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Electrostatics –
Part 5-6: Protection of electronic devices from electrostatic phenomena – Process assessment techniques

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ELECTROSTATICS –

Part 5-6: Protection of electronic devices from electrostatic phenomena – Process assessment techniques

FOREWORD

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IEC PAS 61340-5-6 has been processed by IEC technical committee 101: Electrostatics.

It is based on ANSI/ESD SP17.1-2020. The structure and editorial rules used in this publication reflect the practice of the organization which submitted it.

The text of this PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document
Draft PAS	**Report on voting**
101/654/DPAS	101/663/RVDPAS

Following publication of this PAS, the technical committee or subcommittee concerned may transform it into an International Standard.

A list of all parts in the IEC 61340 series, published under the general title *Electrostatics*, can be found on the IEC website.

This PAS shall remain valid for an initial maximum period of 2 years starting from the publication date. The validity may be extended for a single period up to a maximum of 2 years, at the end of which it shall be published as another type of normative document, or shall be withdrawn.

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ESD Association Standard Practice for the Protection of Electrostatic Discharge Susceptible Items –

Process Assessment Techniques

Approved November 17, 2020
EOS/ESD Association, Inc.

(This foreword is not part of EOS/ESD Association, Inc. Standard Practice ANSI/ESD SP17.1-2020)

FOREWORD

This standard practice[1] describes a set of methodologies, techniques, and tools that can be used to characterize a process where ESD sensitive (ESDS) items are handled. This document's procedures are meant to be used by those possessing knowledge and experience with electrostatic measurements.

This document provides methods to determine the level of ESD risk that remains in the process after ESD protective equipment and materials are implemented.

These test methods' objective is to identify if potentially damaging ESD events are occurring or if significant electrostatic charges are generated on people, equipment, materials, components, or printed circuit board assemblies (PCBA) even though there are static control measures in place.

Sensitivities of items are characterized by industry-standard ESD testing and rated by their withstand voltages. This document is intended to provide methods to determine whether items of a given withstand voltage are at risk in the process.

The wide variety of ESD protective equipment and materials and the environment in which these items are used may require test setups different from those described in this document. Users of this standard practice may need to adapt the test procedure and setups described in Annex A to produce meaningful data for the user's application.

Organizations performing these tests will need to determine if on-going process characterization is necessary, and if so, the time interval between observations. It may also be important to make these observations when new products are introduced or when process changes occur. Examples of process changes may include tools, fixtures, equipment, new items/products, and additional manufacturing steps.

The topics below are not addressed in this document:

- Program Management: see ANSI/ESD S20.20 Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)
- Compliance Verification: see ESD TR53-01 Compliance Verification of ESD Protective Equipment and Materials
- Troubleshooting: ESD TR53-01
- ESD Program Certification: see ANSI/ESD S20.20 Certification Program at www.esda.org

This document was designated ANSI/ESD SP17.1-2020 and approved on November 17, 2020.

[1] **ESD Association Standard Practice:** A procedure for performing one or more operations or functions that may or may not yield a test result. Note, if a test result is obtained it may not be reproducible.

At the time ANSI/ESD SP17.1-2020 was prepared, the 17.0 Subcommittee had the following members:

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ESD Association Standard Practice for the Protection of Electrostatic Discharge Susceptible Items – Process Assessment Techniques

1.0 PURPOSE, SCOPE, LIMITATION, AND EXPERIENCE LEVEL REQUIRED

1.1 Purpose

The purpose of this document is to describe a set of methodologies, techniques, and tools that can be used to characterize a process where ESD sensitive (ESDS) items are handled. The process assessment covers risks by charged personnel, ungrounded conductors, charged ESDS items, and ESDS items in an electrostatic field.

1.2 Scope

This document applies to activities that manufacture, process, assemble, install, package, label, service, test, inspect, transport, or otherwise handle electrical or electronic parts, assemblies, and equipment susceptible to damage by electrostatic discharges. This document does not apply to electrically initiated explosive items, flammable liquids, or powders. The document does not address program management, compliance verification, troubleshooting, or program manager/coordinator certification. In this version of the document, risks due to electromagnetic sources that produce AC fields are not considered.

1.3 Limitation

No detailed description of the processes and measurement techniques is given. An example of a simple risk assessment of a discharge from a charged human body is described in Annex D.

Due to the sampling nature in this document's procedures, deficiencies may exist that are not detected at the time the measurements are made. The measurements described are valid only at the time the measurements are made and may or may not change with time.

NOTE: Environmental parameters such as temperature and relative humidity (RH) may significantly impact the measurement results.

1.4 Experience Level Required

The procedures in this document are for use by personnel possessing advanced knowledge and experience with electrostatic measurements. The interpretation of the results from the measurements described in this document requires significant experience and knowledge of the physics of ESD and the process.

2.0 REFERENCED PUBLICATIONS

Unless otherwise specified, the following documents of the latest issue, revision, or amendment form a part of this standard to the extent specified herein:

ESD ADV1.0, ESD Association Glossary of Terms[2]

ANSI/ESD S20.20, For the Development of an Electrostatic Discharge Control Program for –Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)[2]

IEC61340-5-1, Electrostatics–Part 5-1: Protection of Electronic Devices from Electrostatic Phenomena – General Requirements[3]

[2] EOS/ESD Association, Inc. 7900 Turin Road, Bldg. 3, Rome, NY 13440, Ph: 315-339-6937; www.esda.org

[3] IEC – International Electrotechnical Commission, www.iec.ch

3.0 DEFINITIONS

The terms used in the body of this document are in accordance with the definitions found in ESD ADV1.0, ESD Association's Glossary of Terms available for complimentary download at www.esda.org.

process. A unique combination of tools, materials, methods, and people engaged in producing a measurable output.

NOTE: The term "process" can refer to a complete assembly process or a minor step, such as a pick-and-place process.

process assessment. A methodological framework to evaluate the process capabilities regarding defined parameters.

process capability. Parameters for different ESD risks that allow safe handling of items with a given ESD withstand voltage.

4.0 PERSONNEL SAFETY

THE PROCEDURES AND EQUIPMENT DESCRIBED IN THIS DOCUMENT MAY EXPOSE PERSONNEL TO HAZARDOUS ELECTRICAL CONDITIONS. USERS OF THIS DOCUMENT ARE RESPONSIBLE FOR SELECTING EQUIPMENT THAT COMPLIES WITH APPLICABLE LAWS, REGULATORY CODES, AND BOTH EXTERNAL AND INTERNAL POLICY. USERS ARE CAUTIONED THAT THIS DOCUMENT CANNOT REPLACE OR SUPERSEDE ANY REQUIREMENTS FOR PERSONNEL SAFETY.

GROUND FAULT CIRCUIT INTERRUPTERS (GFCI) AND OTHER SAFETY PROTECTION SHOULD BE CONSIDERED WHEREVER PERSONNEL MIGHT COME INTO CONTACT WITH ELECTRICAL SOURCES.

ELECTRICAL HAZARD REDUCTION PRACTICES SHOULD BE EXERCISED, AND PROPER GROUNDING INSTRUCTIONS FOR EQUIPMENT MUST BE FOLLOWED.

THE RESISTANCE MEASUREMENTS OBTAINED THROUGH THE USE OF THIS TEST METHOD SHALL NOT BE USED TO DETERMINE THE RELATIVE SAFETY OF PERSONNEL EXPOSED TO HIGH AC OR DC VOLTAGES.

5.0 MEASUREMENT TECHNIQUES FOR ESD RISK ASSESSMENT

Specific test equipment is needed for specific measurement techniques to perform a proper risk assessment. The appropriate instruments are required to measure if a material fulfills given requirements. Additionally, the charging status of an object or even the discharge current waveform of this object must be measured. Each process step might need a different technique and tool to measure whether there is a risk to the ESDS items being processed. This chapter describes the basic measurement techniques that can be used to assess various risks in different scenarios.

Table 1 lists tools that can measure parameters to assess whether there is a risk for the items handled in a process. Measurement of the object's actual discharge under consideration is desirable but difficult to accomplish in a production environment. The discharge waveform then could be compared with the qualification waveform, and the risk could easily be assessed. However, this is often difficult to achieve, especially in a production environment. Therefore, indirect parameters must be assessed, such as charging of the object, although this parameter does not tell the user whether a catastrophic discharge is happening. If it is not possible to measure charging, measurements such as resistance to ground may need to be used (see Figure 1). A detailed description of all the test methods is given in Annex A.

NOTE: All measurements should be performed with verified test equipment to ensure that the measurements are not influenced by defective equipment.

Table 1 – Overview of Possible Measurement Equipment Used for Different Scenarios to Assess ESD Risk

Parameter (Document)	Personnel	Conductors	Insulators	Devices/PCBs
Grounding (Annex A.2)	Resistance measurement apparatus	Multimeter	–	–
Electrostatic fields (Annex A.3)	Field meter	Field meter	Field meter	Field meter
Charge (Annex A.4)	Electrometer Current probe	Faraday cup Electrometer Current probe	Faraday cup	Faraday cup Electrometer Current probe
Electrostatic voltage (Annex A.5)	Charged Plate Monitor Walking Test Kit ESVM[a] HIDVM[b] Field meter[c]	ESVM[a] HIDVM[b] Field meter[c]	ESVM[a] Field meter[c]	ESVM[a] HIDVM[b] Field meter[c]
Resistance of material contacting ESDS item (Annex A.6)	Resistance measurement apparatus	Resistance measurement apparatus, Multimeter	–	Resistance measurement apparatus
Discharge events (Annex A.7)	Antenna with oscilloscope ESD event detector	Antenna with oscilloscope ESD event detector	–	Antenna with oscilloscope ESD event detector
Discharge currents (Annex A.8)	Current probe Pellegrini target	Current probe Pellegrini target CDM test head	–	Current probe CDM test head

[a] ESVM = non-contact electrostatic voltmeter

[b] HIDVM = contact-based high-impedance digital voltmeter

[c] used as non-contact electrostatic voltmeter

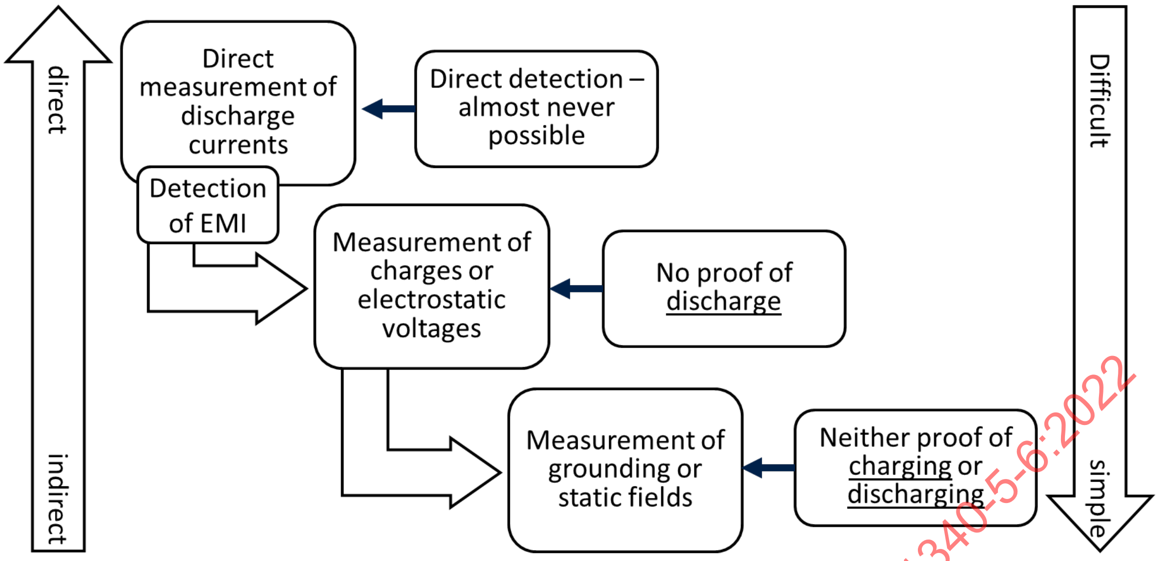

Figure 1 – Direct (Best Correlation) and Indirect (Least Correlation) Measurements to Assess an ESD Risk

6.0 ESD ROBUSTNESS OF ESDS ITEMS USED IN PROCESSES

For a successful process assessment, one or more of the electrical/physical parameters listed in Table 1 and the process assessment flows in Section 7.0 must be measured and compared against set limits. However, the parameters' limits depend on the process, measurement methodologies and techniques, and ESD robustness of the ESDS items. Therefore, it is not possible to define one limit for the parameters of all ESDS items and processes. It is particularly important to distinguish between handling a single integrated circuit (IC) and electronic assemblies. For example, a single device with relatively high robustness against a charged device model (CDM) discharge may be more susceptible to damage once installed on a PCBA. The PCBA has a larger capacitance than the single device, which may result in more severe stress (higher peak current, higher charge).

