Table 12-1 Triboelectric Series

POSITIVE	
1. Air	18. Hard rubber
2. Human skin	19. Mylar[a]
3. Asbestos	20. Epoxy glass
4. Glass	21. Nickel, copper
5. Mica	22. Brass, silver
6. Human hair	23. Gold, platinum
7. Nylon	24. Polystyrene foam
8. Wool	25. Acrylic
9. Fur	26. Polyester
10. Lead	27. Celluloid
11. Silk	28. Orlon
12. Aluminum	29. Polyurethane foam
13. Paper	30. Polyethylene
14. Cotton	31. Polypropylene
15. Wood	32. PVC (vinyl)
16. Steel	33. Silicon
17. Sealing wax	34. Teflon[a]
	NEGATIVE

[a]Trademark of E. I. du Pont de Nemours.

Table 12-2 Typical Electrostatic Voltages

Means of Static Generation	Electrostatic Voltage	
	10 to 20% Relative Humidity	65 to 90% Relative Humidity
Walking across carpet	35,000	1500
Walking on vinyl floor	12,000	250
Worker moving at bench	6000	100
Opening a vinyl envelope	7000	600
Picking up common polyethylene bag	20,000	1200
Sitting on chair padded with polyurethane foam	18,000	1500

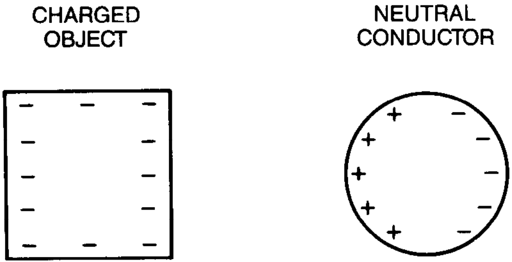


Figure 12-1. *The charge on a neutral conductor separates in the vicinity of a charged object.*

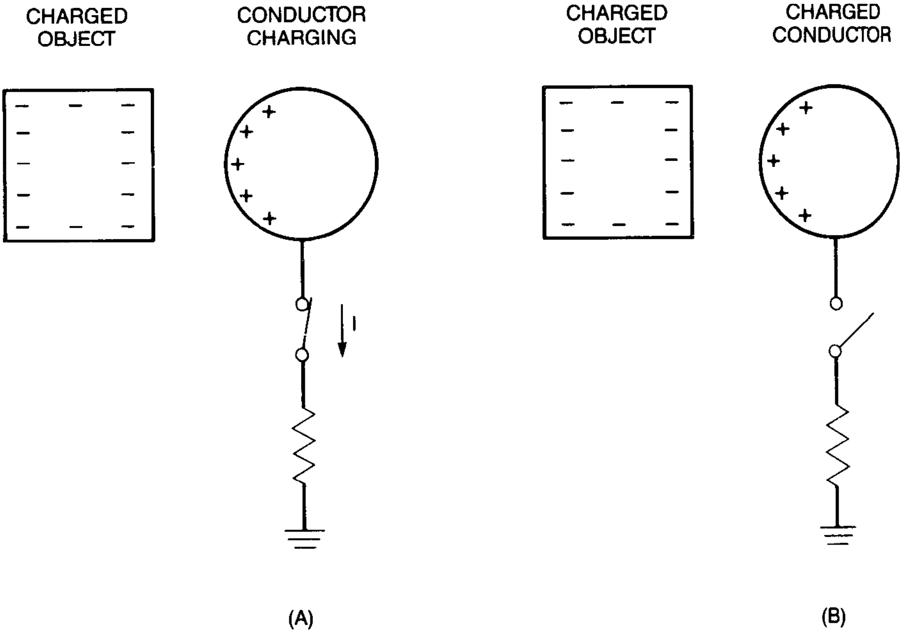


Figure 12-2. *If the conductor of Fig. 12-1 is momentarily grounded* (*A*), *the negative charge will bleed off and leave the conductor charged* (*B*).

