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Electrostatic Discharge (ESD)—Facts and Faults—A Review

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PART II†

REQUIREMENTS OF PACKAGING MATERIALS

General

Figure 4 provides an overview of how different materials may be classified according to their electrical properties. For an effective evaluation of the usefulness of ESD protective materials, Beels[28] and Stevens[29] list three questions which need to be answered.

(i) Will the material generate charges through triboelectricity, i.e. is the material easily charged by rubbing, wear or separation?
(ii) Where do charges go once they have been generated or induced? This can be determined by surface and volume resistivity.
(iii) How quickly will charges decay? The decay time must not be too short because it could cause hazardous sparks. On the other hand, the decay time must not be too long, because the material would then be too electrically isolating and more likely to cause a build-up of high charges. A systematic approach to ESD damages includes the following four issues:

  (a) Minimizing build-up of charges;
  (b) 'Drainage' of charges;
  (c) Neutralization of charges;
  (d) Minimizing the field and the charging effects.

When selecting ESD protection, Armstrong[30] recommends that the following factors are taken into account in selecting the packaging material:

- Sensitivity of the product;
- The nature and size of potentially damaging events;

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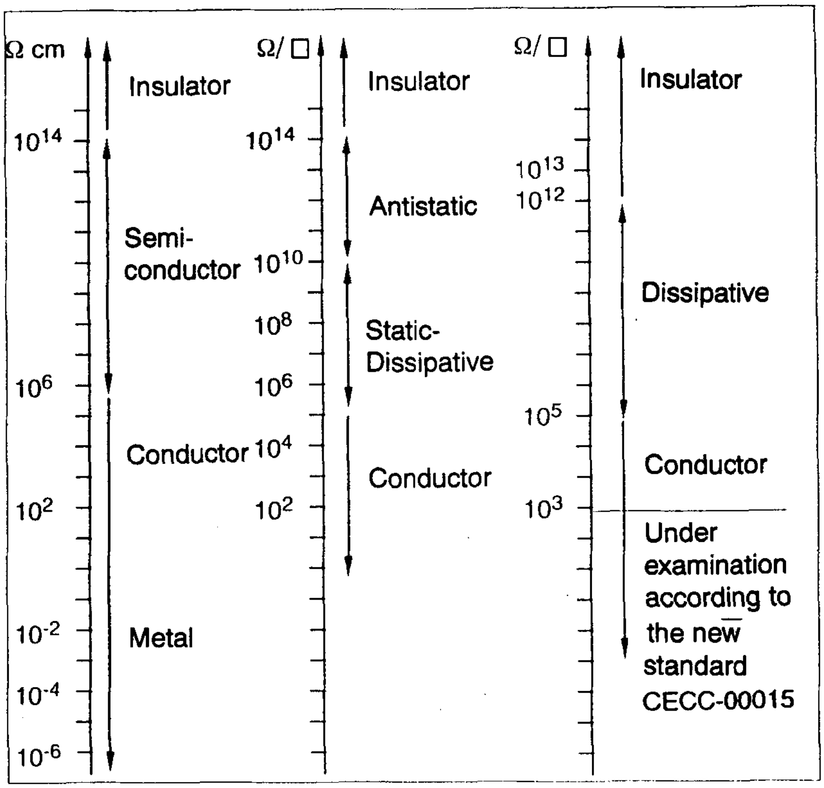

Figure 4. An overview of materials classification (from Eklöf *et al.*[11]).

- An estimate of protection level when using different materials;
- Consideration of possible reactions between the product and the material (e.g. corrosion, contamination, transfer of particles, etc.);
- Total cost for using the respective materials.

As with other types of product there is a vast selection of materials/combinations of materials and designs from which to choose when selecting packaging for electronic products. This includes bags, films, sticks, boxes or filling/shock absorption materials.

The following properties can be considered to be purely ESD ones (electric properties): antistatic, shielding, dissipative, discharge protection, discharge of batteries, (content of) conductive particles. There are also some other aspects worth considering: transparency, ageing, mechanical durability, disposable/re-usable, corrosion risk, allergy causing, soiling, humidity dependence, water- and dustproof, checking possibilities and, of course, price/performance.

