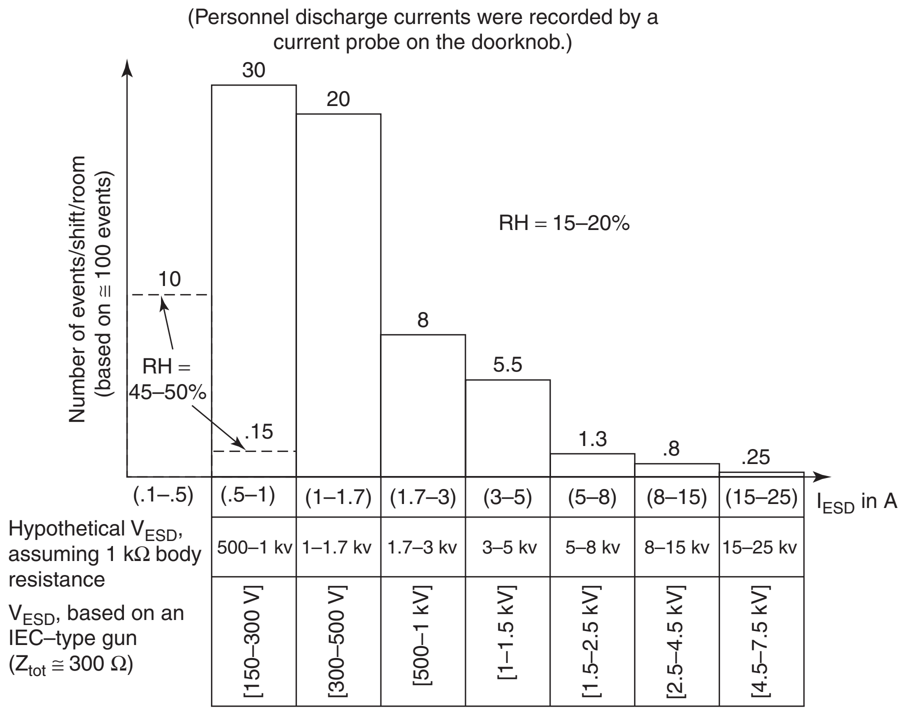


Figure 1.12 Reconstituted histogram. Events/shift for personnel ESD.

with the personnel ESD survey, site selection was not a problem because a large sample of locations was available. The situation was different with computer rooms: Sites with a significant history of ESD events were sometimes modified prior or during the survey, for instance, by increasing the RH%, or replacing some furniture with antistatic type, to correct a serious ESD problem. As a result, the measured event rate was biased by artificially reduced ESD voltages. Simonic did his best to document such situations when they could not be avoided.

The highlights of the analysis are:

- The sites selected were locations with ESD problems, preferrably where no corrective measures had yet been taken.
- The two kinds of sites were:
  - Computer rooms with raised metal floor and humidity control: 10 sites, 11 machines, totaling 3360 eight-hour shifts
  - Carpeted offices with no humidity control: 8 sites, 8 terminals, 282 shifts
- All machines were floor standing units with metal covers.

- This time, the ESD event detector was a current probe placed around the machines input/output and power cables.
- The detector was sensing the peak current and was calibrated to correlate with a given discharge at typical contact points on the machine.
- The detector was optimized for furniture ESD, that is, voltage source (low impedance metal object). Then the readout was converted into an assumed ESD source voltage (see Note 1).
- The detector 3-dB bandwidth was 100 MHz. As for the personnel study, the recorder had nine channels with preset levels, which counted each occurrence where the treshold was exceeded.

Note 1 The idea behind this detector was that a charged furniture behaves much like a voltage source. By knowing the average value of the discharge path impedance, which includes the total loop resistance, the arc resistance and the loop inductance, the unknown ESD voltage can be derived as $V_{\mathrm{ESD}} = I_{\mathrm{peak}} \times Z_{\mathrm{loop}}$. The only questionable point would be how dependable is the conversion factor when the actual ESD current waveform did not fit the standard "template."

A calibration setup, simulating the minimum (worst-case) loop impedance of the ESD is shown in Figure 1.13. Its dynamic R,L,C impedance is approximately 45 Ω , therefore:

$$V_{\mathrm{ESD}}(\text{unknown}) = I_{\mathrm{peak}}(\text{measured}) \times 45\ \Omega$$

For such an RLC network with $R < 2\sqrt{L/C}$, the discharge is an underdamped oscillatory waveform, with a 20–80% rise time T_r approximately equal to the charging time constant, that is, ≈ 10 ns.

It is important to stress once more that this calibration assumes the furniture discharge to behave as a voltage source, whose current is only dependent on the load, that is, the above discussed loop impedance. As a consequence, a personnel-type discharge will be also seen by the recorder, with its true current, but the derivation of the actual ESD voltage would be wrong, the human body having a significantly higher internal resistance.

In contrast to the former personnel discharge measurements, where the probe on a door handle prevented any other-than-people ESD from being captured, here the furniture ESD survey had no means to segregate between actual furniture

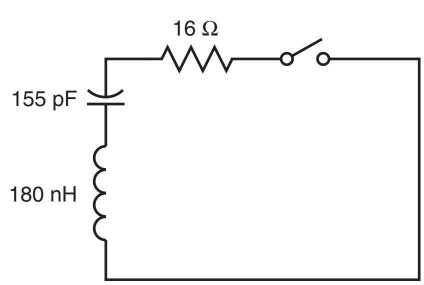


Figure 1.13 Circuit used for the reference discharge.

events and possible human events. A more thorough examination of the statistic curves will provide us, nevertheless, with a basis for this differentiation.

Figure 1.14 shows the event rate (events/machine/shift) in the 10 computer rooms surveyed, with the table on top giving the spread of RH for both the computer and the terminal rooms. The curve labeled *mean* is the mean of all recorded events (all machines and seasons combined), weighted by the number of shifts monitored at each site. For instance, the likelihood of having a 1-kv furniture discharge (corresponding to approximately 22-A discharge current) on a computer frame is about 0.11 per shift, that is, 50 times a year for 250 working days and 2 shifts/day. This does not seem catastrophic unless the dependability of the system is such that one error per week is intolerable.

