CABLES AND CONNECTORS

INTRODUCTION

The electrical and mechanical designer spends much of his interference control efforts in the design of components without due regard to interconnecting cables and harnesses. The mechanical engineer designs the case or chassis seams with RF gasketing material, controls the machining and finishes of mating surfaces, covers holes with screening or honeycomb cells, and applies other mechanical controls. The electrical engineer specifies the power line filters, designs the grounding system, adds the transient noise suppressors and protectors, specifies the internal harnessing configuration, selects the connectors, and provides other electrical controls. However, unless the component is designed to operate independently from all other components or equipment, such as T.V., oscilloscope, radio, etc., the harness and cable configuration is delegated to subsystem and system engineers. Thus, the component design engineers only do half of the job.

Cable and harness configurations are critical in the component design to reduce the propagation of electrical noise (EMI) and its effects. The best electronic box, shielded enclosure or shielded room can always be compromised by poorly designed interconnecting cables. Cables provide a convenient path by which electrical noise is conducted out of the enclosure and then radiates or couples to adjacent wiring and equipment. The reverse process also occurs with external noise pick-up on cables being conducted into a well-shielded container. The filtering of the interconnecting lines does not always solve the problem. Lines which conduct clock pulses, digital signals, video signals, etc., cannot tolerate filters which affect the signals. These signals also appear as noise to other circuits when coupling to other lines occurs.

Systems engineers treat interconnecting harnessing very seriously in respect to noise control and electromagnetic compatibility. They realize that crosstalk is a real everyday problem, and intentional system radiation can have backdoor effects if it is allowed to get into system wiring. This problem is not limited to military applications or systems. It can occur in the home, industrial plant, in office buildings, scientific centers, hospitals, automobiles, aircraft, as well as electronic laboratories. A car radio can be jammed by electrical noise radiation from unsuppressed truck ignition systems. Noise from the fluorescent lights, razor, vacuum cleaner, etc., interferes with T.V. and radio reception. Computers are extremely vulnerable to the coupling of transients generated by air-conditioners or time-clocks. In the hospital, patient monitors are disturbed by the magnetic fields emitted by power lines, heating blankets and other electronic equipment. Electric typewriters and other office machines can make communications nearly impossible. Electronic fly killers have been known to affect aircraft navigational equipment. In all of these examples, the method of radiation and pick-up of the electrical noise is through cables. The primary means of protecting electro-explosive devices is through the design of its cables.

CABLE SEPARATION

The coupling of signals and noise between wires and cables is a function of the distance between cables. Thus, it is most advantageous to categorize the various types of cable signals and to provide maximum separation between them. This is not always easy to accomplish, especially on space vehicles, or in complex electronic facilities where there are numerous cables and harness restrained by limited cable troughs. It also becomes a problem when wires of different categories share the same cable connector. However, an attempt should be made to provide whatever separation is practical. The following categories are illustrative only, and are usually modified to match the partial line voltages, signal levels and frequencies:

a. Category P, Power:

1. 115 volts and 240 volts single phase and three phase to motors, transformers, blowers, etc.
2. Control wiring which includes relay logic, stepping switches, indicator light cricuits (incandescent), etc.
3. RF power, primarily transmitter outputs.

b. Category S, Sensitive Wiring:

This category includes moderately susceptible circuitry which is easily protected such as limited bandwidth audio amplifiers, input medium-level wide bandwidth video lines, properly designed digital computer input circuitry, clean dc power, etc.

c. Category VS, Susceptible Wiring:

This includes very sensitive circuitry such as a servo null circuit working to a null level of less than 100 microvolts, electro-explosive devices, high-impedance, low-level high-accuracy sensor circuitry (such as 10 millivolt, 10,000 ohm, and 0.5 percent accuracy), and antenna input circuitry.

As an aid, these three categories of wires might have an identifying color for ease in wiring and identification. The three categories should be run separately via different routing and should cross at right angles.

COUPLING MECHANISM

The physical model for analyzing the coupling between cables is that two or more cables run parallel. The coupling may be expressed in terms of the transfer impedance. The transfer impedance can be defined as the ratio of the voltage appearing between the conductors of the second cable to the current applied at the first. At low frequencies, i.e., those frequencies for which the total length of one is short compared to the wavelength (these are defined as those cables shorter than one-sixteenth wavelength), the current and voltage along the cable may be considered to be constant; therefore, it does not matter at which end of the cable the current or voltage is measured. At higher frequencies, standing waves on the cables must be taken into account if the cables are not terminated in their characteristic impedances.

