

IEEE Guide on Electrostatic Discharge (ESD): Characterization of the ESD Environment

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IEEE Guide on Electrostatic Discharge (ESD): Characterization of the ESD Environment

Sponsor
**Surge-Protective Devices Committee
of the
IEEE Power Engineering Society**

Approved March 19, 1992
IEEE Standards Board

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Abstract: This guide describes the electromagnetic threat posed to electronic equipment and subassemblies by actual Electrostatic Discharge (ESD) events from humans and mobile furnishings. This guide organizes existing data on the subject of ESD in order to characterize the ESD surge environment. This guide is not an ESD test standard. It is intended to be a resource for equipment designers, and for preparers and users of ESD test standards. The manufacturing, handling, packaging, and transportation of individual electronic components, including integrated circuits, are not discussed, and this guide does not deal with mobile items such as automobiles, aircraft, or other masses of comparable size.

Keywords: electromagnetic, electrostatic discharge, ESD, surges

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Foreword

(This foreword is not a part of IEEE Std C62.47-1992, IEEE Guide for Electrostatic Discharge (ESD): Characterization of the ESD Environment.)

An electrostatic discharge (ESD) event can cause equipment malfunction as well as physical damage. Equipment malfunction may include corruption of data and equipment lock-ups. Physical damage may include equipment damage and even loss of life.

In order to achieve meaningful ESD immunity, the design of an entire system must be considered, both for direct discharge and for fields. Various design tools are available to assist in increasing the ESD immunity of electronic equipment. The utility of these tools is limited, however, if the character of the ESD threat is not understood.

There are standards for simulating the ESD environment at the equipment level. They have been published by several organizations, including IEC and ECMA; others are in preparation, including one by ASC C63. However, much has been learned about ESD since early versions of some of these standards were published. In addition, all of these standards are exclusively test standards; repeatability has been a major goal, sometimes at the expense of realism. Therefore, these standards are not necessarily fully accurate sources of information regarding the ESD threat itself; presentation of such information is typically not their purpose.

To date, no other organization has written a guide that describes the characteristics of the real-world ESD event itself. This guide has been written to fill that void. *This guide is not an ESD test standard.* Rather, it is intended to be a resource for equipment designers, and for preparers and users of ESD test standards. This guide will allow all those who are responsible for ESD immunity to judge the relative realism of proposed ESD tests by comparing them to the real-world ESD events described.

The reader of this guide is encouraged to use an appropriate test standard to define actual ESD immunity tests for equipment.

At the time this guide was completed, the working group on ESD had the following membership:

Warren Boxleitner, *Chair*

Francis Drake
Peter A. Goodwin
Phil Jedlicka

Ray D. Jones
Mark T. Ma
Edward H. Marrow
Bill Rhoades

Louis Shulman
Dennis Symanski
Arthur W. Woltman

Other individuals who have contributed significant review and comments are:

G. J. Bagnall

J. E. Brunssen
Peter Richman*

Kevin Smith

*Initiated working group and served as chair until 1989.

At the time that it balloted and approved this standard for submission to the IEEE Standards Board, the Surge-Protective Devices Committee had the following membership:

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D. C. Dawson
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P. A. Goodwin

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J. L. Koepfinger
W. A. Maguire
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Figs 21, 22, 24, and 25 were taken from Weil, G., "Making Accurate and Repeatable Measurements of the ESD Current Waveform in the Regime of 1 GHz and Above," in *Proceedings of the 8th EMC Symposium*, pp. 355–360, 1989.

Figs B10, B11, and B12 were taken from Daout, B., Ryser, H., Germond A., and Zweijacker, P., "The Correlation of Rising Slope and Speed of Approach in ESD Tests," in *Proceedings of the 7th EMC Symposium on EMC*, pp. 461–466, 1987.

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IEEE Guide on Electrostatic Discharge (ESD): Characterization of the ESD Environment

1. Scope and Purpose

The purpose of this guide is to describe the electromagnetic threat posed to electronic equipment and subassemblies by actual Electrostatic Discharge (ESD) events from humans and mobile furnishings. This guide organizes existing data on the subject of ESD in order to characterize the ESD surge environment. This guide is not an ESD test standard. An appropriate ESD test standard should be selected for equipment testing ([1], [3], [B1]).¹

The manufacturing, handling, packaging, and transportation of individual electronic components, including integrated circuits, are not discussed, and this guide does not deal with mobile items such as automobiles, aircraft, or other masses of comparable size.

