1 A Model of the Electrostatic Discharge (ESD) Event

In order to fully understand electrostatic discharge (ESD) effects, it is necessary to understand the causes. In this chapter, the ESD event is described in detail. To make the explanation more concrete, the description is based on the example of a person walking across a carpet and then touching an item of electronic equipment. The specific item of equipment used in the example is a computer keyboard. However, it should be remembered that ESD can be generated in many other ways, such as movement of paper within a printer, and that ESD can impact any item of equipment or an entire system. The basic concepts discussed will apply no matter how the ESD occurs.

To begin the discussion of the charging process, assume the person is not electrically charged. As the person walks across the carpet, the soles of the person's shoes come into direct frictional contact with the carpet. Depending on the molecular structure of the shoes and the carpet, there is a tendency for one surface to strip electrons from the other. This is commonly called triboelectric charging, although the primary charging effect is probably not triboelectric, but contact charging. Many sources reference a triboelectric series that claims to indicate which dielectric will strip electrons from which. In fact, there has been little success establishing a precise series which can be proven repeatedly by experiment. In one experiment, rayon may strip electrons from rubber, and in the next experiment the opposite may occur. This is thought to be caused by surface impurities on the dielectrics. As a result, it is probably not possible to predict whether the shoe soles will become positively or negatively charged. However, some charge will develop on the shoes and an opposing charge will be left in each footprint on the carpet. As the person walks, the charge on the shoe soles tends to become progressively greater with each step. However, there is a limit on the charge which may be stored.

Opposing the charge buildup is a small return current, some of which flows via the dielectric of the air, but most flows via the shoes and the carpet. High humidity reduces the resistance of most dielectrics and will thus increase the return current. This means the charge on the shoes will reach an equilibrium point where triboelectric charging equals the return current. (Temperature also effects dielectric resistance, but to a much smaller degree than humidity.)

Thus far, the discussion has been confined to the dielectrics of the shoes and carpet. There is also a conductor, which is the human body. Students of electrostatics will recognize that the shoe soles are crude electrets, which have an electrostatic field. As a result of this field, the conductive tissues and moisture layers on the soles of the feet will develop a charge opposed to the charge in the shoe soles. In the process of charging the feet, charge is redistributed within the body. (Except for the skin, most body tissues are fairly good conductors.) This means the remainder of the body, not including the feet, will typically have a charge opposite to that of the feet. (However, the actual situation may be complicated by additional charge sources such as socks and other items of clothing.) As a simple example, assume the shoe soles strip electrons from the carpet. This leaves positively charged footprints on the carpet and a negative charge on the shoe soles. This negative charge on the shoe soles results in a positive opposing charge on the soles of the feet. However, if positive charges have moved to the feet, that leaves the rest of the body with a negative charge. The level of the charge on the human body is limited by the return current previously discussed, which at very high voltage includes corona discharge.

In the previous discussion, only the charging of the person was considered. The example keyboard will now be added to the picture to complete the discussion of the charging process. (A keyboard was chosen for this example because it is an item of equipment commonly touched by the operator; however, all items of equipment within a system must, of course, be designed for ESD immunity.) As the person walks toward the keyboard, assume the triboelectric charging and return currents continue to keep the charge level on the person stable.

During the approach to the keyboard, the charge on the person will generate an opposing charge in the keyboard. Since the keyboard is grounded, its charge will be developed by electrons flowing in the keyboard ground line within the keyboard cable. (Ungrounded items will have their charge redistributed to oppose the charge on the person.) In the example, with the person's body negatively charged, the keyboard will develop a positive opposing charge through loss of electrons, via the ground path to earth. The closer the person approaches, the greater the opposing charge on the keyboard. It should be noted that the rate at which charging current flows in the keyboard ground path is dependent on the speed at which the person approaches. However, even a fast approach would result in a slow rate of rise in charging current. Therefore the charging current that flows prior to the discharge will have no significant impact on the keyboard operation.

More important than the charging current is the actual electrostatic field that exists between the person and the system prior to the discharge. This field can induce unequal voltages within items of equipment. Sufficiently large unequal voltages could even result in destruction of components such as integrated circuits (ICs). (This indicates that the discharge itself is not the only source of potential problems.)