Transfer Impedance

The transfer impedance is clearly dependent upon the impedances terminating between the source and the susceptible cable. It will depend upon both magnetic and capacitive coupling effects. At low frequencies capacitive coupling is easily prevented by placing one or both of the cables in metallic shields. If the concern is with individual sensors in a cable, this shielding will not be possible, and both magnetic and capacitive coupling will be significant.

Magnetic Coupling

Magnetic coupling is most noticeable as a contributor to interference when the cables are terminated with low impedances at each end. Interference voltages are induced into a wire by flux linkages. The source of interference will be a generator of magnetic flux which may be a relay coil, transformer, solenoid, or just another current-carrying wire. The voltage induced in a loop by an adjacent wire of infinite length carrying current as illustrated in Figure 1 will be

$$E = (3.19 \times 10^{-8})\, fLI \ln \frac{r_2}{r_1}$$

where

f = frequency, Hertz
L = length, inches
I = current, amperes
E = induced voltage, volts
r_1 and r_2 = loop distance, inches

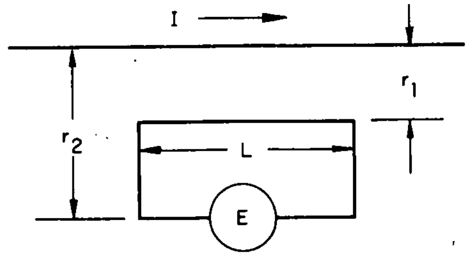


Figure 1 Voltage Induced in a Loop

If the susceptible loop is at an angle to the interference source, the following holds true. Figure 2 illustrates a source loop coupled to a sensitive wire loop.

$$E = (1.595 \times 10^{-8})\, fLI \left[\ln - \left(\frac{R_1^2 + W^2 + 2R_1 W \cos\theta}{R_1^2 + W^2 - 2R_1 W \cos\theta}\right) - \ln \left(\frac{R_2^2 + W^2 + 2R_2 \cos\phi}{R_2^2 + W^2 - 2R_2 \cos\phi}\right)\right]$$

The induced voltage increases with an increase in frequency, source current, and length of closed loop. The induced voltage also increases with effective area enclosed by the pick-up loop and will affect circuits by driving current through the impedances in the pick-up loop and its loads. For low frequencies, the impedance of the pick-up loop will consist primarily of wire resistance, and maximum power will be delivered to a load of low resistance. It should be assumed that the source circuit is a low impedance circuit since the most significant interference will result from a high current source. The voltage delivered to the circuits attached to the pick-up loops will rise to half the induced voltage as the load impedance in the pick-up loops rises to match the driving impedance due to the coupling. As the load impedance rises from this point, the voltage at the circuit loads will rise to the full induced voltage as a maximum.

Capacitive Coupling

In long cable runs, an appreciable capacitance will most likely exist between adjacent wires and from each wire to ground or shield and capacitance will exist at connectors and associated wiring. The voltage induced into one wire from an adjacent wire is a function of these capacities. Figure 3 illustrates one model for the capacitive coupling in a cable. The interfering voltage, (E_o) couples through stray capacity (C_c) to produce a voltage (E_x) on the adjacent cable. The interfering cable and the adjacent cable have stray capacities to ground (C_a and C_b). Each cable has its system loads (Z_1, Z_2, Z_3, and Z_4) across which the stray capacities appear. If cable load impedances are high, the frequency spectra of voltages (E_o) and (E_x) may be affected by (C_a) and (C_b). The voltage division ratio will be

$$\frac{E_x}{E_o} = \frac{Z_x Z_b / (Z_x + Z_b)}{Z_c + Z_x Z_b / (Z_x + Z_b)}$$

If Z_x is a high resistance load

$$\frac{E_x}{E_o} = \frac{C_c}{C_c + C_b} \sqrt{\frac{R_x^2}{R_x^2 + [\frac{1}{2}\pi f(C_c + C_b)]^2}}$$

At high frequencies (rf), any open-ended wire should be given careful attention to determine if it is a pick-up point for high frequency excitation. Since small stray capacities provide effective coupling to a high impedance point, wires can frequently be excited when they are attached to vacant connector pins or open switch contacts. At a quarter wavelength distance, such open wires will be carrying maximum current and can readily couple into other wiring or circuits by the fields generated. An open wire will represent an effective antenna in the presence of electromagnetic fields. High radio frequencies are readily coupled into power wiring either magnetically or electrically, depending upon the standing wave which may be excited in the power wiring at the coupling point.