But one must remember that this is an average figure. It is very likely that the majority of these events will be concentrated in the low RH period, that

	RH in %		
Season	Min	Max	V_{MAX} Recorded
Winter & Spring	14	55	5.4 kV
Summer	42	53	1.7 kV

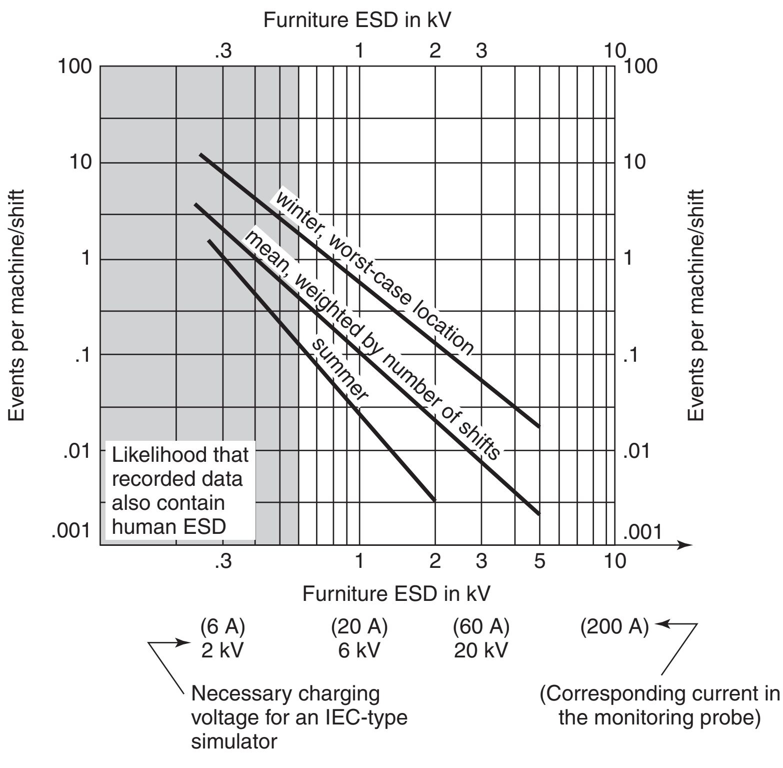


Figure 1.14 Computer room furniture ESD events (3360 shifts, 10 sites, 11 machines). Graph combines sites dependency and season dependency.

is, January to March, which may actually translate into one error per day! The threshold between what a computer user feels as being tolerable and what is not is always subtle, and by no means a step function, but a system experiencing one error per day, during several weeks, is generally unacceptable.

In Figure 1.14, the 95% confidence interval is shown as an upper bound of worst-case locations (site and season) and a lower bound of least occurrences. Keeping our previous example of a 1-kV furniture ESD, one sees that there is high probability (95%) that more than 0.025 events/shift exceeds that level, but only 5% chances (1−0.95) that it occurs more than 0.5 times/shift.

From the statistical regression analysis, an equation was derived, giving (more accurately than the curves) the furniture ESD events exceeding a certain voltage. For low values of P ($P \leq 1$), the mean event rate/shift is

$$P_{\text{furn}} = 10^{A} \times E(\text{volts})^{B} \tag{1.6}$$

with, for computer rooms:

$$A = 6.37, \qquad B = -2.44$$

for terminal rooms (carpeted floor, no RH control):

$$A = 5.5, \qquad B = -1.86$$

Example In computer room, the average number of event/shift exceeding 1 kV will be

$$P_{\text{furn}} = 10^{6.37} \times 1000^{-2.44} = 0.11$$

Although the study does not specifically give a quantitative correlation between a given event rate and a given RH%, this can almost be deduced from the data. For a 20-A($\approx$ 1 kV) discharge, there is a 25 : 1 ratio between the highest and lowest event rate extremes. There is a strong chance that the highest voltages (5 kV) were recorded during the lowest RH periods, and the lowest on the highest RH period (although some low readings could occur during dry season as well, if a piece of furniture did not have the time to yield a high static voltage before a contact occurred).

Addressing terminal rooms (severe environment), Figure 1.15 is even more revealing. The 8 carpeted offices with workstations show a spread of $E_{\max}/E_{\min} = 62$ times. In the personnel statistics for carpeted offices, Eq. (1.5) showed that for a given event rate P, the ESD current was varying like $(\text{RH})^{-3.39}$ for $15 \leq$ RH ≤ 55. If we apply this relationship to the carpeted offices for furniture ESD (there is no reason to believe that carpets would not behave the same way), the predicted ratio of $E_{\max}/E_{\min}$ would be 71 times, which is close to what it was in reality. The mean event rate for a 1-kV furniture discharge in these carpeted offices without RH control is about 1 per machine per shift.

When attempting to determine what fraction of these readouts could be due to personnel ESD being mixed in the presumed furniture data, we must keep

	RH in %		
Season	Min	Max	V_{MAX} Recorded
Winter & Spring	20*	25	5.6 kV
Summer	?	53	.09 kV

*RH can go as low as 5% at times.

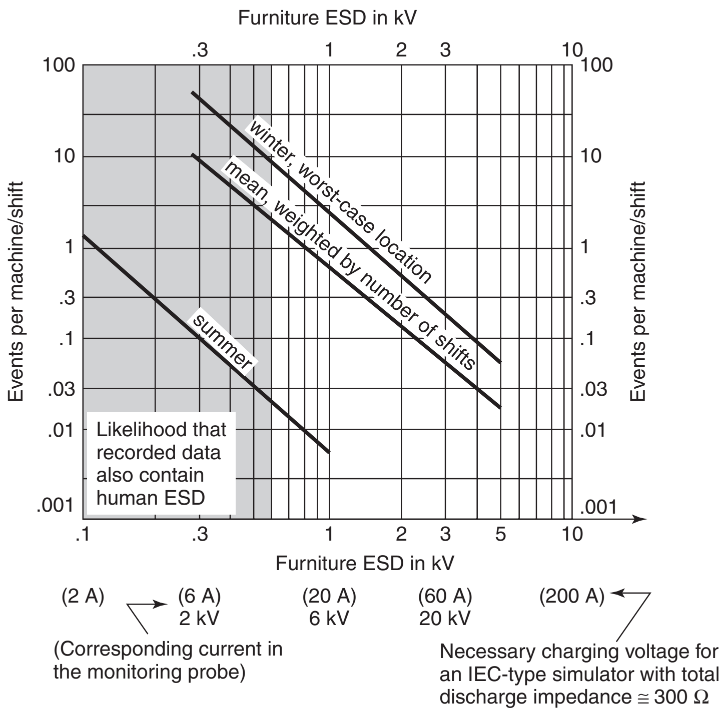


Figure 1.15 Terminal room furniture ESD events (282 shifts, 8 sites, 8 machines). Graph combines sites dependency and season dependency.

in mind that the highest voltage a person can realistically build up and keep more than a few seconds is about 20 kV. With a typical human body resistance during an ESD being 1 kΩ, the highest likelihood of personnel ESD data being inadvertantly mixed in furniture data woud be $I_p = 20$ A, which would appear as 800 V on the event rate curves in Figures 1.14 and 1.15 and Fig. 1.16 histogram. This has been shown as a shaded area on the left in both figures.