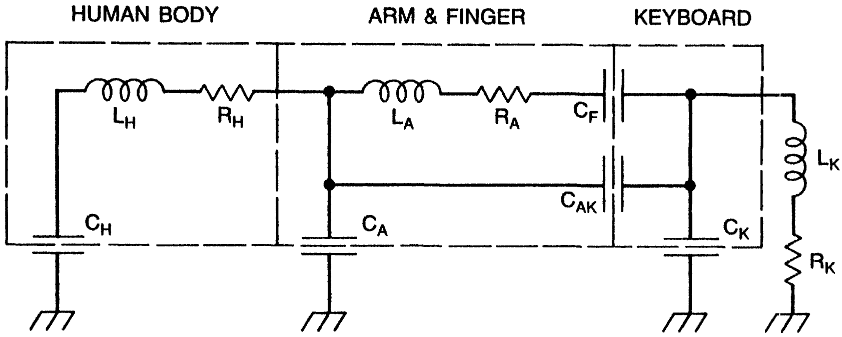

Fig. 1: *Electrical model of human and keyboard ESD system.*

To complete the discussion of the ESD charging process, the circuit in Figure 1 has been developed to serve as a model for the person/keyboard system used in this example. In Figure 1,

C_H = Lumped capacitance between the human body and earth
R_H = Lumped resistance of the human body
L_H = Lumped inductance of the human body
C_A = Lumped capacitance between the person's arm and earth
C_{AK} = Lumped capacitance between the person's arm (and near portions of the body) and the keyboard
R_A = Lumped resistance of the person's arm's discharge path
L_A = Lumped inductance of the person's arm's discharge path
C_F = Capacitance between person's finger, hand, and the keyboard
C_K = Lumped capacitance of the keyboard to earth
R_K = Lumped resistance of the keyboard earth ground path
L_K = Lumped inductance of the keyboard earth ground path.

Resistance and inductance between C_F, C_{AK}, and C_K is very small and thus not included in this model.

Five points should be emphasized about this model:

1. Although lumped values are used here, one should keep in mind that in the real world these effects are distributed. (Transmission line theory would be more suited to precisely describing the ESD process.)
2. C_H, C_A, and C_K are often referred to as "free space" capacitance because the two capacitance elements (e.g., the body and the earth) often have a large physical separation, and may thus approach free space values. It should be noted that this is not always the case. A person physically close to ground will have a higher body capacitance than a person far from ground.
3. There is no inductance or resistance between C_{AK} and the keyboard or between C_A and C_H and earth ground. This means an ESD generator designed to simulate this model must be designed very carefully. Even the inductance of a wire could impact the results dramatically.

4. This model represents equipment which is connected to ground. Hand-held or portable equipment would not have L_K or R_K, but would be the same otherwise.
5. Although this model was developed to explain the person/keyboard example being used, the model is in fact quite general. By changing the R, L, and C values in the model, many other ESD situations may also be modeled. In each case L_H, R_H, and C_H represent the bulk of the charge source; L_A, R_A, and C_A represent portions of the charge source which are physically nearer the discharge point, and through which current from C_H must flow; C_{AK} represents the capacitance from these nearer portions of the charge source, which couples to the electronic equipment; C_F represents the capacitance from that part of the charge source which is closest to the discharge point to the electronic equipment; and C_K, L_K, and R_K represent any item of electronic equipment.

The introduction of the previous model completes the discussion of the charging processes that take place in an ESD event. The remainder of the discussion deals with the discharge phase of the ESD event. In the previous example, the person was poised with their finger almost in contact with a computer keyboard. As the person's finger draws nearer the keyboard, the electrostatic field intensity between finger and keyboard will eventually become so great that dielectric breakdown occurs in the air between them. This begins with a streamer, which establishes an ionized path of conduction, and progresses into the familiar spark, in which the majority of the charge is transferred.

Although the person's approach speed prior to initiation of arc formation is not critical, the speed of approach during arc formation itself is very important. The formation of the arc requires much more time than the duration of the arc. Since the person's finger is moving closer to the keyboard during this long arc formation process, a fast approach will result in a narrower arc gap than a slow approach, even when the voltage level is the same. Therefore, for a fast approach, the voltage is unnaturally high related to the arc gap length. This results in a more intensive discharge with faster associated current rise times and peaks.

A slight modification to the previous model will allow an explanation of the very important discharge process. As seen in Figure 2, the basic model remains unchanged, except that the resistance and inductance of the arc discharge path are added in parallel with C_F. The values for R_S and L_S are not actually constant, but vary during the arcing process. This is especially true of R_S which starts as a relatively high resistance and drops as the air becomes more and more ionized.

