The Protection of Electro-Explosive Devices (EEDs) and Electronics from Electrostatic Discharge (ESD) Hazards

Horace Billon

Explosives Ordnance Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

This report is a review of the various electrostatic discharge (ESD) threats to EEDs and electronics. Methods of overcoming these hazards are outlined. A description is also presented of the methods and standards used for vulnerability testing.

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Executive Summary

This report reviews the electrostatic threats to electro-explosive devices (EEDs) and electronics as well as methods of protection against these threats. The concern expressed over these threats is valid because of the current heavy reliance of the ADF on electro-explosive devices coupled with a growing reliance on microelectronics. AMRL has been tasked with providing advice to the Australian Ordnance Council to assist in formulating a structured electrostatic discharge (ESD) protection policy. This report will not attempt to describe the protection policy but will provide the scientific basis for that policy.

Electrostatic charge generation processes include triboelectrification, induction, conduction and corona. Static discharge in air occurs when the electric field exceeds 3×10^6 V/m. A conductor usually releases a larger quantity of charge when it discharges than an insulator.

Electro-explosive devices (EEDs) are electrically initiated devices designed to produce an explosive output by converting chemical energy into heat. There are various modes of ESD initiation of these devices. ESD can also cause dudding.

ESD poses a grave threat to microelectronics, which are vital to the functioning of modern computer systems. It is likely that this threat will increase with increasing miniaturization. A major problem is "latent damage" to electronics which leaves the device within specification following discharge but which causes the device to degrade with the passage of time.

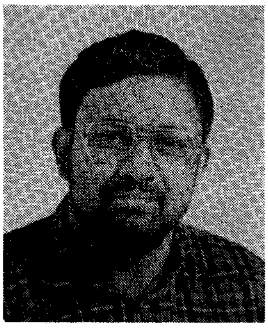
Protection of EEDs and electronics against ESD hazards requires a static control program which is implemented during assembly, storage and handling of devices. Salient features of the program include training of personnel, provision of antistatic/conducting footwear and flooring, earthing of metal objects and restrictions on insulating materials. ESD protection devices for EEDs are also available. Other aspects of a static control program include the use of conductive/static dissipative work surfaces, flooring, exclusion of static generating materials and provision of protective packages for devices. Methods for preventing

the generation or accumulation of electrostatic charge include the use of eliminators and various additives to improve the static properties of insulators.

Simulation of ESD is required to determine the sensitivity of EEDs or electronics to ESD hazard. Many standards specify a network that is inadequate for the simulation of worst-case human discharge. This has been remedied by the new "true ESD" simulator.

The U.S. MIL-I-23659 standard and the Swedish Försvarsstandard FSD 0112 are typical EED test standards. The European IEC 801-2 standard, the U.S. ANSI C63, the European ECMA TR-40 and the U.S. military MIL-STD-883D are typical standards used in the testing of electronics.

Author



Horace Billon
Explosives Ordnance Division

Horace Billon graduated from Royal Melbourne Institute of Technology with a BSc in Applied Physics. He also has a Graduate Diploma in Mathematical Methods from Royal Melbourne Institute of Technology. After working in the RAAF Quality Assurance Laboratories at Highett he joined AMRL in 1986. He works in the Explosives Ordnance Division, and his primary areas of interest are explosives rheology and electrostatics.

Contents

1. Introduction

Modern armed forces, including the Australian Defence Force (ADF), rely increasingly on electro-explosive devices (EEDs). In parallel with this trend is a growing reliance on microelectronic circuits in safety and arming mechanisms, fire-control and initiation systems. Both EEDs and electronics are vulnerable to the damaging effects of electrostatic discharge (ESD), which can either damage sensitive components or induce unintended operation. ESD hazards to dangerous materials have been acknowledged for some time and a number of regulations have been formulated. Current ESD policy suffers from many inadequacies, however, which stem from the fact that it has been produced in an ad-hoc manner. In many cases there has been insufficient scientific direction in developing the existing policy on ESD.

To improve the ability of the ADF to counter ESD problems, AMRL is conducting a task with the aim of advising the Australian Ordnance Council on drafting a structured electrostatic discharge protection policy. An important aspect of this process is a review of scientific literature relevant to the protection of EEDs and electronics from ESD hazards.

A brief outline of the electrostatic charge generation process is provided as background. The various methods of generation are discussed in detail prior to explaining aspects related to EEDs and electronics. An overview of the possible ESD hazards to EEDs and electronics and a brief description of the mechanisms by which these hazards arise are presented in detail. Techniques employed in mitigating these hazards and an outline of the methods and standards for vulnerability testing are also presented.

2. The Generation and Discharge of Static Electricity

2.1 Charge Generation Processes

An understanding of the various charge generation processes is vital to the understanding and suppression of electrostatic hazards. The processes are explained below in approximate order of importance.

2.1.1 Triboelectrification

The generation of electrostatic charge is described in terms of two separate pieces of material or bodies. When two (initially neutral) bodies are in contact with each other a charge transfer occurs from one to the other and an electrical double layer is created at the interface. The two layers are of opposite charge and are only a few molecular diameters apart [1]. On separating the two bodies, charge is often retained on both the surfaces originally in contact. A further consequence of separation is that the capacitance between the two bodies is reduced, causing an increase in the potential difference between the two layers [1, 5, 29]. Harper [33] divides triboelectrification into the two categories of frictional or contact charging. A triboelectric series [44] (Table 1) is a guide to the type and level of charging to be expected when different materials come into contact. Cotton is used as a reference material. Materials listed above cotton tend to become positively charged while those listed below cotton tend to become negatively charged. The triboelectric series is subject to interpretation and shows some variation between different authors [43]. This is largely due to a lack of reproducibility caused by surface conditions and humidity [31].