Figure 4 illustrates the frequency versus voltage coupling in adjacent wires and the function of their separation. Figure 5 shows the typical capacitance which exists for various configurations of shielded AN wires.

Not all connectors are designed to preclude the entry of RF energy. Each connector surface represents an impedance discontinuity of the cable shield. Even though there is mechanical contact with the shield through the outer mating section of the connector, a good RF connection is not assured. Radio frequency energy could enter at this point and cause a hazardous situation. A good connector is one in which the shielding effectiveness of the mated connector equals or exceeds that of an equal length of the cable utilized in the circuit. If the effectiveness of cable shields is to be maintained, the cable shield must be properly terminated. In an otherwise adequately shielded enclosure, RF currents that are conducted along the shields will be coupled to the system wiring from the point of improper cable termination.

In a properly terminated shield, such as when a Glenair backshell adaptor is used, the entire periphery of the shield is grounded to a low impedance reference, minimizing any RF potentials at the service of the termination. The use of epoxy or other synthetic conducting material has been found to be unacceptable for bonding in this situation.

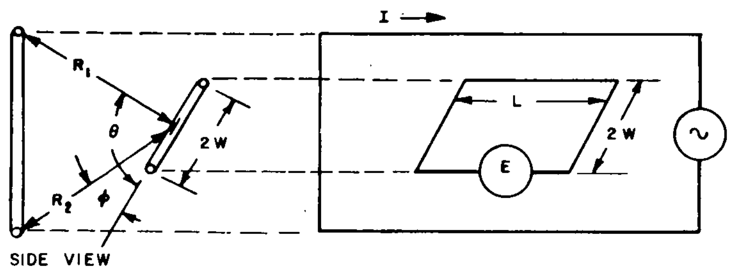


Figure 2. Susceptible Loop at an Angle

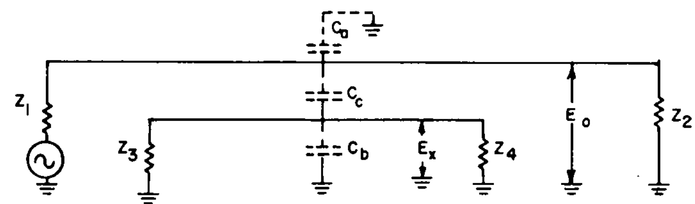


Figure 3: Capacitance Coupling in a Cable

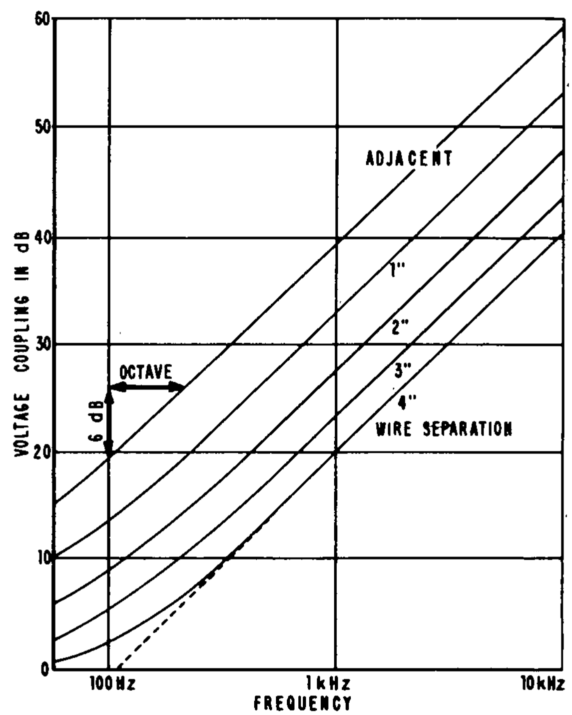
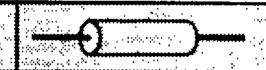
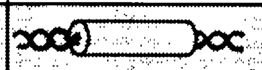
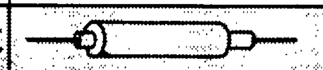


Figure 4: Frequency Versus Voltage Coupling in Wires.