Defining limits requires some knowledge about the ESD robustness of the ESDS item that is being handled in the process and knowledge about the process itself. As the ESD robustness of the ESDS item in this process is better known, and the process is analyzed in greater detail, more accurate limits can be determined. Otherwise, reasonable assumptions must be made.

The discharge event is the most critical point of a process or application, and determining the discharge current is the most direct parameter for the risk assessment. Comparing the discharge current as measured in the process with the withstand current obtained during ESD qualification tests is theoretically the best approach. However, discharge currents from qualification data are often unknown and not easily obtainable directly in process measurements. Hence, more indirect parameters must be used for ESD risk assessment. In most cases, the charging and the ESD robustness voltage of the ESDS item are used for the assessment. Each uncertainty in the ESD robustness of the ESDS item or the knowledge about the process reduces the accuracy and, consequently, results in a higher effort combined with a possible larger margin that has to be taken to exclude any risk.

Section 6.1 discusses how the withstand current of the different discharge scenarios can be either derived from qualification data or from limits defined in ANSI/ESD S20.20 or IEC 61340-5-1. A similar discussion of withstand currents of electronic assemblies is outlined in Section 6.2. These withstand currents are the basis for assessing the limits of the measurement parameters listed in Table 1 and the process assessment flows in Section 7.0.

6.1 ESD Withstand Currents of Single Devices (Components)

6.1.1 Human Body Model

Component manufacturers use the human body model (HBM) test to determine ESDS items' sensitivity to discharge from a simulated charged person. Current HBM qualification procedure is described in the standard ANSI/ESDA/JEDEC JS-001 [1]. Typically, in HBM qualification, the HBM discharge voltage V_{HBM} is reported, not the HBM discharge current I_{HBM}, which is the real damaging parameter. However, the HBM withstand current I_{HBM} can be derived from the HBM withstand voltage rather accurately by $I_{HBM} = V_{HBM}/R_{HBM}$ with R_{HBM} = 1500 ohms being the serial resistance in the HBM discharge network.

- If the HBM robustness in terms of withstand voltage VHBM of the component is known, the withstand current can be calculated by $I_{HBM} = V_{HBM}/R_{HBM}$. For example, a component with an HBM robustness of 1000 volts has an HBM withstand current of I_{HBM} = 1000 volts/1500 ohms ≈ 670 milliamperes.

  NOTE: If the HBM robustness of the component is unknown, but similar products with the same power supply concept and set of I/O cells have been qualified according to HBM, this qualification value can be used as HBM robustness.

- If the HBM robustness of the component is not known, 100 volts HBM robustness can be used as a reasonable lower limit of ESDS items that can be handled in an EPA according to ANSI/ESD S20.20. For most of the components, this value might be quite conservative, but still can be achieved rather easily in a process. The maximum HBM withstand current I_{HBM} is then 67 milliamperes.
- If the component's HBM robustness is unknown, and the application does not tolerate any ESD-related failures, the assumed HBM robustness could be lowered; however, a lower HBM robustness might require additional ESD control measures.

6.1.2 Discharge of Charged Conductors

The risk of a component being damaged by the contact to a charged conductor while at least one pin of the component is on a different potential (typically grounded) was previously thought to correlate to the "machine model" (MM) test. However, MM is no longer used for component ESD qualification due to severe deficiencies in repeatability and reproducibility. Therefore, MM qualification results are typically not available.

NOTE: A discharge of a charged conductor to a floating device is modeled by CDM because it is the closest approximation.

- If HBM qualification is available, HBM thresholds divided by ten could act as a reasonable approach to correlate with a charged conductor's discharge into a component on a different potential. According to [2], the correlation between V_{HBM} and V_{MM} is in the range of 3:1 to 30:1. According to [3], the MM withstand current is 1.75 amperes per 100 volts. As an example, if the HBM robustness of a component is 500 volts, the corresponding MM withstand voltage can be estimated to be $V_{MM} = V_{HBM}/10$ = 50 volts, and the MM withstand current to be I_{MM} = 1.75 amperes x (V_{MM}/100 volts) = 880 milliamperes.
- If the HBM robustness of the component is not known, 35 volts MM robustness against a discharge of a charged conductor can be used as a reasonable lower limit of ESDS items that can be handled in an EPA according to ANSI/ESD S20.20. For most of the components, this value might be quite conservative, but still can be achieved rather easily in a process. A withstand voltage of 35 volts corresponds to approximately 600 milliamperes MM withstand current.
- If the component's HBM robustness is unknown, and the application does not tolerate any ESD-related failures, the assumed MM robustness could be lowered; however, a lower MM robustness might require additional ESD control measures.

6.1.3 Charged Device Model

The phenomenon of a charged component or a component in the presence of an electric field being discharged when contacted by a conductive item is referred to as a charged device model event. The current version of this model is described in the standard ANSI/ESDA/JEDEC JS-002 [4]. For assessing the risk of damage in this CDM scenario, the CDM robustness of the component must be known.

- If the CDM robustness in terms of withstand current I_{CDM} of the component is known, the withstand current can be used and correlated directly to the discharge current in the process. For example, if the qualification withstand current I_{CDM} of the IC is 3.0 amperes, discharge currents of 3.0 amperes in the process should not damage the component.
- If only the CDM withstand voltage VCDM is known, the CDM withstand current ICDM must be estimated. For components with small capacitance (< 10 pF), the CDM current correlates to the CDM voltage with ~1.0 ampere/100 volts, which means I_{CDM} = 1.0 ampere x (V_{CDM}/100 volts), knowing that this is extremely conservative for very small components. For example, for components with larger capacitance (~50 pF), the correlation is I_{CDM}/V_{CDM} = 2.0 amperes/100 volts, that means I_{CDM} = 2.0 ampere x (V_{CDM}/100 volts). The capacitance of the component in the CDM tester can be approximated from a comparison with the size of the modules used for the verification of CDM qualification testers.

  NOTE: If the component's CDM robustness is unknown, but similar components with the same power supply concept, set of I/O cells, and the same die size and package have been qualified according to CDM, this qualification value can be used as a realistic approximation of the CDM robustness.
- If the CDM robustness of the component is not known, 200 volts CDM robustness (corresponds to 2.0–4.0 amperes CDM current) can be used as a reasonable lower limit of ESDS items that can be handled in an EPA according to ANSI/ESD S20.20. Experience has shown that a 100-volt CDM robustness (corresponding to 1.0–2.0 amperes CDM current) is sufficient to handle components in most of the processes without ESD damage; however, it requires advanced charge and discharge control techniques in the process.

6.2 ESD Withstand Currents of Electronic Assemblies

6.2.1 Discharge of Charged Personnel

For electronic assemblies/systems, in most cases, no HBM qualification is performed. However, as the current and energy of an HBM event do not change whether discharged to a single device (component) or an electronic assembly, the worst-case approximation is that all the discharge current is dissipated through one component. The robustness of the entire system is then determined by the component with the lowest HBM robustness.

For the HBM robustness of the single component, the same considerations as in Section 6.1.1 apply.

6.2.2 Discharge of Charged Conductors

For risks of electronic assemblies by charged conductors, the same considerations are valid as for HBM risk of electronic assemblies (Section 6.2.1). As the discharge current and energy of a charged conductor does not change whether discharged to a component or an electronic assembly, the worst-case approximation is that all the discharge current is dissipated through one component. The robustness of the entire system is then determined by the component with the lowest HBM robustness.

For the robustness of the single component, the same considerations as in Section 6.1.2 apply.

NOTE: Charged cables and the risk of a cable discharge event (CDE) can also be assessed as charged isolated conductors.

6.2.3 Discharge of Boards/Systems

The worst-case HBM risk for electronic systems could be correlated to the component's HBM robustness. In contrast, for the discharge of a charged board (charged board event, CBE) or system or a board/system in an electric field, no easy correlation to any component robustness qualification exists. The reason for this is that even if on a board, a component pin is contacted directly, the charge stored at the board is typically significantly higher compared to the charge stored on a single component. Knowing the discharge peak current is required to establish any worst-case approximation. No qualification method exists yet for boards and electronic assemblies.

As a very simple worst-case approximation, the maximum allowed peak discharge current of a board (that is, the current flowing through the conductive item that contacts the board) can be estimated from the component's CDM threshold currents, see Section 6.1.3. As the charge stored at the board is larger than the charge stored on a single component, resulting in a wider full-width half maximum of the discharge current waveform and consequently more severe stress, a safety factor should be included. From experimental data, a safety factor of two seems to be a reasonable estimate [5]. For example, if all components on the board or in the system do not fail 3 amperes CDM current, very likely, a board discharge current of 1.5 amperes will not cause damage to the components on the board. This worst-case approximation requires that the discharge current in the process can be measured, which is rarely the case.

If the discharge current of the board cannot be measured, the only reasonable approach is to avoid "all" possible discharges or limit the charging of the board/system to an exceptionally low and safe value. From data in the literature (for example, see [13] and references therein), a worst-case approximation could be to limit the charging of the board/system to one-tenth of the minimum CDM robustness of all devices. For example, if the minimum CDM robustness of all components is known or assumed to be 200 volts, then the charging of the board should not exceed 20 volts.

NOTE: Another option is to limit the discharge current by contacting the ESDS item with a dissipative or insulative material. See the assessment flows in Sections 7.4 and 7.5.

7.0 PROCESS ASSESSMENT FLOW

7.1 General Considerations

Standards such as ANSI/ESD S20.20 and IEC 61340-5-1 give guidance on implementing an ESD control program for handling ESDS items in EPAs. ESD failures can still happen even in well-equipped EPAs, as reported in many publications (see references in [6]). A detailed risk assessment is needed for the various process steps to avoid failures coming from the production process. A process assessment needs to cover risks induced by charged personnel, ungrounded conductors, charged insulators, and charged ESDS items.

Although automated processes dominate many production areas, manual process steps still exist, especially at process transition points and manual PCBA handling processes. Therefore, assessing operator grounding and charging of personnel is necessary. Standards such as ANSI/ESD STM97.2 [7] provide good guidance on measuring an operator's body voltage using footwear/flooring grounding. Without such an assessment, ESD protective elements might not fit together and are not as effective.

Isolated conductors can charge and discharge into ESDS items. Hence, it is also important to care for isolated conductors when handling ESDS items. These failures can be avoided by removing charges from all conductors, especially those in direct or close contact with the ESDS item. Following ANSI/ESD S20.20, the maximum voltage difference between an ESDS item and a conductor shall not exceed 35 volts to limit possible discharge currents between the conductor and the ESDS item to an acceptable level.

