STATIC

...as the static cling of clothing, as when one touches a doorknob or other metal object, and as was known to the ancient Greeks over 2000 years ago. Electrostatic effects as part of their studies in electricity have been harnessed to perform useful functions. Products using this principle are electrically-activated air cleaners, and electrostatic spray paint guns.

Static shock or discharge (ESD) has become a significant issue since the early 1960s it has been used in semiconductor devices, metal-oxide-semiconductor (MOS) circuits, and other electrical parts such as film resistors, which are susceptible to damage by electrostatic discharge. Smaller and faster, their susceptibility to ESD is even greater.

As a result, the overall subject of EMC. As will be described in later chapters, the susceptibility of a system to ESD is a major factor in control radiation.

The static generation is the result of contact and subsequent separation of charges between solids, liquids, or gases. When two nonconducting materials are in contact, same charge (electrons) is transferred to the materials, and when the two materials are then separated, the charged material since charge is not very easily movable, they are left permanently charged either negatively or positively.

Electricitity is referred to as the triboelectric effect. Some materials are more likely to absorb electrons while others tend to give them up. The following is a listing of materials in order of increasing electrification. Table 12-1 is a typical triboelectric series. The table easily give up electrons and are called positive; those materials at the bottom of the table easily absorb electrons and therefore acquire a negative charge. It should be kept in mind, however, that this series is only approximate.

When two materials are in contact, electrons will be transferred from the material higher on the list to the material lower on the list. The degree of separation of two materials in Table 12-1 does not necessarily indicate the magnitude of charge created by the triboelectric effect. The magnitude depends not only on the ordering of the materials in the series but also on the surface cleanliness, pressure of the contact, amount of rubbing, surface area in contact, smoothness of surface, and the speed of separation. A charge can also be generated when two pieces of the same material are in contact and then separated; a good example is the opening of a plastic bag.

The relationship between charge, voltage, and capacitance is

\[ V = \frac{Q}{C} \]  

(12-1)

As two materials are separated, the charge imbalance \( Q \) remains fixed; therefore the product \( VC \) is a constant. When the materials are close together, the capacitance is large; hence the voltage is low. As the materials are separated, the capacitance decreases and the voltage increases.

For example, if the capacitance is 75 pF and the charge is 3 \( \mu \)C the voltage will be 10,000 V.

<table>
<thead>
<tr>
<th>Table 12-1 Triboelectric Series</th>
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<td>29.</td>
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<td>30.</td>
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<td>31.</td>
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<td>32.</td>
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<td>33.</td>
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<tr>
<td>34.</td>
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</tbody>
</table>

*Trademark of E. I. du Pont de Nemours.
This effect also occurs when an insulator is separated from a conductor, but it will not occur between two conductors. In the latter case, as soon as separation starts, the charge returns to the original material because the mobility of the charge is large in a conductor.

Thus both conductors and insulators can easily be charged by contact and separation with another insulator. Intimate contact is all that is needed to give rise to a static charge. Rubbing just tends to bring more of the surface in good contact and hence increases the charge transfer. Faster separation gives less time for charge reflow and also increases the stored charge, and the voltage.

Table 12-2, from DOD-HDBK-263, shows typical electrostatic voltages that can be generated under various conditions. The generation of 10 to 20 kV on common materials in the home and work environment is not unusual.

Static electricity is a surface phenomenon. The charge exists solely on the surface of the material and not inside. The charge on an insulator remains in the area in which it is generated, and it is not distributed over the entire surface. For this reason, grounding an insulator will not eliminate the charge. Unlike an insulator, a charged conductor will lose its charge if grounded.

Electrostatic discharge is normally a three-step process: (1) a charge is generated on an insulator, (2) this charge is transferred to a conductor by contact or induction, and (3) the charged conductor comes near a metal object, usually grounded, and a discharge occurs.

For example, when you walk across a carpet, the soles of your shoes (insulators*) become charged as they contact and separate from the floor. This charge is then transferred to your body (a conductor). If you then touch a metallic object, grounded or not, a discharge occurs. When a discharge occurs to an ungrounded object (e.g., a doorknob), the discharge current flows through the capacitance between the object and ground.

<table>
<thead>
<tr>
<th>Means of Static Generation</th>
<th>Electrostatic Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking across carpet</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>Walking on vinyl floor</td>
<td>35,000</td>
</tr>
<tr>
<td>Worker moving at bench</td>
<td>12,000</td>
</tr>
<tr>
<td>Opening a vinyl envelope</td>
<td>6000</td>
</tr>
<tr>
<td>Picking up common polyethylene bag</td>
<td>20,000</td>
</tr>
<tr>
<td>Sitting on chair padded with polyurethane foam</td>
<td>18,000</td>
</tr>
</tbody>
</table>

*Some shoes are static dissipative (e.g., those with leather soles).

A charged insulator by itself is not free to move, it cannot produce a spark; its current is limited by its capacitance to a few microamperes. Static damage is done by conductors. Conductors include metals, carbon, and people (due to their capacitance).

**Inductive Charging**

An electrically charged object (insulator*) in the presence of an electrostatic field. If a charged object is brought near a conductor, the electrostatic field will cause the conductor to separate. The polarities of the charged body will be on the surface of the conductor, and the opposite charge will be on the other side of the neutral body, farthest away. If the conductor is momentarily touched by a grounded person, the charge will be transferred to the ground, releasing the induced charge.

**Charge Storage**

The charge that accumulates on an object. Normally, we think of capacitance in terms of parallel plates. However, all objects have their own, with the second plate in effect the object's own capacitance that an object can have. The capacitance of an irregularly shaped object is primarily a function of its geometry.
A charged insulator by itself is not directly a problem. Since the charge is not free to move, it cannot produce a static discharge. The danger from an insulator comes from its potential for inducing a charge on a conductor. Static damage is done by conductors. The most important of these are metals, carbon, and people (due to the conductivity of their moist skin).

Inductive Charging

An electrically charged object (insulator or conductor) is surrounded by an electrostatic field. If a charged object is brought into the vicinity of a neutral conductor, the electrostatic field will cause the balanced charges on the neutral conductor to separate. The polarity of charge opposite to that on the charged body will be on the surface of the conductor nearest the charged body, and the opposite charge will be on the surface farthest away, as shown in Fig. 12-1. The conductor will remain neutral, however, with equal amounts of positive and negative charge.

If a temporary connection is then made to ground (e.g., if the object is momentarily touched by a grounded person or object), the charge on the side of the neutral body farthest away from the charged object will bleed off, as shown in Fig. 12-2. This leaves the conductor charged, without ever having come in contact with a charged body. The ground connection necessary to produce the induced charge can have considerable impedance (a megohm or more).