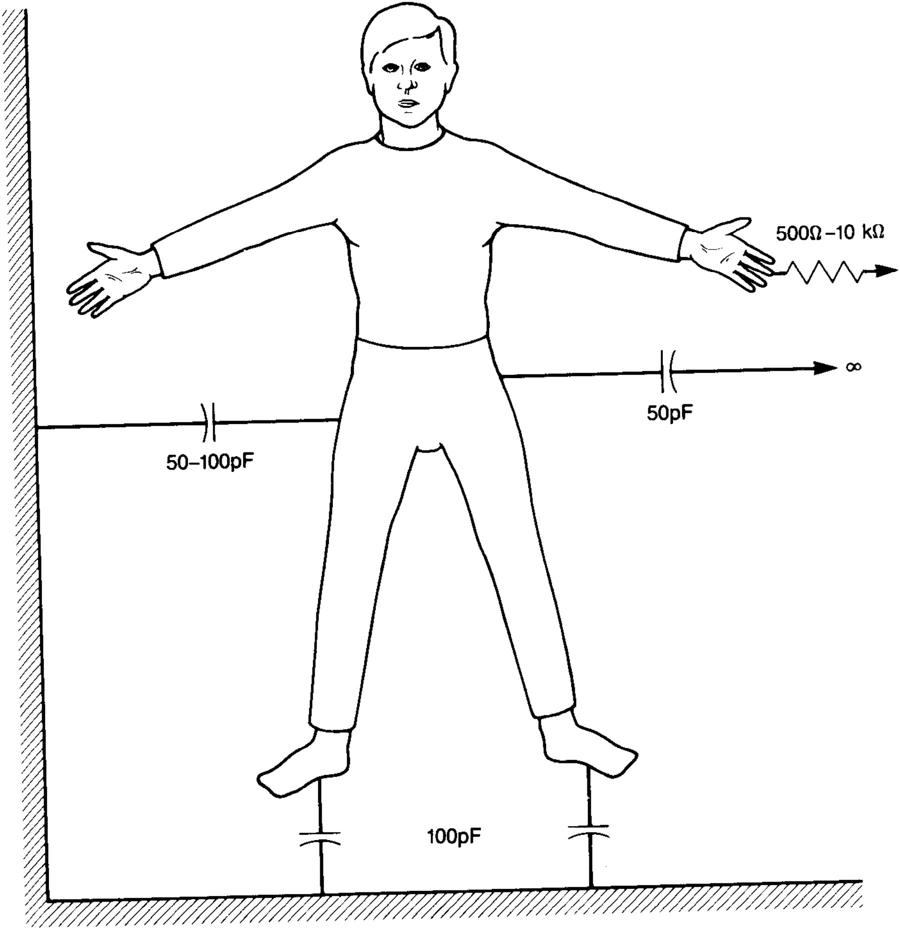
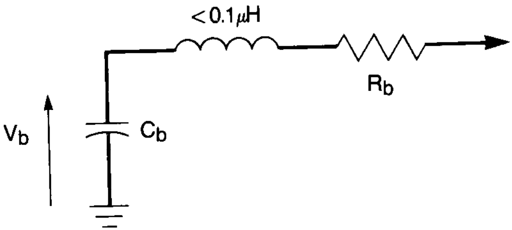


Figure 12-3. *Human body capacitance and resistance.*



RANGE OF VALUES

C_b	50 to 250 pF
R_b	500 Ω to 10 kΩ
V_b	0 to 20 kV

Figure 12-4. *Electrostatic discharge model of the human body.*

Table 12-3 Typical Human Body Model Component Values

Source	C (pF)	R (Ω)	V (volts)	Energy (mJ)
IEC 801-2	150	150	15,000	16.9
SAE	200	250	15,000	22.5
DOD-HDBK-263	100	1500	15,000	11.3
Company A	250	1000	20,000	50
Company B	150	500	20,000	30
Company C	50	10,000	20,000	10
Company D	300	500	15,000	33.8
Company E	350	100	15,000	39.4
Company F	100	500	10,000	5.0