1.5. WAVEFORMS OF ELECTROSTATIC DISCHARGES

1.5.1. Personal ESD Waveforms

In trying to match the measured waveforms with the physical explanations of Sections 1.2 and 1.3, simple waveforms for the ESD current have been devised

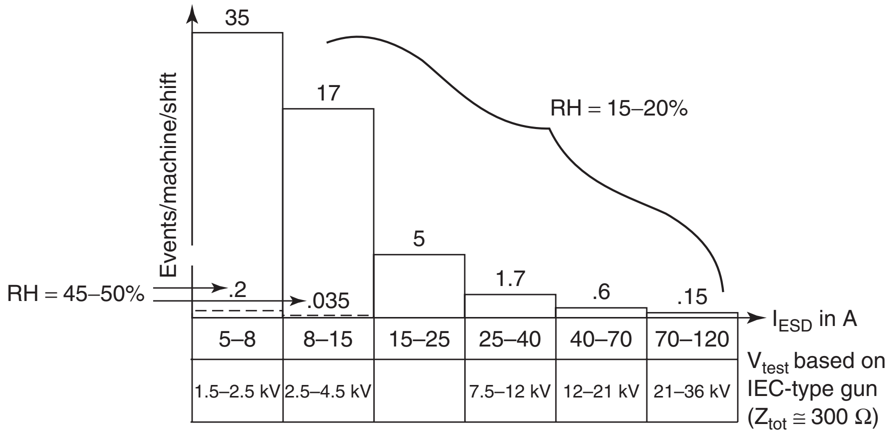


Figure 1.16 Reconstituted histogram, events/machine/shift for furniture ESD.

with the following parameters:

I = peak value of the current

t_r = rise time of the current, measured between the10 and 90% points (approximate fit to the rise time of the triangle envelope)

τ = pulse width at 50% amplitude = $0.7RC$

If we concentrate on the human body discharge, the main electrical parameters that play a role in the rise and fall of the current are:

L = self-inductance of the loop formed by the body, its arm, the machine, and the ground return. The range of values is 0.3 to 1.5 μH, with 0.7 μ H typical

R_d = resistance of the discharge loop, dominated by body resistance, practically ranging from 1 to 30 k Ω (Fig. 1.17)

C = capacitance of human body to ground, with the following range of values:

$$\text{min} = 50 \text{ pF}$$
$$\text{max} = 300 \text{ pF}$$
$$\text{typ.} = 150 \text{ pF}$$

The pulse rise time would be infinitely small if the capacitor simply discharged in a resistive network. In reality, this rise time is dictated by the charging time constant L/R_d. The pulse width of the discharge depends on the RC time constant of the circuit.

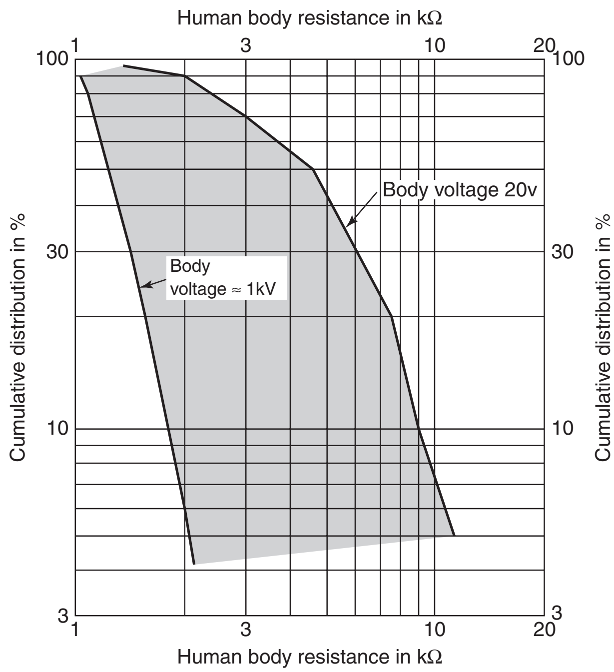


Figure 1.17 Distribution of human body resistances.

Table 1.4 gives a recap of the approximative range of rise times (t_r) and pulse widths (τ), given all combinations of the extremes values for R, L, and C. They correlate rather well with actual measured waveforms.

One could be tempted to combine some average values and come up with a "standard" waveform. However, this is quite risky—an average figure for a normal distribution represents the value that is met in 50% of the cases, hence *exceeded in 50% of the cases*. A specification designed upon this criteria would "underprotect" the equipment. It is safer to consider a reasonable maximum, such as the upper decile, for instance (the value that is exceeded in 10% of the cases only).

To come up with a reasonably severe waveform, let us look at the table showing the influence of R, L, and C and select the combination that provides the worst influence of each: For the human model R_d is generally larger than L/dt, the inductive impedance of the loop; when L decreases, the charging time constant decreases, when R_d decreases, the peak current increases, for a given static voltage, but this also slows down the rise time by varying the charging time constant.

Byrne (12) has performed a thorough analytical study of human ESD by assimilating the body to a set of cylindrical shapes with their respective capacitances and inductances. He ends up with some low-end extremes of 30 ps

Table 1.4 Possible Combinations of R, L, C Variables for Personal ESD and Their Influence on Pulse Rise Time and Fall Time

L	Min	Min	Max	Max	Typ	Typ[c]
R_D	Min	Max	Min	Max	Typ	Min
Current rise $\tau_r \cong 1.4$ L/R[a]	420 psc	13 ps[b]	2.1 ns	63 ps	280 ps	980 ps
C	Min	Min	Max	Max	Typ	Typ
R_D	Min	Max	Min	Max	Typ	Min
Decay time constant $\tau_C = RC$	50 ns	1.5 μs	300 ns	10 μs	750 ns	150 ns

[a]The 20–80% rise time is approximately equal to 1.4 times the charging time constant L/R. The 50% pulse width would be $\cong 0.69\tau_C$.

[b]The interest of this figure is purely academic. It would correspond to a peak current of a few hundred milliampere. However, dI/dt would still be there.

[c]The spread of human body inductances is not very large; therefore, a standard waveform based on a typical value of L is justified. In contrast, the spread of human body resistances is huge, and a standard waveform for a "reasonable worst case" should aim to the lower bound of human body R_D.

for the rise time. Such short rise times were not found in actual measurements. This does not mean they cannot exist; displaying a 30-ps rise without distortion requires an analog bandwidth of 12 GHz, which was not within the possibilities of memory oscilloscopes at the time. In any case, such a discharge would be associated with large values of R_d corresponding to smaller peak current: Therefore, the dI/dt derivative, which is, what counts for the magnetic coupling of the pulse to the victim, is fairly constant.