Table 1: The triboelectric series

Air	
Human Hands	
Asbestos	
Rabbit Fur	
Glass	
Mica	
Human Hair	
Nylon	
Wool	
Fur	
Lead	
Silk	
Aluminum	↑
Paper	INCREASINGLY POSITIVE
Cotton	--
Steel	INCREASINGLY NEGATIVE
Wood	↓
Amber	
Sealing Wax	
Hard Rubber	
Nickel, Copper	
Brass, Silver	
Gold, Platinum	
Sulfur	
Acetate Rayon	
Polyester	
Celluloid	
Orlon	
Saran	
Polyurethane	
Polyethylene	
Polypropylene	
PVC (vinyl)	
KEL-F (Chlorotrifluoroethylene polymer)	
Silicon	
Teflon	

It is frequently observed that the amount of charge transfer can be increased by rubbing two bodies together. It is believed that this is mainly due to an increase in the area of the double layer where rubbing causes more of the surface area to contact and take part in charge transfer. Rubbing can cause secondary effects by raising surface temperatures or altering the nature of the surfaces [1]. In fact it is possible to create separation of charge between two identical surfaces by asymmetric rubbing [2, 33]. Probably the charge transfer is, in most cases, carried by electrons but ion movement may also be involved [1].

A net charge separation usually occurs for a material pair of the form insulator/conductor or insulator/insulator. Charge separation also occurs during metal/metal contact but a back flow of charge [5] takes place during object separation resulting in no net charge transfer. However, separation charging of metals is reported in some circumstances [33]. Elsewhere [43], no significant charge is reported on either material when two conductors are separated.

Accumulation of electrostatic charge can be detected on materials wherever the separation or rubbing process occurs. This can occur in transport, industry or the home. The flow of air across the aileron of an aircraft can cause the generation of high voltages. Likewise the transport of material at high speed through pipes can cause electrostatic effects. This can cause problems for powders or droplets such as with spray painting. Voltages of 50 kV have been observed in powder processes while aircraft may generate voltages of around 200 kV [50].

The accumulation of personal electrostatic charge is common. It can be caused by the rubbing or separation of footwear and clothing. The voltages generated depend on the type of clothing and shoe worn, the type of floor surface and the relative humidity of the atmosphere. A table of representative values for personal activities is shown in Table 2.

Table 2: Representative values of electrostatic voltages [42]

	Relative Humidity	
	Low (10-20%)	High (65-90%)
Walking across carpet	35,000	1,500
Walking over vinyl floor	12,000	250
Worker at bench	6,000	100
Vinyl envelopes for work instruct	7,000	600
Poly bag picked up from bench	20,000	1,200
Work chair padded with urethane foam	18,000	1,500

2.1.2 Induction Charging

Induction charging occurs when a conductor is brought into the vicinity of an electric field and then temporarily grounded and removed from the field. According to one definition of induction charging [5] the polarity must be the opposite to that of the body causing the field. Other descriptions [43, 50], however, state that the polarity of the charged body may be either the same as, or opposite to the polarity of the body causing the field. Induction charging is known to have produced hazardous charges on firing circuits [50].

2.1.3 Conduction Charging

Conduction charging occurs when an initially charged object is placed in physical contact with an initially neutral object. Charge transfer occurs during contact and both objects are left with charge of the same polarity [5] on separation.

2.1.4 Corona Discharges

The corona process will be explained in section 2.3. The ions that result from a corona discharge are capable of charging surfaces and particles [43].

2.1.5 Double-layer Charging

Double-layer charging [43] is a consequence of the dissolution of ionic material in liquid which possesses a high dielectric constant. The high dielectric constant decreases the attractive force between the oppositely charged ions and the ionic material dissociates. If an interface with the original liquid is provided (solid-liquid, gas-liquid or liquid-liquid) one polarity of charge will be bound at the interface. Ions of the opposite polarity will be attracted to the bound charge but will be held only weakly and will form a diffuse layer. This diffuse layer extends into the liquid a distance which increases with the resistivity of the liquid. If the liquid is in motion it can carry the loosely bound charge layer with it, thereby creating a separation of charge.

2.1.6 Charging by the capture of small particles

Particles may become charged by the capture of smaller charged particles. Further information on this process is presented in [43].

2.1.7 Photoelectric and thermionic emission

It is possible to liberate charge from a metal by means of incident electromagnetic radiation [34]. This photoelectric emission is not very significant as a charging mechanism [34].

More significant is charging due to the emission of electricity from hot bodies [34] which is known as thermionic emission.

2.2 The process of static discharge

After accumulating an electrostatic charge an object often loses that charge to another object in its proximity by electrostatic discharge. In air, discharge takes place when the electric field exceeds the breakdown electric field value of 3×10^6 V/m [5,43]. Local protrusions can significantly intensify the field to cause ESD when the uniform field is about a tenth of this value [43]. Depending on the resistance and inductance in the circuit the ESD may be a single pulse or exhibit oscillatory behaviour [25].

In many cases the charge source for an ESD is an electrically isolated conductor while the charge sink may be either floating or grounded [5]. Discharge can occur from non-conductors [6 ,24], although the amount of charge involved in this case is usually smaller than it is in the case of discharge from a conductor [31]. The presence of metallic inserts in insulating materials may substantially increase the spark energy [26].

When an earthed electrode is brought sufficiently close to a charged insulating surface, the air breaks down forming a multichanneled spark called a brush discharge [43]. Brush discharges from positively charged surfaces are much less incendiary than discharges from negative surfaces [43].

If a grounded metal plate or equivalent is placed behind an insulating surface then it is possible for the charge density on the insulating surface to exceed the normal limit in air. This high charge density makes the surface more conducting which allows charge to spread. This, in turn, permits a spark from an earthed electrode to discharge a large area of surface. This is known as a Lichtenberg or "propagating brush" discharge [43].

2.3 Electrostatic discharge components

Five distinct components have been found for ESD [7]. A brief description of each component is given in the following sections.

2.3.1 Pre-discharge corona

Corona is a partial discharge. The pre-discharge electric field causes ionization but is insufficient to cause a complete ESD. Discharge occurs in a localised high-field ionization region where the local electric field exceeds the breakdown field of the gas. The energy density in a corona discharge is much less than in a spark discharge but the ionization that accompanies corona discharge can enhance the spark discharge process so that longer gaps than normal can be traversed [43].

The pre-discharge corona generates RF interference. Interference generated by corona discharge has been responsible for airplane losses [34].