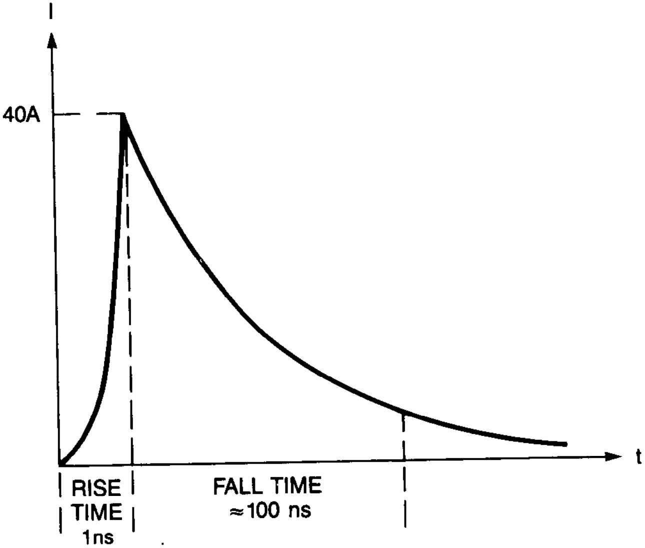


Figure 12-5. *Typical electrostatic discharge current waveform.*

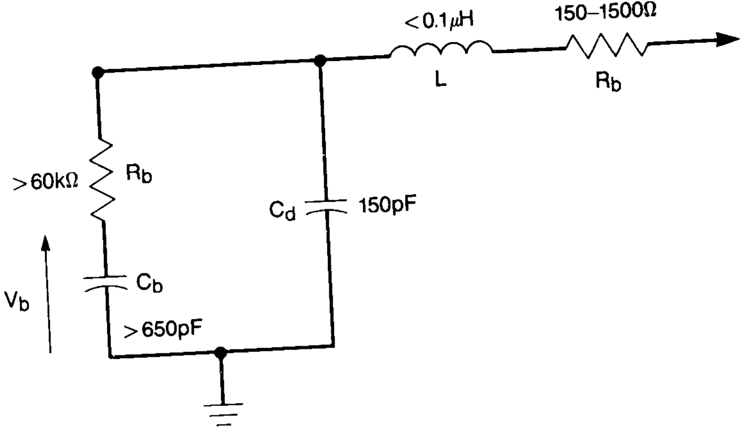


Figure 12-6. *Multiple discharge, human body model.*

Table 12-4 Surface Resistivity of Various Classes of Materials

Material	Surface Resistivity (Ω/Square)
Conductive	0 to 10^5
Static dissipative	10^5 to 10^9
Antistatic[a]	10^9 to 10^{14}
Insulative[a]	$>10^{14}$

[a] 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.

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 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.

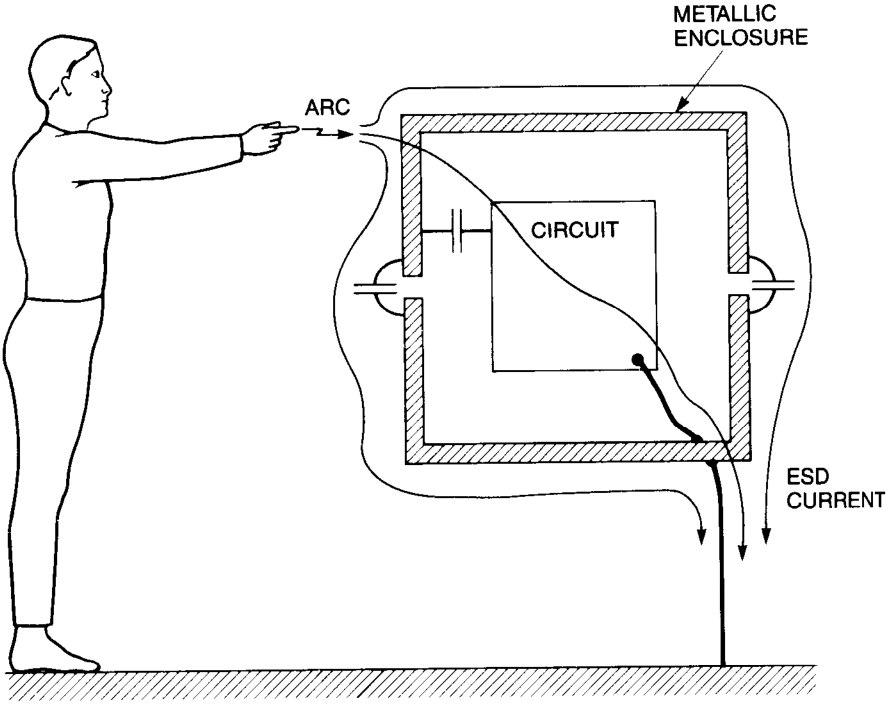


Figure 12-7. *Electrostatic discharge to a metallic enclosure that does not have electrical contact across the seams.*