Issues with CDM-type discharges are becoming more and more dominant. Many handling steps are now almost completely automated without interaction from people. A fact that imposes a high risk here is that many processes use insulators to aid in the process of producing a product or are part of the product itself. One basic idea of CDM protection is to control the charge on insulators, thereby avoiding charging and electrostatic fields wherever possible. This can be achieved by removing all nonessential insulators and controlling/reducing the charging of process required insulators to a safe level – including charging of both devices and printed circuit board assemblies (PCBAs).

The following sections describe this in more detail.

7.2 Manual Handling Steps

7.2.1 Introduction

Like automated systems, manual handling steps must be checked for charge generation and the potential for direct discharge paths into ESDS items. According to ANSI/ESD S20.20, the charging is limited to an electrostatic voltage of 100 volts on the personnel in an EPA. Whether this value or any other value obtained in the process can cause damage to an ESDS item handled by the personnel has to be evaluated.

The time to complete the steps being evaluated must be considered during the evaluation. If the evaluation is slower than the process, potential critical discharging or charging could be missed.

7.2.2 Parameter Limits for ESD Process Assessment in Manual Handling Steps

Four different parameters can be measured to assess the risk of an ESDS item damaged by charged personnel. The results of the measurements can vary depending on the personnel and the grounding mechanisms. This variation must be considered in the assessment.

1. <u>Discharge current (time-dependent).</u> The discharge peak current of charged personnel into ground can be related directly to the HBM withstand current of an ESDS item (see Sections 6.1.1 and 6.2.1). For a correlation, the decay time of the measured pulse must be below 170 ns. The decay time is the time interval between when the current is at maximum and when the pulse current is decayed to 36.8% of the maximum. Typically, the HBM stress in a commercial HBM qualification tester is much more severe than the discharge of a human being charged to the same voltage [8] and does not need any additional margin. Therefore, the HBM withstand current I_{HBM} can be an approximation of the upper limit for the personnel's discharge peak current. For example, an IC with a component HBM current threshold I_{HBM} = 1 ampere should not be damaged by a discharge current of 1 ampere from personnel (or according to Section 6.1.1, by a discharge current of personnel charged to 1500 volts).
2. <u>Contact resistance of personnel.</u> With a measured contact resistance of personnel $R_{contact}$, the maximum discharge current of charged personnel $I_{personnel} = V_{personnel}/R_{contact}$ can be derived by Ohm's law and compared with the component HBM qualification withstand current I_{HBM}. For this, a worst-case maximum electrostatic potential of the personnel (that is, the personnel's charging) must be known. If the personnel work in an ANSI/ESD S20.20-compliant ESD protected area, the maximum charging of personnel is limited to 100 volts. For example, with HBM qualification withstand current I_{HBM} = 1 ampere, the minimum contact resistance of personnel $R_{contact}$ can be calculated by $R_{contact}$ = 100 volts/1 ampere = 100 ohms. In contrast, if the personnel are working outside an EPA and can consequently be charged to voltages as high as 30,000 volts, the minimum resistance is higher, $R_{contact}$ = 30,000 volts/1 ampere = 30 kilohms.
3. <u>Electrostatic voltage of personnel.</u> Quite often, the electrostatic voltage of personnel can be measured rather easily, and it is simply compared with the HBM withstand voltage VHBM of the ESDS item. This works well as a worst-case approximation, as the HBM stress in a commercial HBM qualification tester is, in general, more severe than the discharge of a human being charged to the same voltage [8]. However, this approximation does not consider possible serial resistances in the discharge path from the personnel to the ESDS item (see above), limiting the personnel's discharge current. For example, a component with an HBM robustness of V_{HBM} = 1500 volts should not be damaged by a discharge of personnel charged to 1500 volts. However, if the personnel wears gloves with, for example, $R_{contact}$ = 100 megohms which do not break down at high voltages, there is no risk of a critical discharge even for electrostatic voltages of personnel far beyond V_{HBM} = 1500 volts, which is not considered in the simple assessment based on electrostatic voltages.
4. <u>Grounding of personnel.</u> The resistance to ground of personnel can be roughly correlated to the body voltage of personnel. According to ANSI/ESD S20.20, a resistance-to-ground of R_g = 35 megohms limits personnel's electrostatic voltage to less than 100 volts, with a roughly linear dependence. For example, if R_g = 100 megohms is measured, the personnel's maximum electrostatic voltage can be estimated to 250 volts. That electrostatic voltage can then be correlated as a worst-case scenario to the HBM withstand voltage V_{HBM}; see item 3 above.

7.2.3 Detailed ESD Risk Assessment Flow

All locations within the entire facility where personnel handles the ESDS items need to be defined to determine the facility's HBM process capability. Once these locations are defined, measurements can be done to determine the HBM process capability, according to Figure 2.

1. Measure the discharge current of an ESD event from the finger of charged personnel to ground using a Pellegrini Target or a current probe. If personnel are using gloves during operations in the EPA, the discharge current should be measured with gloves.
2. If the measurement is possible, move to step 8; if not, continue with step 3.
3. Measure the contact resistance of personnel using a hand-held electrode and a resistance measurement apparatus.
4. If the measurement is possible, move to step 8; if not, continue with step 5.
5. Measure the electrostatic voltage of personnel using a charged plate monitor, a walking test kit, a non-contact electrostatic voltmeter, a contact-based high-impedance digital voltmeter, or a field meter used as a non-contact electrostatic voltmeter.
6. If the measurement is possible, move to step 8; if not, continue with step 7.
7. Measure the grounding of the personnel using a resistance measurement apparatus.
8. Compare the measured value (discharge current, contact resistance of personnel, electrostatic voltage, and grounding) with the defined limit.
9. If the measured value is not within the defined limits, continue with step 10. If the measured value is within the defined limits, conclude the assessment with the result that there is low ESD risk by personnel.
10. Check the handling procedure and any possible personnel contacts to any ESDS item.
11. If personnel do not come into close contact with the ESDS item in the entire process (or EPA),
    a. Conclude the assessment with the result that there is low ESD risk by personnel.
    b. Otherwise, measures should be taken to reduce the ESD risk, for example, by reducing the charging of personnel or changes in the process.

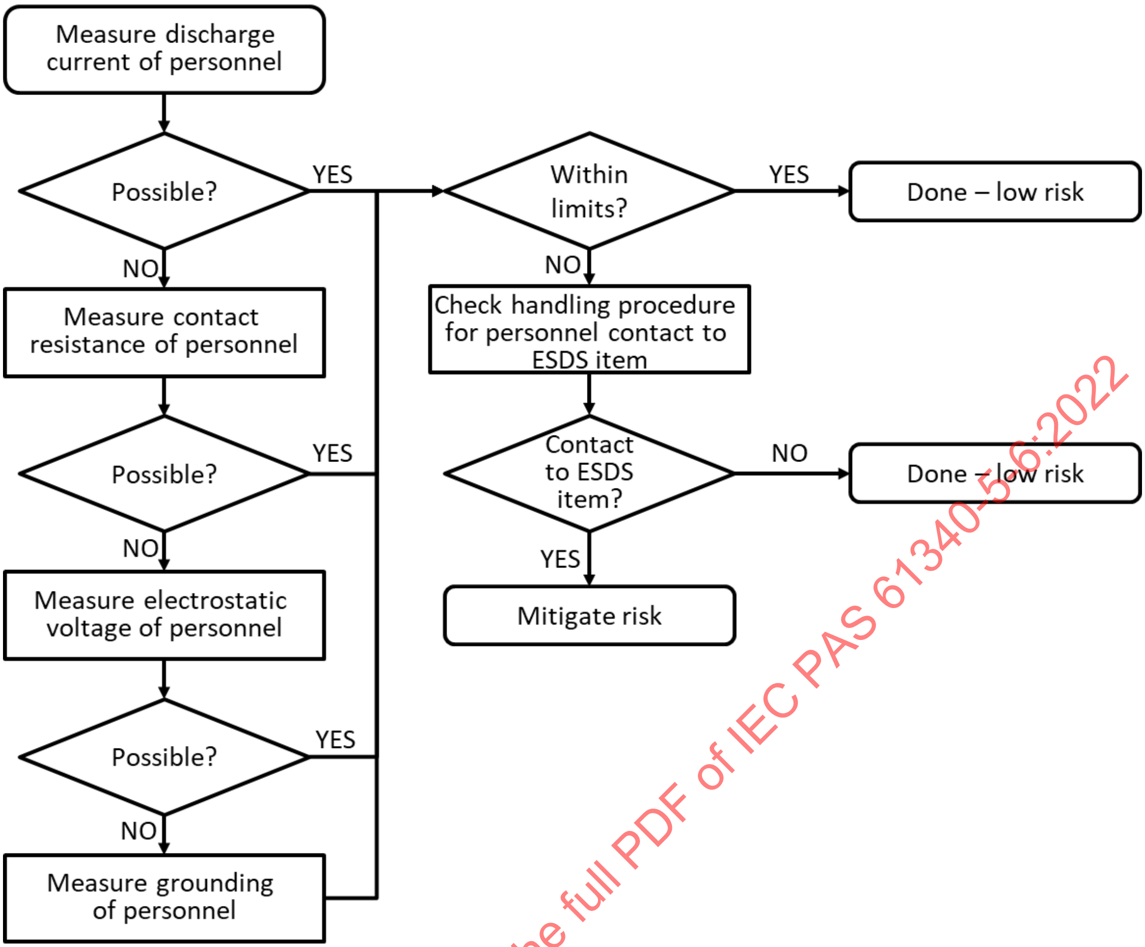

Figure 2 – Flow to Assess ESD Risk Induced by Personnel

NOTE: It is not necessary to follow the flow from measurement with "best correlation" to measurement with "least correlation" (see Figure 1). Steps can be taken in any order.

7.3 Conductors

7.3.1 Introduction

A conductor is a material that measures point-to-point resistance of less than 1.0 x 10^4 ohms. An isolated conductor is defined as a conductor with a point to ground resistance larger than 1.0 x 10^9 ohms.

The most important ESD control principle is to ensure all electrical conductors are interconnected (bonded) and, when possible, connected to ground. However, there are instances in many processes where a conductor is isolated from ground. Isolated charged conductors, in particular very low resistance conductors, can become a significant hazard when charged during a process.

Any accumulated charge can discharge rapidly from a charged conductor so the discharge energy can be significant (depending on the capacitance of the isolated conductor). This discharge has little or no resistance if the contact is made at a conductive part of the ESDS item.

The conductor's risk of becoming isolated increases as the length of time between the equipment grounding verification increases. Moving conductors can cause them to break free from their grounding connections, causing an intermittent loss of ground. This allows charge generation and potential discharging at a later step in the flow.

NOTE: An additional risk of charged conductors in a process is that they are a source of an electrostatic field and, consequently, inductive charging. For assessing this risk, see Section 7.5.