There are several material combinations from which to choose in bags for printed circuit boards. One example is a multi-layer bag which combines polyethylene and polyester to give both antistatic properties and strength, along with an outside conductive metal layer which has a wear resistant cover. According to the manufacturer, there are several metal layers with different properties from which to choose. Nickel is durable and tough: as well as soft and pliable and does not crack easily when creased. Aluminium, on the other hand, is fragile and cracks more easily when creased. Polyester is used to make the combined material tough and strong. The outer surface is often waffled, which reduces friction and thereby the likelihood of charging when the circuit board is pushed into or pulled out of the bag. Furthermore, to avoid problems with the release of gasses, the layers should not be glued together. For printed circuit board bags the bottom is often the most likely fault risk area, because it may crack and thereby destroy the shielding effect. Carbon-loaded bag materials often have a 'window' through which the labels on the board can be read or a transparent plastic bottom serving the same purpose.

Durability is a particularly important property of antistatic bags for printed circuit boards. Will the antistatic agent dissipate? Head[31] found that the antistatic agent had a tendency to disappear when it came into contact with absorbing materials used as transport packaging around the printed circuit board. He recommended that the air flow around the antistatic package is minimized. Kolyer and Anderson[32] conducted extensive tests on property changes over time of a number of pink poly materials. They found that the surface resistivity varied by a factor of 10^6 or more between 25 and 90% RH.

When using bags, particular consideration must be given to their folds and seals. According to Lacy[33] they can play a critical role with regard to conductivity. Cracks, for example, can reduce the shielding capacity. Furthermore, the packaging material must be 'compatible' with the product. Deigan[34] and O'Shea[27] mention that components containing polycarbonate have been seen to crack when in contact with amines in pink poly materials. Fogging of optical devices may also occur with pink poly materials.

Kitzer[35] mentions a particular advantage of using metal foils, namely that several, partly contradictory, requirements can be met, such as:

- an antistatic inner surface prevents triboelectric charging;
- a metallic or 'metallically steamed' middle surface shields from electrostatic fields;
- a conducting outer surface rapidly discharges.

Polymers

A recent development of polymers with antistatic properties has taken off with the introduction of electron beam treatment. The first laboratory tests on these were conducted in 1971.[36] The purpose of electron beam radiation is to break down and recombine polymer chains in a specific way.

A well-known material/trademark is Staticure, from Metallised Products Inc. in the US.[37] Further developments of this material have been used in the American space industry, where the ESD requirements are very high due to the risk of explosions.

Shock absorbing materials of cellular plastic are electrically isolating and normally have high resistivity values, which makes it possible to charge them triboelectrically. Antistatic treatment can be given, either by submerging them in or spraying them with an antistatic agent, but it is more common that the agent is added to the granules when the raw material is manufactured or that it is added to the raw material before moulding. Adding it to the raw material results in more even electrical properties. This method was not introduced to the market until 1990 for expanded polystyrene (EPS) and expanded polyethylene (EPE), and will be available in 1995 for expanded polypropylene (EPP). Attention must be given to possible migration/contamination and to the corrosion risk caused by the saline solutions used. The cellular plastic may also be given a coating of conductive varnish or be metallized, which is done for demanding, mostly military, applications.

Carbon-loaded materials

The so-called conductive foam is an example of a carbon-loaded material. It is a cellular plastic material with an additive of carbon black, ground carbon, which consequently makes it black. It is found in a number of combinations, the harder ones being used to short circuit the soldering pegs of the circuits and the softer ones for shock absorbing packaging materials. The material provides good ESD protection, but some care has to be taken when the printed circuit boards have battery back-ups, or the batteries may be discharged. Contamination may also occur if carbon particles loosen from the foam.

The important properties of conductive foam, according to the manufacturer BXL Plastics Ltd, are:

- volume resistivity $< 10^4$ ohm.cm.;
- no particle separation;
- non-corrosive;
- no discolouring;
- good chemical resistance;
- permanent conductivity (conductivity does not decay with time);
- if closed cells are used, the water absorption is very low;
- can be cut, laminated and heat moulded.

Corrugated and solid fibreboard are other examples of materials which use carbon to achieve conductive properties.

Paper

Packaging materials of paper, liner board or corrugated fibreboard are often used for the outer packaging of electronic components, mostly in carbon-coated or other processed forms.

Paper is fairly close to the middle of the triboelectric series, which means that electrons are neither easily emitted or taken up through rubbing or friction. When the Swedish Packaging Research Institute conducted experiments on non-coated linerboard at room temperature, rubbing tests merely resulted in charges in the 20–50 V range, which is considered very good from an ESD protection point of view. If, on the other hand, charges are somehow induced in the material, these charges remain there for a long time, particularly in uncoated papers. In these cases discharge times may be as long as tens of seconds. Charges could, therefore, be transferred to components. The electric properties of paper vary substantially with surrounding humidity and a higher water content increases conductivity. As a result, several paper types, except carbon-coated ones, often have too long a discharge time in the strict climate (15–20% RH) used for most ESD standards.