Charge Storage

The charge that accumulates on an object is stored in that object’s capacitance. Normally we think of capacitance as something occurring between parallel plates. However, all objects have a free-space capacitance of their own, with the second plate in effect at infinity. This is the minimum capacitance that an object can have. The free-space capacitance of even an irregularly shaped object is primarily a function of its surface area. There-

<table>
<thead>
<tr>
<th>Electrostatic Voltage</th>
<th>10 to 20%</th>
<th>65 to 90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidity</td>
<td>Relative</td>
<td>Relative</td>
</tr>
<tr>
<td></td>
<td>Humidity</td>
<td>Humidity</td>
</tr>
<tr>
<td>35,000</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>12,000</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>7000</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>20,000</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>Carpet</td>
<td>18,000</td>
<td>1500</td>
</tr>
</tbody>
</table>

(with leather soles).

Figure 12-1. The charge on a neutral conductor separates in the vicinity of a charged object.
Before the free-space capacitance can be approximated by considering the simple geometry of a sphere with the same surface area as the object.

The capacitance between two concentric spheres (Hayt, 1974, p. 159) is

$$C = \frac{4 \pi \epsilon}{(1/r_1) - (1/r_2)} \quad \text{(12-2)}$$

where $r_1$ and $r_2$ are the radii of the two spheres ($r_2 > r_1$), and $\epsilon$ is the dielectric constant of the region between the spheres.

For free space $\epsilon = 8.85 \times 10^{-12} \text{ F/m}$. If the radius of the outer sphere is allowed to go to infinity, Eq. 12-2 becomes

$$C = 114 \pi r \quad \text{pF} \quad \text{(12-3)}$$

where $r$ is the radius of the sphere in meters. Equation 12-3 represents the capacitance of an isolated body in space and can be used to estimate the minimum capacitance of many objects. For example, a person has a surface area approximately equivalent to that of a 1-m diameter sphere; therefore Eq. 12-3 gives a capacitance for the human body of about 50 pF. The earth has a free-space capacitance of slightly more than 700 $\mu$F, and an object the size of a marble has a free-space capacitance of slightly more than 1 pF.

**HUMAN BODY MODEL**

Besides the capacitance given by Eq. 12-3, a parallel plate capacitance (due to the human body and surrounding objects) also exists.

**HUMAN BODY MODEL**

Humans are a prime source of electrostatic capacitance. They readily transfer their charge to a person's skin, which has a capacitance of $10^{-9}$ F.

In addition to the 50 pF of free-space capacitance, the human body contributes to the capacitance of the human body-ground capacitance. The capacitance between the soles of the feet and ground is typically $10^{-9}$ F.

**Figure 12-2.** If the conductor of Fig. 12-1 is momentarily grounded (A), the negative charge will bleed off and leave the conductor charged (B).
Besides the capacitance given by Eq. 12-3, additional capacitance (parallel plate capacitance) exists due to the proximity of an object to other surrounding objects.

**HUMAN BODY MODEL**

Humans are a prime source of electrostatic discharge. A charged object readily transfers its charge to a person's conductive skin layer.

In addition to the 50 pF of free-space capacitance, the primary contribution to the capacitance of the human body comes from the capacitance between the soles of the feet and ground, as shown in Fig. 12-3. This is

\[
\frac{4\pi\varepsilon}{r_1} - \left( \frac{1}{r_2} \right)
\]

(12-2)

where \( r_2 > r_1 \), and \( \varepsilon \) is the permittivity of free space in F/m. If the radius of the outer sphere is 0.5 m, then

\[
110 \, \text{pF},
\]

(12-3)

The capacitance in meters. Equation 12-3 represents the capacitance of a single sphere and can be used to estimate the capacitance of a person. For example, a person has a surface area slightly more than 700 m², and an object the size of the human body of about 50 pF. The earth is the capacitance of slightly more than 1 pF.

Figure 12-3. Human body capacitance and resistance.
typically 100 pF. An additional capacitance from 50 to 100 pF may exist due to the proximity of the person to some surrounding objects, such as walls. Therefore the capacitance of the human body is the combination of free-space capacitance plus parallel-plate capacitance, and it varies from about 50 to 250 pF.

A model for electrostatic discharge from a human body is shown in Fig. 12-4. The charge is stored in the body capacitance. The discharge occurs through a resistor, which represents the resistance of the body. The inductance, although often left out of the model, is important in determining the rise time of the discharge current and should be included.

The body resistance can vary from about 500 to 10,000 Ω, depending on which part of the body the discharge occurs. If the discharge is from the tip of the finger, the resistance will be about 10,000 Ω; if from the palm of the hand, about 1000 Ω; if from a metal object (e.g., a key) held in the hand, it will be approximately 500 Ω. If the discharge occurs from a large metal object, such as a chair or shopping cart, the resistance can be as small as 50 Ω.

The circuit of Fig. 12-4 can be used in testing, to simulate the human body discharge. There is no industry standard or agreement as to what values should be used for the components of the circuit. Typical values used by industry are given in Table 12-3.

The rise time and the energy of the discharge are the primary parameters that determine the severity of the event. Table 12-3 lists the energy in millijoules for the various models.

Figure 12-5 shows a typical ESD current waveshape produced by a 150-pF, 500-Ω human body model when charged to 20,000 V. The peak amplitude is 40 A, with a rise time (10 to 90%) of 1 ns and a fall time of 100 ns. The rise time is determined by the inductance in series with the discharge probe. Minimizing this inductance is important in the design of ESD testers. Its value should be as small as possible.

Two of the more commonly used models are the International Electrotechnical Commission (IEC) Model 801-2 and 1500 pF, 1500 Ω specified in DOD-HDBK-263.

More elaborate models that produce more realistic actual human discharges have also been proposed. To date, however, only the simple model shown here has been widely accepted for testing purposes.

A discharge from a voltage of less than 1000 V would not be expected to injure a person involved. Since many electronic components are

![Figure 12-4. Electrostatic discharge model of the human body.](image-url)

![Figure 12-5. Typical electrostatic discharge waveshape.](image-url)
The discharge from 50 to 100 pF may exist due to the surrounding objects, such as walls, and the human body is the combination of free capacitance, and it varies from about 50 to 1000 pF.

A typical discharge from a human body is shown in Fig. 12.5. The capacitance of the body is the resistance of the body. The inductive model, is important in determining the model should be included.

Typically, 50 to 10,000 Ω, depending on the discharge occurs. If the discharge is from the tip of about 10,000 Ω, if from the palm of the object (e.g., a key) held in the hand, it is a discharge occurs from a large metal object. The resistance can be as small as 10 Ω.

It is used in testing, to simulate the human body in any standard or agreement as to what the elements of the circuit. Typical values used are determined by the discharge are the primary parameters in the event. Table 12-3 lists the energy in the model.