7.3.2 Parameter Limits for Process Assessment of Conductors

Three different parameters can be measured to assess the risk of an ESDS item damaged by charged conductors:

1. Discharge current (time-dependent). The discharge peak current of a conductor into ground can be directly correlated to a conductor's withstand current into an ESDS item. The discharge current into an ESDS item can be derived from the component HBM withstand current I_{HBM} or voltage V_{HBM} (see Section 6.1.2). The direct correlation requires that the period of the major pulse t_{pm} measured between the first zero-crossing point and the third zero crossing point (t_{pm} in [3]) is less than 100 ns. For example, an ESDS item with a component HBM withstand voltage of 1500 volts will withstand a discharge of a capacitor with 200 pF (MM) of roughly 150 volts, corresponding to 2.6 amperes (Section 6.1.2). Thus, a discharge current measured in the process of less than 2.6 amperes with t_{pm} < 100 ns should not damage that ESDS item.
2. Electrostatic voltage and charge of a conductor. If the charge stored at the conductor $Q_{conductor}$ and the electrostatic voltage at the conductor $V_{conductor}$ can be measured, the energy stored in the conductor can be calculated by $W_{conductor} = 0.5 \times Q_{conductor} \times V_{conductor}$ and $Q_{conductor} = C_{conductor} \times V_{conductor}$. The charged conductor's energy can be compared with the energy of a component MM qualification test derived from HBM qualification data. For example, a component HBM withstand voltage of V_{HBM} = 1000 volts results in an estimated component MM withstand voltage of V_{MM} = 100 volts (see Section 6.2.2). With a capacitor of C_{MM} = 200 pF, the withstand energy in the qualification test is $W_{MM} = 0.5 \times C_{MM} \times V_{MM}^2$ = 1 µJ. A discharge from a conductor with a stored charge of $Q_{conductor}$ = 40 nC and an electrostatic voltage of 35 volts, resulting in a stored energy of 0.7 µJ, should not damage the ESDS item.
3. Grounding of a conductor. The grounding of the conductor (the resistance to ground R_g) determines the maximum dynamic charging of the conductor. One possibility is to measure the AC voltage at the conductor during operation. From experience over many years and processes, ESDS items with an HBM withstand voltage of 100 volts can be handled safely if the AC voltage on the conductor is below 50 millivolts. Larger or smaller measured AC voltages would allow handling ESDS items with less or higher HBM withstand voltage. To a first approximation, linear scaling can be used to calculate the lowest acceptable HBM withstand voltage.

7.3.3 Detailed ESD Risk Assessment Flow

Here the first step in an ESD process assessment is to thoroughly analyze possible steps in which conductors can come into close proximity or direct contact with any ESDS item.

NOTE: Close proximity is a distance where an air discharge can occur, that depends on many factors, including potential difference, capacitance, shape, and speed of approach

Although there might be many conductors in equipment, there is no risk without close or direct contact with an ESDS item. If a conductor comes into close proximity or direct contact with an ESDS item, the conductor's charging must be assessed according to Figure 3. This can be done either directly by measuring the charge or indirectly by measuring grounding parameters.

1. Assess whether the conductor comes into close proximity or direct contact with the ESDS item during the process. If there is no close proximity or direct contact of the conductor to an ESDS item, conclude the assessment that there is low ESD risk by this conductor.
2. Measure the conductor's discharge current using a current probe, a Pellegrini target, or a CDM test head.
3. If the measurement is possible, move to step 7; if not, continue with step 4.
4. Measure the electrostatic voltage at the conductor using a non-contact electrostatic voltmeter, a contact-based high-impedance digital voltmeter, or an electrostatic field meter used as a non-contact electrostatic voltmeter. Additionally, measure the conductor's charge using an electrometer, a current probe, or a faraday cup.
5. If the measurement is possible, move to step 7; if not, continue with step 6.
6. Measure grounding-related parameters, for example, by an AC voltage check or a resistance-to-ground measurement of the conductor during movement.
7. Compare the measured parameter (discharge current, electrostatic voltage and charge and surface resistance, grounding) with the defined limit.

8. If the measured parameter is within the defined limits,
   a. Conclude the assessment with the result that there is low ESD risk by the conductor.
   b. Otherwise, measures should be taken to reduce the ESD risk, for example, by improving the grounding of the conductor or changes in the process.

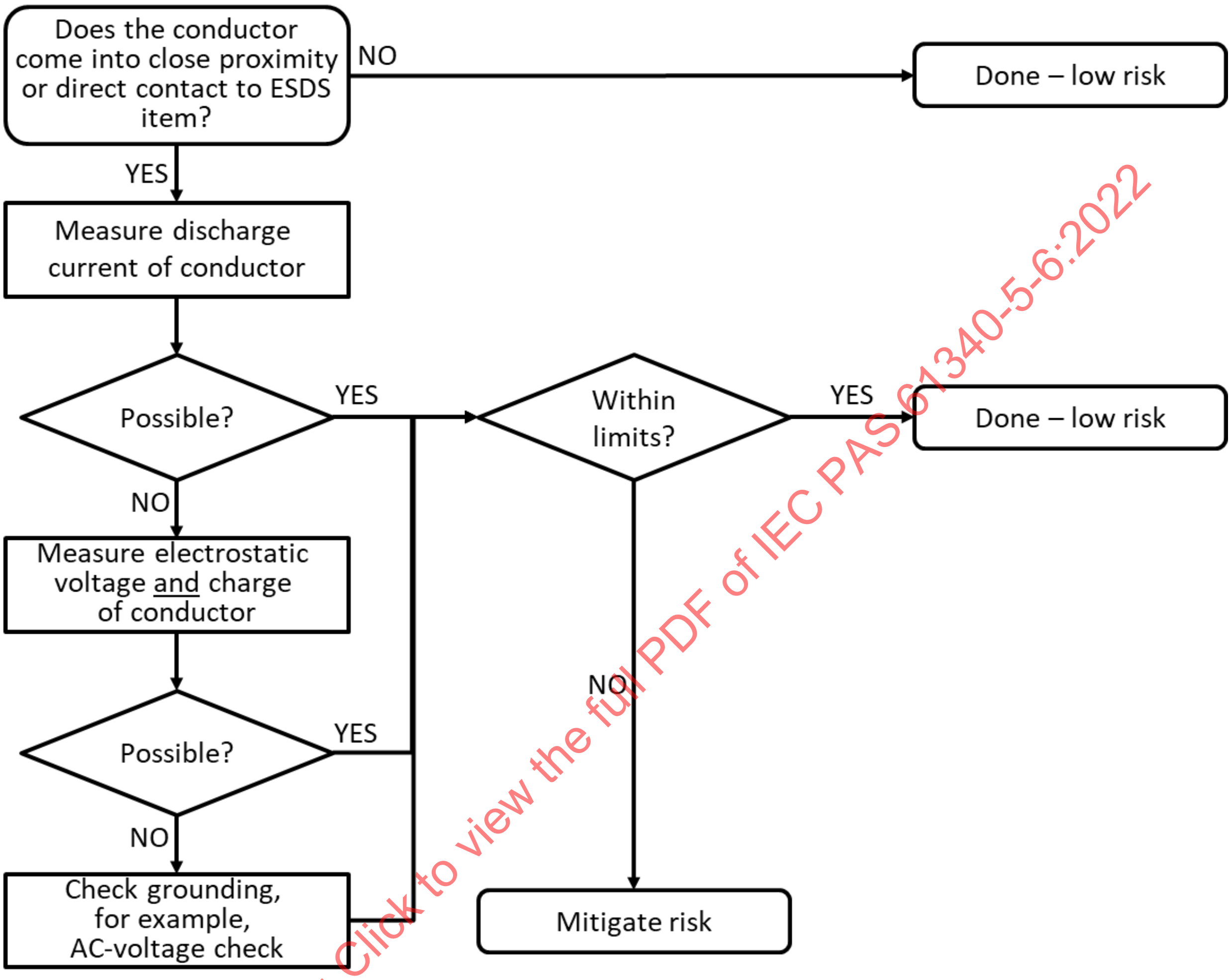

Figure 3 – Flow to Assess the ESD Risk Induced by Conductors

NOTE: It is not necessary to follow the flow from measurement with "best correlation" to measurement with "least correlation" (see Figure 1). Steps can be taken in any order.

7.4 Charged ESDS Items

7.4.1 Introduction

Often in automated handling processes, the component or PCBA is charged and eventually sees a hard discharge. A hard discharge is a discharge through a low ohmic contact; it is the most severe discharge compared to a discharge through a higher resistance contact. The charged device model describes the discharge of a single component and not the discharge of a complete PCBA. Nevertheless, the techniques used to assess ESDS items' risk are the same for components and PCBAs.

7.4.2 Parameter Limits for Process Assessment of Charged ESDS Items

Three different parameters can be measured to assess the risk of an ESDS item damaged when contacting a conductive material at a different potential:

1. Discharge current (time-dependent). The discharge peak current of an ESDS item into a conductive object can be directly correlated to the withstand current of an IC derived from the component CDM withstand current ICDM or component CDM withstand voltage VCDM (see Sections 6.1.3 and 6.2.3). The direct correlation requires that the ESDS item's capacitance in the discharge scenario is roughly equal or smaller than the component's capacitance in the CDM qualification tester. For example, an IC with a CDM withstand current of 3.0 amperes will typically withstand a discharge current of 3.0 amperes in the process (Sections 6.1.3 and 6.2.3).
2. Electrostatic voltage at ESDS item. The electrostatic voltage of a single component measured in the process can often be correlated directly to the CDM withstand voltage VCDM of the device measured during component qualification. Typically, the capacitance of the component in the CDM qualification tester is higher than the component's capacitance in the discharge scenario in the process. Thus, the CDM qualification voltage acts as a worst-case correlation. ICs with a CDM robustness of VCDM = 250 volts should withstand discharges in a process when being charged to 250 volts or lower.

   NOTE: The electrostatic voltage can also be estimated from the ESDS item's charge and its capacitance.

   For electronic assemblies, the electrostatic voltage cannot be correlated directly to the CDM robustness of single components because the capacitances of electronic assemblies or systems are typically much larger, and the discharge path on board is not exactly known. Some considerations are discussed in Section 6.2.3.
3. Resistance-to-ground (R_g) and surface resistance of the item enabling the ESDS item to discharge. The surface resistance and the resistance-to-ground of the item contacting the ESDS item and enabling the ESDS item to discharge determine the CDM discharge current. As a rule of thumb, all items contacting the ESDS item should be in the dissipative range (10^4 ohms to less than 10^{11} ohms). In more detail, the resistance can be estimated by applying Ohm's law to limit the discharge current: $R_{contact} > V_{charge}/I_{CDM}$. For charging of an ESDS item with a component, CDM qualification withstand current I_{CDM} = 4.0 amperes in a process of V_{charge} = 200 volts, the surface resistance of the contacting item should be $R_{contact}$ > 200 volts/4.0 amperes = 50 ohms. For processes with a higher electrostatic voltage or with more sensitive components (for example, in PCB assembly processes), the item contact resistance must be correspondingly higher.

7.4.3 Detailed ESD Risk Assessment Flow

The assessment follows the steps in Figure 4.

1. Assess whether the ESDS item comes into proximity or direct contact with a conductive surface during the process. If there is no proximity or direct contact of the ESDS item to a conductive surface, conclude the assessment with the result that there is low ESD risk for the ESDS item.

   NOTE: The surface resistance of the conductive surface is assumed to be less than 10^4 ohms when measured with a resistance measurement apparatus. If the surface resistance of the item contacting the ESDS item is higher than 10^4 ohms measured with a resistance measurement apparatus, the risk for a charged ESDS item is low.
2. Measure the discharge current of the ESDS item using a current probe or a CDM test head.
3. If the measurement is possible, move to step 7; if not, continue with step 4.
4. Measure the ESDS item's charge using an electrometer, current probe, or Faraday Cup. Alternatively, the electrostatic voltage at the ESDS item may be measured by a non-contact electrostatic voltmeter, contact-based high-impedance digital voltmeter, or electrostatic field meter used as a non-contact electrostatic voltmeter.
5. If the measurement is possible, move to step 7; if not, continue with step 6.
6. Measure the resistance-to-ground (R_g) and the surface resistance of the item enabling the ESDS item to discharge using a resistance measurement apparatus.

   NOTE: Surface resistance is required to assess the risk of a “hard” discharge of the ESDS item into the object.
7. Compare the measured parameter (discharge current, charge, electrostatic voltage, R_g, and surface resistance) with the defined limits. If the measured value is not within the defined limits, continue with step 8. If the measured value is within the defined limits, conclude the assessment with the result that there is low ESD risk by the charged ESDS item.

8. Define measures to mitigate the ESD risk, for example, by reducing the charging of the ESDS item or changes in the process to avoid critical contacts.