As an attempt to allocate R,L,C elements to the human body, Figure 1.18, top, displays what resembles their physiological location, although it is not strictly workable as an equivalent model for simulation software tools. Different models have been devised that produce close-to-real ESD waveforms. Of the many equivalent circuits that have been tried, one is described on the lower schematic of Figure 1.18. It generates in a 1-Ω shunt a current pulse very similar to the standard IEC hand/metal test. The hand/metal sharp current spike and the longer human body pulse can be seen separately by the two dedicated 1-Ω shunts, acting as current mirrors. To see the whole pulse at once, the user needs to run a plot adding the voltages across R_{01} and R_{02}.

Figure 1.19 shows a simplified waveform corresponding to a "standard" severe case, with a sharp 1-ns rise time and a long exponential decay. A simplified frequency spectrum of this pulse is also shown based on a triangular waveform; being a single event, the pulse repetition period is infinite, and the corresponding spectrum has no discrete spectral lines: It is a Fourier integral, with spectral density given in amperes per megahertz of bandwidth.

The spectrum starts (at a frequency equal to 1/infinity) with an amplitude of $2I_{\text{peak}}\tau$ (for I in amperes and τ in microseconds). The A/MHz envelope is flat up to the first corner frequency $F_1 = 1/\pi\tau$, then decrease like $1/F$, or -20 dB per decade slope, up to the second corner frequency $F_2 = 1/\pi t_r$ reciprocal of the rise time and often referred to as the "occupied bandwidth." From then on, the amplitude rolls off like $1/F^2$, or -40 dB per decade.

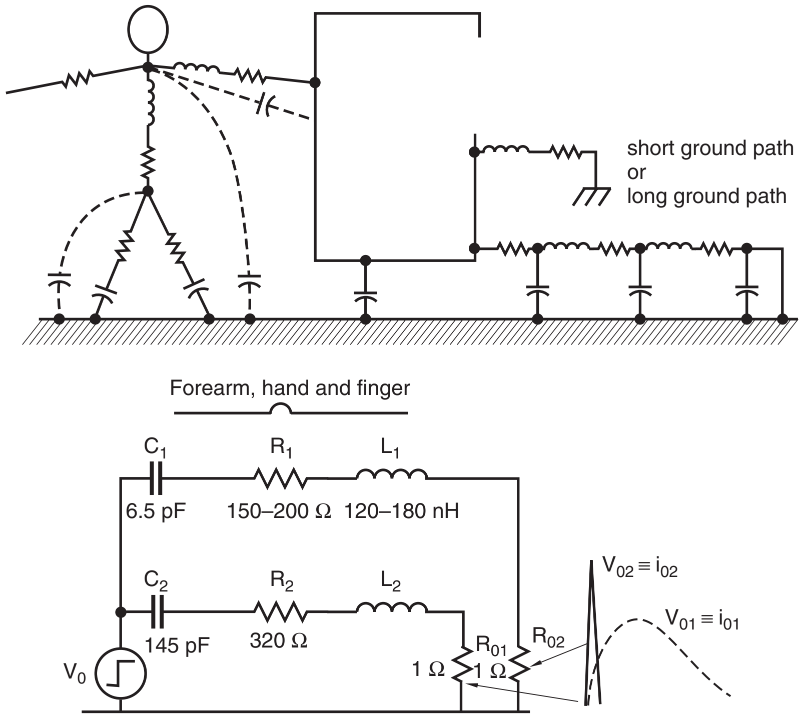


Figure 1.18 More complete lumped-element model of personnel ESD.

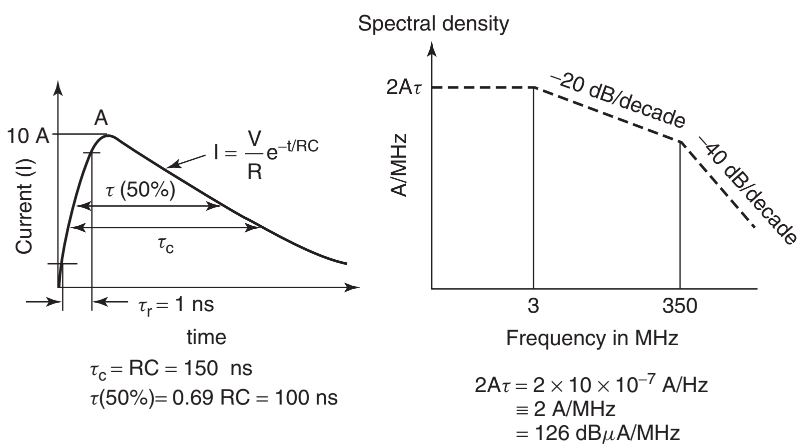


Figure 1.19 Simplified current waveform and spectrum occupancy, for a 10-kV personnel ESD (1-kΩ human body resistance assumed).

1.5.2. Furniture ESD Waveforms

If we look now at the furniture or large-object discharge, the parameters are significantly different, as seen below:

L = self-inductance of the loop formed by the furniture (e.g., a cart), the victim (equipment, device etc.) and the ground return. The range of values is

$$\text{min}: 0.03\,\mu\text{H} \qquad \text{max}: 1\,\mu\text{H} \qquad \text{typ}: 0.3\,\mu\text{H}$$

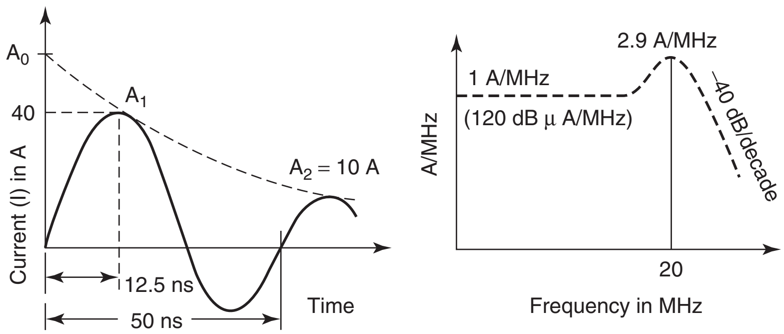
R_d = resistance of the discharge loop. This can be extremely low, a few ohms, for instance.

C = capacitance of the furniture or object to ground; can vary widely, from 30 to 500 pF.

Here the inductive part of the loop cannot be neglected versus R_d. Compared to the human body discharge, the charging time constant has increased. On the other hand, the peak current will reach much higher values. Worst is that, instead of a slow falling slope, we now have a damped sine wave, typical of an underdamped, "ringing" *RLC* circuit. Chapter 2 will explain the impact of this ringing on the severity of the radiation coupling into nearby electronics.