Paper-based materials should also be suitable for transport packages, i.e. where not directly in contact with the electronic equipment. However, there are rigorous restrictions on their use in EPA in the European norm EN 100 015-1. Added to this is the risk of dust, loose fibres, etc., in clean room environments.

Handling of ESD-sensitive products

ESD protection is extremely important when printed circuit boards and components are handled in different production units and are moved between different departments in the company. Therefore, it is vital that companies which handle ESD-sensitive products introduce and follow strict routines for such handling. ABB Automation in Västerås, Sweden, for example, has introduced the following requirements for their storage and packaging section (according to Komponent-Bulletinen no. 1, 1990).

- The packaging of incoming goods is inspected. If the wrong material has been used, the goods are returned.
- The unpacking site and other handling areas have conductive floors and the personnel wear conductive shoes.
- Electronic components are kept in boxes of conductive material (carbon-coated corrugated fibreboard, carton board, carbon-loaded plastic or some other conductive material).
- Storage shelves are grounded to the conductive floor.
- Plastic folders for films, etc., are treated with an antistatic agent.
- Transport trollies and wheeled tables have conductive contact with the conductive floor.
- A neutralizing ion generator is used at critical handling sites where electrostatic charging levels have to be <200 V.
- All handling staff receive instruction on ESD protection measures. This also applies to new employees.

ABB Automation has also taken action regarding packaging materials, for example by not allowing any unprocessed plastics inside EPA.

Fuqua and Dekkers[38] have developed a commercial expert programme to make it easier for the user to introduce ESD protection measures. This includes topics such as identification of sensitivity levels and advice on organizational measures which need to be taken.

INDUSTRIAL CASE STUDIES

Industries all over the world, which manufacture electronic equipment where rigorous safety regulations are applied to avoid the risk of explosions, etc. use elaborate ESD protection programmes. Some examples follow:-

McDonnell-Douglas Corporation

The aircraft manufacturer McDonnell-Douglas Corporation in Long Beach, CA, invests heavily in ESD protection and its staff member Donald Frank has published several articles in this field.[39–41] The Douglas Aircraft Company became aware of the ESD problem in 1979, when they replaced older systems with several new technology systems. The new systems with new components were compatible with the existing systems and equivalent from a functional point of view (seen as block charts). However, during the implementation it was discovered that 3–4 times as many 'soft failures' occurred. Soft failures were defined as failures which could not be detected by testing the system components. The subsequent failure analysis discovered that more than one third were caused by components degrading as a result of ESD. For example, these soft failures were bit errors that gave different results on different occasions, creating a great deal of work in various trouble-shooting attempts.

The difficulty in dealing with these failures caused more problems than pure product failures, which can be more readily isolated. This led to the development of extensive ESD investigations and programmes. For example, the electrostatic susceptibility of different components was tested, and these tests showed that temperature is an important factor for the sensitivity level. Statistical tests on complementary metal oxide semiconductor (CMOS) devices showed that the 50% percentile at the normal storage and mounting temperature of 25°C was at 380 V.

As a result of all these soft failures due to ESD problems, the company decided to upgrade its ESD protection and introduce a control system before, during and after the systems went through the plant. A training programme was also started with 50 of their main suppliers, both within and outside the US. One of the aims of this programme was to convince the company management that, although only ~10% of the ESD problems resulted in hard failures, 90% of the ESD damage was caused by failures which it was very difficult to detect. More about the company's ESD policy is given in Frank.[39]

Siemens Medizintechnik AG

An example of the work on ESD protection issues in a European industry is related by Buchheim *et al.*,[42] who describe Siemens Medizintechnik in Erlangen, Germany. The plant, with some 4700 employees, produces electronic products, ranging from hearing aid equipment which weigh only a few grams to constructions for nuclear spectroscopy weighing several tons. All of this production must follow GMP (good manufacturing practice) according to, among others, the regulations of the American FDA (Food and Drug Administration). As part of this quality assurance, a proper ESD protection had to be introduced. Therefore, a three man team was appointed at Siemens with the responsibility to introduce and maintain ESD protection measures. To assist them, they had centrally issued production manuals with basic regulations for the handling of ESD at arrival, material preparation, internal transport, storage and delivery. The investment also led to information meetings, group lectures, regular evaluations (audits), etc. ESD has to be seen as part of the TQM process (Total Quality Management), which in principle affects all personnel in the company.