The DC current waveshape produced by a capacitor when charged to 20,000 V. The peak rise (10 to 90%) of 1 ns and a fall time of 100 ns by the inductance in series with the

![ charging model of the human body. ]

**Table 12-3 Typical Human Body Model Component Values**

<table>
<thead>
<tr>
<th>Source</th>
<th>C (pF)</th>
<th>R (Ω)</th>
<th>V (volts)</th>
<th>Energy (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 801-2</td>
<td>150</td>
<td>150</td>
<td>15,000</td>
<td>16.9</td>
</tr>
<tr>
<td>SAE</td>
<td>200</td>
<td>250</td>
<td>15,000</td>
<td>22.5</td>
</tr>
<tr>
<td>DOD-HDBK-263</td>
<td>100</td>
<td>1500</td>
<td>15,000</td>
<td>11.3</td>
</tr>
<tr>
<td>Company A</td>
<td>250</td>
<td>1000</td>
<td>20,000</td>
<td>50</td>
</tr>
<tr>
<td>Company B</td>
<td>150</td>
<td>500</td>
<td>20,000</td>
<td>30</td>
</tr>
<tr>
<td>Company C</td>
<td>50</td>
<td>10,000</td>
<td>20,000</td>
<td>10</td>
</tr>
<tr>
<td>Company D</td>
<td>300</td>
<td>500</td>
<td>15,000</td>
<td>33.8</td>
</tr>
<tr>
<td>Company E</td>
<td>250</td>
<td>100</td>
<td>15,000</td>
<td>39.4</td>
</tr>
<tr>
<td>Company F</td>
<td>100</td>
<td>500</td>
<td>10,000</td>
<td>5.0</td>
</tr>
</tbody>
</table>

![ Typical electrostatic discharge current waveform. ]

Discharge probe. Minimizing this inductance is one of the primary concerns in the design of ESD testers. Its value should be kept to less than 0.1 μH.

Two of the more commonly used models are 150 pF, 150 Ω, specified in the International Electrotechnical Commission (IEC Standard 801-2, 1984), and 100 pF, 1500 Ω specified in DOD-HDBK-263.

More elaborate models that produce multiple discharges corresponding to actual human discharges have also been proposed. Figure 12.6 shows such a model. To date, however, only the simple R-L-C model of Fig. 12.4 has been widely accepted for testing purposes.

A discharge from a voltage of less than 3500 V will not be felt by the person involved. Since many electronic devices are sensitive to damage...
Electrostatic discharge from 50 to 100 pF may exist due to the capacitance of the body and exposure to surrounding objects, such as walls. The capacitance of the human body is the combination of free and bound capacitance, and it varies from about 50 pF to 2000 pF. The discharge current from a human body is shown in Fig. 12-4. The discharge occurs through the resistance of the body. The inductance of the human body, shown in Fig. 12-5, is important in determining the energy that should be dissipated by the ESD tester.

The resistance of the body is about 500 to 10,000 Ω, depending on the point where the discharge occurs. If the discharge is from the tip of a finger, the resistance should be about 10,000 Ω; if from the palm of the hand, the resistance may be as small as 500 Ω.

Parallel circuit elements in the body can be used in testing, to simulate the human body in an ESD test system or agreement to what is considered a representative discharge voltage to the components of the circuit. Typical values used in ESD models are 100 pF, 500 kΩ, and 20,000 V.

The sources of the discharge are the primary parameters involved in the ESD discharge event. Table 12-3 lists the energy in the discharge source. Table 12-3 lists the energy in the discharge source. Table 12-3 lists the energy in the discharge source.

<table>
<thead>
<tr>
<th>Source</th>
<th>C (pF)</th>
<th>R (Ω)</th>
<th>V (volts)</th>
<th>Energy (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 801-2</td>
<td>150</td>
<td>150</td>
<td>15,000</td>
<td>16.9</td>
</tr>
<tr>
<td>SAE</td>
<td>200</td>
<td>250</td>
<td>15,000</td>
<td>22.5</td>
</tr>
<tr>
<td>DOD-HDBK-263</td>
<td>100</td>
<td>1500</td>
<td>15,000</td>
<td>11.3</td>
</tr>
<tr>
<td>Company A</td>
<td>250</td>
<td>1000</td>
<td>20,000</td>
<td>30</td>
</tr>
<tr>
<td>Company B</td>
<td>150</td>
<td>500</td>
<td>20,000</td>
<td>10</td>
</tr>
<tr>
<td>Company C</td>
<td>50</td>
<td>10,000</td>
<td>20,000</td>
<td>33.8</td>
</tr>
<tr>
<td>Company D</td>
<td>300</td>
<td>500</td>
<td>15,000</td>
<td>39.4</td>
</tr>
<tr>
<td>Company E</td>
<td>250</td>
<td>100</td>
<td>15,000</td>
<td>5.0</td>
</tr>
<tr>
<td>Company F</td>
<td>100</td>
<td>500</td>
<td>10,000</td>
<td></td>
</tr>
</tbody>
</table>

The energy in the discharge source is calculated as:

\[ E = \frac{1}{2} C V^2 \]

where

- \( E \) is the energy in the discharge source in millijoules,
- \( C \) is the capacitance of the discharge source in picofarads,
- \( V \) is the voltage of the discharge source in volts.

Discharge probe. Minimizing this inductance is one of the primary concerns in the design of ESD testers. Its value should be kept to less than 0.1 μH.

Two of the more commonly used models are 150 pF, 150 Ω, specified in the International Electrotechnical Commission (IEC Standard 801-2, 1984), and 100 pF, 1500 Ω specified in DOD-HDBK-263.

More elaborate models that produce multiple discharges corresponding to actual human discharges have also been proposed. Figure 12-6 shows such a model. To date, however, only the simple R-L-C model of Fig. 12-4 has been widely accepted for testing purposes.

A discharge from a voltage of less than 3500 V will not be felt by the person involved. Since many electronic devices are sensitive to damage
from discharges of only a few hundred volts, component damage can occur from a discharge that is not felt, heard, or seen. At the other extreme, discharges at potentials greater than 25 kV are painful to the person involved.

**STATIC DISCHARGE**

Charge accumulated on an object usually leaves the object by one of two ways, leakage or arcing. Since it is better to avoid arcing, leakage is the preferred way to discharge an object. Charge can leak off an object through the air, due to humidity. The higher the humidity, the faster the charge will leak off the object. The charge on an object can also be counteracted by using an ionizer to fill the air with an opposite charge. The ions will be attracted to the object and will neutralize the charge on it. The more ions, the faster the charge will be neutralized.

Leakage from a charged conductor can be made to occur by intentionally grounding the object. This ground may be a "hard ground" (close to zero impedance) or a "soft ground" (a large impedance, typically a megohm, that will limit the current flow). Since the human body is conductive, grounding it with a wrist strap, for example, will drain off the charge. However, grounding a person will not drain the static charge from his or her clothing (nonconductors), or from a plastic object held in the hand, such as a Styrofoam coffee cup. To remove the charge from these objects, ionization or the application of high humidity can be used. When grounding a person, a hard ground should be avoided because of the safety hazard that would exist if the person came in contact with an ac power line. The minimum impedance used in grounding a person should be 250 K-Ω (wrist straps usually have 1 MΩ of resistance to ground, the longer it will take for the charge to leak off.