2.3.2 Pre-discharge electric field

This electric field exists around an object following charging. If the pre-discharge field encompasses a metal object or an electronic circuit, a current can be induced in that object or circuit, possibly causing electronic upsets. It has also been found that some primary explosives can be sensitized by exposure to an electric field [51,52].

2.3.3 Discharge electric field collapse

While discharge is taking place the pre-discharge electric field is collapsing. This collapsing field can cause currents to flow in adjacent electronic circuits causing interference and possible damage.

2.3.4 Discharge magnetic field

As a result of the current flow which occurs during discharge, a magnetic field is produced which can cause currents to flow in adjacent electronics causing interference and possible damage. In addition some radiated electromagnetic interference (radiated EMI) is generated during a rapid discharge.

2.3.5 Discharge current-wave injection

This represents the actual current pulse that is injected into the victim on discharge. It can do direct damage to e.g. electronics by overloading circuits etc. Secondary effects include large transient voltages and additional fields generated by the current flowing in both circuits and ground [9].

3. The Hazards of ESD to EEDs

3.1 Introduction

Electro-explosive devices (EEDs) are electrically-initiated devices designed to produce an explosive output by converting chemical energy into heat [3]. The electrical stimulus causes an exothermic reaction in the device. EEDs are called igniters or detonators depending on whether the rate of advance of the reaction is less than or exceeding the velocity of sound (in the detonation products), respectively.

EEDs may be classed as either high-voltage or low-voltage types [3]. EEDs may also be classed as single or double pole devices depending on the number of input electrodes to the device. Important parameters in assessing EED performance are energy and power sensitivity as well as response speed and resistance [3].

Double pole EEDs can be initiated either by a discharge directly between the poles (pin-to-pin discharge) or by discharge between the pins and the case via the explosive filling (pin-to-case discharge) [69].

One amp, one watt type EEDs should not be regarded as immune to ESD initiation [61].

3.2 Bridge-wire or film bridge EEDs

These low voltage EEDs consist of a resistive (wire, film or tape) bridge in close thermal contact with an explosive. They are initiated by passing a current through the bridge to produce a temperature rise in the explosive sufficient to cause a self-sustaining thermal reaction, leading to explosion [3].

Depending on the device parameters, these EEDs may be vulnerable to ESD initiation in both the pin-to-pin or pin-to-case discharge modes. Additionally, these devices may be de-sensitised by sub threshold currents [3].

3.3 The semiconductor bridge

The semiconductor bridge (SCB) [54] consists of a phosphorus-doped silicon or polysilicon area on a sapphire or silicon substrate [55]. This area forms the crossbar of a H pattern in contact with an aluminum overlay. Explosive powder is pressed against the SCB. The SCB is much smaller than a hot wire and can therefore be heated much faster. An electrical pulse converts the doped region into a plasma, causing an instantaneous explosion. The plasma propagates into the surrounding explosive, releasing heat of condensation and causing ignition [54].

According to [56] the SCB can exhibit very good ESD characteristics when tested with the current pulse from a 500 pF capacitor charged to 25 kV in series with a 5000 Ω resistor.

3.4 Conducting composition (CC) EEDs

These are single pole, low voltage, devices which consist of primary explosive mixed with a small percentage of fine graphite [3] or a metal powder [58]. These particles form electrically conducting chains. In the case of graphite, when sufficient voltage is applied across the chains, power concentrations at graphite junctions lead to graphite sputtering onto explosive crystals causing ignition [3]. CC EEDs can be sensitive to low energy inputs because the applied energy is concentrated in a few junctions [3]. Some devices of this type are very ESD sensitive [58] (see Table 3).

3.5 Exploding bridge-wire (EBW) EEDs

Exploding bridge-wire (EBW) EEDs are high voltage devices. EBWs consist of a low-resistance bridge-wire in intimate contact with a low density secondary explosive [3]. To activate such a device a large amount of energy is dissipated in the bridge-wire in a small time interval (typically less than 1 μs). The resultant high power causes the BW to explode and detonate the explosive [3].

EBWs may be initiated by ESD in either the pin-to-pin or pin-to-case modes [48]. In addition EBWs are susceptible to dudding if a discharge raises the temperature of the explosive in contact with the wire to a level which modifies its physical condition [3, 48] or melts the bridgewire [48]. Dudding is also possible in the pin-to-case mode due to powder displacement from the bridge [48]. For the pin-to-case discharge mode the shorter the path from bridge to case, the lower the threshold for dudding or initiation [48].

3.6 Slapper detonators

Slapper detonators are high voltage devices which consist of a foil or film bridge in contact with a plastic disc which is separated from a secondary explosive pellet by a barrel [3]. During operation a high energy impulse is applied to the bridge causing it to explode and form a plasma. The expanding plasma punches a "flyer" from the plastic disc along the barrel to impact the explosive and cause its detonation. According to [3] slapper detonators are similar to EBWs in terms of sensitivity but are less prone to dudding because the bridge is physically separated from the explosive charge.

3.7 The semiconductor ignitor

The semiconductor ignitor (SCI) is a new type of EED that has been designed as an RF-insensitive replacement for conventional EEDs in a hazardous electromagnetic environment [53]. The SCI is an electrothermal transducer that converts a low energy electrical discharge into a thermal impulse.

The operational description of an SCI is of a back-to-back diode configuration. The top diode contacts a primary explosive mix while the bottom diode contacts the button of the primer. The top diode area is very small compared with the bottom diode area leading to a high current concentration there, under operation, which melts the aluminum metallization of the top surface. Since the melting point of aluminum (660 °C) exceeds the ignition temperatures of most explosives (250-600 °C), this device will easily initiate an EED.

The RF insensitivity of this device stems from the fact that it is essentially capacitive at RF thus little heat is generated from resistive losses [53]. No information has been found on the ESD sensitivity of this device.

Table 3: No-fire thresholds for conducting composition EEDs

Device	ESD no-fire threshold
M52A3B1 primer (CC EED)	17 µJ [4]
M52 MRL MKII primer (CC EED)	590 µJ [70]

4. The Hazards of ESD to Electronics

ESD poses the greatest threat to microelectronics, which are vital to the functioning of modern computer systems (which often form part of modern weapon systems). With the trend towards ever-increasing miniaturization and integration it is likely that the ESD threat to electronics will increase in future.