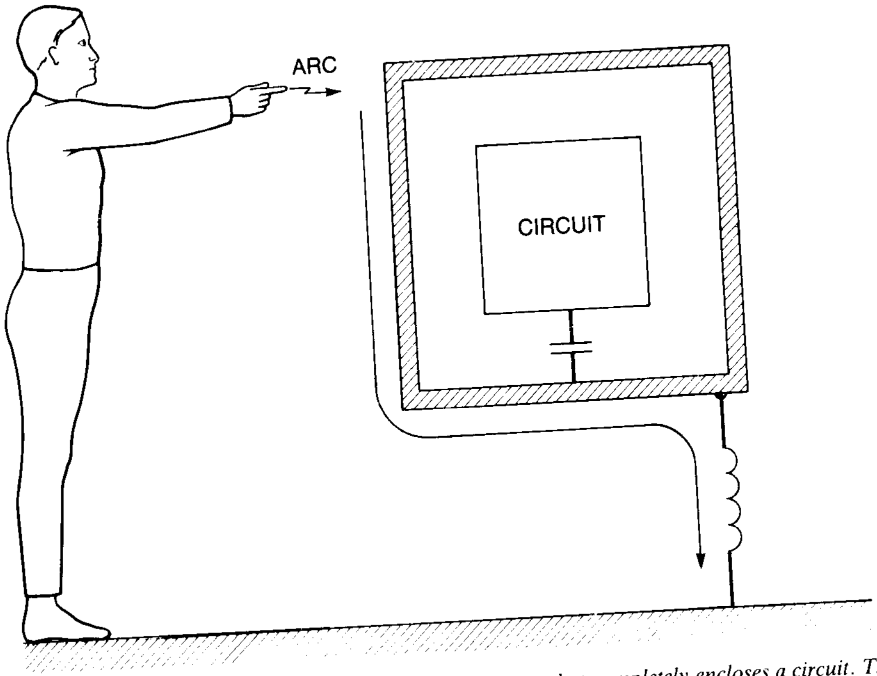


Figure 12-8. *Electrostatic discharge to a metallic enclosure that completely encloses a circuit. The circuit has no external connections.*

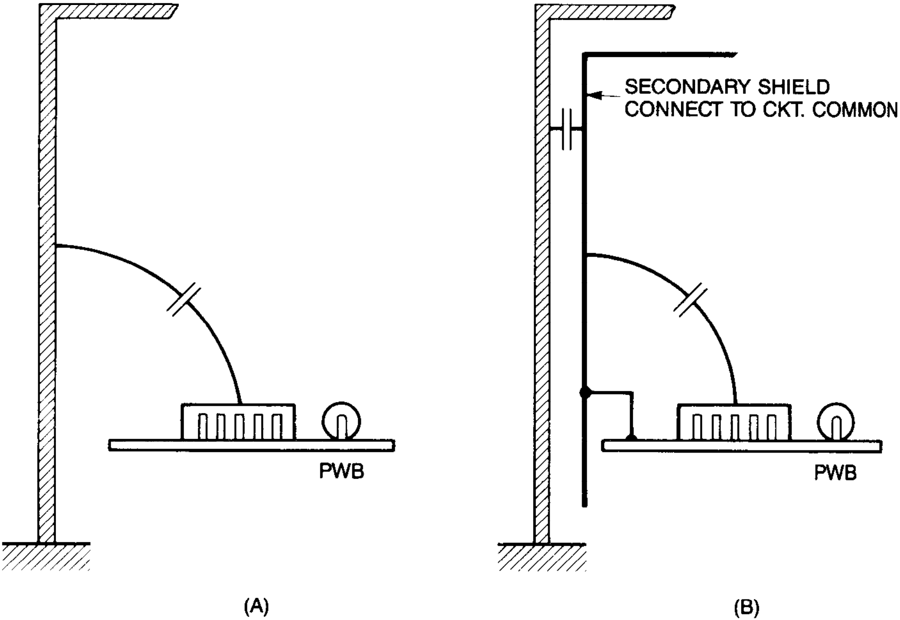


Figure 12-9. *Capacitive coupling between a metallic enclosure and a circuit (A). A secondary shield (B) can be used to block the capacitive coupling between a circuit and a metallic enclosure.*