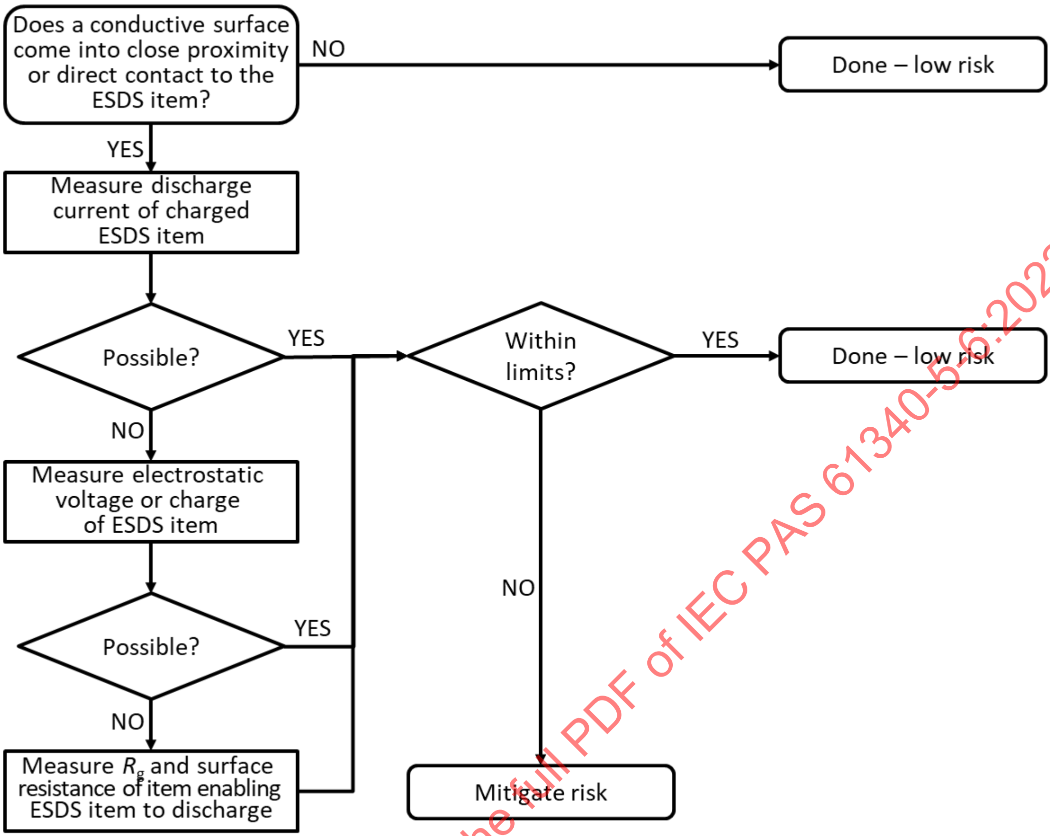

Figure 4 – Flow to Assess the ESD Risk Induced by Charged ESDS Items

NOTE: It is not necessary to follow the flow from measurement with "best correlation" to measurement with "least correlation" (see Figure 1). Steps can be taken in any order.

7.5 Risks Due to Process-Required Insulators

7.5.1 Introduction

Insulators can become charged in a process but are not a significant discharge threat since current does not flow readily from a charged insulator. The primary risk of a charged insulator in a process is that they are a source of an electrostatic field and, consequently, inductive charging. A charged insulator produces an electrostatic field that will cause ESDS items that are momentarily grounded in the presence of that electrostatic field to discharge. Removal of nonessential insulators is a major step in reducing electrostatic discharge risks. Replacement or treatment of insulating materials to render them dissipative is also a way to reduce risk, but possible contamination of the manufacturing process should be considered.

7.5.2 Parameter Limits for Process Assessment of Process-Required Insulators

Four different parameters can be measured to assess the risk of an ESDS item damaged due to contacting a conductive object in the presence of an electrostatic field generated by a process-required insulator. The assessment for discharge currents and electrostatic voltages at the ESDS item is identical to Section 7.4.2.

1. Discharge current (time-dependent). The discharge peak current of an ESDS item into a conductive object can be directly correlated to the withstand current of an ESDS item derived from the CDM withstand current ICDM or CDM withstand voltage VCDM (see Sections 6.1.3 and 6.2.3). The direct correlation requires that the ESDS item's capacitance in the discharge scenario is roughly equal or smaller than the ESDS item's capacitance in the component CDM qualification tester. For example, an IC with a component CDM withstand current of 3.0 amperes will typically withstand a discharge current of 3.0 amperes in the process (Sections 6.1.3 and 6.2.3).
2. Electrostatic voltage at ESDS item. The electrostatic voltage of a single component measured in the process can often be correlated directly to the CDM withstand voltage V_{CDM} of the component measured during device qualification. Typically, the capacitance of the component in the CDM qualification tester is higher than the component's capacitance in the discharge scenario in the process. Thus, the CDM qualification voltage acts as a worst-case correlation. Components with a CDM robustness of V_{CDM} = 250 volts should withstand discharges in a process when being charged to 250 volts or lower.

   NOTE: The electrostatic voltage can also be estimated from the ESDS item's charge and its capacitance.

   For electronic assemblies, the electrostatic voltage cannot be correlated directly to the CDM robustness of single devices as the capacitances of electronic assemblies or systems are typically much larger. Additionally, the discharge path on the board is not exactly known. Some considerations are discussed in Section 6.2.3.
3. Electrostatic field at the location of the ESDS item. Currently, there is no established correlation between the electrostatic field at the location where the ESDS item is contacted and the charging of the ESDS item. According to ANSI/ESD S20.20, the electrostatic field at the location where a conductive object contacts the ESDS item must not exceed 5000 volts/meter (125 volts/inch). As ANSI/ESD S20.20 assumes safe handling of ESDS items with a CDM robustness of 200 volts or higher, the electrostatic field limit can be roughly correlated to the maximum allowed charging. If the maximum allowed charging of the ESDS item in the process is 100 volts, the electrostatic field limit should be reduced accordingly to 2500 volts/meter.
4. Electrostatic potential measured at the surface of the process-required insulator. ANSI/ESD S20.20 and IEC 61340-5-1 give two limits for the electrostatic potential at the surface of the process-required insulator, which should enable safe handling of devices with a CDM robustness of 200 volts and higher[4]. For a surface potential of greater than or equal to 125 volts and less than 2000 volts, ESDS items can be handled safely 2.5 cm or larger from the charged surface. If the surface potential is equal to or greater than 2000 volts, ESDS items must be kept at least 30 cm away from the charged surface.

[4] Instead of the surface potential, ANSI/ESD S20.20 measures the electrostatic field of the insulator in 1-inch distance. For homogeneous fields, this results in the same limits.

5. In a very rough estimation, these limits could be correlated to the maximum allowed charging of the ESDS item in the process. For example, for components with a CDM robustness of 100 volts, the maximum allowed surface potentials at the process-required insulator should be half of the values defined in ANSI/ESD S20.20 and IEC 61340-5-1 or the distance of the ESDS item to the process-required insulator should be increased.

A recent study [9] shows that the limits for the surface potential at the process-required insulator, as defined in ANSI/ESD S20.20 and IEC 61340-5-1, might underestimate the risk considerably. The risk for damaging an ESDS item depends on the discharge current and, hence, the charging of the ESDS item in the presence of the electrostatic field of the process-required insulator. However, the electrostatic field at the ESDS item's location caused by the charge on the process-required insulator depends on the distance of the ESDS item to the process-required insulator and the charging of the process-required insulator.

The process-required insulator's size plays an important role and is not considered in the rough estimation of ANSI/ESD S20.20 and IEC 61340-5-1. It is advisable to measure the electrostatic field at the ESDS item's location or consider adding a safety factor of 2-5 for the surface potential of insulative objects with a size of 10 cm x 10 cm and larger. For example, if the limit of the surface potential is 2,000 volts at the insulator, for larger charged objects, the limit of the surface potential should be lowered to 400 to 1,000 volts or the ESDS item's distance to the charged surface could be increased accordingly.

7.5.3 Detailed ESD Risk Assessment Flow

The assessment follows the steps in Figure 5.

1. Assess whether the ESDS item comes into proximity or direct contact with a conductive surface during the process while in the presence of an electrostatic field of the process-required insulator. If there is no proximity or direct contact of the ESDS item to a conductive surface while in the presence of the electrostatic field, conclude the assessment with the result that there is low ESD risk for the ESDS item.

   NOTE: The surface resistance of the conductive surface is assumed to be less than or equal to 10^4 ohms when measured with a resistance measurement apparatus. If the surface resistance of the item contacting the ESDS item is higher than 104 ohms measured with a resistance measurement apparatus, the risk for the ESDS item in the presence of the electrostatic field of the process-required insulator is low.

2. Measure the ESDS item's discharge current in the insulator's electrostatic field using a current probe or a CDM test head.
3. If the measurement is possible, move to step 9; if not, continue with step 4.
4. Measure the charge of the ESDS item by an electrometer or a current probe. Alternatively, the electrostatic voltage at the ESDS item may be measured using a non-contact electrostatic voltmeter, contact-based high-impedance digital voltmeter, or electrostatic field meter used as a non-contact electrostatic voltmeter.
5. If the measurement is possible, move to step 9; if not, continue with step 6.
6. Measure the electrostatic field at the location of the ESDS item by an electrostatic field meter.
7. If the measurement is possible, move to step 9; if not, continue with step 8.
8. Measure the electrostatic voltage at the surface of the process-required insulator using a non-contact electrostatic voltmeter or electrostatic field meter used as a non-contact electrostatic voltmeter.
9. Compare the measured parameter (discharge current, charge, or electrostatic voltage at the ESDS item, the electrostatic field at the ESDS item's location, the electrostatic voltage at the surface of the insulator) with the defined limits. If the measured value is not within limits, continue with step 10. If the measured value is within the defined limit, conclude the assessment with the result that there is low ESD risk by the process-required insulator.
10. Define measures to mitigate the ESD risk, for example, by reducing the charging of the process-required insulator or changes in the process to avoid critical contacts.