ESD results in a sudden transfer of charge between bodies of differing electrostatic potentials. In this guide, the term ESD includes charge transfer whether or not an arc occurs or is perceived.

ESD phenomena generate electromagnetic fields over a broad range of frequencies, from direct current (dc) to low gigahertz. The term *ESD event* includes not only the discharge current, but also the electromagnetic fields and corona effects before and during a discharge.

In this guide the intruder is often a human, but it may be any object that is moved, such as a chair, an equipment cart, a vacuum cleaner, or the equipment victim itself, whether or not it is in conductive contact with a human. The equipment victim is usually a fabricated electronic equipment or subassembly and is generally, although not necessarily, at local electrostatic ground potential.

The equipment victim may be the receptor to which the discharge takes place from the intruder; less frequently, the equipment victim may be the intruder. Alternatively, the equipment victim may be affected by the electromagnetic fields generated by a discharge between an intruder and a receptor. Receptors and intruders that may not themselves be equipment victims include furniture such as metal chairs, carts, tables and file cabinets, as well as other electronic equipment.

This guide discusses and cites references that describe the ways in which a body builds up charge and the characteristics of discharge currents and fields. Descriptions and references are also given for electrical equivalent circuits to be used in understanding and simulating the discharge current between intruder and receptor masses.

Publications that are specifically referenced in the text of the guide are listed in the Section 3, while Section 9 cites additional publications in both ESD and related areas.

Most of the work that has been published in connection with actual ESD is related to discharges from humans, usually grasping or in association with a metal object. Far less published data exists for discharges from humans without metal objects, and from mobile furnishings, and virtually no data exists for discharges from human torsos or clothing. For this reason, primary emphasis is placed on discharges from humans with associated metal objects, with some additional material relating to ESDs from mobile furnishings. All discharges are assumed to take place in an air environment.

Finally, all of the published time-domain data on which this guide relies were taken using instrumentation with either a 400 MHz or a 1 GHz bandwidth.

¹The numbers in brackets correspond to those of the references in Section 3, and the numbers preceded by the letter "B" in brackets correspond to those of the bibliography in Section 9.

2. Definitions

antistatic. A property of materials that resist triboelectric charging.

approach speed. The rate at which the intruder approaches the receptor.

body/finger ESD. An electrostatic discharge from an intruding human finger or hand. Also called body/finger discharge.

body/metal discharge. See **hand/metal ESD**.

body/metal ESD. See **hand/metal ESD**. *Syn:* body/metal discharge.

brush-by. An electrostatic discharge from the human torso, such as from the hip or shoulder. *Syn:* brush-by ESD, brush-by discharge.

brush-by discharge. See **brush-by**.

brush-by ESD. See **brush-by**.

charge voltage. The voltage difference between the intruder and the receptor just prior to an ESD.

DES. Discharge Electrostatic; an alternative name for ESD.

direct ESD event. An ESD event that takes place between an intruder and a receptor in which the intruder or the receptor, or both, is an equipment victim.

equipment victim. The electronic equipment or subassembly that is subjected to the effects associated with an ESD event. It may be the intruder or receptor, or it may be in proximity to the discharge between the intruder and receptor and therefore subjected to the stress of ESD-related electromagnetic fields.

ESD. Electrostatic Discharge: the sudden transfer of charge between bodies of differing electrostatic potentials.

ESD current wave. The waveform of the discharge current between an intruder and a receptor.