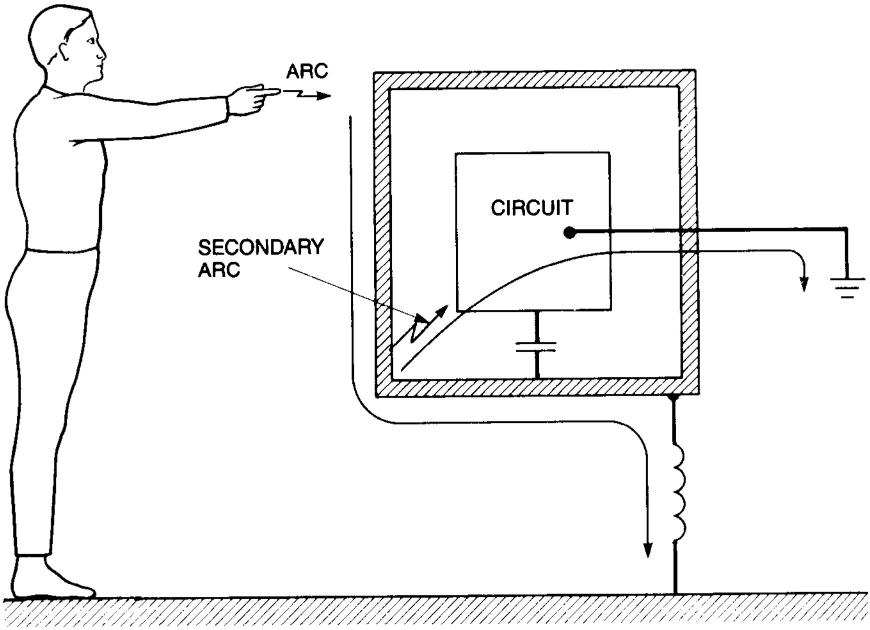


Figure 12-10. *Electrostatic discharge to a metallic enclosure containing a circuit with an external ground connection.*

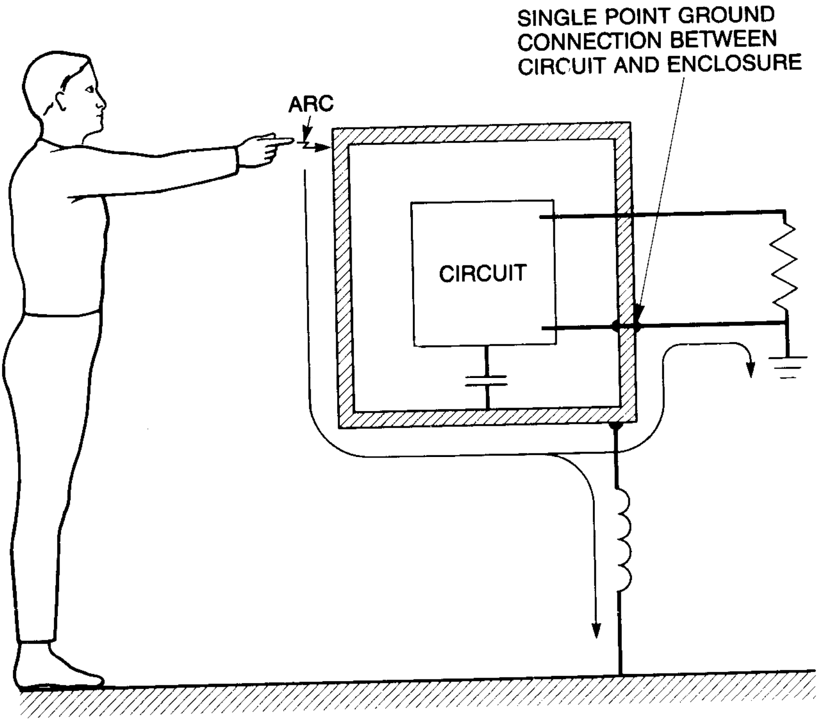


Figure 12-11. *Electrostatic discharge to a metallic enclosure containing a circuit with a single-point connection between the enclosure and the circuit.*

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.

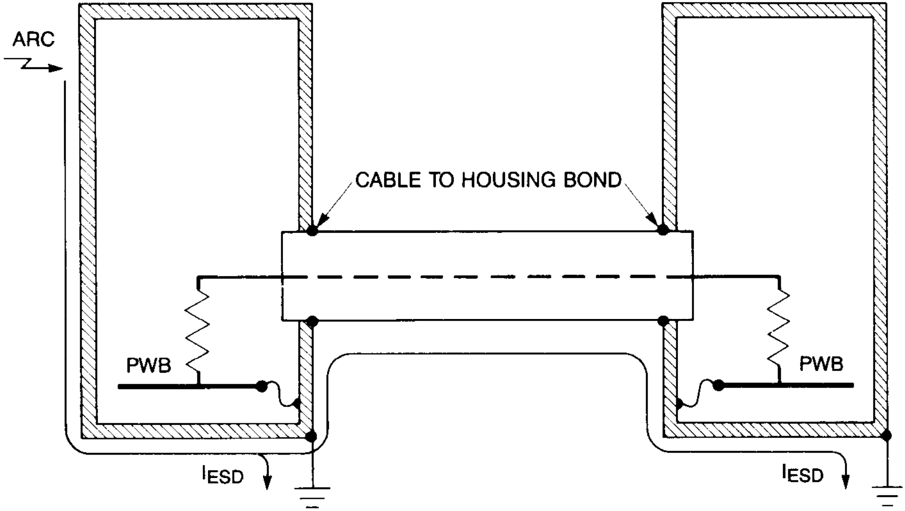


Figure 12-12. *Two enclosures connected with a shielded cable, in an attempt to turn the two into one continuous enclosure.*