In 1990 the annual cost for ESD measures totalled ~1 000 000 DM. As pointed out by Buchheim *et al.*, the investment costs could be easily estimated, but it was not as easy to assess the cost savings. The measures were not introduced all at once and they cannot be removed for economic assessment. However, their estimates show that the savings due to reduced repairs in the plant or after sale clearly exceed the costs. From a competitive point of view, the crucial aspects of quality and reliability of the products should also be included.

Bofors AB

The Swedish company Bofors AB develops and manufactures sophisticated defence products in areas such as ammunition, gun systems, combat vehicles, small calibre weapons, antitank weapons, missiles, torpedoes and propellants and explosives. The company produces and markets products such as the recoilless gun Carl-Gustaf, the antitank missile BILL, the anti-aircraft missiles RBS 70 and RBS 90, howitzer 77, the STRIX antitank mortar round, the TRINITY system, torpedoes and ammunition for both the Swedish defence forces and the export market.

In the Brickegård unit the anti-aircraft missiles RBS 70 and RBS 90 and the anti-tank missile system BILL are manufactured. Because of the strict reliability requirements for the products, i.e. a missile taken out after 15 years of storage must function perfectly, Bofors has very strict requirements for ESD safety. Their policy is that all electronics are considered ESD sensitive, so they try to 'over-protect' the product. By doing so, the risk of latent failures is reduced. At Bofors they have found that the little ESD damage which occurs, is the tip of the iceberg of the total damage and malfunctions. In principle, the whole company's electronic production unit is an EPA, with conductive floor surfaces, chairs and table tops. They also give considerable training for the 350 staff in the production unit. The personnel have their wrist bands and shoes tested once a week and this is checked by a supervisor. Furthermore, other ESD protection equipment is checked and signed correct on a monthly basis.

The requirements for packaging materials are that they should be antistatic and/or conductive. They mainly use carbon-loaded polyethylene bags and black conductive plastic crates. Internal transport is in black, conductive, thin, vacuum-formed polystyrene packages, often made in-house.

The packaging material for mechanical parts, which are not by themselves ESD-sensitive but which arrive at the electronic production unit in plastic crates, must also be antistatic and/or conductive. As a result, they are also packaged in conductive bags. These bags are not re-used. To better comply with the CECC 00 015 requirements on transparency, and to re-use some of the wrappings for precision tools in EPA, there are plans to introduce metallized shielding bags. The electronics workshop is subject to clean room requirements, normally using clean room climate 322 (earlier called class 3B) and, where gyros or similar equipment are mounted, clean room climate 422. Therefore, uncoated paperboard or corrugated fibreboard must not be used, because they release too much fibre, etc., into the air. However, plastic-coated or waxed cardboard and corrugated cardboard are allowed for clean room climate 322. The requirements for shielding are not as high and the black, conductive, carbon-mixed plastics provide sufficient shielding.

So-called pink poly, i.e. plastics mixed with an antistatic agent, is used as little as possible, partly because the antistatic protection has a limited life and partly because the materials are 'greasy' and sticky and emit substances to the electronic products. Furthermore, the products commonly have viewfinders and during temperature tests at 60°C pink poly materials emit amines or other compounds which condense on the cold surfaces of the optics, leading to so-called fogging. It is very difficult to get rid of this coating. Therefore, pink poly is banned in principle and the only area in which the use of pink poly is still allowed is for plastic folders for drawings and work instructions. No printed circuit boards with a battery back-up are used at Bofors and this avoids problems with conductive materials.

Packaging materials are tested by FFV Materialteknik in the near-by Björkborn area. Because Bofors has studied ESD issues carefully since 1981, packaging issues in general have also received greater attention.

Purchased *components* are subject to testing of samples or in some cases to testing of all components. In contrast to some civil companies, Bofors does not test components for 'ESD limits', but rather mainly buys MIL components, where testing is included, and uses the 'overprotection policy' mentioned earlier. In principle, this means that no voltage exceeding 100 V should come near the components and at such levels it is very difficult to measure currents, fields and other electrical properties of the semiconductors.