ESD event. An interval that includes the ESD current, electromagnetic fields, and corona effects before and during an ESD.

fast approach. Approach speeds that engender short, subnanosecond risetime ESD current waves. Fast-approach speed depends on the voltage difference between the intruder and receptor, e.g., for rounded electrodes of 8 mm diameter, greater than 0.05 m/s, 1 m/s, and 10 m/s at charge voltages of 4 kV, 8 kV, and 16 kV respectively [13].

furniture ESD. An electrostatic discharge in which the intruder is an inanimate object such as a cart or chair, with or without a human in electrical contact with the object.

hand-to-metal impedance. The impedance between the human hand and the metal object with which it is associated in a hand/metal ESD. The metal object is usually the intruder discharge electrode. Examples of hand-to-metal impedance include resistance and capacitance

between the fingers and a key, between the wrist and a metal watch or bracelet, and between the hand and a screwdriver.

hand/metal discharge. See **hand/metal ESD**.

hand/metal ESD. An electrostatic discharge from an intruding human hand which occurs from an intervening metal object such as a ring, tool, key, etc. *Syn:* hand/metal discharge.

indirect ESD event. An ESD event taking place between an intruder and a receptor in proximity to equipment that is the victim.

initial current pulse. The subnanosecond risetime, and greater than 1 ns to perhaps 3 ns duration pulses that can occur at the start of the current wave from an ESD. Also called initial pulse, initial spike, and fast discharge mode. Its leading edge is the initial slope.

initial slope. The slope, in amperes per nanosecond (A/ns), that occurs at the start of the ESD current wave. *Syn:* rising slope.

intruder. The body that is in motion in an ESD event. The intruder is usually but not necessarily charged relative to its surroundings. It is always at a potential different from that of the receptor.

intruder electrode geometry. The size and shape of that surface of the intruder, termed the intruder electrode, at which the ESD takes place.

main discharge current wave. The relatively long portion of the ESD current wave that follows the initial current pulse, or that occurs by itself when the initial current pulse does not exist. It may be unidirectional or oscillatory; its initial slope may be fast or slow.

multiple ESD event. An ESD event in which more than one discharge occurs. The time interval between successive discharges may be several microseconds to several tens of milliseconds. Related terms include multiple ESD, multiple discharge, and multiple.

normalized peak ESD current. Ratio of the peak current to the charge voltage (e.g., 5A/kV).

normalized rising slope. Ratio of the initial slope to the charge voltage (e.g., 3.75 A/ns/kV).

proximity discharge. See **proximity ESD**.

proximity ESD. See **indirect ESD event**. *Syn:* proximity discharge.

receptor. The body that is at rest in an ESD event. The receptor is usually but not necessarily at the same potential as its surroundings. It is always at a potential different from that of the intruder.

receptor electrode geometry. The size and shape of that surface of the receptor, termed the receptor electrode, at which the ESD takes place.

rising slope. See **initial slope**.

SED. Static Electric Discharge; an alternate name for ESD.

static dissipative. Having a level of resistivity that typically leads to charge dissipation. (See Table 1.)

triboelectric charging. The generation of electrostatic charges when two pieces of material are brought into intimate contact and are then separated. *Syn:* triboelectrification.

triboelectric series. A list of substances in an order of relative positive to negative charging as a result of the triboelectric charging effect. (See Appendix A.)

triboelectrification. See **triboelectric charging**.

3. References

This standard shall be used in conjunction with the following publications:

3.1 Standards Publications

[1] ECMA TR-40, Electrostatic Discharge Immunity Testing of Information Technology Equipment, 1987.²

[2] EIA 571 (March 1991), Environmental Considerations for Telephone Terminals.³

[3] IEC Pub 801-2 (1991), Electromagnetic compatibility for industrial process measurement and control equipment. Part 2: Electrostatic discharge requirements.⁴

[4] MIL-STD 883D, Test Methods and Procedures for Microelectronics.⁵

[5] NEMA, "Environmental Testing for Electronic Controls—Residential Controls," Part DC-33, Draft proposed June 24–25, 1982.

[6] SAE J1113 (Aug. 1987), Electromagnetic Susceptibility Measurement Procedures for Vehicle Components (Except Aircraft).⁶

[7] UL 991-1989, The Standard Test for Safety-Related Controls Employing Solid-State Devices.⁷

3.2 Other References

[8] AT&T Technologies, *Electrostatic Discharge Control Handbook*, Issue 3, 1990.

²ECMA publications are available from ECMA, 114 Rue du Rhone, CH-1204, Genève, Switzerland/Suisse. ECMA publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

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⁵MIL publications are available from the Director, U.S. Navy Publications and Printing Service, Eastern Division, 700 Robbins Avenue, Philadelphia, PA 19111, USA.