**Decay Time**

Since the charge on an object may be reduced to a given percentage of 
(sometimes called the relaxation time) is

\[
\tau = \frac{\epsilon}{\sigma}
\]

where \(\epsilon\) is the dielectric constant for the material

(Moore 1973, p. 26, Eq. 15). The decay time \(\tau\) depends on the resistivity \(\rho\) of the material and is

\[
\tau = \epsilon / \rho
\]

From Eq. 12-5 we see that the decay time can be used as a measure of the resistivity of a material.

Since static electricity is a surface phenomenon, it is influenced by the surface resistivity. Surface resistivity is a measure of the resistance per unit length of the measuring electrodes to the surface of the material. For two electrodes that form the opposite ends of a length of the measuring electrodes, the resistance measurement is divided by the length of the electrodes. That is, if the electrodes are 1 in. apart.

Based on the surface resistivity, DOIs are divided into four categories, as listed in Table 12-4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductive</th>
<th>Static dissipative</th>
<th>Antistatic</th>
<th>Insulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface resistivity</td>
<td>(10^3) Ω/square</td>
<td>(10^5) Ω/square</td>
<td>(10^{11}) Ω/square</td>
<td>(10^{12}) Ω/square</td>
</tr>
</tbody>
</table>

* A surface resistivity of \(10^3\) Ω/square is conductive, \(10^5\) Ω/square is static dissipative, \(10^{11}\) Ω/square is antistatic, and \(10^{12}\) Ω/square is insulative.
usually have 1 MΩ of resistance to ground). The higher the impedance to ground, the longer it will take for the charge to bleed off the object.

**Decay Time**

Since the charge on an object may leak off over a period of time, an important parameter is the decay time—the time it takes for the charge to be reduced to a given percentage of its initial value. The decay time (sometimes called the relaxation time) is equal to

$$\tau = \frac{\epsilon}{\sigma},$$

(12-4)

where \(\epsilon\) is the dielectric constant for the material and \(\sigma\) is the conductivity (Moore 1973, p. 26, Eq. 15). The decay time can also be written in terms of the resistivity \(\rho\) of the material and is

$$\tau = \frac{\epsilon}{\rho}.$$  

(12-5)

From Eq. 12-5 we see that the decay time can be used as an indirect method of measuring the resistivity of a material.

Since static electricity is a surface phenomenon, materials can be classified by their surface resistivity. Surface resistivity has the dimensions of ohms per square. It is equivalent to the resistance measured across a square section of the material. Surface resistivity is measured with a fixture having two electrodes that form the opposite sides of a square. As long as the length of the measuring electrodes is the same as the spacing between the electrodes, the resistance measurement will be the same regardless of the length of the electrodes. That is, if the two electrodes are 1 in. long, they must be placed 1 in. apart.

Based on the surface resistivity, DOD-HDBK-263 classifies materials into four categories, as listed in Table 12-4.

**Table 12-4 Surface Resistivity of Various Classes of Materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface Resistivity (Ω/Square)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductive</td>
<td>0 to 10^5</td>
</tr>
<tr>
<td>Static dissipative</td>
<td>10^6 to 10^9</td>
</tr>
<tr>
<td>Antistatic*</td>
<td>10^9 to 10^14</td>
</tr>
<tr>
<td>Insulative*</td>
<td>&gt;10^14</td>
</tr>
</tbody>
</table>

* A surface resistivity of 10^14 is high for the transition from antistatic to insulative. A more realistic value would be 10^12 Ω/square.
Materials with surface resistivities of $10^9 \Omega$ per square or less can be discharged rapidly by grounding. If a charge already exists on an object, it should be discharged slowly in order to limit the current and avoid damage. Conductive materials are the fastest to dissipate charge and can be dangerous when used near an already charged device. If a charged device should come in contact with a grounded conductive material, it will be rapidly discharged with a large peak current, and damage may result.

Static-dissipative materials are preferred to conductive materials because charge dissipation occurs at a slower, safer rate. Grounded static-dissipative materials can be used to prevent charge buildup and to safely discharge objects already charged.

Antistatic materials are the slowest to dissipate charge. Nevertheless, they are useful because they can dissipate charge faster than it is generated and therefore prevent an object from accumulating a charge. An example of this is a pink polyethylene bag. To prevent triboelectric charging the surface resistivity of the material should not exceed $10^{12} \Omega$/square.

Neither static-dissipative nor antistatic materials will charge when separated from themselves or any other materials. They have similar applications and are sometimes grouped together. They are the preferred materials to use in an ESD-sensitive environment.

Insulators do not dissipate charge but retain whatever charge they have. Examples are a polyethylene bag and Styrofoam packing material. They should not be allowed in an ESD-sensitive environment.

**ESD PROTECTION IN EQUIPMENT DESIGN**

Energy from a static discharge can be coupled to an electronic circuit in three ways:

1. By direct conduction.
2. By capacitive coupling.
3. By inductive coupling.

Direct conduction occurs when the discharge current flows directly through the sensitive circuit. This often results in damage to the circuit. Capacitive and inductive couplings occur when there is a discharge to a nearby metal object or cable, and the resulting fields are coupled to the susceptible circuit.

A circuit or system may be protected from a static discharge by

1. Eliminating the static buildup on the source.
2. Insulating the product to prevent a discharge.

3. Providing an alternative path for the circuit.
4. Shielding the circuit against the charge.
5. Protecting the circuit against the charge.

Most of what has been written on the subject of preventing charge buildup and/or preventing damage to the hardware (items 1 and 2 of the list). Although the system from ESD damage in the process of shipping, they cannot be forced on the manufacturer.

ESD-induced effects in electronic products are classified into categories: hard errors, soft errors, and actual damage to the product. Hard errors are the result of memory bit or a program locked in an incorrect state not causing an error, but it is perceptible, refusal to display, or the momentary flushing of a product, and systems should be designed to avoid damage (hard error) and often are usually tolerated.

The first step in designing equipment to prevent ESD damage is to divert the current from flowing to the ESD-sensitive components of the system. This can be accomplished either by using an alternative path for the current flow, or by insulating the product from any other elements of the system. Antistatic materials and electronics should be designed to avoid damage (hard error) and often are usually tolerated.

In order to divert the ESD current to an alternative path, the metallic components of the system must be interconnected electrically continuous; otherwise, a portion of the current will flow through the internal circuitry, as well as the frequency electrical continuity (multiple joints, hinges, and so forth. For an understanding of the system, the ESD current paths are considered as a resistance network system and its environment.
of \(10^9\) \(\Omega\) per square or less can be used to dissipate charge faster than it is generated. These materials will not accumulate a charge. An example of a material that is used to dissipate charge is known as a static-dissipative material. Static-dissipative materials will charge when separated from other materials. They have similar applications to conductive materials but retain whatever charge they have. Examples include plastic, rubber, and Styrofoam packing material. They are useful in a static-sensitive environment.