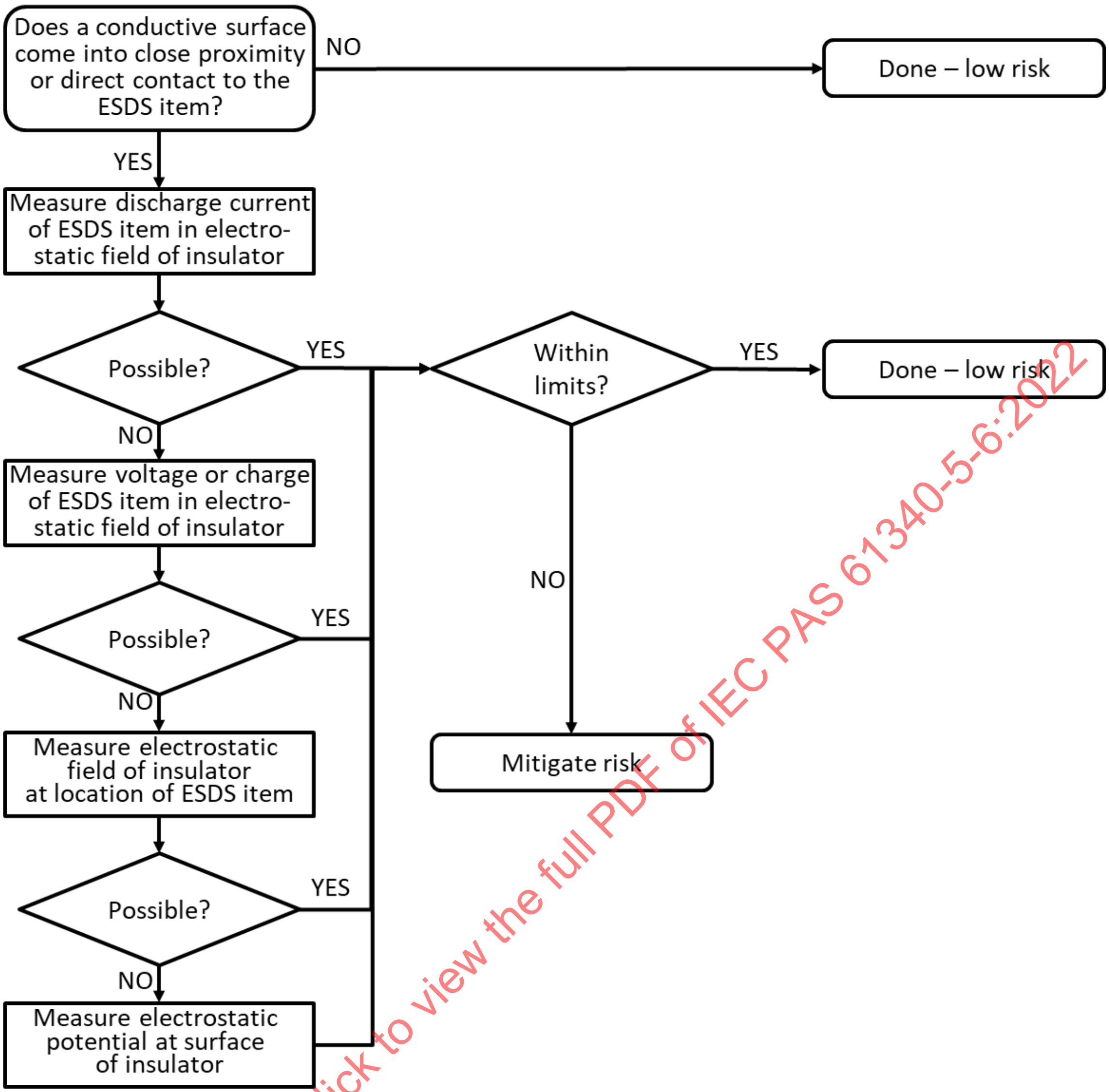

Figure 5 – Flow to Assess the ESD Risk Induced by Process-Required Insulators

NOTE: It is not necessary to follow the flow from measurement with "best correlation" to measurement with "least correlation" (see Figure 1). Steps can be taken in any order.

7.6 Process Assessment by ESD Event Detection

7.6.1 Introduction

The possible direct measurement technique applied to real processes is detecting electrostatic discharges by radiated electromagnetic signals. Direct measurements of discharge currents are typically limited to lab experiments and, such as other process parameters discussed above, require stopping the process before making the measurements. Detection of the electromagnetic signals resulting from ESD can be done while the process is operating normally.

Two different approaches are used for ESD event detection. In both cases, an antenna receives the radiated electromagnetic signal. Either the signal is processed by an ESD event detector, which in most cases gives an alarm when the signal exceeds a certain threshold, or the signal is directly recorded by a high-speed oscilloscope and stored for further analysis. In both cases, the correlation of the radiated signal to the magnitude of the discharge current is difficult or even impossible, as the strength of the electromagnetic signal depends on many factors. Some of these factors can include the distance and the angular position of the antenna to the discharge point, the directional characteristic and the antenna's sensitivity, and nearby objects that can alter the path or absorb the electromagnetic signal.

ESD event detection can be used to assess a single process step in which a conductive part of the ESDS item comes into contact or close contact with a conductive object. See the flow in Figure 6. However, ESD event detection can also monitor ESD events on an entire process, including many single steps.

7.6.2 General Procedure

A typical flow for the process assessment using ESD event detection is shown in Figure 6. The assessment starts with an analysis of possible location or process steps in which a conductive part of the ESDS item comes into contact or close contact with a conductive object. If there is no possibility of a low-ohmic contact, for example, a metal-to-metal contact, with the ESDS item in the process, there is obviously no risk of a hard discharge, and further assessments are not required.

It is important to understand that there are many electromagnetic signal sources in a typical environment with automated equipment, such as motors, actuators, switches, etc. It is necessary to filter out any electromagnetic background noise. Therefore, a dry run without an ESDS item should be conducted to record the electromagnetic signals coming from the environment. Removing the signals caused by this dry run without the ESDS item from the run with the ESDS item can indicate the electromagnetic signals caused by ESD.

If the electromagnetic signals detected are caused by real ESD events in the process, the magnitude of the ESD event must be estimated to assess the potential ESD risk. As this estimation is often not reliably possible, the corrective action is to avoid the discharge completely by making process changes. After corrective actions have been implemented, ESD event detection can be used again to prove the measure's effectiveness.

7.6.3 Detailed ESD Risk Assessment Flow

1. Assess whether the ESDS item comes into proximity or direct contact with a conductive surface during the process. If there is no proximity or direct contact of the ESDS item to a conductive surface, conclude the assessment with the result that there is low ESD risk for the ESDS item.

   NOTE: The surface resistance of the conductive surface is assumed to be less than or equal to 10^4 ohms when measured with a resistance measurement apparatus. If the surface resistance of the item contacting the ESDS item is higher than 10^4 ohms measured with a resistance measurement apparatus, the ESDS item's risk in the electrostatic field of the process-required insulator is low.

2. Place antenna of ESD event monitor or antenna connected to a high-speed oscilloscope as close as reasonable to the points of these metal-to-metal contact.
3. Run the process (step) *without* the ESDS item (“dry run”). Measure radiation by an ESD event detector, or an antenna and a high-speed oscilloscope.
4. Run the process (step) *with* the ESDS item present. Measure radiation by an ESD event detector, or an antenna and a high-speed oscilloscope.
5. Compare the radiation recorded for the run with and without the ESDS item and identify possible radiation originating from ESD.
6. If there are no new radiation signals, conclude the assessment with the result that there is low ESD risk in this process step.
7. Correlate the radiation originating from ESD with the specific process step to isolate the critical process step.
8. Follow flows in Figures 2 to 5 to assess the ESD risk in the critical process step.

   NOTE: It is recommended to repeat the entire procedure after taking risk mitigation steps.

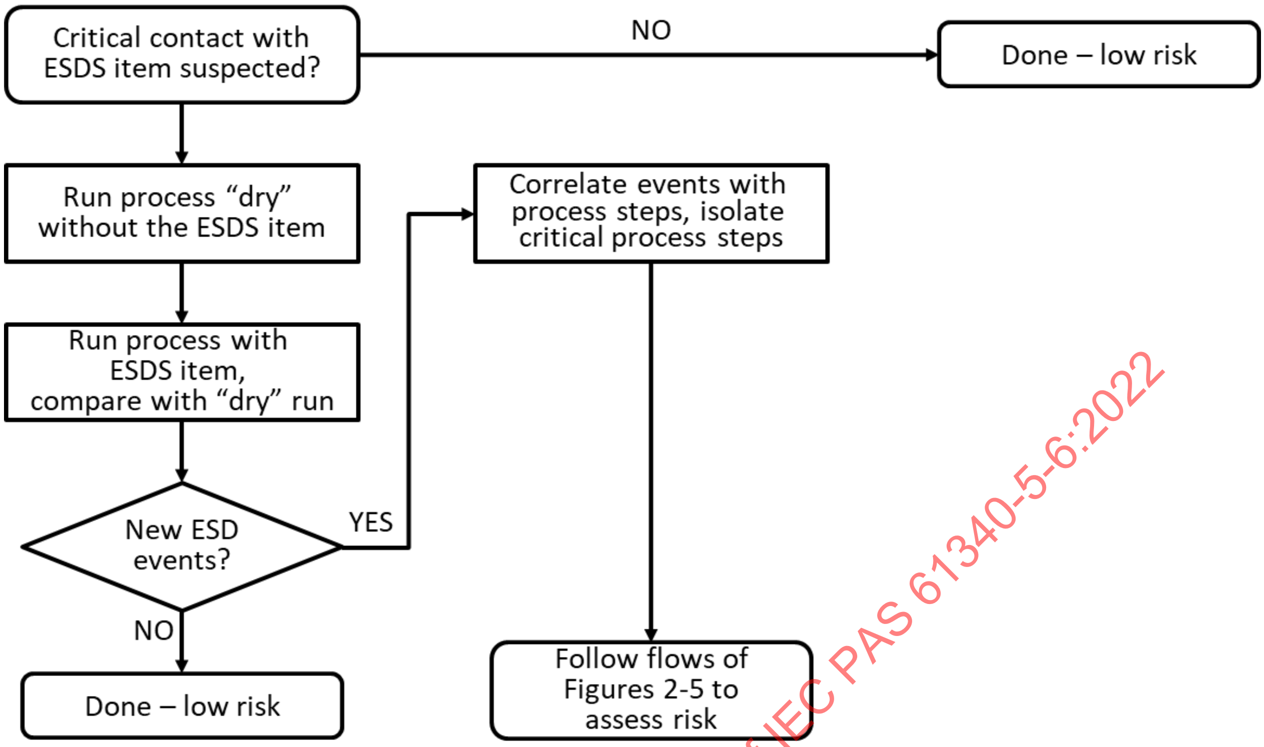

Figure 6 – Flow to Assess the ESD Risk by Detecting the Electromagnetic Radiation Using ESD Event Detectors or Antennas and Oscilloscopes

(This annex is not part of EOS/ESD Association, Inc. Standard Practice ANSI/ESD SP17.1-2020)

ANNEX A (INFORMATIVE): MEASUREMENT TECHNIQUES AND EQUIPMENT

A.1 General Considerations

All measurement methodologies listed in Table 1 must be performed by personnel possessing advanced knowledge and experience with electrostatic measurements or having completed adequate training.

Before starting any measurements, all the equipment used must be verified. At least the minimum and the maximum of the measurement range must be determined, preferably also one or more measurement points. As a simple example, a resistance meter, including leads and probes, should be verified on the lower limit of the measurement range, typically a metal material, which simulates a short, and on the upper limit of the measurement range, typically a high-ohmic insulative material. Additional verification points could be fixtures with defined resistors, preferable in the critical measurement range. Please note, although being within the calibration cycle, the equipment and the entire measurement chain might be defective.

Several measurement techniques, for example, resistance-to-ground, electrostatic fields, electrostatic voltages, refer to ground, which is, in most cases, the ESD ground. It is strongly recommended to verify that the ground used as reference ground is connected to the chosen ESD ground.

A.2 Measurements of Grounding

A.2.1 Resistance Measurement Apparatus

I. Background Information and Application to Process Assessment

Measurement of the resistance to ground (R_g) in the dissipative/insulating resistance regime requires a defined test voltage, depending on the resistance value measured, and a defined electrode.

For standard R_g measurement of worksurfaces or ESD packages, the electrodes are well defined, for example, in ANSI/ESD STM4.1 [10] for R_g measurements of work surfaces or in ANSI/ESD STM11.11 [11] concentric-ring electrode for measurement of surface resistance of planar dissipative materials, or in ANSI/ESD STM97.1 (hand-held electrode for R_g of personnel) [12]. However, for process assessment techniques, these electrodes might not always be applicable. Application-dependent electrodes might need to be defined, which can contact the measured item with acceptable repeatability and reproducibility.

For process assessment flows as described in Section 7.0, measurements with a resistance measurement apparatus are used to assess the grounding of personnel (Section 7.3) or the resistance-to-ground or the surface resistance of objects contacting ESDS items (Section 7.5).

II. Equipment

- A meter that can make measurements from 1.0 x 10^a ohms to 1.0 x 10^b ohms. The meter may have various test voltages. These meters shall be correlated to the product qualification meter or laboratory meter before use.