Polysilicon resistors are used as input protection devices to microelectronics but these are susceptible to thermal damage since they are thermally insulated from the silicon substrate by a surrounding SiO_2 or glass layer. This layer prevents the silicon substrate from acting as a heatsink [10].

The dominant failure mechanism in metal oxide semiconductor (MOS) devices and capacitors is dielectric breakdown [10]. The low capacitance of the thin gate oxide structures in MOS devices makes them especially vulnerable to ESD damage [10]. Another failure mode is thermal damage caused by current flow. Current flow can cause thermal damage in a number of ways [43], such as:

(a) temperature increase in a thin silicon film can cause thermal vaporisation,

(b) thermal runaway can occur in silicon with a negative resistance coefficient. (This depends on the temperature exceeding a doping-dependent critical value),

(c) silicon dissolves in aluminum at a relatively low temperature resulting in a solid solution. Heat dissipated in aluminum-silicon junctions can therefore result in alloying or in the formation of a metal spike across an insulating layer and

(d) thin metal layers on insulating substrates may partially melt due to the inability to lose heat dissipated in them.

Indirect damage to microelectronics can also occur due to conducted or radiated EMI from ESD. This EMI can result in false triggering of electronic logic devices such as flip-flops [10, 40].

Gaseous arc breakdown from ESD is known to cause problems [10]. It occurs in closely spaced unpassivated thin electrodes [45]. The arc discharge causes vaporization and metal movement.

Latent damage of electronics occurs as a result of prior exposure to ESD. The prior exposure leaves the device within specification immediately following the discharge. However, the device degrades to an out-of-specification condition with time [10]. According to [45], only certain part types seem to be susceptible to latent damage. There is also a cumulative degradation at low levels of ESD exposure [10].

The damage levels of ESD to various electronic devices is shown in Table 4. By comparing values in Table 2 with those in Table 4 it can be seen that ESD from a person is capable of damaging a variety of electronic device types. It can be concluded that damage is possible even when the discharge is below the quoted 1-2.5 kV [29] threshold of sensitivity. The levels in Table 4 are those required to damage devices, however components can be significantly degraded at one-fourth of these values [46]. Electrostatic charge may be transmitted directly from personnel to the circuit by contact with a device pin or a switch or keyboard connected to the device [43]. Charge may also be coupled indirectly from a spark in the vicinity of the device. This spark may cause a secondary current in nearby circuits by inductive coupling due to the rapid current rise characteristic of ESD [43]. A discharge to a metal part on the outside of an insulating container may be capacitively coupled to devices inside the container [43].

Table 4: ESD damage levels for electronic devices

Device	ESD damage level
Bipolar operational amplifier	≥ 500 V [36]
Bipolar transistors	380-7000 V [44]
MOS device with 1000 Å oxide layer	80-120 V [37]
	60-100 V [38]
MOSFET	100-200 V [44]
CMOS	250-2000 V [44]
VMOS	30-1800 V [44]
256K MOS memory with 250 Å oxide layer	25 V [39]
JFET	140-17000 V [44]
GaAs FET	200-300 V [44]
Soft failure due to ESD-induced EMI	≥ 2500 V [40]
Schottky-barrier diode with Pt-Ti-Mo-Au metallization.	1600 V [41]
Schottky-barrier diode with Ti-Mo-Au or Ti-Au metallization	300-400 V [41]
Schottky diodes.	300-2500 V [44]
Schottky TTL	1000-2500 V [44]
SCR	680-1000V [44]
Film resistors	300-2500 V [44]
EPROM	100 max [44]
OP AMPS	190-2500 V [44]
SAW	150-500 V [44]
ECL (Hybrid, PB level)	500-1000 V [44]

ESD-sensitive electronic devices can be listed by class according to their sensitivity range. According to [45] these classes are:

Class 1: Sensitivity range 0 to < 1000 V

Class 2: Sensitivity range > 1000 to ≤ 4000 V

Class 3: Sensitivity range > 4000 to ≤ 15 000 V.

It should be noted that these classes include hybrids utilizing parts selected from the classes themselves. However MIL-STD-883D [14] uses a different classification system:

Class 1: 0 to 1999 V

Class 2: 2000 to 3999 V

Class 3: 4000 V and above.

Identification of ESD damage to electronic devices can be extremely difficult. There are two reasons for this. The first reason is the lack of facilities and trained personnel to perform the failure analysis that would lead to the recognition of ESD as the cause of the systems failure. The second reason is that ESD-induced failures can be mistaken for other failure modes. It is more difficult to determine the ESD mechanism in a bipolar device than in a MOS device [45].

5. Methods of Protecting EEDs Against ESD Hazards

5.1 The need for a static control program

The protection of EEDs against ESD requires the implementation of a static control program. The objective of this program will be to protect EEDs from ESD during assembly, storage and handling. As was necessary to achieve the protection of electronics, the importance of training cannot be over-emphasized. Without appropriate training it is likely that personnel ignore or inadvertently circumvent the regulations imposed.

5.2 Requirements for buildings/rooms where EED-containing devices are handled

Buildings and rooms in which EED containing devices are handled must comply with a number of regulations. In general the regulations are aimed at reducing the charge accumulated on personnel or dissipating it in a controlled way. The requirements are enumerated in more detail below.

(1) Personnel must be trained as to the program requirements.

(2) The provision of documentation detailing the static control procedures necessary.

(3) The provision of conducting or static dissipative flooring, workbenches [28], stools and floormats [59]. These items must be tested regularly to ensure compliance with requirements. It has been stated that conductive grade flooring be used where systems containing EEDs with less than 1 mJ NFT (no-fire threshold) energy are assembled and tested. Anti-static grade flooring may be used where the NFT energy exceeds 1 mJ [3].