## ESD Protection in Equipment Design

Electronic equipment should be coupled to an electronic circuit in order to prevent damage from static electricity. Discharge current flows directly through the system, resulting in damage to the circuit. Capacitive coupling can occur when there is a discharge to a nearby metal that already has stored charges. These charges are coupled to the susceptible element and can be neutralized by discharging through the metal. Static electricity can also be neutralized from a static discharge by shorting the source of the charge to ground. If the charge builds up on the source, it can cause a discharge.

3. Providing an alternative path for the discharge current to bypass the circuit.
4. Shielding the circuit against the electric fields produced by the discharge.
5. Protecting the circuit against the magnetic fields produced by the discharge.

Most of what has been written on the subject of ESD discusses methods of preventing charge buildup and/or preventing a discharge from occurring (items 1 and 2 of the list). Although these methods are useful in protecting a system from ESD damage in the process of manufacturing, handling, and shipping, they cannot be forced on the users of the product.

ESD-induced effects in electronic circuits can be divided into three categories: hard errors, soft errors, and transient upset. Hard errors cause actual damage to the hardware (e.g., destruction of an IC). Soft errors affect system operation but do not physically damage it (e.g., a changed memory bit or a program locked in an infinite loop). Transient upset does not cause an error, but it is perceptible (e.g., snow, rolling of a CRT display, or the momentary flashing of an indicator light). Electronic products and systems should be designed to tolerate an electrostatic discharge without damage (hard error) and often without soft error. Transient upsets are usually tolerated.

The first step in designing equipment to be immune to ESD is to prevent the direct discharge current from flowing through the susceptible circuits. This can be accomplished either by insulating the circuit or by providing an alternative path for the current flow. If insulation is used, it must be complete, since a spark will jump across an air gap at a discontinuity, such as the air gap between the plastic keys of a keyboard.

In order to divert the ESD current from sensitive circuits, all exposed metallic components of the system must be grounded. Since the discharge current follows a path that is dependent on the physical layout of the product, the number and location of metallic structures and their ground ties are very important.

The basic principle of ESD-protective grounding is to use low inductance multipoint grounds where ESD current flow is desired and single-point grounds where discharge current flow is not wanted.

In the case of a grounded metallic enclosure, the housing can be used to divert the discharge current to ground. To be effective, the case must be electrically continuous; otherwise, a portion of the current may be forced to flow through the internal circuitry, as shown in Fig. 12-7. Good high-frequency electrical continuity (multipoint) must be provided across all joints, hinges, and so forth. For an ungrounded or improperly grounded system, the ESD current paths are complex and unpredictable, flowing through the capacitance among the parts of the system and between the system and its environment.
Metallic Enclosures

Consider the situation shown in Fig. 12-8 of a circuit insulated from and completely enclosed by a grounded metal box. The circuit has no connection to anything outside the metallic enclosure. When a discharge occurs to the box, the box rises in potential due to the inductance of the ground lead. In the case of a 20,000-V discharge, the box may rise in potential by a few thousand volts. The circuit inside the box also rises to a few thousand volts with the box, so there are no potential differences between points of the circuit or the circuit and the box. No damage will be done, provided the box completely encloses the circuit.

Discontinuities in the enclosure (e.g., seams or holes) can cause differential voltages to appear on the enclosure. These voltages, combined with the parasitic capacitance between the portions of the enclosure and the circuit, can produce voltages in the circuit that may affect its operation. There are two approaches to solving this problem. The first is to make the enclosure as complete as possible. The second is to add an internal shield to block the capacitive-coupling between the enclosure and the circuit. This second shield should be connected to the circuit common, as shown in Fig. 12-9.

A more practical case is shown in Fig. 12-8. The circuit has a connection to an outside ground conductor or through capacitance to ground (as through the enclosure). When a discharge occurs, the box may rise in potential. The circuit, however, due to its capacitance, will remain at the ground or close to it. There will be potential differences between the box and the circuit, and this may produce damage between them. This secondary arc occurs if the resistance and produces currents much larger than the discharge.

A similar effect occurs if the metallic enclosure instead of rising to a few thousand volts due to the capacitance to ground, the enclosure may rise close to power ground. Therefore all exposed metal parts should be connected to power ground to limit this voltage rise.

The secondary arc can be prevented by connecting all metal parts and the circuit common to a grounded enclosure. The gap should be as large as possible, in this case, at least 25,000 V.
A more practical case is shown in Fig. 12-10, where the enclosed circuit has a connection to an outside ground either through a cable (I/O or power) or through capacitance to ground (as the result of holes or discontinuities in the enclosure). When a discharge occurs to the box, the box rises in potential. The circuit, however, due to the external ground connection, will remain at the ground or close to it. There is now a large potential difference between the box and the circuit, and this may cause a secondary arc to occur between them. This secondary arc occurs without the current-limiting body resistance and produces currents much larger, and more destructive than the primary arc.

A similar effect occurs if the metallic enclosure is ungrounded. However, instead of rising to a few thousand volts, as in the case of a grounded enclosure, the enclosure may rise close to the potential of the source. Therefore all exposed metal parts should be grounded to the green wire ac power ground to limit this voltage rise.

The secondary arc can be prevented by providing sufficient space between all metal parts and the circuit or by connecting the circuit to the metallic enclosure. The gap should be able to withstand about 1500 V for a grounded enclosure and at least 25,000 V for an ungrounded enclosure. For
engineering purposes the breakdown electric field strength is about 30 kV/cm (75 kV/in.); therefore minimum 0.020 in. metallic shielding is required for grounded metal parts, especially if they are grounded metal parts.

Even without the secondary arc, the metal box and the circuit shield inside the metal box will be at a lower ground potential to the circuit. This second, unexposed shield is connected to the circuit ground, as was shown in Fig. 12-10. This is a part of a ground plane on an existing circuit board.

If the circuit is connected to the metal box, a single ground connection should be made at one point only to prevent ground currents from flowing through the circuit. The configuration is shown in Fig. 12-11. When a discharge occurs to the box, the box acts like a potential divider on the resulting bond. The box is the negative side of the bond and the circuit is the more positive side. The result is that a few-thousand-volts potential is generated between the box and the circuit. This may cause incorrect operation or damage to the electronics within the circuit.

Figure 12-9. Capacitive coupling between a metallic enclosure and a circuit (A). A secondary shield (B) can be used to block the capacitive coupling between a circuit and a metallic enclosure.

Figure 12-10. Electrostatic discharge to a metallic enclosure containing a circuit with an external ground connection.

Figure 12-11. Electrostatic discharge to a metallic enclosure containing a circuit with a point connection between the enclosure and the circuit.
Figure 12-9. Capacitive coupling between a metallic enclosure and a circuit (A). A secondary shield (B) can be used to block the capacitive coupling between a circuit and a metallic enclosure.

Figure 12-10. Electrostatic discharge to a metallic enclosure containing a circuit with an external ground connection.