  NOTE: 1.0 x 10^a should be one order of magnitude below the lowest measurement, and 1.0 x 10^b should be one order of magnitude above the highest measurement. The lowest and highest measurement depends on the application in the process assessment.
- Electrode for measuring R_g of personnel: A hand-held electrode is stainless steel, brass, or copper round or tubular stock, approximately 25 mm in diameter x 75 mm or greater in length, with a banana plug receptacle or screw connector attached to one end of the cylinder.
- Electrode for measuring surface resistance or R_g of small items: A conductive item with appropriate shape to give good contact to the measured item, with a connector attached to the electrode.
- Two leads with appropriate tips or connectors to contact the electrode, the meter, and ground.

III. Measurement Technique

The measurement is done in the following way using a resistance measurement apparatus and an electrode:

1. Connect one lead to the electrode and the resistance measurement apparatus.
2. Connect the other lead to the equipment ground and the resistance measurement apparatus.
3. Contact the electrode to the test item.
4. Set the test voltage of the resistance measurement apparatus to 10 volts.
5. Energize the measurement equipment.
6. If the indicated resistance is less than 1.0 x 10^6 ohms, record the value after 5 seconds, and stop the measurement.
7. If the indicated resistance is equal to or greater than 1.0 x 10^6 ohms, de-energize the equipment.
8. Energize the measurement equipment at 100 volts. Record the resistance after 15 seconds or as defined by the electrification period and stop the measurement.

   NOTE: If switching the test voltage to 100 volts results in a resistance reading of less than 1.0 x 10^6 ohms, then the reading made with the 100-volt test voltage is used.

IV. Limitations

The repeatability of the resistance measurements defined in the ESD control standards is based on the electrodes' accurate definition, which guarantees good and repeatable contact to the measured items. Using any other electrode might significantly reduce the repeatability, particularly as the contact area and contact force are often not well defined in the application. Examples are resistance measurements on flexible items, such as suction cups. It is recommended to assess the measurement's repeatability by a statistical analysis of a series of measurements.

Also, the defined resistance limits for ESD-appropriate work surfaces or packages might not apply to measurements with a self-defined electrode. The resistance measurements might have to be correlated with other parameters, for example, charge decay times (upper limit) or discharge currents (lower limits) of contacted ESDS items.

In some applications, materials with a very conductive surface must be equipped with a special coating in the dissipative resistance range. Commonly used examples for such applications are metallic transport boats of a handler in automated test equipment. These transport boats are made of aluminum and coated with an anodized layer on the surface to avoid a hard discharge if a charged device is placed onto it. These anodized layers tend to break through at higher voltages; that means when measured with, for example, 10 volts or 100 volts, the material shows resistance in the range of 10^{10} ohms. However, when measured with 500 volts, the anodized might breakthrough, and the resistance is in the range of less than 10 ohms, resulting in a risk of hard discharge for the device. Therefore, such coatings should be analyzed at higher voltages to get an idea of breakthrough effects.

A.2.2 Multimeter (Ohmmeter)

I. Background Information and Application to Process Assessment

A simple measurement of the grounding of a conductor is the measurement of the conductor's resistance to ground.

For process assessment flows, as described in Section 7.0, measurements with a multimeter are used for assessing the grounding of conductors or conductive surfaces (Section 7.3). All conductors and conductive surfaces should be well grounded to avoid voltage to be built up at the conductor, which either can cause a risk of discharge from the conductor to the ESDS item or can generate an electrostatic field.

II. Equipment

- A meter (multimeter, ohmmeter) that can make measurements of resistances from 0.1 to 50 ohms with an accuracy of ± 10%.
- Two leads with appropriate tips or connectors (for example, alligator clips) to contact the object under test and the ground connection.

III. Measurement Technique

1. Switch the multimeter to resistance measurement mode, preferable in a “low-ohmic” range (50 ohms).
2. Connect one lead to the surface/object under test and the multimeter.
3. Connect the other lead to the equipment ground conductor (protective earth) and the multimeter.
4. Measure the resistance from the surface/object under test to the equipment ground conductor (protective earth).

IV. Measurement Limitations

For stationary conductors, the resistance-to-ground typically gives a reliable and repeatable result.

NOTE: Unexpected DC voltages on the conductor can result in an offset of the resistor measurement.

However, the resistance-to-ground of the conductor might be significantly different if the conductor is in movement. As an example, consider the arm of a handler in a pick & place process. During movement, the arm might be well grounded or not grounded at all. As an alternative method, the AC voltage check (see Annex A.2.3) can be performed.

There is no upper limit for the resistance-to-ground of a conductor defined. The resistance-to-ground of an “isolated conductor” used in ANSI/ESD S20.20 or IEC 61340-5-1 is also not defined. It can be assumed that a conductor’s resistance-to-ground of less than 1 ohm guarantees that any charge on the conductor is dissipated immediately to ground. No voltage can be built up at the conductor, similar to the considerations for the connection of a common-point-ground to the ESD ground. However, also, much higher resistance-to-ground values might be acceptable. For the assessment of a conductor, the measurement of the electrostatic voltage at the conductor during movement will possibly allow a better correlation to the ESD robustness of the ESDS item.

A.2.3 AC Voltage Check

I. Background Information and Application to Process Assessment

The resistance-to-ground measurement of a conductor sometimes does not give a reliable result or is only possible when the equipment is switched off. As an alternative method, the so-called AC voltage check can be performed. The AC voltage check uses the fact the voltage coming from the mains is capacitively coupled into the conductors of a machine when the machine is powered.

The main application area of the AC voltage check during a process assessment is the use of moving equipment, for example, handlers. While (fast) moving parts can hardly be connected by static voltmeters or HIDVM, the AC voltage check can often be used. It requires only an electrical connection by a simple cable to the moving equipment and a connection to the stationary ground.

II. Equipment

- A meter (multimeter, voltmeter) that can make measurements of AC voltages from -500 to +500 millivolts.
- Two leads with appropriate tips or connectors (for example, alligator clips) to contact the object under test and the ground connection.

III. Measurement Technique

1. Switch the voltmeter to AC-voltage measurement mode with a range of 500 millivolts.
2. Connect one lead to the surface/object under test and to the voltmeter.
3. Connect the other lead to the equipment ground conductor (protective earth) and to the voltmeter.
4. Measure the AC voltage on the surface/object under test.

IV. Measurement Limitations

Today, there is no standard practice or any other document on the AC voltage check and a correlation of the measured AC voltage to a grounding parameter. Hence, for an ESD risk, the limits of the AC voltages are only based on experience. As a rough estimation, grounding is considered good if the measured AC voltage is below 100 millivolts and should be improved if higher than 100 millivolts.

A correlation to a discharge current or even to an electrostatic potential on the equipment is not possible.

A.3 Measurements of Electrostatic Fields

A.3.1 Electrostatic Field Meter

I. Background Information and Application to Process Assessment

Electrostatic field meters are available in many configurations and several types from numerous instrument companies. Field meters are available in two basic types – biased plate and chopper stabilized. All field meters measure the electrostatic field at the opening of the instrument. The electrostatic voltage of an object can be derived from the electrostatic field measured and the meter's distance to the object, assuming a constant electrostatic field.

For process assessment flows, as described in Section 7.0, measurements with an electrostatic field meter are used for assessing the electrostatic fields at the position of the ESDS item (Section 7.5.2).

II. Equipment

- A non-contacting sensing instrument used to measure the electrostatic field that results from the static charge on a material. The meter shall be capable of measuring from zero to ± 5000 volts/meter (125 volts/inch) or greater.
- A lead with appropriate connectors to connect the meter to ESD ground.

III. Measurement Technique

1. Connect one end of the lead to the meter and the other end to a verified ESD ground.
2. Ensure that the meter is in the electrostatic field range.
3. Zero the electrostatic field meter using a large (150 mm x 150 mm or larger) grounded metal plate.
4. Locate the electrostatic field meter at the position of the ESDS item.
5. Measure the electrostatic fields in all possible spatial directions or the direction of a charged object and read the electrostatic field.

IV. Measurement Limitations

If the electrostatic field meter is used to measure electrostatic fields at the location of the ESDS, care must be taken that all possible spatial directions are considered.

If the electrostatic field meter is used to estimate the electrostatic potential of a charged object, for example, a charged insulator or a charged ungrounded conductor, one has to consider that this works only for homogeneous fields of large objects in small distances. Typically, a meter's electrostatic field is calibrated to give the electrostatic voltage of a charged flat plate conductive plate with a size of at least 150 mm x 150 mm in a 25 mm distance. Any other sized or shaped object or larger distances of the meter to the charged object will result in measurement errors.

NOTE: The accurate measurement of electrostatic fields requires that the person making the measurement is familiar with the operation of their measuring equipment. An electrostatic field meter responds to the electrostatic field emanating from a charged surface. It converts the field into a voltage when the meter is positioned at the meter's stipulated distance. When measuring relatively large conductors, the electrostatic field meter reading is the actual voltage on the conductor when measured at the meter's stipulated measuring distance. However, for non-uniformly charged insulators, the field meter's voltage (measured at the meter's stipulated measuring distance) is an average of the charged insulator's electrostatic field strengths.

A.4 Measurements of Charges

I. Background Information and Application to Process Assessment

Measuring the amount of charge of any charged object is a good way to assess the risk that a device might see. If the device's charge and voltage are known in the respective process step, its capacitance can always be determined [13].

It can be used to assess the risk with ungrounded conductors (Section 7.3), charged ESDS (Section 7.4), and process-related insulators (Section 7.5).

II. Equipment

Charge can be measured using a Faraday Cup, an electrometer, or a current probe.

III. Measurement Technique

For measuring the charge on a charged object, either the voltage on a well-defined capacitor (Faraday cup, electrometer) or the integral of the discharge current (current probe) is measured.

IV. Measurement Limitations

In general, the charge on ESDS items is difficult to determine in production since it must be measured in the actual process where every contact with the device might change the charging condition.

A.4.1 Faraday Cup

I. Background Information and Application to Process Assessment

A Faraday cup is used to measure electron or ion currents, for example, in mass spectrometers. It can also measure the charge on (small) objects, independent of whether the objects are insulative or conductive.

II. Equipment

A Faraday cup consists of two open metal cans positioned inside each other and well isolated from each other. An electrometer with high input impedance is connected to the two cans to measure the voltage difference between both metal cans.

III. Measurement Technique

Since the Faraday cup's inner side is free of any electric field, the charge of any charged object is transferred to the inner can directly (with and without contact). Since the setup has fixed dimensions, the capacitance C of it is well known. When measuring the voltage difference V between both cans, it is easy to calculate the charge Q on the object inside the Faraday cup by $Q = V \times C$.

IV. Measurement Limitations

Although the inner side of the Faraday cup is free of electric fields, it "sees" the charged environment to a certain extent, especially when the Faraday cup has a big opening. This makes it difficult to use Faraday cups with big dimensions and make repeatable measurements that means that measurements are mainly made with devices and not with boards.

NOTE: The Faraday cup will measure the total charge on the item, including the charging of insulators and conductors. The action of "picking up" the item can change the item charging, providing potentially misleading information.

Another limitation might be that there is typically a lot of electrical noise in factories. Therefore, Faraday cup measurements are mainly made in labs and not in production lines.

A.4.2 Electrometer

I. Background Information and Application to Process Assessment

Charge can also be measured using an electrometer (nanocoulomb meter). Since the charge must flow from the charged object, an electrometer cannot be used to assess the risk with process-related insulators (Section 7.5), but only with ungrounded conductors (Section 7.3) and charged ESDS (Section 7.4).

II. Equipment

Charge meters have an accurately known integrating capacitor. Voltage is proportional to the integral of the input current.

III. Measurement Technique

The meter shall be properly connected to the electrical reference (for example, earth ground) before making the measurements. Sufficiently isolated voltage probes of oscilloscopes can be used for capturing charges. A measurement shall last until charges are completely transferred. It is important to realize that the ESD source may have slowly and quickly moving charges. Generally, the measurement takes several seconds, while the charge transfer of a static discharge lasts only nanoseconds. Therefore, the charge meter often indicates higher charge transfer than can be captured during ESD.