Figure 1.20 shows the waveform of a severe furniture discharge. Note that the ESD voltage at which the furniture was charged is significantly less than for the human discharge. This seems to contradict the fact that furniture discharge often appears more severe. However, consider this: The furniture has a capacitance to the surounding (i.e., the ground and the victim equipment) that is typically larger than for the human body case. This is due to the larger dimension of the conductive areas facing each other. A cart or metallic chair may have two to five times more capacitance than a person. Given that the quantity of electricity involved is about the same as for human—in fact in many cases, the furniture has been charged from a human source, by charge transfer—the equation $Q = CV$ implies that for a given energy storage Q, if C increases, the corresponding voltage has to be less.

Figure 1.20 also displays a corresponding frequency spectrum, with the rise in spectral amplitude around the ringing frequency. Several well-documented measurements, such as those of King (16) support this model of a low-impedance ringing circuit. Together with Simonic's study (see Section 1.4) they tend to prove that the classical triangular pulse of human ESD is not enough to cover the variety of possible ESD events, and a furniture-type test with a discharge network having less than 50 Ω impedance would be a necessary supplement. To facilitate extrapolation, Figure 1.21 shows a typical furniture ESD waveform normalized to a 1-kV charging voltage.



Initial electrostatic voltage = 2000 Volts

$L = 0.3\ \mu H$

$R_D = 15\ \Omega$

$C = 200\ pF$

$R_D < 2\sqrt{L/C}$, Underdamped oscillation

$$\text{damping} = \frac{\ell_n A_1/A_2}{2\pi} = R/2\sqrt{C/L} = .195$$

$$A_0 = \frac{V}{\sqrt{L/C - R^2/4}} \qquad A_1/A_2 = \ell_n^{-1}(\pi R \sqrt{C/L})$$

$$A_1 = \frac{V}{\sqrt{L/C + 1.6\, R\, (L/C)^{1/2}}}$$

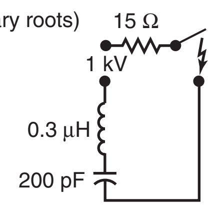
Figure 1.20 Furniture ESD current waveform and frequency spectrum.

Solution for underdamped oscillation, i.e., $R<2\sqrt{L/C}$ (imaginary roots)

$$I_{peak} = \frac{V}{\sqrt{L/C + 1.6\, R\, (L/C)^{1/2}}}$$

$\omega_0 = 1.28 \times 10^8$ rad/s

$f_0 \cong 20$ MHz (pseudo-frequency of oscillation)



$I_2 \cong 0.3 I_1$

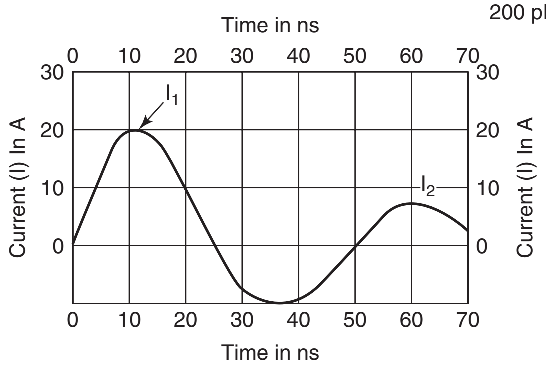


Figure 1.21 Furniture ESD current waveform, normalized to 1-kV initial charge.

	① Personnel R = 1000 Ω	② Furniture R = 15 Ω L = 0.3 μH, C = 200 pF	③ Personnel (IEC) with hand / metal contact
V_{ESD}	10,000 V	2,000 V	8,000 V
ΔI/Δt	10 A/ns	≅ 5 A/ns	30 A/ns (initial peak)
Duration of steepest current change	≅ 3.5 ns	≅ 10 ns (during the negative going of the 1st pulse)	1 ns

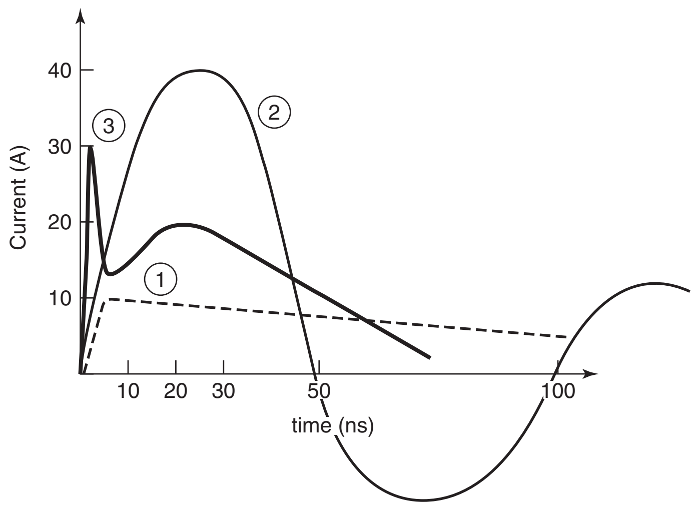


Figure 1.22 Comparison of dynamic parameters of typical personnel and furniture ESD.

1.5.3. Summary: Comparison of Dynamic Parameters for Personnel and Furniture ESD

In order to compare the dynamic characteristics of personnel versus furniture discharge, two typical waveforms, representing a severe (but not overly severe) case, have been overlaid in Figure 1.22.

An interesting result is that, given two ESD events having similar probabilities of occurring in a busy work space with uncontrolled RH, the personnel discharge is the one that seems to have the highest *dI/dt*, and therefore likely to create the worst-case couplings. However, the duration of the steep change, that is, the time during which the derivative exists is 20 larger for the furniture discharge than for personnel. The important consequences of this will be discussed in Chapter 2.

1.5.4. Actual versus Idealized ESD Waveforms

No two electrostatic discharges look alike. Pretending that the personnel or furniture ESD waveforms seen before are close to what actually happens would be presumptuous. The idealized waveforms such as those in Figures 1.21 and 1.22 have been devised as a repeatable test criterion, such as equipment that resists such standard ESD waveforms is likely to resist real ESD waveforms of similar amplitudes in the field.

As early as the end of the nineteenth century, engineers tried to figure out what sort of electrical circuit could be equivalent to a charged human body. The prime concern at the time was the spontaneous explosions in coal mines and ammunition or gunpowder storage. They came up with the resistor/capacitor set very similar to the basic human body model (HBM) in use today. It was only around the 1960s that accurate ESD current measurements began to be performed. (Fig. 1.23, 1.24)

Mazdy (13), one of the first to measure ESD waveshapes, has selected a group of fearless volunteers who charged themselves to a high-voltage power supply, then discharged on a grounded 1-Ω shunt. The waveform was recorded, then a calculation was made to retrieve what *RC* network would best fit with actual data. Figure 1.24 shows a summary of the results. No inductance was put into the model because the study was mainly aimed at determining the destructive effect of ESD when handling modules, that is, the pulse duration was the concern, not the rise time. However, at a time where no standard existed for ESD immunity of integrated circuits, Mazdy's data and the simulator he built using them, has been widely used by IBM for the quality control of its modules.