The quality analysis department carried out elaborate procedures for testing of components. Since 1978 all faulty components are subject to quality analysis. Around five of the faults in 1000–2000 components tested each year are caused by ESD. This is a very low rate, thanks to the overprotection policy described earlier. The workshop can easily follow up and trace all components used through the computerized MASQ (Measuring data, Analysis, Statistics, Quality) system. If, for example, a customer in Australia discovers in three years time a malfunction in a missile, statistics for each printed circuit board of that missile can be retrieved, from which particular supplier it came, what components were used and their parameters as measured at the arrivals inspection. This provides an excellent feed-back for further product development and correction of faults. The quality analysis contains a number of feed-back loops at various stages and for long time periods, from product development and manufacture to guarantee times, etc., spanning long periods, up to 30 years or more.

Extensive testing is done, both on arrival and in production. Printed circuit boards and mounted missile parts, containing a lot of flex cabling and flexible boards, are tested for function in three different climates, −40°C, room temperature and +60°C. Each unit is also subject to a vibration test. The normal climate in the production plant is 23 ± 3°C and 45 ± 5% RH.

At the system level in- and outgoing connections are the only sensitive ESD points of the products, which are protected by black conductive plastic and conductive bags. The product itself is EMI protected (Faraday's cup). All equipment has built-in protection circuits with diodes which must not be inactivated or the ESD protection disappears.

The Bofors experience from their great efforts in the fields of ESD and quality assurance are generally very positive. ESD damages simply must be avoided for the company to deliver products to defence customers. To begin with there were some objections by personnel, for example to the discomfort of wearing wrist bands. With the expansion of ESD protection, the control and quality system has become more automatic and ESD awareness has become a natural part of production.

Ericsson Telecom AB

For many years Ericsson Telecom AB has had regulations that all ESD-sensitive electronic material, such as semiconductors, printed circuit boards and mounted electronic units, be handled, packaged and transported in an ESD-safe way.

This means that the packaging material must be either 'antitriboelectric', i.e. not cause electrostatic charging when handled (rubbing), or that the material has a surface and volume resistivity low enough to swiftly conduct away any possible charges and also acts as a shield against electrostatic fields.

The two types of material presently used for packaging in Ericsson Telecom are polyethylene plastics treated either with an antistatic agent or carbon. A further requirement is that filling and shock absorbing materials, such as cellulose plastics, in packages are antistatically treated.

Polyethylene plastic with an antistatic agent is used for short-term packaging (< 6 months), while carbon-treated plastic is used for long-term storage of, for example, spare parts. Carbon-treated plastic was chosen for long-term storage because of two drawbacks with the other type. The antistatic effect vanishes over time and there is a risk of the antistatic agent causing corrosion of the electronic equipment.

When purchasing electronic components Ericsson Telecom demand that they are packaged in an ESD-safe way. However, the demand for antistatic packages applies not only to ESD-sensitive electronic components, but also to other components used in electronic production, such as transformers and relays, the packages of which might be placed immediately beside sensitive components during assembly.

Ericsson Telecom's demands on packaging and handling are based on technical specifications for components, customer requirements and on the company's own experience of ESD damages.

In conclusion, Ericsson's ESD policy regarding packaging design is that ESD-safe packaging is vital for the electronics industry.

FURTHER RESEARCH

This paper has reviewed the problems of ESD protection based on extensive literature studies and contacts with a number of industries and research centres.

Very comprehensive research is being conducted all over the world on various ESD aspects. It should be clear from this paper that this is a complex field, which still leaves several gaps in our knowledge and uncertainties.

The following is a list of suggestions for further research tasks and projects in the ESD field, primarily aiming to clarify ESD protection issues.

- Studies of quality variations within and between different packaging products.
- Evaluation of methods given in different standards, of application fields and their advantages and disadvantages. Interpretation of measurement data. Today, for example, several different charging levels and limits for acceptable discharge time to a chosen level which also varies, are used. There are also reproducibility problems. Consensus should be sought in this area.
- Comparative studies of different packaging materials with regard to antistatic properties, such as chargeability, discharge time and shielding ability. The relationship between these properties and material structure, relative humidity, etc. Seals and folds in bags are potential problems, particularly from a shielding point of view.
- Studies on the effects of various environmental factors (vibration, cold, heat, etc.) on the antistatic and shielding properties of packaging materials.
- Studies on the effect of ESD protection at various levels; component, printed circuit board and equipment or system levels.
- The relationships between the different ways of defining the antistatic properties of a material in terms of chargeability, discharge time and surface resistivity have proven to be rather complicated.[5,9] Further studies in this field are imperative.
- Several new materials, mostly of polymer form, in the form of self-conductive polymers, etc., have been developed. More extensive investigations of these are needed.
- No conclusive answers are available yet as to whether conductive or statically dissipative materials are best suited for a certain application. This needs further study.

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