⁶SAE publications are available from SAE, Customer Sales, 400 Commonwealth Drive, Warrendale, PA 15096, USA.

⁷UL publications are available from Underwriters Laboratories, Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096, USA.

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4. Principal Methods of Charging Humans and Mobile Objects

Static electrification or charging refers to all processes that produce segregation of positive and negative electrical charges into relatively stationary groupings. This section describes

those processes considered directly relevant to the purposes of this guide. Supplemental information is given in Appendix A.

4.1 Triboelectric Charging. The most common charging mechanism is triboelectric charging. This mechanism involves electron or ion transfer upon contact, due to the frictional localized heating of microscopic contact areas on solid surfaces. The localized microscopic regions of material are melted, allowing increased charge mobility.

Distinctions among various levels of material resistivity are based on surface and volume resistance. Categories with corresponding ranges of surface and volume resistivity are given in Table 1. The electrostatic charge that can be developed between two materials is a function of their relative position in the triboelectric series, and of their resistivity. Those materials in the series that also have a higher resistivity can accumulate significant charge because a longer time is required for charge to bleed off such materials. However, under certain circumstances even conductive materials, such as metals, can be charged (see Table A1).

Table 1
Resistivity Classification for Purposes of Electrostatic Discharge

Classification	Surface Resistivity (Ω per square)	Volume Resistivity (Ω cm)
Conductive	$< 10^5$	$< 10^4$
Static-Dissipative	$10^5 - < 10^{12}$	$10^4 - < 10^{11}$
Nonconductive	$\geq 10^{12}$	$\geq 10^{11}$

4.2 Induction. Induction, or electrostatic induction, is a means by which portions of humans or other items can become differentially charged.

Such charge redistribution takes place on a body when the electrostatic field of a nearby charged object, such as the face of a cathode ray tube, polarizes charges of a nonconductive body or redistributes charges on a conductive body. As a result, even though the person or object as a whole may remain electrically neutral, its charge may be distributed unequally, thereby creating the possibility of an electrostatic discharge from some portion of the person or object.

4.3 Physical Charge Transfer. This type of charging occurs when charged particles are physically transferred to an object that is itself not creating the charge. For example, a person who is pushing an equipment cart, which is accumulating charge due to rolling friction, may be charged by the cart. Also, charging via an ion stream is another example of physical charge transfer.

4.4 Examples of Common Charging Processes

4.4.1 Motion, Walking, and Friction. One of the most common methods of charging is the act of walking. The human body, in the process of walking, builds up electrical charge with respect to its surroundings. Walking on a floor with footwear of an insulating material leads to charge buildup on the underside of the shoe sole by triboelectrification. The charged shoe soles cause charge redistribution on the human body by induction. As each step is taken, this charge redistribution increases. The maximum total electrostatic charge that can accumulate is on the order of microcoulombs, and significant electrostatic potentials can thus be devel-

oped. For example, walking across a synthetic fiber carpet in a relatively dry room (less than about 30% relative humidity) can easily result in an electrostatic potential from several kilovolts to over 10 kV. (See 5.2). Walking across many other floor coverings can also produce an electrostatic charge. In addition, waxing a floor may worsen the situation, thus adding to the electrostatic charge that may be developed. Rolling mobile furnishings, including chairs and carts, can also lead to charge buildup due to contact between the rollers and the floor. Other friction-based charging methods exist. For example, the simple movement of the body within clothing can develop large electrostatic potentials.

4.4.2 Ion-Generation Imbalance. Ionizers are often used to reduce the tendency of materials to build up or store electrostatic charge. However, if the ionizing equipment does not produce both positive and negative ions more-or-less equally, the ion stream may actually charge objects in its path. The electrostatic charging in this situation is not eliminated and may, in fact, be intensified.