As early as 1968 Tucker (14) recorded current waveforms from body discharges. His data show differences between ESD from the fingertip, ESD from the side of hand, and ESD enhanced by a sharp handheld tool (the most severe; see Fig. 1.23). Later, King (15) began a thorough study of ESD waveshapes (Figs. 1.26, 1.27) involving mainly personnel, except in one case where an oscilloscope cart pushed against the discharge set was used. The bulk of King's data for personnel is shown in Figure 1.25. One sees that with the classical personnel discharge, with the finger approaching not too fast, such as ionization occurs, the measured waveforms are fairly close to the idealized waveshapes of Figure 1.20.

In contrast, when the field is locally enhanced by a sharp tool, the raising edge shows some odd shapes, with a "precursor" current spike having only a few hundred picoseconds of rise time. This is somewhat reminiscent of lightning where a precursor is often followed by one or several restrikes. This sharp precursor mostly appear with fast speed of approach and the so-called hand/metal ESD. It does not happen with the hand alone, which generates less peak current.

King and other ESD pioneers attribute this precursor to a localized generator where the hand (and the handheld tool) distributed capacitance to the target object is discharged first, and so fast that this segment of the body is likely disconnected from the rest.* This mechanism could be described as follows: When the charged

**This also occurs with wristbands, rings, coins, keys, and the like.*

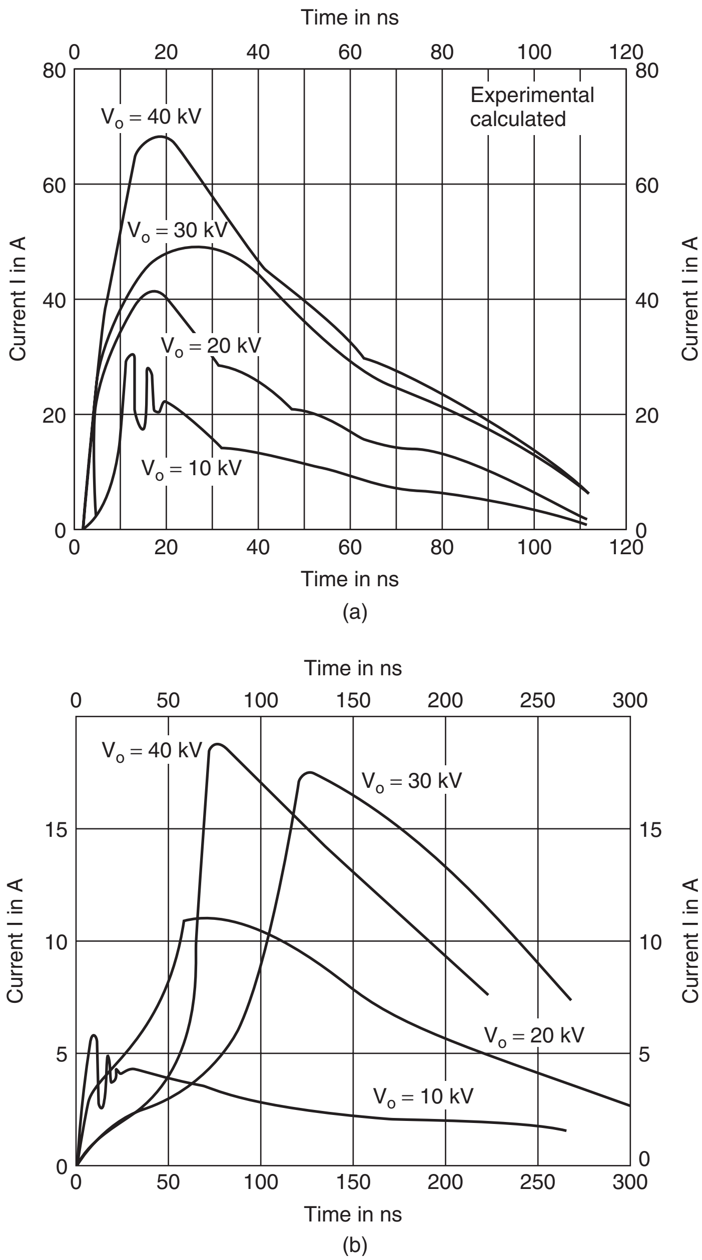
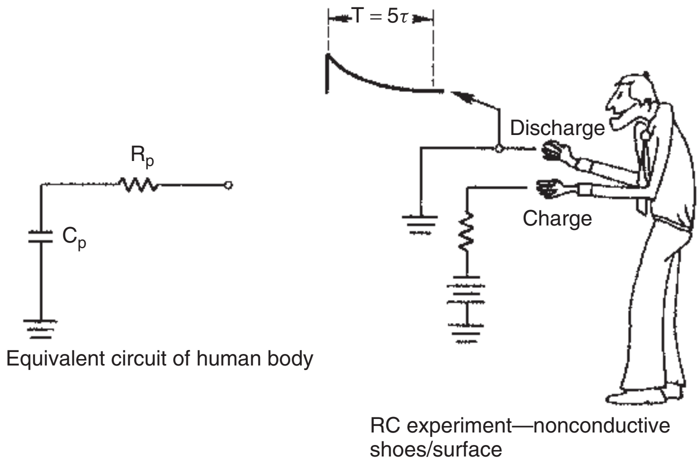


Figure 1.23 (a) Personnel ESD waveforms recorded with an artificially charged person discharging via a handheld metal tool (14). (b) Personnel ESD waveforms recorded with an artificially charged person discharging by his fingertip (14).



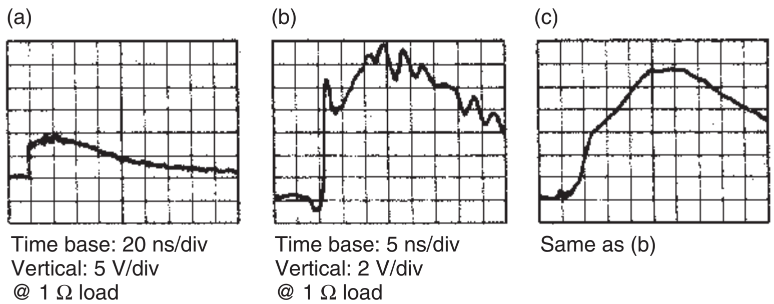
C_p/R_p experimental results

Person #	C_p (pF)	τ (μs)	R_p (kΩ)
1	140	.30	2.1
2	145	.30	2.0
3	140	.30	2.1
4	170	.40	2.3
5	180	.35	1.9
6	80	.15	2.4
Average	142.5	.30	2.1

Figure 1.24 Experiment validating an equivalent circuit of the human body (13).

tool edge comes close enough to the target surface, the strong local E field is causing the local air gap breakdown. The corresponding current circulates in the small loop formed by the finger, target, and forearm. Then the current decreases for a few hundred picoseconds, with eventually a deionization of the path, until the rest of the charges left behind reach the finger area and are responsible for the main discharge, with the current returning by the entire human–machine–ground loop.