The resistance (to earth) limits for anti-static grade flooring are $50 \times 10^3\ \Omega \leq R \leq 2 \times 10^6\ \Omega$ [3] while conductive grade flooring possesses a resistance to earth of less than $50 \times 10^3\ \Omega$ [3]. Conductive and anti-static flooring should be installed in accordance with [3, 22]. Reference [59] outlines a method for the laying and earthing of conducting flooring. The essential elements of this method are:

(a) low inherent electrical resistance to earth;

(b) a permanent low-resistance contact with the flooring;

(c) resistance to corrosion and mechanical damage

The flooring should be kept free of insulating deposits [26, 59]. Such deposits include oils, resins and waxes [59]. According to [59] carpets fabricated from a mixture of synthetic polymer materials and conducting material may be sufficiently conducting. However, carpets made entirely of synthetic polymer materials are generally insufficiently conductive.

(4) Temporary or limited antistatic measures such as antistatic sprays and static discharge mats are sometimes used. However, these measures vary in effectiveness [59].

(5) The provision of earthing bars which are electrically linked to the flooring.

(6) It is to be a requirement that any repairs in/on the premises must comply with static control requirements.

(7) The wearing of conductive/static dissipative footwear on the premises by all personnel. According to [59], antistatic footwear should be used in situations where an electric shock hazard may arise while conducting footwear is recommended for use in areas where there is no risk of electric shock. The resistance limits for antistatic footwear are $50\ \text{k}\Omega \leq R \leq 50\ \text{M}\Omega$ [59] while the resistance of conducting footwear shall not exceed 150 kΩ [59].

Footwear must be periodically tested for compliance with the required resistance limits as resistance can change with wear [30, 59]. According to [3] the voltage used for testing conducting footwear should not exceed 100V. A device suitable for testing personnel (including footwear) resistance is detailed in [59].

(8) According to [59], it is recommended that persons working in hazardous locations not wear metal articles apart from finger rings.

(9) According to [59], flame-resistant cotton garments are most suitable where sensitive primary explosives are handled. Garments of nylon, polyester or other synthetics should not be used.

(10) It is recommended that a personnel test meter be used to check the resistance to earth of all personnel upon entering explosives buildings [3, 50].

(11) Personnel working with systems containing EEDs should equalise their body potential with the system by placing their hands on the exposed metalwork of the munition before commencing an operation [3]. Workers may also electrically connect themselves to a conducting bench top via a conducting wrist strap [28].

(12) Sheets of non-conducting plastic materials are prohibited from premises where EED-containing devices are handled.

(13) The humidity may be kept at a high level, above 65 % [28], however very high humidity can lead to problems such as corrosion [9]. As stated above, ionizers may be more effective in some circumstances [10]. However, some types of ionizers are hazardous for use with explosives [65].

(14) An earthed plate or mesh with resistance not exceeding 10 Ω should be available at the entrances. The plate or mesh should be so sited that personnel and trolleys carrying EED must make contact with it [3]. Similar plates or meshes should be available at each EED work station [3]. Additionally, a metal earthing bar should be provided along a wall leading to each door [3].

5.3 Requirements for the transportation of EED-containing devices

The transportation of EED-containing devices is subject to a number of requirements. There are five distinct requirements which are listed below.

(1) Trolleys and cradles used for transporting assemblies and sub-assemblies containing EEDs should be of metal construction and with at least one conducting wheel and tyre. The resistance between munition and earth should not exceed 5×10^4 Ω [3, 23].

(2) The internal furniture of containers used for transporting EEDs should, where antistatic protection is required, be constructed of anti-static material [3]. The leakage resistance from the body of the packaged item to the container should not exceed 1 MΩ (if the item's energy sensitivity is 1 mJ or less) or 100 MΩ (if the item's energy sensitivity exceeds 1 mJ) [3]. The antistatic material should be of the bulk-impregnated type [3]. Containers should be provided with 2 adjacent earthing studs for make-before-break earthing, if required [3]. The resistance of cables for earth bonding should not exceed 0.5 Ω [3].

(3) The metalwork of hoists and similar equipment should be electrically bonded directly to the building earthing system [3]. Rope or any non-conducting load bearing cable used between the hoist and the lifting hook should include an integral conducting lead [3].

(4) When it becomes necessary to bond a packaged item to the container by a low resistance cable, it should be ensured that this is the only connection between them because more than one connection may permit large EMP or lightning induced currents to flow through the item [3].

(5) Aircraft are capable of accumulating considerable static charge. It must be ensured that aircraft are linked to earth by an earth bonding cable before EED-containing stores are loaded or unloaded [50].

5.4 Requirements for the firing of EEDs

When it becomes necessary to fire EEDs the following precautions should be observed:

(1) If it has been determined that the firing lines can accumulate a dangerous level of static charge then it will be necessary to fit electrostatic discharge resistors to every relevant section of line [3].

(2) To reduce the possibility of introducing electrostatic charge on the firing lines, all plugs and sockets fitted in a firing system should be connected so that the firing lines are terminated at recessed female pins [3].

(3) Cartridges and ammunition which are handled should possess recessed firing contacts to minimize the risk of accidental contact with charged bodies [3].

5.5 Protection devices for EEDs

Techniques exist to reduce the susceptibility of EEDs to ESD initiation. These techniques include the use of coded firing signals [66], the substitution of bridgewires requiring high voltage and/or amperage [66], and the use of ferrite beads [66]. A shunt spark gap [68] and resistive dissipation techniques [68] can be used to reduce the hazard from pin-to-case discharge. Reference [67] describes the use of ferrite chokes and electrostatic tape to achieve protection against ESD initiation. The electrostatic tape is described [66] as consisting of a thin metal printed circuit network deposited on a mylar substrate. The tape is not conductive at firing voltages but becomes conductive at high ESD voltages and thereby shunts the ESD discharge [66].

6. Methods of Protecting Electronics Against ESD Hazards

Electronics that are critical to the safe operation of munitions can also be susceptible to ESD. The protection of electronics can in this case be as important as the protection of EEDs. Once the need for a protection program for electronics is recognized a number of protection methods for the program and workstations can be identified.

6.1 The need for a static electricity control program

The effective mitigation of ESD hazards requires the implementation of a static control program to minimize the impact of ESD to system safety and reliability and to reduce life cycle costs [10].