4.4.3 Cathode Ray Tubes (CRTs). CRTs are used as display devices and sometimes as input devices (e.g., touch screens) for computer terminals, oscilloscopes, and television sets. They can be sources of charge because they involve a beam of electrons accelerated by a high internal voltage. It is typically the field surrounding the screen that can charge humans and nearby objects, including other portions of the CRT assembly, because charges may be redistributed on objects near, but not touching, the CRT. (See 4.2.) However, if a person or a small mobile furnishing should physically contact the CRT, a portion of the CRT charge may be transferred to the person or object. (See 4.3.)

4.4.4 Additional Triboelectric Charging Methods. Any frictional contact between materials can lead to electrostatic charging of personnel and/or mobile furnishings. The tendency to charge is maximized as the electrical dissimilarity between contacting surfaces is increased, humidity reduced, and kinetics of contact become more violent. For example, driving belts are often significantly charged during their movement, as is adhesive tape when it is removed from a dispenser. Personnel or furnishings in contact with such charged items may therefore have significant charge induced.

5. Charge Accumulation: Characteristics and Variables

The static charge that can be accumulated by an object is influenced not only by the physical characteristics of the object itself, but also by the environment in which the object is located.

5.1 Charge. The electrostatic potential or potential difference that exists between two charged objects, or between a charged and an uncharged object, may be considered to exist between two electrodes of a charged capacitor, where the objects represent the capacitor electrodes. The charge Q , expressed in coulombs, is related to the capacitance and voltage by the equation:

$$Q = CV \quad (\text{Eq 1})$$

where

C = Capacitance (in farads)
 V = Voltage (in volts)

The values of C and V depend upon the composition and geometry of the materials and the environment. Depending upon the exact physical and environmental conditions, the charge

may range from a fraction of a microcoulomb to several microcoulombs. The geometry of the surface of a charged object limits the surface charge density and the electric field intensity associated with it. For a given electrostatic charge on a body, charge density is greater at sharp edges or corners. The corona discharge voltage, approximately 3×10^6 V/m, limits the amount of charge that an object can sustain [12].

Consider the example of a person walking across a carpet and becoming charged to 10 kV. Assuming a body capacitance of 100 pF, the charge the person carries may be calculated as $Q = CV = [100 \times 10^{-12}] [10 \times 10^3] = 1 \mu\text{C}$.

5.2 Electrostatic Potential. The voltage that is developed on both human bodies and on mobile objects, with respect to local electrostatic ground potential, is a strong function of a number of environmental variables. Foremost among them are relative humidity and the materials of floor coverings, clothing, etc. High relative humidity increases the conductivity of many materials and thus permits charge to drain from the object, lowering the maximum achievable electrostatic potential. Conversely, low relative humidity allows an object to achieve a relatively high electrostatic potential. Nonconductive materials will retain a charge almost indefinitely while static-dissipative and conductive materials permit charge to drain off.

The voltage on a human body or on a mobile object can therefore vary widely from one environment to another. It can remain well below 5 kV in controlled humidity situations involving only antistatic or static dissipative materials. It can range from 5 kV to over 10 kV in low humidity environments with synthetic materials.

The general expression relating Q , C , and V , i.e., $Q = CV$, indicates that if the capacitance of a body is reduced, its voltage must increase as long as its charge does not change. This occurs, for example, when a seated person elevates his or her feet, e.g., placing them on a cross-member under a table. The resulting reduction in body capacitance with reference to earth causes a multiplication of the voltage carried just prior to lifting the feet. The voltage multiplication factor can be 1.5 or even higher in extreme cases.

Finally, it has been claimed that charge voltage can be as high as 20 kV to 25 kV when both extremely low humidity environments—below 20% to 30% relative humidity—and nonconductive synthetic materials are involved [11], [25], [33], [34]. An ultimate limit for such extreme environments would be 30 kV to 40 kV, at which voltage levels corona would bleed off charge via rings, watches, and other sharp points on the human body or mobile object [11]. However, more recent work may put some of these extremely high-charge voltages in question; at issue is the inaccuracy of some charge meters when the charged object is as large as the human body.

The minimum voltage necessary for a person to be aware of his or her involvement in an electrostatic discharge is approximately 3000 V. Nevertheless, electrostatic discharges that occur below this threshold of human perception may contain sufficient energy to cause upset or damage to electronic equipment. In fact, the faster initial slopes of current waveforms that result from ESD events at these low voltage levels can make such discharges even more disruptive than ESD events originating at higher charge voltages. (See 7.2.)