TYPE	ONE WIRE SHIELDED				TWO WIRE SHIELDED				THREE WIRE SHIELDED		ONE WIRE DOUBLE SHIELDED	
CONFIGURATION												
WIRE SIZE	16	18	20	22	16	18	20	22	20	22	22	22
CONDUCTOR TO SHIELD pf/ft	89	91	74	98	68 (EITHER CONDUCTOR TO SHIELD)	65	64	62.5	60 (ANY CONDUCTOR TO SHIELD)	52	98 (CONDUCTOR TO INNER SHIELD)	340 (INNER SHIELD TO OUTER SHIELD)
CONDUCTOR TO CONDUCTOR pf/ft					42	39.5	38	36.5	36	30		

Capacitance of Various Shielded AN Wires

REFERENCE MATERIAL

When you have cabling problems, your best bet is to call the technical representatives of the advertisers in *ITEM* or others listed in the Sales Office Directory. If you want depth in the subject, the IEEE Transactions on Electromagnetic Compatibility provides an excellent source of information. The following papers appear in these *Transactions*, as noted:

1. "Shielding Tests for Cables and Small Enclosures in the 1 to 10 GHz Range"–W. Jarva–February 1970.
2. "Magnetic Fields of Twisted-Wire Pairs"–S. Shenfeld–November 1969.
3. "Effects of Partial Shields on Transmission Lines at Low Frequencies"–N. Farhot, Y. Loh, & R. Showers–March 1968.
4. "Magnetic Field Pick-up by Flexible Braid Coaxial Cables" –J. Bridges and R. Zalewski–March 1968.
5. "Measurement of RF Leakage in Multipin Electrical Connectors"–F. Schor–March 1968.
6. "Coupling Between Open and Shielded Wire Lines Over a Ground Plane"–R. Mohr–September 1967.
7. "EMC of High Density Wiring Installations by Design or Retrofit"–W. D. McKerchar–March 1965.
8. "Coupling Between Lines at High Frequencies"–R. J. Mohr–December 1967.
9. "Analysis of Cable-Coupled Interference"–Greenstein & Tobin–March 1963.
10. "Leakage of EMI Along Stationary Conductors Passing Through Conducting Walls"–Lombardine & Goldhirsh–March 1963.
11. "Wiring of Data Systems for Minimum Noise"–J. V. White–March 1963.
12. "Predicting Magnetic Fields From a Twisted Pair Cable"–Moser & Spencer–September 1968.
13. "Anti-Interference Wires, Cables and Filters"–F. Mayer–September 1966.
14. "Shield Grounding Effectiveness in Interference Reduction in the 50 Hz to 15 KHz Frequency Region"–McDonald & Taylor–March 1966.
15. "Modeling of Fields Produced by Currents on Power Supply Wiring"–R. M. Showers–November 1971.
16. "A Model for Currents and Voltages Induced Within Long Transmission Cables by an Electromagnetic Wave"–Bates & Hawley–November 1971.
17. "Crosstalk on Cables: A Communication Theoretic Approach"–R. L. Swarts–May 1972.
18. "Transmission Line Coupled to a Cylinder in an Incident Field"–King & Harrison–August 1972.
19. "Excitation of a Coaxial Line Through a Transverse Slot"–Harrison & King–November, 1972.
20. "Calculation of Magnetic Fields due to Line Currents"–S. Sabaroff–May, 1973
21. "Response of a Terminated Transmission Line Excited by a Plane Wave Field for Arbitrary Angles of Incidence"–C.W. Harrison & C.D. Taylor–Aug. 1973
22. "On the Exertation of a Coaxial Line by an Incident Field Propagating Through a Small Aperture in the Sheath"–C.W. Harrison & C.D. Taylor–Aug. 1973
23. "Terminal Response of Braided-Shield Cables to External Monchromatic Electromagnetic Fields - S. Frankel - Feb. 1974
24. "Cable Shielding Effectiveness Testing" - E. D. Knowles & L. W. Olsen - Feb. 1974

1968 IEEE EMC Symposium Record

- "Internal Voltages and Currents in Solid Shielded Cables"–Vance & Nanevicz
- "Common Mode Coupling Matrices"–T. H. Herring
- "Coupling Between Open Wires Over a Ground Plane"–R. Mohr
- "Penetration of Coaxial Cables by Transient Fields"–Miller and Torelios.