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

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

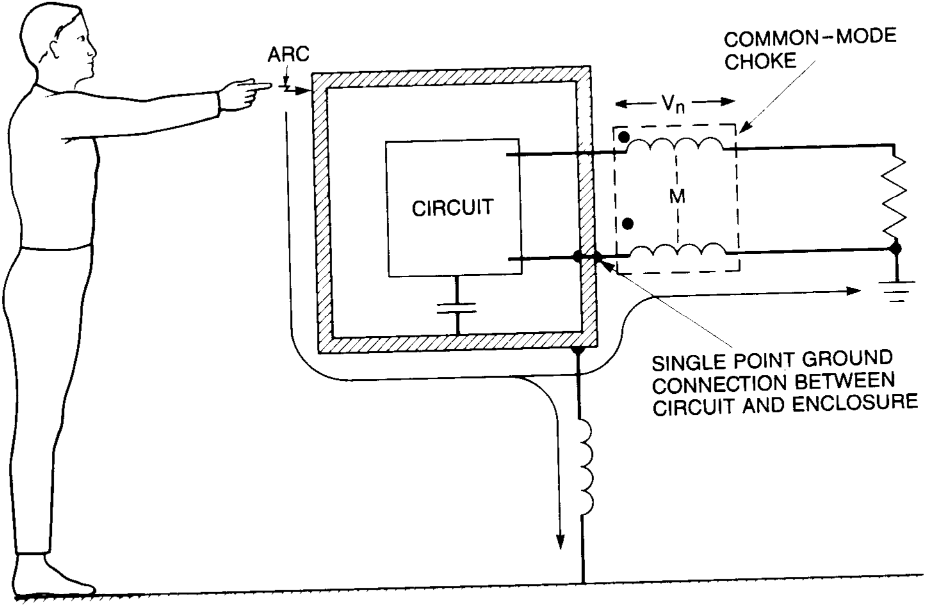


Figure 12-13. *A common-mode choke can be used on the interface cable to drop the ESD-induced noise voltage* (V_N).

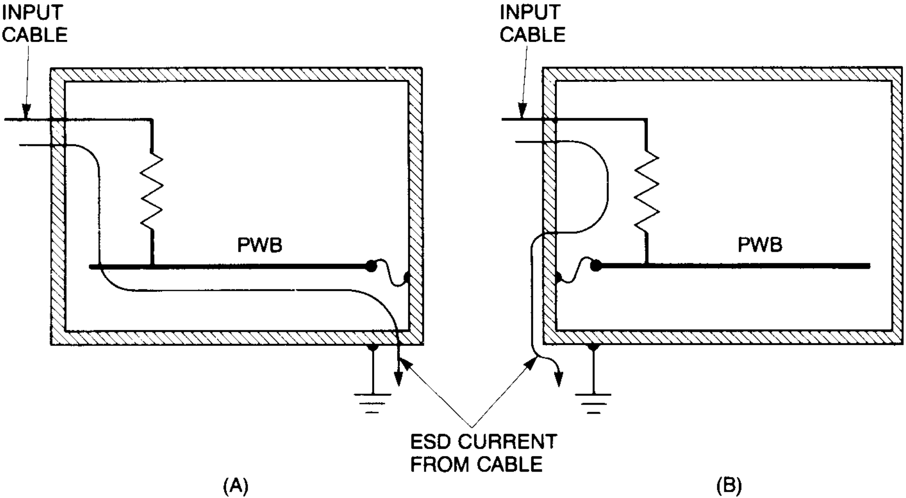


Figure 12-14. *Improper connection between PWB and chassis (A) forces ESD currents on cables to flow through the PWB. Proper connection (B) diverts ESD current from PWB.*