5.3 Capacitance. The capacitance of an object with reference to its surroundings is directly proportional to the size of the object and is a function of the proximity and characteristics of the surroundings. The shape or geometry of the object also affects its capacitance. A body with no nearby surroundings still has capacitance to free space. There is typically only a small difference between capacitance to free space and capacitance to objects more than a meter away.

As an example, effective human body capacitance is on the order of 60 pF to 300 pF. The range of variation includes not only size and geometry, but proximity to grounded surfaces or objects and the dielectric constant of the intervening material(s), e.g., air and shoe sole material.

5.4 Energy. The energy stored on a human body or mobile object is a function of its capacitance and its voltage and is determined by the relationship:

$$W = (1/2) CV^2 \quad (\text{Eq 2})$$

where

C = Capacitance (in farads)
 V = Voltage (in volts)
 W = Energy (in joules)

As an example, consider a person walking across a carpet and becoming charged to 10 kV. Assuming a body capacitance of 100 pF, the stored energy would be determined as $W = (1/2)CV^2 = [1/2] [100 \times 10^{-12}] [10 \times 10^3]^2 = 5 \text{ mJ}$.

5.5 Environmental Factors. Variables such as relative humidity; temperature; atmospheric pressure; materials; contaminants; object shapes; and the proximity of the intruder, the receptor, and the equipment victim will control the charge that is developed on the bodies with respect to each other and with respect to local electrostatic ground. Of all these variables, materials and relative humidity are prime factors in determining the relative ease with which objects will become charged to a given voltage.

In addition, the geometry of the object surfaces, as well as object spacings, affect charge density and electric field intensity. All of these factors must be considered when evaluating an electrostatic environment.

6. ESD: Characteristics and Variables

6.1 Intruders, Receptors, and Equipment Victims. The intruder is often a human hand, with or without an associated metal object such as a key, ring, or tool. But it may be any object such as a chair, an equipment cart, a vacuum cleaner, etc.

The receptor is the stationary object that the intruder approaches and to or from which it transfers charge. Often the receptor is at local electrostatic ground potential.

The equipment victim is an electronic device that is often the receptor, but may also be the intruder or an object that is neither the intruder nor the receptor. In this last case, the equipment victim is in close proximity to the ESD event and may be upset or damaged by the electromagnetic fields generated by the discharge between the intruder and the receptor.

When either the intruder or the receptor is an equipment victim, the ESD is termed direct. When the equipment victim is neither the intruder nor the receptor, the ESD is termed indirect.

Fig 1 shows a direct ESD event. The intruder may be human (Figs 2 and 4), inanimate (Fig 8), or a combination of the two (Figs 3, 6, and 7).

Table 2 lists the various kinds of intruders, with the names of the ESD events that result from each.

In the case of a human intruder, the ESD event may be a body/finger ESD that takes place directly from the skin (Fig 2). It may also be a brush-by that takes place from the torso (Fig 4) [12].

In the case of a human in contact with a small metallic object, a body/metal or hand/metal ESD is one that takes place from a metallic object associated with a hand such as a ring, watch, screwdriver, or key (Fig 3). If the human is not in conductive contact with the small metallic object, the source of the ESD charge is only the metallic object (Fig 8).

In the case of a large inanimate intruder, the ESD event is called a furniture ESD and takes place from a specific conductive location on the intruder. Inanimate intruders include equipment carts without a human (Fig 5), with a human (Fig 6), and chairs (Fig 7).