After King, several authors (17–19) have closely studied this predischarge and the way to simulate it. They found that the dI/dt during the predischarge can be as high as 30 A/ns if a finger is approached fast enough, and the phenomenon can be adequately modeled with an additional R,L,C element replicating the human hand (Fig. 1.28). The investigations of Ryser and Daout (18) and Frei and co-workers (20) also reveal that, for personal ESD, the dI/dt of the rising edge is strongly dependent on the speed of approach; these measurements were made by using an artificial finger with a motor-driven movement, such that the speed could be recorded accurately. More recent studies, so far, are generally in



Measurement conditions: The above data were taken under the conditions of

- Initiating level: 5000 V
- Human subject holding metallic intervening object (screwdriver) as the ESD path
- Motion: Discharge load slowly approached to allow maximum ionization to occur.

V_{volts}	Extremes of I_{ESD} range (Amp)	I_{ESD} aver.	$Z_{aver.} = V/I_{aver.}$
500	0.9 to 1.8	1.3	385 Ω
1000	1 to 3.6	2.3	435 Ω
2000	4 to 5.8	3.5	570 Ω
4000	1.8 to 7.6	4.25	940 Ω
6000	1.2 to 26	10	600 Ω
8000	1.8 to 8	6	1250 Ω
10,000	4 to 6.5	5.2	1920 Ω

Figure 1.25 A few of the personnel ESD waveforms recorded by King (15) using artificially charged volunteers and enhanced discharges with screwdrivers. Pictures (b) and (c) with expanded scale show large variations of rise times—1–15 ns—between different persons and attitudes. Currents/voltages compilation reveal an increase of dynamic impedance with voltage. This nonlinearity can be explained (to some extent) by the increasing arc impedance.

accordance with these former findings. However, increasing attention has been paid to this predischarge spike because it is extremely aggressive for modern high-speed digital circuits and complicates the making and repeatability of ESD tests (see Chapters 2 and 4).

At low levels, say up to 6 kV, the localized charge distribution between hand/finger and the target creates the precursor current spike (Fig. 1.29). At higher levels, the increased arc path length and inductance (a 1.5-cm arc has about 15 nH of inductance, presenting 15 Ω to a nanosecond current rise) slow down the rise front and permit a more complete transfer of the whole body charges, without the sharp spîke seen at lower levels. The transition between

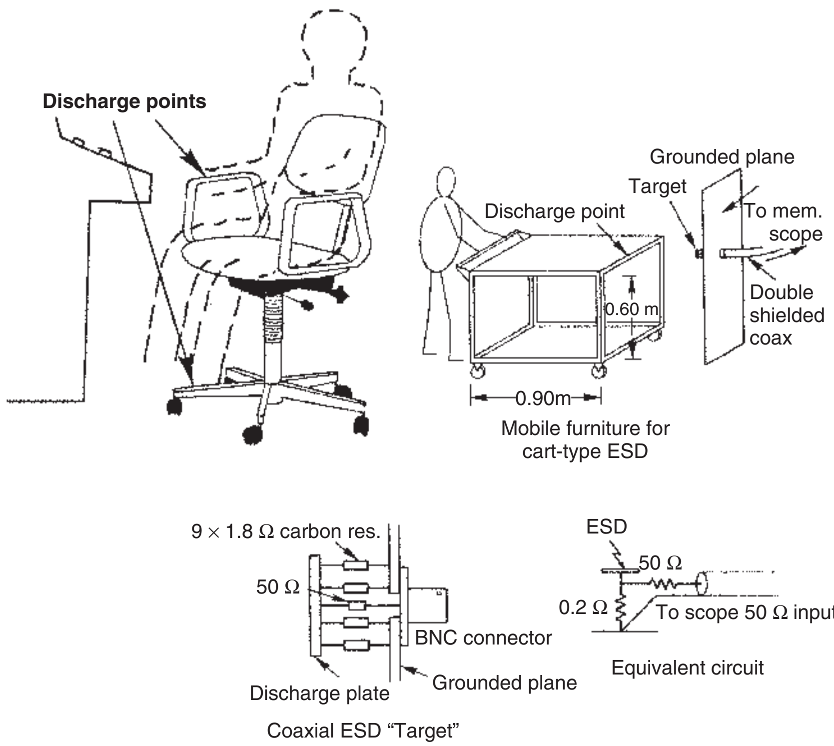


Figure 1.26 Test setup used by King (16) for furniture discharge study. For the chair and the cart, the person was initially charged through a dc power supply.

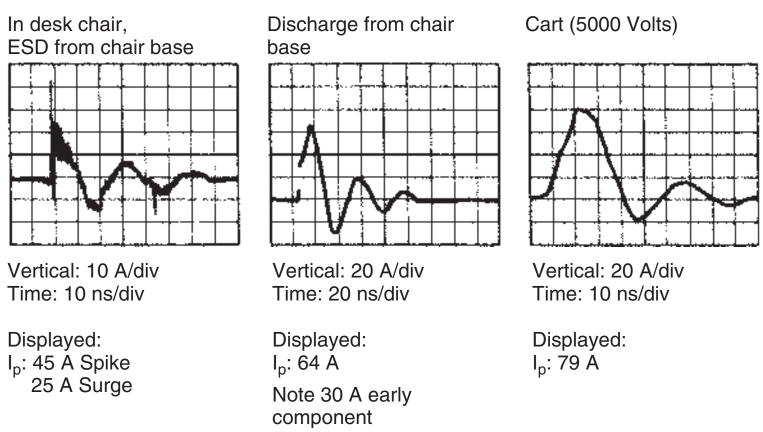


Figure 1.27 A few of the 50 furniture ESD signatures recorded by King (16). Large variations are attributed to small changes in speed of motion toward the target. The predischarge phenomenon is visible, as in personnel ESD, but disappears above 2.5 kV, instead of 6–8 kV for personnel.