Figure 12-11. Electrostatic discharge to a metallic enclosure with a point connection between the enclosure and the ground.
engineering purposes the breakdown strength of air is considered to be 30 kV/cm (75 kV/in.); therefore minimum spacing should be 0.05 cm (0.020 in.) for grounded metal parts, and 0.84 cm (about 3/8 in.) for ungrounded metal parts.

Even without the secondary arc, the strong electric field produced between the metal box and the circuit can cause a problem. Often a second shield inside the metal box will be needed to break the electric field coupling to the circuit. This second, unexposed shield should be connected to the circuit ground, as was shown in Fig. 12-9. This could be a separate shield or part of a ground plane on an existing printed wiring board.

If the circuit is connected to the metallic enclosure, this connection should be made at one point only to prevent the discharge currents from flowing through the circuit. The configuration shown in Fig. 12-11 illustrates the result. When a discharge occurs to the box, the box rises in potential. However, since the circuit ground is tied to the box, the circuit potential rises with the box, and there is no potential difference between points on the circuit or between the circuit and the box. What happens then to the few-thousand-volts potential on the box? It is transferred as a common-mode voltage to the interface cables and applied to whatever is connected at

Figure 12-11. Electrostatic discharge to a metallic enclosure containing a circuit with a single-point connection between the enclosure and the circuit.
the other end of the cables. Therefore the problem is transferred from the circuit to the enclosure to the circuit at the other end of the cables. If the cable is the ac power line, momentarily applying a few thousand volts into it will not do any harm. But, if the cable is a signal cable connected to a logic gate, the gate will be damaged.

The situation can also be reversed, with the discharge applied to the circuit at the end of the cable and the damage done to the circuit inside the box. For a complete conductive enclosure, which is connected to the circuit ground at one point, the primary ESD problem involves the interface cables. These cables must be treated to prevent ESD damage.

**Input/Output Cable Treatment**

Interface cables can be protected from ESD by the following methods:

1. Use of cable shielding.
2. Common-mode chokes.
3. Overvoltage clamping devices.
4. Cable bypass filters.

Figure 12-12 shows two metallic enclosures connected with a shielded cable. This is an attempt to convert the two enclosures into one, by use of the cable shield. The bonding of the shield to the enclosures is the most significant parameter that determines performance during a discharge. The data shown in Table 12-5 are from tests measured between the cable signal conductor and 10,000 V discharge occurs to the other bond to the box where the discharge on the other end is varied.

A common-mode choke placed in the circuit can be seen to induce noise voltage (Vn).
the other end of the cables. Therefore the problem is transferred from the circuit in the enclosure to the circuit at the other end of the cables. If the cable is the ac power line, momentarily applying a few thousand volts into it will not do any harm. But, if the cable is a signal cable connected to a logic gate, the gate will be damaged.

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Figure 12-12 shows two metallic enclosures connected with a shielded cable. This is an attempt to convert the two enclosures into one, by use of the cable shield. The bonding of the shield to the enclosures is the most significant parameter that determines performance during a discharge. The

![Diagram](image)

**Figure 12-12.** Two enclosures connected with a shielded cable, in an attempt to turn the two into one continuous enclosure.

---

**Table 12-5 The Effect of Shield Terminations (Palmgren, 1981)**

<table>
<thead>
<tr>
<th>Shield Termination Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No shield, or shield not connected to cabinet</td>
<td></td>
</tr>
<tr>
<td>Drain wire ground connection</td>
<td></td>
</tr>
<tr>
<td>Shield soldered to connector; connector in contact with cabinet through jackscrews only</td>
<td></td>
</tr>
<tr>
<td>Shield soldered to connector; a 360° contact between connector and cabinet</td>
<td></td>
</tr>
<tr>
<td>Shield clamped directly to cabinet with 360° contact (no connector)</td>
<td></td>
</tr>
</tbody>
</table>

The data shown in Table 12-5 are from ESD voltages measured between the cable signal conductor and ground. A 10,000 V discharge occurs to the other end of the bond to the box where the discharge occurs, and the data on the other end is varied.

A common-mode choke placed in the circuit can reduce the transient discharge voltage to be dropped across the circuit connected to the other end.
the problem is transferred from the one enclosure to the other end of the cables. If the same is not done, applying a few thousand volts into it is a signal cable connected to a logic level signal processor, with the discharge applied to the other end, damage done to the circuit inside the processor, which is connected to the circuit outside the processor. ESD problem involves the interface between the two. To prevent ESD damage,

In ESD by the following methods:

1. Bonding enclosures connected with a shielded cable. One or more enclosures into one, by use of the shield to the enclosures is the most effective approach to performance during a discharge. The

<table>
<thead>
<tr>
<th>Shield Termination Method</th>
<th>Induced Signal Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>No shield, or shield not connected to cabinet</td>
<td>&gt;500</td>
</tr>
<tr>
<td>Drain wire ground connection</td>
<td>16</td>
</tr>
<tr>
<td>Shield soldered to connector; connector in contact with cabinet through jack screws only</td>
<td>2</td>
</tr>
<tr>
<td>Shield soldered to connector; a 360° contact between connector and cabinet</td>
<td>1.25</td>
</tr>
<tr>
<td>Shield clamped directly to cabinet with a 360° contact (no connector)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Data shown in Table 12-5 are from Palmgren (1981) and list the voltage measured between the cable signal conductor and ground in one box when a 10,000 V discharge occurs to the other box. In all cases the shield has a 360° bond to the box where the discharge occurs, whereas the shield termination on the other end is varied.

A common-mode choke placed in the interface cable will cause the transient discharge voltage to be dropped across the choke rather than across the circuit connected to the other end. This is shown in Fig. 12-13.

Figure 12-13. A common-mode choke can be used on the interface cable to drop the ESD-induced noise voltage ($V_n$).
the problem is transferred from the middle of the cable to the other end of the cables. If the cable is short, applying a few thousand volts into it is a signal cable connected to a logic circuit, with the discharge applied to the middle of the cable. The damage done to the circuit inside the enclosure, which is connected to the circuit on the other end, ESD problem involves the interface between the two circuits to prevent ESD damage.

There are several methods for preventing ESD by the following methods:

1. Connect the enclosures connected with a shielded cable. Connecting two enclosures into one, by use of the shielded cable. Connecting the shield to the enclosures is the most convenient way of performing during a discharge. The

Table 12-5 The Effect of Shield Termination on ESD-Induced Voltage (from Palmgren, 1981)

<table>
<thead>
<tr>
<th>Shield Termination Method</th>
<th>Induced Signal Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>No shield, or shield not connected to cabinet</td>
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<tr>
<td>Shield clamped directly to cabinet with a 360° contact (no connector)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

data shown in Table 12-5 are from Palmgren (1981) and list the voltage measured between the cable signal conductor and ground in one box when a 10,000 V discharge occurs to the other box. In all cases the shield has a 360° bond to the box where the discharge occurs, whereas the shield termination on the other end is varied.