1967 IEEE EMC Symposium Record

- "RFI Shielding with Conductive Pressure-Sensitive Adhesive Tapes"–Olyphant & Dahlen
- "Resonance Properties of the Shield of a Coaxial Cable
- Over a Ground Plane"–DeMitt, Loh & Showers

1970 IEEE EMC Symposium Record

- "Specifications for Flexible Conduit for EMI Shielding"–W. J. Prysner.

1971 IEEE EMC Symposium Record

- "Measuring Connector Shielding Effectiveness During Vibration"–Knowles & Brossier
- "Cable Shield Effectiveness Testing"–Knowles & Olson
- "Shielding of Cylindrical Tubes at Low Frequencies"–Johnson & Shenfeld
- "The Measurement of Coaxial Cable Immunity to an Electromagnetic Field in the VHF Range"–E. Nano

1973 IEEE EMC Symposium Record

- "Coupling of Transient Radiated Fields into Lines"–R.J. Mohr
- "Interwire Coupling of Fast Risetime Signals"–C.E. Avio–C. Torinese
- "Use of Magnetic Materials for Improvement of Screening Properties of Different Types of Cables"–L. Halme, J. Annanpalo

1974 IEEE EMC Symposium Record

- "Sensitivity of Multiconductor Cable Coupling to Parameter Variations" - C. R. Paul
- "Electromagnetic Induced Signals on Conduit Protected Cables" - D. J. Leverenz, J. T. Verdeyen, W. Croisant

ORDNANCE SHIELDING

Firing Circuit

The use of shielding to protect the EED and firing circuit from stray voltage is practical engineering. The weapon or device which uses the EEI to ignite solid propellants or other explosive materials and which requires external wiring (leg wires or umbilical cables) for the firing circuit presents the greatest problem. The leg wires or umbilical cables of the firing circuits must be completely shielded to prevent transmission of RF energy to the EED. The leg wires themselves, which connect the EED to the firing switch and power source should represent a lossy transmission line to radio frequencies, preferably being fabricated from either parallel or twisted-pair wires with insulation of high RF loss characteristics. The practice of using a shunt external to the EED to decrease the sensitivity is not a satisfactory solution of the problem. The shunt will offer fairly good protection at low frequencies but at high frequencies it may actually assist the ignition process. This is because the physical distance between the EED and the shunt may be considerable in terms of radar half-wavelength (or multiples thereof.) If this is the case, the shunt no longer acts as a "short." When a shunt is placed across the leg wires, it may form a virtual transmission line or resonant circuit. As a transmission line, the shunt will have negligible effect on the RF current required to ignite the EED, but as a resonant circuit, it will favor ignition of the EED. Figure 5 presents some basic firing circuit diagrams and the desirable or undesirable features of each concept. Another approach is to install suitable filters in the firing circuit to attenuate induced RF currents. Since it is not entirely predictable what RF frequencies the EED will be exposed to during combat and tactical operations, obviously this is only a partial solution. Another approach is to place the entire firing circuit inside a weapon, missile, or aircraft and construct the outer skin of the weapon/missile/aircraft so that it affords complete shielding. This method affords adequate protection but has limited applications. A potential hazard not necessarily concerned with shielding is shown in Figure 6. The arrangement of the elements within the EED circuit is thus an important safety design consideration, and is not to be overlooked.