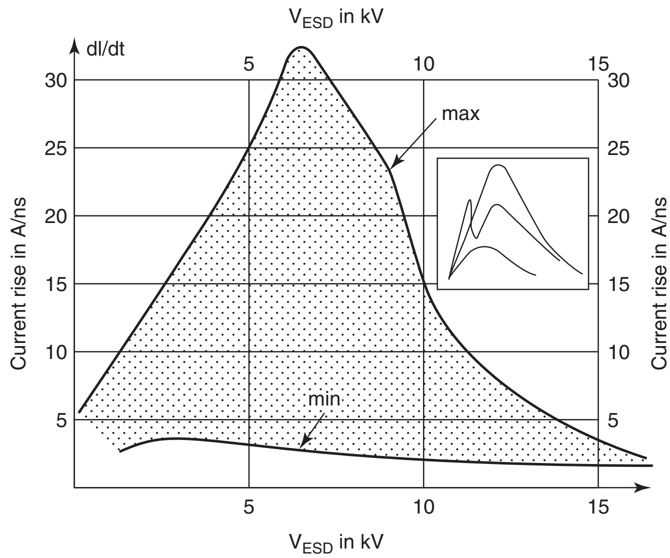


Figure 1.28 Range of *dI/dt* reported by Ryser (18), depending on the speed of approach of discharge probe. In top right corner, see the ambiguity in *dI/dt* caused by the precursor and other odd wave shapes.

low- and high-level behavior occurs around 6–8 kV [a phenomenon also shown in the earlier measurements by Tucker (14)]. An additional explanation for this is that around 6–8 kV, the physics of arc discharge, that is, the transition from simple gap breakover to corona effect, introduce some nonlinearity between V_{ESD} and I_{peak}. For instance, if a real 5-kV initiation generates a 10-A peak current, a 15-kV level does not necessarily create a 30-A current.

Nevertheless, although personnel ESD waveforms seem to vary widely, in a random, unpredictable manner defeating any serious simulation, they appear as essentially governed by three basic variables: electrode geometry, electrostatic voltage, and speed of approach of the charged finger or electrode. Once these varaibles are set, the spread of discharge waveforms is greatly reduced. Pommerenke (21) developed a mathematical model that replicates closely this hand/metal discharge.

In a follow-up of these experiments, King (16) adressed furniture discharge. The main findings are shown in Figure 1.26–1.27. The decaying oscillations typical of an underdamped R,L,C circuit with $R < 2\sqrt{L/C}$ are clearly seen. The peak currents are impressive as well. King's experiments were conducted with many precautions concerning the high-frequency response of his setup. A copper ground plane was used to avoid uncontrolled parasitic inductance in the return path. The shunt used to read the current was a coaxial mount and the instrument 3-dB bandwidth was larger than 500 MHz.

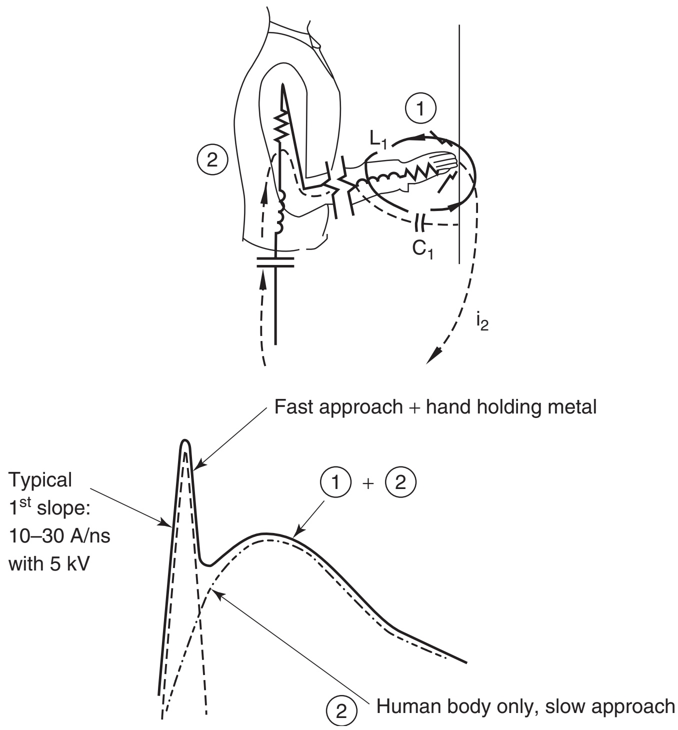


Figure 1.29 Proposed explanation for the precursor discharge. C_1 and L_1 being very small, the rise time and duration of the current are very short.

REFERENCES

1. Jowett, C. E. *Electrostatics in the Electronics Environment.* McMillan, New York, 1976.
2. Horvath, A., and Berta, I. *Static Elimination.* Wiley New York, 1982.
3. Testone, A. *Static Electricity in Electronic Industry*. Testone Enterprise, Lee, MA. 1981.
4. Jonassen, N. *Static Electricity.* Applied Physics Laboratory, Technical University of Denmark, 1991.
5. Aguet, M. *Décharges d'origine electrostatique*. Bulletin SEV/VSE 74, Switzerland, 1983.
6. Richman, P. *ESD Protection Handbook*. Keytek Instrument Corp., 1983.
7. Kirk, W. Eliminate Static Discharges. *Electronic Design*, March, 1976. p. 80–85.
8. Yenni, D. Huntsman, J. and Mueller, G. *3M Static Products Documentation*, 1995.
9. ISO-TC 22, 1989.
10. Simonic, R. *Personnel ESD Statistics*. IEEE/EMC Symposium, Boulder, CO, 1981.
11. Simonic, R. *Furniturel ESD Events Rates*. IEEE/EMC Symposium, Santa Clara, CA, 1982. p. 191–197.
12. Byrne, W. *An ESD Model for Electronic Systems*. IEEE/EMC Symposium, Santa Clara CA. 1982, p. 199–205.

13. Mazdy, T. *Static Discharge Modelling*. EMC Symposium, Montreux, Switzerland, 1975, p. 134–139.
14. Tucker, T. Spark Initiation Requirements. *Annals of New York Academy of Sciences*, Vol. 152, Oct. 1968.
15. King, M. *Dynamic Waveforms of Personnal ESD*. EOS/ESD Symposium, Denver, 1979, p. 78–87.
16. King, M. *Pulse Waveforms of Personnel/Furniture ESD*. IEEE/EMC Symposium, Santa Clara, CA, 1982, p. 212–219.
17. Hyatt, H. and Mellberg, H. *Bringing ESD Testing into the 20th Century*. IEEE/EMC Symposium, Santa Clara, CA, 1982, p. 220–225.
18. Ryser, H. and Daout, B. *Fast Discharge Mode in ESD*. EMC Symposium, Zurich, 1985, p. 41–46.
19. Richman, P., and Tasker, A. *ESD Testing: Interface between Simulator and EUT."* EMC Symposium, Zurich, 1985, p. 25–30.
20. Frei, S., Senhgaas, M., and Jobava, R. *Influence of Speed of Approach and Humidity on Intensity of ESD*. EMC Symposium, Zurich, 1999.
21. Pommerenke, D. and Aidam, M. ESD Waveform Calculation of Human & Simulated ESD. *Journal of Electrostatics*, Vol. 38, Nov. 1996, p. 33–51.