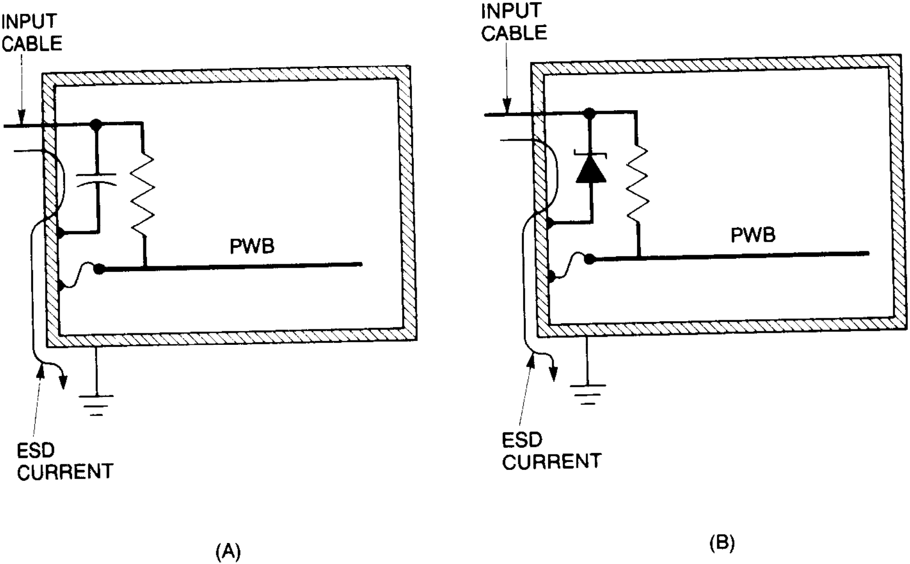


Figure 12-15. *A capacitor (A) or surge diode (B) can be used to bypass the ESD current from the cable to ground.*

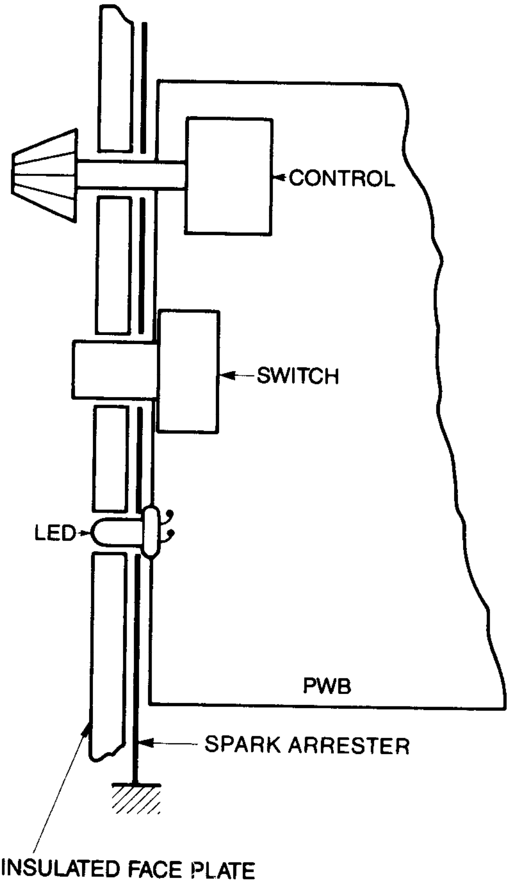


Figure 12-16. *Metallic spark arrestor placed behind an insulated face plate to divert the ESD current to ground.*