6.2 Elements of the static electricity control program [10]

An effective static control program needs to be developed with consideration to the following guidelines.

(1) Training of relevant personnel as to the requirements of the program.

(2) Documentation which clearly specifies static control methods and procedures [11].

(3) Identification and classification of ESD sensitive devices.
Reference [59] specifies a standard plastics adhesive label.

(4) The requirement for ESD protected areas and workstations.

(5) Appropriate handling procedures for devices. These include ensuring that all elements involved in operations are at the same potential [59].

(6) The need for protective packaging of ESD sensitive devices. Some existing protective packages have been found to be ineffective [43]. Antistatic materials to prevent charge accumulation have a resistivity in the range 100 Ω m to 100 MΩ m [43]. However, in order to provide electromagnetic screening, materials must be continuous and metallic [43]. This packaging may have to exceed MIL-B-81705 to be effective in protecting VLSI circuits and a resistivity test is suggested in [39].

6.3 Requirements of a typical grounded workstation [10, 43]

Workstations where ESD-sensitive electronics are handled must be subject to a number of protective measures. These apply to the bench top surface, floor, seating materials and the operator.

(1) A conductive or static dissipative work surface.
(Connected to ground via a current limiting resistor of typical value 1 MΩ). Antistatic grade bench tops are preferable in many cases because a slower discharge rate will reduce damage to ESD sensitive devices. Conducting grade material has a resistance to ground value of $R < 50 \times 10^3\ \Omega$. Antistatic grade material has a resistance to ground value in the range $50 \times 10^3\ \Omega < R < 5 \times 10^6\ \Omega$ [23]. Further the higher resistance reduces the current through an operator that could arise through an accidental electric shock from electrical equipment. The human body can pass currents of the order of 8-9 mA before the effects become dangerous [35]. With a resistance of $50 \times 10^3\ \Omega$ in circuit, a maximum of only 5 mA will flow for a 250 V line voltage.

(2) A conductive floor mat, stools without rubber feet or plastic seat covers [43]. All trays and containers on which devices might be placed to be conducting [43].

(3) Conductive wrist straps to be provided to personnel to ensure that the human body is at ground potential. These require a series resistance of 1 MΩ to earth [43] to limit the current through an operator in the event of an electric shock from electrical equipment.

(4) Conductive flooring.

(5) ESD sensitive devices need to be in protective packages when they enter a grounded workstation. They can only be handled if devices, personnel and work area are all at ground potential [10].

(6) All static generating materials should be excluded from the area.

(7) Alternatively if there is an exemption, then their effect must be reduced by the use of air ionizers to neutralize any static charge. Ionizers have been found to be more effective than 40 % to 50 % relative humidity control in limiting static electricity accumulation [10]. However problems associated with air ionizers include the generation of ozone and the possibility of remote static field buildup [10]. If ionizers are used they must generate both positive and negative ions to ensure neutralization [9]. There is a shortage of data on the effectiveness of electrostatic eliminators in the electronics environment [43].

7. Antistatic Devices and Materials

7.1 Electrostatic eliminators

Electrostatic eliminators reduce static charge by producing ions. They fall into the two broad categories of passive and active eliminators. The characteristics and the advantages and disadvantages of both types are detailed below.

7.1.1 Passive eliminators

A simple eliminator may take the form of an array of earthed points or an earthed wire. The electric field caused by the charge is increased at the points and a corona discharge results which creates ions of opposite polarity to the original charge. The corona discharge persists until the field at the points is below the corona threshold. However, such a "passive" eliminator can only reduce the charge to moderate levels [43]. Passive eliminators work best for surfaces with a high field and should therefore be placed where the charged surface is far from other earths [43]. Passive eliminators may be used in flammable atmospheres where the minimum ignition energy does not exceed about 0.2 mJ (BS 5958) [43].

7.1.2 Active eliminators

Active eliminators neutralize a surface charge by producing ions of both polarities. The ions are produced either by a radioactive source or by means of an AC corona discharge. The advantages of radioactive eliminators are [43]:

(1) They give more complete neutralization than other active eliminators for low electrostatic charge levels.

(2) Radioactive eliminators do not require a power source, they are therefore safer with respect to electrical shock and spark induced hazards.

The disadvantages are [43]:

(1) Charge neutralization is frequently insufficient for industrial applications.

(2) Radioactive eliminators are relatively expensive.

(3) Radioactive eliminators cannot be used in environments where they might become contaminated.

(4) Radioactive eliminators must be replaced as their activity falls. (e.g. the half-life of a polonium 210 source is 138.4 days).

(5) Polonium eliminators (the most frequent type) cannot be used in some applications because of polonium contamination.

(6) There may be a possibility of radiation hazard [31].

AC (alternating current) corona eliminators are based on a series of sharp points or a wire to which an AC voltage is applied. The corona discharge produces ions of both polarities on alternate halves of the cycle. However, equal amounts of charge are not produced on alternate half-cycles. Larger diameter wires and points produce more negative than positive ions while the reverse is true for smaller diameters (at low frequencies).

The advantages of AC corona eliminators are:

(1) It is possible to design an AC eliminator which is safe in flammable atmospheres.

(2) For low initial electrostatic charge levels, AC eliminators are more efficient than passive eliminators.

The disadvantages of AC corona eliminators are:

(1) Some AC eliminators can ignite flammable atmospheres [57].

(2) AC eliminators require a power source.

(3) Ozone production [31] can be a problem. So can nitric oxide [34]. These two gases can cause respiratory problems [34].

(4) An electric shock hazard exists with high voltage eliminators [31].

Electrostatic eliminators are occasionally used, sometimes with ducted air to extend their range [50]. However, the effective range of eliminators is usually too short to make them universally applicable [50].

7.2 Carbon black

Rubbers and plastics are usually insulating but they may be rendered conductive by the addition of carbon black fillers. Carbon black consists of small (< 50 nm) carbon particles which are formed by incomplete hydrocarbon combustion [43]. The particles usually occur in the form of clusters or chains.