A common-mode choke placed in the interface cable will cause the transient discharge voltage to be dropped across the choke rather than across the circuit connected to the other end. This is shown in Fig. 12-13.

![Figure 12-13. A common-mode choke can be used on the interface cable to drop the ESD-induced noise voltage ($V_n$).](image-url)
Due to the fast rise time of the ESD pulse, stray capacitance across this choke must be minimized in order for it to be effective (see Chapter 3 for a discussion of the effect of stray capacitance across a common-mode choke). When the circuit is connected to the enclosure at only one point, this point should be near where the cables enter the enclosure as shown in Fig. 12-14.

Bypass capacitors, on the order of 500 pF, or surge diodes may be placed on the input leads to shunt the transient currents to ground. These devices must be able to respond to the ESD pulse faster than the protected system and should not interfere with the normal operation of the system. This requires that the protective device respond to a voltage transient in less than a nanosecond. These components should be placed so that the ground currents they produce do not flow through the circuit ground; that is, they should connect to a separate I/O ground or to the chassis. This is shown in Fig. 12-15.

The cable input protection methods just discussed will prevent component damage but may not prevent soft errors or transient upset, since noise voltages may still be present on the inputs. In order to prevent soft errors, noise signals must be controlled by building additional noise immunity into the input circuitry. This can be done by additional filtering, use of balanced inputs, strobed input circuitry, or by software design.

**Insulated Enclosures**

In the case of a metallic enclosure the chassis or enclosure is used as a low inductance path to route the ESD current around the internal circuitry. In the case of a nonmetallic enclosure this is not possible, which makes ESD more difficult to contain. In this case, placing a metal plate of chassis ground to minimize noise, and connecting it to the common frame ground usually results in soft errors.

If all cables, including power, enter the system on one side, a separate I/O ground plane is used (see Fig. 12-16). This can be done by the ESD cable currents to ground, but the effective routing is not be as effective, due to the larger inductance of the cable to ground.

**Figure 12-15.** A capacitor (A) or surge diode (B) is placed across the cable to ground.

---

Additional control methods include keyboards and control panels. Keyboards and control panels must be shielded to prevent ESD discharge. In the case of an insulated chassis, ESD discharge can go directly to ground without affecting electronics. In the case of an insulated chassis, the discharge current. This is achieved by placing a metal frame ground, and not to circuit ground. ESD protection methods shown in Fig. 12-16, and/or a large knob to prevent a discharge to ground.

**Keyboards and Control Panels**

Keyboards and control panels must be shielded to prevent ESD discharge. In the case of an insulated chassis, ESD discharge can go directly to ground without affecting electronics. In the case of an insulated chassis, the discharge current. This is achieved by placing a metal frame ground, and not to circuit ground. ESD protection methods shown in Fig. 12-16, and/or a large knob to prevent a discharge to ground.
pulse, stray capacitance across this path may not be effective (see Chapter 3 for a discussion across a common-mode choke). If the enclosure at only one point, this point will be the enclosure as shown in Fig. 12-14. A 0-pF or surge diodes may be placed to divert currents to ground. These devices respond faster than the protected system to a transient, but transients of the system. This can be placed so that the ground is through the circuit ground; that is, it is a path to the chassis. This is shown in Fig. 12-15. A capacitor (A) or surge diode (B) can be used to bypass the ESD current from the cable to ground.

In the case of a nonmetallic enclosure this low inductance path does not exist, which makes ESD more difficult to control. Circuit ground can be used in place of chassis ground to minimize the damage done by ESD, but this usually results in soft errors.

If all cables, including power, enter the system in the same area and a separate I/O ground plane is used (see Chapter 11), this ground can be used to bypass the ESD cable currents to the green wire ground. In this case the techniques used for the metallic chassis are applicable, although they will not be as effective, due to the larger inductance involved. It is an advantage to have a large metal structure somewhere in the system to act as both a reference potential and a low inductance path for ESD current flow.

**Keyboards and Control Panels**

Keyboards and control panels must be designed in such a way that a discharge can go directly to ground without passing through the sensitive electronics. In the case of an insulated keyboard a metal spark arrester can be placed between the keys and the circuit to provide an alternative path for the discharge current. This spark arrester should be grounded to the case or frame ground, and not to circuit ground, as shown in Fig. 12-16. Other protection methods shown in Fig. 12-16 are the use of an insulated shaft and/or a large knob to prevent a discharge to a control or potentiometer and the use of an insulator over the keyboard, with no air gaps.
CMOS devices are not only sensitive to high voltage, but also to additional problem of latch-up. Latch-up occurs when a pn-pn device on the substrate is turned on by an input or output with a high dv/dt or power-supply voltage levels. The SCR is in series with the power supply. Once the SCR is triggered, a low impedance path between the power supply and ground, heating and possibly device failure. On printed wiring boards all loops are possible because they are susceptible to high dv/dt transient ESD currents. This includes looped power, ground as well as signal and ground.

The act of plugging a printed wiring board from backplane, is a frequent cause of ESD.

Circuit Design and Board Layout

Edge-triggered inputs are very susceptible to the transients caused by ESD; therefore inputs should not be edge triggered but strobed and latched. This way only a coincidence between the ESD event and the strobe can cause an error.

It is best to avoid printed wiring board layouts that bring sensitive MOS device leads directly to connector pins that are prone to ESD. If sensitive leads are connected to connector pins, protection can be provided by adding series resistance, shunts, or voltage clamps to these leads or by buffering them with less ESD-sensitive logic families. Additional protection to MOS devices can be provided by adding series resistance to the inputs. Most CMOS gates can tolerate 1000 $\Omega$ or more of series-input resistance.
CMOS devices are not only sensitive to ESD damage, but also have the additional problem of latch-up. Latch-up is due to the presence of a parasitic pnpn device to the substrate. This pnpn device can behave like a silicon-controlled rectifier (SCR). Additional information on CMOS latch up can be found in RCA application note ICAN-6525. The parasitic SCR can be turned on by an input or output voltage transient that is outside the power-supply voltage levels. The SCR can also be turned on by a large dV/dt on the power supply. Once latch-up occurs, it produces a low-impedance path between the power supply and ground, resulting in overheating and possibly device failure. Once the parasitic pnpn device is turned on, the only way to turn it off is to remove power.

On printed wiring boards all loop areas should be kept as small as possible because they are susceptible to the magnetic fields produced by the transient ESD currents. This includes loop areas formed between power and ground as well as signal and ground.

The act of plugging a printed wiring board into a mother-board, or backplane, is a frequent cause of ESD damage. If the person handling the

Figure 12-17. Guard ring on PWB used to protect board from ESD damage when board is handled and subsequently plugged into the system.
software checkpoints, error traps, "no-op" codes, and the trapping of unused interrupts.