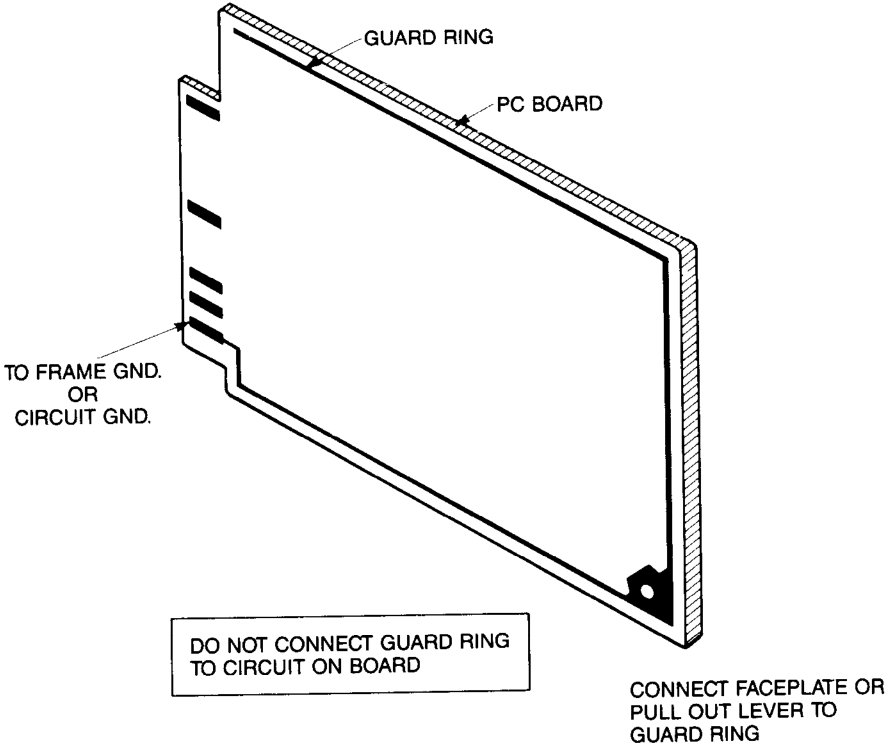


Figure 12-17. *Guard ring on PWB used to protect board from ESD damage when board is handled and subsequently plugged into the system.*

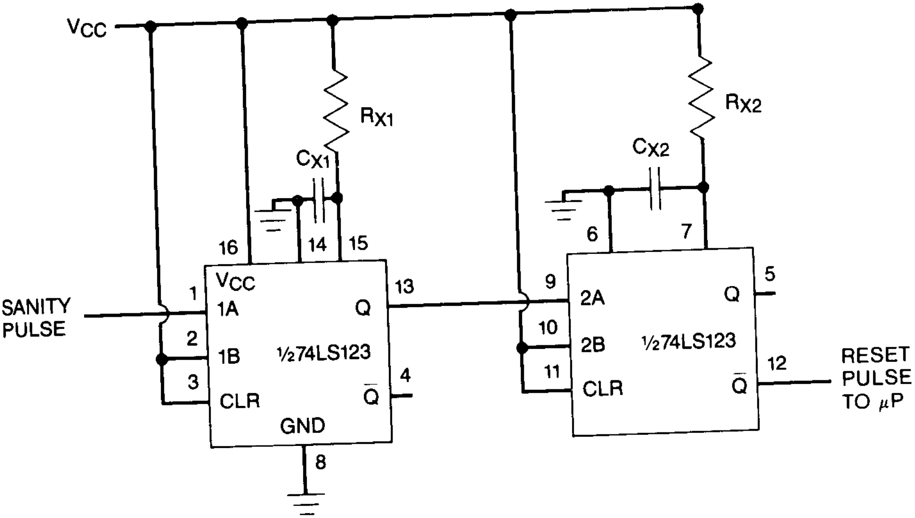


Figure 12-18. *A hardware sanity timer made from a dual retriggerable multivibrator.*

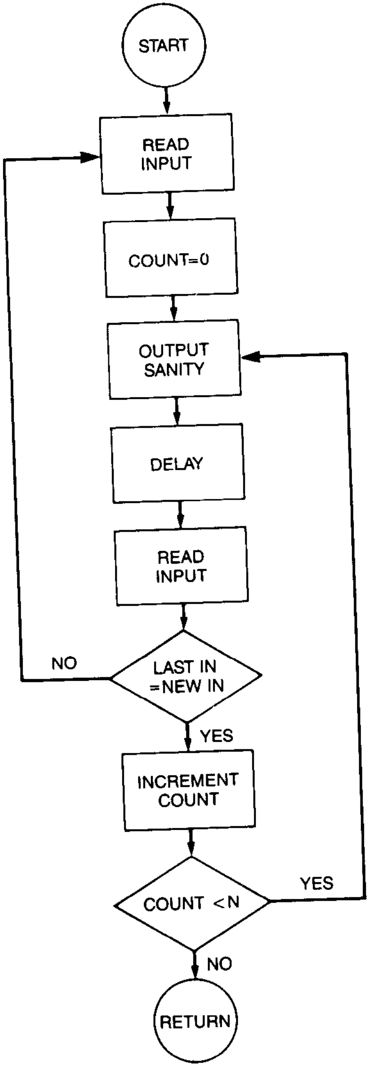


Figure 12-19. *Software subroutine for filtering input data and outputting a sanity pulse.*

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 (Mardiguian, 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.

- 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, not to circuit 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.
- 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.
- Input errors can be minimized by software filtering.
- Hardening a system against ESD will also make it immune to most other sources of radio-frequency interference.