The addition of carbon black results in materials with resistivities which lie in the range 0.01 Ω.m - 10^{13} Ω.m [32]. The resistivity usually decreases sharply as the carbon black loading is increased to around 15 % by weight after which higher loading decreases the resistivity at a lower rate [43]. At low carbon concentrations the resistivity is non-ohmic i.e. conductivity, and therefore resistivity is not constant for different values of current density and electric field strength. At high concentrations the resistivity becomes ohmic [43]. The resistivity of highly conductive rubbers is approximately ohmic at low voltage gradients but this is not necessarily true at high voltage gradients [32].

7.3 Hydrophilic antistatic additives

Hydrophilic antistatic additives are mainly surface-active agents of the form:

$$R — S$$

where R is a hydrophobic (water-repelling) group and S is a hydrophilic (water-attracting) group. There are various categories of these agents [43]. Examples of hydrophilic additives are quaternary ammonium salts, aminophosphoric acid esters and polyether glycols.

The functional characteristic of these additives is a surface-active agent oriented so that its hydrophilic end protrudes into the air and attracts water molecules [43]. The adsorbed water increases the surface conductivity of the material. These additives are dependent upon sufficient atmospheric humidity for their effectiveness with a relative humidity of 25 % usually taken to be a lower limit [43].

Antistatic additives are often easily washed from the underlying fabric [43]. To prevent this, the additive can be deposited onto a fabric as a monomer and then polymerized in situ [43]. The crosslinking of the additives generally increases fabric stiffness [43]. Conductivity may also be increased by adding an antistatic in polymer form directly to an original fabric [43]. Antistatic properties of fabrics can be lost during storage which is, presumably, due to additive migration into the polymer [43]. Antistatic properties may be recovered by means of fabric softeners [43].

7.4 Metallic antistatic additives

A major disadvantage of hydrophilic additives is their reliance on atmospheric moisture which may be below the 25 % relative humidity level and so insufficient [43]. Metallic additives can overcome this problem [43]. Following are some techniques for applying metallic additives to textiles:

(1) Organic fibres are coated with metal and blended with normal fibres [43].

(2) Fine (4 - 12 mm) metal fibres in small proportions (0.1 % to 1 %) are added to the original fabric. The fibres interact and cause local electric field intensification with accompanying electrical breakdown if the field breakdown level is reached. The charge is dissipated in this way to earth throughout the garment, minimizing charge accumulation. This technique is used in carpets [43].

(3) A metal fibre is woven into the fabric [43].

(4) Silver-coated glass beads may be used as a filler in a polymer to improve conductivity [43].

Metallic additives must usually be immune to oxidization in order to facilitate electrical contact betweeen fibres. For this reason metallic additives are commonly made of silver or stainless steel [43].

7.5 Epitropic fibres

Epitropic fibres consist of two sections, a core and a sheath which possesses a lower softening point temperature than the core. The sheath is manufactured by thermally softening and embedding conducting particles into it [43]. A few per cent of an epitropic fibre incorporated into a 100 % polyester garment can decrease resistance by six orders of magnitude [43].

7.6 Charge control agents

Charge control agents are additives which function by generating a static charge of opposite polarity to the charge which normally occurs on the host material. By this means the friction-generated charge on the material may be limited to a low level [43].

7.7 Inherently conducting polymers

Much effort is being devoted to the development of polymers with enhanced electrical conductivity. While it is possible to produce such materials their mechanical properties tend to be poor [43]. A further problem with such materials is their poor long-term stability [49].

8. ESD Simulation

In order to determine the sensitivity of EEDs or electronics to ESD hazard it is highly desirable to have the capability to accurately reproduce the ESD waveform under controlled conditions. Many ESD simulators only consist of a capacitor in series with a resistor. The capacitor and resistor are intended to represent body capacitance to earth and resistance, respectively. A number of industry standards specify such a simple R-C network [12-18]. The capacitance values for these standards ranges from 60 pF to 300 pF while the resistance ranges from 150 Ω to 10 kΩ [20]. In addition many manufacturers have established their own test specifications based on a simple R-C network. A wide variation in network values is again found: capacitances range from about 100 pF to several hundred pF and resistances from about 150 Ω to 1500 Ω [20].

The inductance has been ignored by these standards even though it is the dominant factor in determining the discharge current rise time [20]. The simple R-C network model cannot duplicate the worst-case discharge which is from a human holding a metal object [20]. To circumvent the problems associated with an R-C model a new, so called "true ESD" simulator has been devised. The true ESD simulator uses a combination of two resistances (R), capacitances (C) and inductances (L) to create what is known as a dual-RLC circuit [20]. Two values of each of the electrical parameters are necessary to simulate the effect of the human body together with the forearm and hand which are regarded as separate electrical networks [20]. ESD from this dual-RLC circuit demonstrates good correlation with human ESD [20].

The dual-RLC circuit (and human discharge) simulates an ESD event involving a sharp (sub nanosecond risetime, tens of amperes) initial current pulse which can go undetected if the monitoring oscilloscope possesses insufficient bandwidth [21]. It has been found that the rising slope of the initial current pulse is a function of the speed of approach of the test electrode [27].

9. Standards Used in ESD Testing

9.1 Standards used in ESD testing of EEDs

Two main standards for testing ESD effects on EEDs are outlined below. One originates in the U.S. while the other comes from Sweden.

MIL-I-23659 [62] requires:

(1) Simulation circuitry consisting of a 500 pF ± 5 percent capacitor charged to 25 000 V ± 500 V in series with a 5000 Ω ± 5 percent resistor. The total inductance of the circuit is 5 μH.

(2) Simulation to be effected in the EED pin-to-pin and pin to case configurations.

(3) The EED must neither fire nor dud when subjected to the 25,000 V at 70° ± 5° F (21.1°C ± 2.8 °C) and a relative humidity of 50 % or less.

The Swedish Försvarsstandard FSD 0112 [47] for the static sensitivity testing of electric igniters, excluding exploding bridge wire, EBW and exploding foil initiator (EFI), requires:

(1) High tension source for infinitely variable D.C. voltage up to 25 kV.

(2) Voltmeter for measurement of high tension to an accuracy of ± 5%.