The most effective protection against the infinite loop is an external hardware timer. An external hardware counter connected to the system clock is configured to count up to a specified number and then reset the microprocessor. The software is designed to reset the timer by periodically sending a sanity pulse, which prevents the counter from ever reaching its final count unless the system is locked in an infinite loop. Often the sanity pulse code can be added to an existing subroutine that is naturally used by the main program with only a few extra instructions.

A retrigerable monostable multivibrator may also be used as a sanity timer, as shown in Fig. 12-18. The timing on the first multivibrator ($R_{x1}$ and $C_{x1}$) is set to be much longer than the time between sanity pulses from the microprocessor. Under normal operation this multivibrator is retrigered by the sanity pulse before it times out. This input must be edge triggered, not level triggered, since it may be possible for the sanity signal to latch up in either a high or low state.

If the sanity pulse is not received in time, the first multivibrator times out and triggers the second multivibrator. The second multivibrator is timed ($R_{x2}$ and $C_{x2}$) in such a way that its output pulse is of a duration long enough to guarantee the resetting of the microprocessor.

Another, but less effective, technique is the use of software checkpoints. Here a separate program periodically interrupts the operating program and checks to see that certain checkpoints have been reached. If the checkpoints are incorrect, control is transferred to an error-handling program.

If a program is limited to only a certain range of memory, such as a

![Figure 12-18. A hardware sanity timer made from a dual retrigerable multivibrator.](image)
written into the software to prevent the instructions outside the valid range of locations should be filled with "no-op" to an error-handling routine at the end. An unused or nonexistent memory occurs, called.

This is often the source of program-flow on an unused interrupt, it will force a run. If this location is in the middle of a occur. The solution to this problem is to routine in all unused interrupt vector

as detected, it becomes necessary to get a stable state, with as little damage as transferring control to an error-handling system reset. In some instance, however, it's not

proceeding the damage and then repairing the be done depends on the specific system itself in general.

Input

Input can cause incorrect information to be system. Output errors can be detected by and comparing the data to those that

by software filtering (de-bouncing) the data for reasonableness. A very simple to read the input data several times in the readings. This way, a valid input can be determined. For ESD protection a delay of a few readings is sufficient. Figure 12-19 shows the

ends the input until N successive readings this same routine also produces a sanity transients, the program acts as a low-pass

can be provided by checking the reason-

range check, before accepting the data. Detected and flagged before they enter

Figure 12-19. Software subroutine for filtering input data and outputting a sanity pulse.
system at a later time. To detect this type of error, all data taken from memory must be validated before the data are used. Many useful techniques exist for checking the validity of data. Some of these are the use of a parity bit, checksums, cyclical redundancy checks, and use of error-correcting codes. Most of these techniques detect the presence of an error but cannot correct it. For example, by adding one parity bit per data word, all odd number bit errors can be detected. The system uses this information to flag the data and question their validity.

Error-correcting codes, however, are capable of both detecting and correcting certain types of errors. This is accomplished by adding extra data bits to each memory word. For example, by adding six extra bits per sixteen-bit word, single- or double-bit errors can be detected, and single-bit errors can be corrected. The degree of data memory protection required is something that must be determined as part of the system specifications.

**ESD VERSUS EMC**

ESD is a special case of the overall subject of EMC control. The primary difference between ESD and general EMC control is that with ESD much larger currents and voltages are involved; however, both can be controlled by the same techniques. Notice the similarities between the methods used to provide ESD protection, discussed in this chapter, and those used to control common-mode emissions from I/O cables (Chapter 11):

1. All I/O cables should be in one area.
2. A separate I/O ground should be used.
3. The I/O ground should have a low-impedance connection to the earth.
4. Cables should be bypassed to this separate I/O ground.
5. All loop areas should be kept as small as possible.

A system properly designed for ESD control will usually perform well with respect to EMC susceptibility. Furthermore ESD testing can often be used to find flaws in the EMC design of a product (Mardigian, 1985).

**SUMMARY**

- ESD protection should be part of the original system design.
- ESD hardening of a system involves the electrical, mechanical, and software design of a system.
- All exposed metal must be grounded to chassis ground.

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**BIBLIOGRAPHY**

- Keyboards and control panels must be hardened against electrostatic discharge.
- Multipoint ground should be used. If single-point ground must be used, it should be acceptable.
- Secondary shields may be needed in the system to prevent capacitive coupling through the power supply.
- Inputs should not be edge triggered.
- Layouts that put sensitive MOS logic in high voltage areas should be avoided.
- All cables must be treated for ESD protection.
- Use shielded cables are used, 360° shielding should be used.
- Cable bypassing must be done to prevent ESD from going to circuit ground.
- Loop areas on printed wiring boards should be as small as possible.
- A guard ring on plug-in printed circuit boards is recommended.
- In minimizing ESD problems, the solid state device or firmware, should not be overloaded.
- A hardware timer can be used to terminate a circuit.
- Input errors can be minimized by using appropriate error correction.
- Hardening a system against ESD must be done to prevent other sources of radio-frequency interference.


This type of error, all data taken from the same area.

Some of these are the use of a parity check, and use of error-checking and correction methods. The system uses this information to flag is accomplished by adding extra data or by adding six extra bits per byte. Error can be detected, and single-bit errors can be tolerated. The use of data memory protection is part of the system specifications.

12. ELECTROSTATIC DISCHARGE

...subject of EMC control. The primary purpose of EMC control is that with ESD much easier to solve; however, both can be controlled independently. The similarities between the methods used to control ESD in this chapter, and those used to control electromagnetic interference cables (Chapter 11):

- The area where the cables will be used.
- Low-impedance connection to the ground point(s).
- Provide a separate I/O ground.
- Use isolation to ensure that separate I/O grounds can be used as small as possible.

ESD control will usually perform well with electromagnetic interference. Furthermore ESD testing can often be used as a part of the original system design.

This involves the electrical, mechanical, and environmental aspects of the product. The system is designed to be grounded to chassis ground.

BIBLIOGRAPHY

- Keyboards and control panels must be carefully designed to tolerate a static discharge.
- Multipoint ground should be used where ESD current flow is desired, and single-point ground should be used where discharge current flow is not acceptable.
- Secondary shields may be needed between sensitive circuits and the chassis to prevent capacitive coupling from upsetting the circuit.
- Inputs should not be edge triggered but latched and strobed.
- Layouts that put sensitive MOS leads directly to connector pins should be avoided.
- All cables must be treated for ESD protection.
- If shielded cables are used, 360° contact with the shield is essential.
- Cable bypassing must be done to the chassis or a separate I/O ground.
- Loop areas on printed wiring boards should be kept as small as possible.
- A guard ring on plug-in printed wiring boards should be provided.
- A guard ring on plug-in printed wiring boards should be provided.
- In minimizing ESD problems, the role of properly designed software, or firmware, should not be overlooked.
- A hardware timer can be used to check the sanity of a microprocessor.
- Error messages can be minimized by software filtering.
- Hardening a system against ESD will also make it immune to most other sources of radio-frequency interference.

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