Even with its limitations, the model developed gives important insights into the discharge process. When the arc forms, it will first be discharging C_F. The components R_S, L_S, and C_F will form a damped tank circuit. The

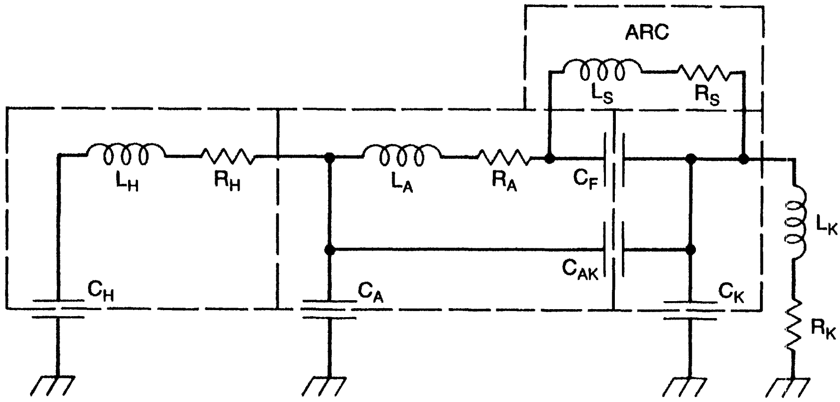

Fig. 2: *ESD model including the arc.*

damping depends on the value of R_S and the tank frequency on C_F and L_S. The value of C_F depends on the size and shape of the person's finger and hand. A smaller hand and more pointed finger will result in a smaller value for C_F, and a smaller C_F would theoretically result in a higher frequency for the tank. However, a more pointed finger will also experience corona discharge at lower voltages. The onset of corona discharge can significantly impact the resulting discharge waveform. In the model, corona could be modeled as a bleeder resistor shunting around C_F, C_{AK}, and C_A. Prior to the actual arc, corona will bleed charge off C_F and even somewhat from C_A and C_{AK}. This means the higher frequency components of the discharge wave will be reduced. Therefore, the maximum frequency of the ESD will depend on the values of R_S, L_S, and C_F, only if corona is not occurring.

As C_F discharges, the parallel combination of C_{AK} with C_K and C_A will also begin discharging. However, the discharge current from this parallel combination must not only go through R_S and L_S, but also R_A and L_A. Also, the capacitance of this parallel combination is larger than C_F. This means the discharge of C_A and C_{AK} will be slower than the discharge of C_F alone. In the case of C_H, the discharge path includes R_H, L_H, R_A, L_A, R_S, and L_S. Also, the discharge path of C_H includes the parallel combination of C_K, with R_K and L_K.

It is important to point out that very little of the discharge currents of C_F, C_{AK}, and C_A flow in the keyboard ground path. Also, any high frequency components of the discharge current from C_H will tend to flow through C_K, not the keyboard ground path. Current in the keyboard ground return is limited to low frequency components of the discharge current from C_H.

The exact value of R, C, and L, in each case, will determine the exact discharge waveform. As previously indicated, the discharge of C_F will tend to create an extremely high frequency. The discharge of C_A and C_{AK} will create high frequencies. Finally, a somewhat lower frequency will be generated by the discharge of C_H. In addition to the frequency ranges indicated above, the fact that the capacitors are discharging will result in a damped oscillation.

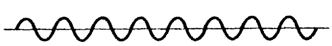

Fig. 3: *Extremely high frequency.*

Fig. 4: *High frequency.*

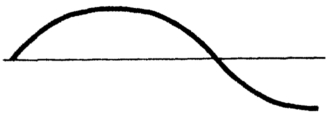

Fig. 5: *Lower frequency.*

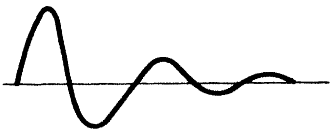

Fig. 6: *Underdamped.*

Fig. 7: *Overdamped.*

This can be either underdamped or overdamped, which is again dependent on the exact R, L, and C values. These various waveform components are indicated in Figures 3 through 7.

Both computer modeling and experimentation indicate that the waveforms will be typically either overdamped or very damped oscillations, depending on the exact position, size, etc., of the person. (Furniture-related discharges may result in underdamped oscillations.) The total current waveform for a typical discharge is shown in Figure 8 (the dotted line shows the waveform with the effect of corona discharge).

In such a waveform the low frequency components will transfer more of the charge than the high frequency components, but the high frequency components will generate the most intense fields. Experimentation has shown that the following time limits can occur for an arc:

T_r (Rise Time) = 200 ps to 70 ns
T_s (Spike Width) = 0.5 ns to 10 ns (if the "spike" exists)
T_t (Total Duration) = 100 ns to 2 μs.