(3) Capacitors 500 pF/25 kV, 150 pF/25 kV and 10 pF/25 kV, accuracy ± 5%.

(4) Series resistors 5 kΩ/25 kV, 150 Ω/25 kV, 10 Ω/25 kV respectively, accuracy ± 5%, not wire-wound.

(5) High voltage circuit breaker (vacuum relay, triggered spark gap or equivalent) providing repeated discharges with decreasing amplitude.

(6) Test circuit with capacitance 150 pF and series resistance 150 Ω (alternatively 500 pF and 5 kΩ respectively).

For 150 pF/150 Ω the highest permitted circuit inductance is 3 μH corresponding to a cable length of about 2 m. Pulse rise time shall then be at most 5 ns.

(7) The test is primarily concerned with the sensitivity between the casing and the filament, but it can also be carried out so that the pulse is supplied between the leads. Connection into the test circuit is specified in separate specification.

(8) The test is carried out with ten igniters of each polarity at charge voltages of 1, 2, 5, 10, 15, 20 and 25 kV respectively.

9.2 Standards used in the ESD testing of electronics

The dominant American test standards for ESD simulation of electronics include the American National Standards Institute's ANSI C63. European standards include the International Electrotechnical Committee's IEC 801-2, and the European Computer Manufacturers Association's ECMA TR-40.

IEC 801-2 [12] requires the following:

(a) Hand/metal, contact-mode simulation using a 150 pF capacitor in series with a 330 Ω resistor.

(b) Hand/metal air discharge simulation using a 150 pF capacitor in series with a 330 Ω resistor.

(c) Indirect ESD simulation using both horizontal and vertical coupling planes.

ANSI C63 [63] requires the following:

(a) Hand/metal, contact-mode simulation using a 150 pF capacitor in series with a 330 Ω resistor.

(b) Hand/metal air discharge simulation using a 150 pF capacitor in series with a 330 Ω resistor.

(c) Indirect ESD simulation using both horizontal and vertical coupling planes.

(d) Furniture, contact-mode simulation, via crossed-vane structure.

ECMA TR-40 [64] requires the following:

(a) Hand/metal, contact-mode simulation using a 150 pF capacitor in series with a 330 Ω resistor.

(b) Indirect ESD simulation using both horizontal and vertical coupling planes.

(c) Furniture, contact-mode simulation, via crossed-vane structure.

MIL-STD-883D [14] (US military standard for the classification testing of microcircuits into the classes in section 4) requires the following:

(1) "Human body" simulation using a 100 pF capacitor in series with a 1500 Ω resistor.

(2) The test voltages (recommended) that are listed in Table 5. Testing usually commences at any step and proceeds to successively lower steps until a step is reached where none of the devices fail. The highest step passed gives the voltage threshold classification.

*Table 5: Simulator charging voltage (V_S) steps versus peak current (I_P). **
(From MIL-STD-883D)

Step	V_S (volts)	I_P (amperes)
1	500	0.33
2	1000	0.67
3	2000	1.33
4	4000	2.67

* I_P is the current flowing through R_2 during the current waveform verification procedure and which is approximately V_S / 1,500 ohms.

(3) Finer voltage steps may optionally be used to obtain a more accurate measure of the failure voltage.

(4) The devices are tested using different combinations of input, output, power supply and ground pins.

10. Summary

This document discusses the protection of EEDs and electronics from electrostatic discharge hazard.

Section 1 describes the necessity for a structured ESD protection policy for the ADF. This policy should cover both EEDs and electronics. The requirement for this literature review is explained.

Section 2 discusses the processes that generate electrostatic charge. A triboelectric series, including some commonly encountered materials, is presented. The electrostatic voltages generated by some commonplace activities are also listed.

Section 2 then describes electrostatic discharge mechanisms. The difference between discharges from conductors and insulators is explained. An exposition is given of the various components of static discharge and their significance.

Descriptions of EEDs are presented in Section 3. Included are descriptions of ESD hazards to the devices together with possible discharge modes. It is stressed that one amp, one watt type EEDs are not necessarily immune to ESD initiation. A table of sensitivities is presented for some EEDs.

Section 4 describes the ESD hazards to electronic devices. The emphasis here is on describing failure mechanisms and on highlighting the problem of latent failure. It is pointed out that ESD damage to some devices can occur well below the shock sensitivity threshold. A table listing the ESD sensitivities of commonly-used electronic devices is presented.

Section 5 describes techniques to mitigate the effects of static discharge on EEDs. The emphasis is on preventing the generation and accumulation of electrostatic charge and on ensuring that potentials are equalized.

A description of techniques that are useful in mitigating the effects of ESD on electronics is presented in Section 6. Again the emphasis is on ensuring that electrostatic charge is not generated or accumulated and on equalizing potentials. Some deficiencies in current standards for the packaging of ESD-sensitive devices are also pointed out.

Descriptions of various antistatic devices and materials are presented in Section 7 and comparisons are made between different classes of electrostatic eliminators. The rôle of additives in reducing electrostatic charge accumulation is also discussed.

Section 8 discusses ESD simulation techniques. The shortcomings of many contemporary simulation circuits are explained. The requirement for circuitry capable of accurately simulating electrostatic discharge is emphasized.

Several standards for the ESD testing of EEDs and electronics are described in detail in Section 9.

Many references have been quoted in this work. At AMRL we have constructed a large database (comprising thousands of references) relevant to electrostatics with a particular emphasis on the hazards of ESD to EEDs and electronics. This database is constantly being updated.

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Horace Billon

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TITLE

The protection of electro-explosive devices (EEDs) and electronics from electrostatic discharge (ESD) hazards

AUTHOR(S)	CORPORATE AUTHOR
Horace Billon	DSTO Aeronautical and Maritime Research Laboratory GPO Box 4331 Melbourne Victoria 3001

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Exploding bridge wire detonators	Electrostatic charge	Antistatic techniques

ABSTRACT

This report is a review of the various electrostatic discharge (ESD) threats to EEDs and electronics. Methods of overcoming these hazards are outlined. A description is also presented of the methods and standards used for vulnerability testing.