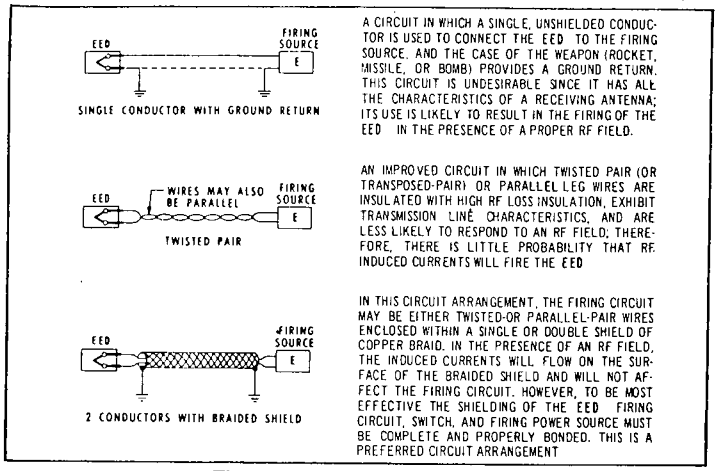


Figure 5: Basic Firing Circuits

Electromagnetic Radiation Hazards

Concern over electromagnetic radiation hazards to electroexplosive devices (or EEDs) arises from the fact that electrical leads to an EED can, under certain conditions, act as an antenna. There have been a few incidents when leads to an EED have extracted sufficient energy from the electromagnetic field environment to cause inadvertant detonation. Under those conditions, at any frequency and in any condition and orientation of the antenna (leadwire), some finite voltage will appear across the bridgewire with a temperature rise in the wire resulting. In most cases this voltage is so small as to be immeasurable. However, in some particular conditions the current induced in the bridgewire will be sufficient to cause premature initiation, dudding, or will affect the firing characteristics in some manner.

Most military and range directives on the subject of EED protection highly recommend (if not demand) that certain general design precautions be taken to defeat the favorable antenna characteristics of the wiring. Design all electrically initiated aircraft weapon systems and electro-initiated explosive devices that require protection against environmental electromagnetic radiation, to meet the requirements of MIL-STD-1512. Waivers to these requirements should be approved by AFISC/SEOE. Design to keep firing leads; isolate firing leads from other circuits; shield firing leads; use only balanced lines; and minimize RF leaks in the skin of the vehicle and other potential RF inputs such as umbilicals. Though universally accepted throughout industry as sound general precautions, they will not provide protection necessary, especially at the higher frequencies so additional precautions may be necessary.

Whenever there is doubt concerning the RF sensitivity of a squib, especially in a given circuit configuration, tests should be conducted by qualified experts in the munitions and radar/radio fields. Intensity measurements and careful analysis of the circuit and the EED characteristics are required to properly assess the circuit hazard potential. The subject of electromagnetic compatibility is covered in DH 1-4. System requirements are contained in DN 4A4.

EED Sensitivity

The present safe distance criteria used by the Air Force assumes a "worst-case" situation which is based on the most sensitive EEDs presently in the inventory, unshielded, and presenting the most effective RF reception characteristics. These criteria are conservatively established to protect those ordnance items that do not conform to the present certification of "one amp-one watt" EED. This certification is to provide safer devices by making them less sensitive to extraneous electrical inputs. The device popularly known as the "one amp-one watt" EED means that the device can pass one ampere and dissipates one watt continuously without dudding or operating. Generally, this insensitivity is attained by providing a heat flow pathway from the bridge element (i.e., heat-conducting metal-oxident mixes), or by use of relatively heat-insensitive primer mixes, or by the use of large diameter bridgewire to reduce the heat flux density out of the bridge.

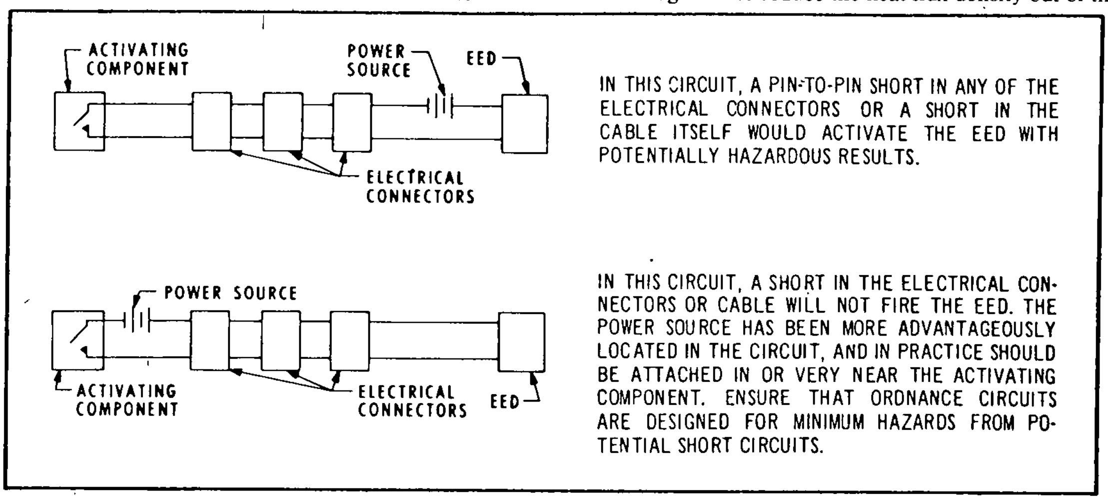


Figure 6: Short Circuit Hazards