Computer modeling indicates even wider ranges are possible.

In addition to timing differences, peak currents can also vary from one amp to over 200 amps. (Computer modeling indicates even higher, and lower, currents are possible.) With this wide range of responses for different conditions, it is no surprise that the ESD response of electronic equipment often appears unpredictable. Fortunately, statistical methods are available to cope with this problem. The important lesson from this analysis is that relatively high energy and high frequency (5 GHz) signals may be generated by the ESD event. Another important point is that C_F, C_{AK}, C_A, L_A, and R_A have a great impact on the generation of high frequencies. Simple RC models used in the past have ignored these components.

Figure 9 shows a simple RC model that ignores most of the components in a true human model. This circuit carries simplification too far, and thus results in a faulty view of the problem.

This nearly completes the discussion of charging and discharging events, and most analysis ends at this point. However, the story is not quite done yet. More than one experimenter has noted that multiple discharges may occur during a single ESD event. These discharges are at successively lower peak current levels, and are separated by 10 μs up to 200 ms. There are two or three effects which could combine to cause these multiple discharges. Looking again at the model, it is seen that a high value for R_H and L_H would allow C_A and C_F to discharge completely even though C_H is still charged. After C_A and C_F are discharged, the arc would quench. Then C_H would recharge C_A and C_F until the air breakdown voltage is again attained. A new arc would result, and C_A and C_F would again be discharged. This would continue until C_H was fully discharged. Much of the charge, associated with capacitance C_H, is in the soles of the feet, and a majority may even be stored in a layer on the bottom surface of the feet. In this case, R_H would include

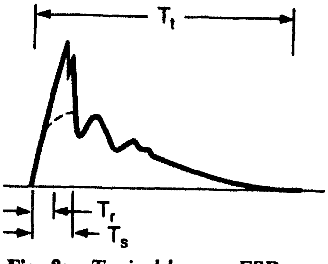

Fig. 8: *Typical human ESD current wave.*

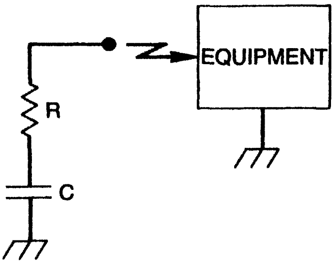

Fig. 9: *Simple RC model of ESD.*

skin resistance which can be relatively large. This would explain discharges separated by tens of microseconds, but it wouldn't explain longer separations. In order to have pulses separated by up to 200 ms, R_H and L_H would have to be very large. In fact, it seems unlikely that the human body could have such a high impedance. In these cases, there are two possible causes for more widely separated multiple discharges. First, the dielectric absorption effect of the shoe soles has to be considered. One way of looking at this is to imagine that the shoe sole is an RC circuit, with a very large R (and thus a very long discharge time). This RC circuit is resupplying charge to the human body, that is C_H, C_A, and C_F.

The other possible cause of widely separated multiple discharges is related to the motion of the person toward the keyboard. As previously mentioned, the arc will quench when there is insufficient energy to maintain the air ionization path. The arc may then not restart until the person's finger has moved closer to the equipment, so the arc gap is shorter and less energy is required to initiate the arc.

If there is recharge of C_F and C_A (and possibly C_H), it will occur even if multiple discharges don't occur. This recharge (and potential multiple discharge) could affect electronic equipment. If the person recharges, the equipment (in the example, the keyboard) must also recharge. Because the recharge current may have a rise time on the order of microseconds or slower, most of the current would flow via the equipment ground path and not C_K. (C_K is typically only tens of picofarads or less.) For fast recharge, with microsecond rise times, the current flow in the ground could have an impact on the operation of the equipment, and could be one more source of relatively low frequency noise associated with ESD. Whichever explanation is used, multiple discharges are more likely when the person has a high initial charge level. Ironically, initial discharges in the sequence are likely to have lower peak currents and slower rise times (because corona is more pronounced at higher voltages) than subsequent discharges in the sequence. The phenomenon of multiple discharges may explain another effect noted by many experimenters. It has been noted that both low voltage and high voltage ESD will often cause more problems than medium voltage ESD. The key to explaining this may be that fast rise time, high peak signals cause the most problems. At low voltages, there is very little corona, and therefore rise times will be fast and peak currents high. At medium voltages, there is corona, which slows rise times and reduces peak currents. At high voltages there is also much corona, but multiple ESD becomes common. In each multiple ESD sequence there are one or more low voltage discharges which will have the fast rise times and high peak currents necessary to cause more severe problems.