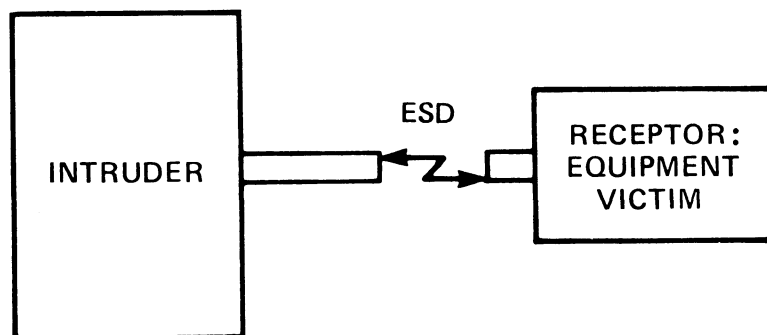


Fig 1
Direct ESD Event

Table 2
ESD Intruders and Resulting ESD

ESD Intruder	Type of Resulting ESD
Human	<i>Body/Finger</i> —from finger without associated metal object
	<i>Brush-By</i> —from hip, torso, or shoulder
Metal object	<i>Hand-Associated</i> —tool or other object not in conductive contact with the hand or body
	<i>Furniture</i> —not in conductive contact with the hand or body
Combination human and metal object	<i>Body/Metal or Hand/Metal</i> —tool, ring, watch, or other metal object in conductive contact with the hand or body
	<i>Furniture and Human</i> —in conductive contact with the hand or body; human seated in chair, pushing cart, or vacuum cleaner; holding and in conductive contact with a tool, etc.

The energy transferred from an intruder to a receptor during an ESD depends on the impedance ratio between them and on the energy dissipated in the arc.

Fig 9 shows an indirect ESD event. The equipment victim is irradiated by fields from three principal sources as a result of the electrostatic discharge: the ESD arc, the intruder mass, and the receptor mass. Additional sources include wires and cables that may be connected to the intruder or to the receptor, and reflections from adjacent objects and walls. All of these fields may affect the equipment victim.

6.2 Conditions Affecting Discharge Current. Just as the environment affects the charging process, it also affects the discharge current. Humidity, atmospheric pressure, and electrode shapes will affect the discharge current wave. In addition, the speed at which the intruder approaches the receptor is important. A rapid approach will result in a discharge current with a faster initial risetime than for a slow approach [13], [26]. (See B1 and B2).

As mentioned in 5.3, the capacitance of both intruder and receptor are dependent on adjacent ground structures. Therefore, the presence of such structures will also impact the discharge current [17].

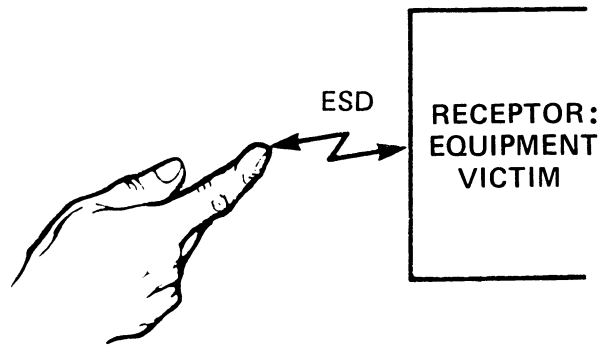


Fig 2
Direct Body/Finger ESD

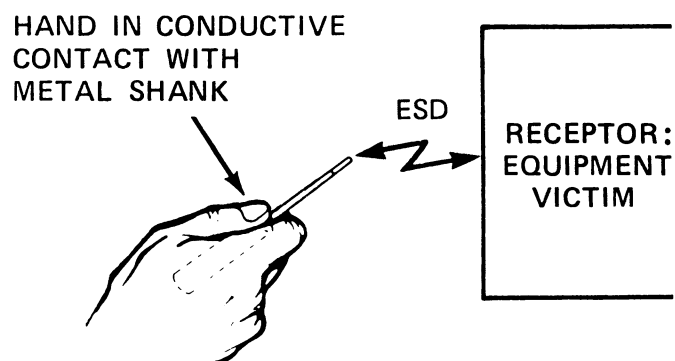


Fig 3
Direct Hand/Metal ESD or Body Metal ESD

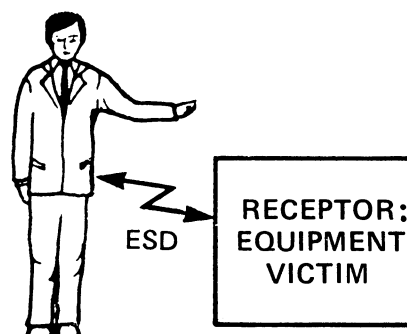


Fig 4
Direct Brush-By ESD