IV. Measurement Limitations

Leakage currents or stray currents may limit the use of an electrometer. The varying reading indicates unstable measurement.

A.4.3 Current Probe or CDM Discharge Head or Pellegrini Target

For determining the charge of a charged object, the discharge current can be measured using a current probe. The current curve *I(t)* can be numerically integrated over time to calculate the charge:

$$Q = \int_0^{t_{\text{end}}} I(t)\,\mathrm{d}t$$

The functions, use, and limitations of the probes are described in Sections A.7.1 to A.7.3.

A.5 Measurements of Electrostatic Voltages

A.5.1 Charged Plate Monitor

I. Background Information and Application to Process Assessment

The basic design of the charged plate monitor (CPM) was first specified in the EOS/ESD Association, Inc. ionization standard, ANSI/ESD S3.1 (now available as ANSI/ESD STM3.1 [14]), in the late 1980s as a means to verify the performance of air ionizers. With this, the CPM is not used as a measurement tool for process assessment directly but rather a measurement tool to check whether a charge mitigation strategy (ionization) is still effective, for example, during compliance verification.

Over the years, the CPM has also been found useful for other applications. For process assessment of charged personnel (see Section 7.2), the CPM can be used to measure the charging of people with a walking test as per ANSI/ESD STM97.2 [7].

II. Equipment

A CPM consisting of a 20 pF isolated plate assembly, a non-contacting means to monitor the voltage induced on the isolated plate, a voltage source to charge the plate, and a timer to monitor discharge of the isolated plate under the influence of any ionization. Once charged, the plate must hold at least 90% of its charge for 5 minutes in the absence of any ionization.

III. Measurement Technique

For measuring the properties of an ionizer, CPMs can make two basic tests described in the ANSI/ESD STM3.1 [14], discharge time and offset voltage.

- Discharge time: Charge the isolated plate to +1000 volts. Measure the length of time necessary for ionization to reduce the plate voltage to +100 volts. Charge the plate to -1000 volts and measure the time to reach -100 volts.
- Offset voltage (balance): Ground the isolated plate shortly to remove any residual charge. Place the isolated plate in the ionized area and note any change in the plate voltage. For pulsed ionizers, note both positive and negative values for the offset voltage.

When using the CPM for measuring the charging of people (walking test), a hand-held electrode is connected to the isolated plate, and the person testing the footwear and flooring combination in use holds the wand. While holding the wand, the person walks in a repetitive pattern, and the voltage generated on the person's body is measured (ANSI/ESD STM97.2 [7]).

IV. Measurement Limitations

When using the CPM for checking ionizers, the self-discharge of CPM must be considered. If the impedance of the measuring instrument is not high enough or the metal plate not isolated from ground well enough, the plate of the ionizer can lose its charge even if an ionizer is not present, and the decay result might be misinterpreted. Another problem with the CPM might be that its reading is not updated often enough. This might result in overlooking the unwanted swing of the ionizer balance voltage (can be solved by connecting an oscilloscope to the CPM output).

When using the CPM as a walking test kit, the influence of the CPM capacitance might be considered; it can reduce the operator's actual body voltage.

A.5.2 Walking Test Kit

I. Background Information and Application to Process Assessment

The body voltage generation of personnel handling ESDS items is an especially important parameter to assess the risk during manual process steps. For the assessment flow described in Section 7.3, a walking test kit is a good solution. It allows the measurement of the voltage generated on the operator without interrupting the process; hence, it gives reliable results.

II. Equipment

- An example of suitable equipment can be found in ANSI/ESD STM97.2 [12]. As defined in ANSI/ESD STM3.1 [14], a CPM with an output capable of being recorded is also acceptable.
- For qualification purposes, a recording device (such as a chart recorder, data logger, or oscilloscope) that can accept the CPM output with sufficient ability to record data over time might help. For process assessment, it might not be needed.
- A metal probe or wrist strap is needed to connect the person to be measured to the equipment described in ANSI/ESD STM97.2 [7] or to the CPM.
- However, any set of instruments that meet these requirements can be used. This includes but is not limited to field meters that can measure a person's voltage, high impedance contacting voltmeters, and field mills.

III. Measurement Technique

The body voltage test should be done in the respective process (sitting or standing/walking operation).

- Record the temperature and relative humidity at the location of each test
- Have the person to be measured hold the hand-held probe or use the wrist strap and then connect the hand-held probe to the measurement device
- Have the person execute the process
- Repeat the measurements with a different person to ensure repeatability.

NOTE: These procedures should be done at the lowest humidity anticipated in the manufacturing process.

IV. Measurement Limitations

These measurement results depend on the complete grounding system and, of course, the relative humidity. The lower the relative humidity, the higher the body voltage typically generated during these tests. Therefore, the measurements should be done at the lowest expected relative humidity in the area to be evaluated.

A.5.3 Electrostatic Voltmeter (ESVM)

I. Background Information and Application to Process Assessment

The ESVM is a contactless voltmeter that can measure the voltage on an ESDS item or the surface potential of any charged objects nearby without draining any charge of the object under test. This is achieved by not making direct contact between the measurement probe and the surface under test (isolated by a small air gap). Due to its size with the small (remote) probe, it has a very good local resolution (depending on the layout) and can easily distinguish whether, for example, a pin of a device is charged up or the mold compound around it. Depending on the distance between probe and surface under test, the ESVM “sees” static fields in the environment.

During process assessment, it can be used in different flows where a good local resolution of voltages is necessary, for example, in Section 7.4 when assessing the ESD induced risk by charged ESDS items or in Section 7.3 to assess the risk imposed by charged conductors.

The ESVM could also be used in the process assessment flow of Section 7.2 to measure the voltages on people handling the product at any step in the manufacturing process.

II. Equipment

There are several types of ESVM available on the market. Depending on their reference voltage, they are known as DC- or AC-feedback static voltmeters. ESVMs all use a tuning fork to convert the DC voltage induced in the probe into an AC voltage that can be measured easier. ESVMs consist of separate components (remote vibrating capacitive sensor probe, the feedback loop for reference voltage, and voltage meter). These components may be integrated into a single instrument.

The ESVM with a DC feedback loop applies a (high) DC voltage to the electrostatic voltmeter probe to null the electrostatic field between the probe and the surface under test. This field-nulling technique and the resulting voltage matching can be achieved over a wide range of probe-to-surface separations. As the voltage on the probe matches the voltage on the surface under test, the voltage on the surface is determined with high accuracy. ESVMs work best when used within a few millimeters of the surface under test. There is little fear of arc-over. The area on a surface that an ESVM resolves is related to the meter’s distance from the surface. At any reasonable distance from the surface, the area measured has a diameter of 4 to 5 times the distance from the surface. For example, at d = 3 mm from the surface, the meter resolves a spot that is 12 mm to 15 mm in diameter. DC-feedback ESVMs are not available as a hand-held meter (since a high voltage supply is needed), and probes are on cables.

AC-feedback ESVMs are not applying a high (DC-) voltage to the probe tip to null the field but use an AC voltage as reference. The local resolution is not as good as with DC feedback ESVMs but still better than the one of field mill type instruments. Since a high voltage supply is not needed, battery-powered handheld equipment is available.

III. Measurement Technique

- For battery-powered equipment (for example, AC feedback ESVM), make sure the battery is charged. Otherwise, the ESVM cannot generate the reference voltage that´s necessary for accurate measurements.
- For non-battery powered equipment, make sure a power outlet and, if necessary, an extension cord for the high voltage reference is available.
- Make sure the ESVM is properly grounded; otherwise, the reference potential is missing, and the reading has an undefined offset
- Before starting the measurement, measure the center of a sufficiently large, grounded metal plate to zero the ESVM. Also, measure a surface charged to a known voltage to verify the meter is working correctly.

IV. Measurement Limitations

As noted above, a process needs to be stopped to make measurements with the ESVM. This might result in voltages on a device or object that are different (normally lower) than those occurring in a moving process. For example, as soon as the process stops, the voltage on an object may begin to decay, depending on its capacitance and resistance to ground. Measurements with the ESVM might need to be done as rapidly as possible after the process is stopped. Another possibility would be to fix the ESVM at a certain distance, but that is also not possible in all processes.

Measurements may need to be done within the equipment or at other points in the process where access with the ESVM probe is difficult. This will affect the need to make measurements soon after the process is stopped.

Air ionizers in a measurement area will affect certain types of ESVMs to make accurate measurements of voltages generated by static charge. If this is a concern, ionizers may need to be turned off just before the measurement of the electrostatic voltage starts.

NOTE: It is recommended to measure with ionizers on/off to understand the impact of ionization on measurement equipment and the process (effectiveness of ionization).

A.5.4 High-Impedance Digital (Contact) Voltmeter

I. Background Information and Application to Process Assessment

The HIDVM is a contact voltmeter that can measure the voltage on an ESDS item or the surface potential of any charged objects nearby without draining any charge of the object under test. Due to its small sharp contacting tip, it has an exceptionally good local resolution. It can easily distinguish whether, for example, a pin of a device is charged up or the mold compound around it.

During process assessment, it can be used in different flows where a good local resolution of voltages is necessary, for example, in Section 7.4 when assessing the ESD induced risk by charged ESDS items, or in Section 7.5 to assess the risk imposed by charged conductors.

The HIDVM could also be used in the process assessment flow of Section 7.2 to measure the voltages on people handling the product at any step in the manufacturing process.

II. Equipment

The HIDVM is a voltmeter with a very high input resistance of at least 10^{14} ohms to avoid that the object that is contacted is discharged through the meter; therefore, the (sharp) tip of the HIDVM is very often made of ceramic to avoid a CDM like discharge into the tip.

The meter must also have an exceptionally low input capacitance (typically 10^{-13} F or lower) so that measurements on exceedingly small objects such as small devices with a capacitance of < 10^{-12} F are not influenced.

III. Measurement Technique

- Make sure the battery is charged. Otherwise, the HIDVM cannot generate voltage for a driven shield, and the measurement will be inaccurate
- Make sure HIDVM is properly grounded. Otherwise, the reference potential is missing, and the reading has an undefined offset
  - For the measurement, make contact to the conductive part to be measured (good local resolution); during approach or on insulative surfaces, the reading might be erroneous or inaccurate

IV. Measurement Limitations

As noted above, a process needs to be stopped to make measurements with the HIDVM. This may result in voltages on a device or object that are different (normally lower) than those occurring in a moving process. For example, as soon as the process stops, the voltage on an object will begin to decay, depending on its capacitance and resistance to ground. Measurements with the HIDVM might need to be done as rapidly as possible after the process is stopped.

Measurements may need to be done within the equipment or at other points in the process where access with the HIDVM voltage probe is difficult. This will affect the need to make measurements soon after the process is stopped.

The presence of air ionizers in a measurement area will affect the ability of the HIDVM to make accurate measurements of voltages generated by static charge. These ionizers may need to be turned off as part of the measurement procedure.

Measurements on insulating surfaces are not reliable; due to the isolator's non-uniform charging and the high local resolution of the HIDVM, the results will vary quite a bit even in small areas. A comparison with given limits is therefore not possible.

A.6 Measurements of Discharge Events

A.6.1 Antenna with Oscilloscope

I. Background Information and Application to Process Assessment

An electrostatic discharge can physically be described as a “collapsing dipole”, where charges are getting neutralized, which leads to a changed voltage and, consequently, to a dynamic electric field. The dynamic discharge current causes a dynamic magnetic field. Antennas can detect electric and magnetic radiations; the antenna signal can be displayed on an oscilloscope with appropriate bandwidth.

The advantage of using an antenna and an oscilloscope to detect electromagnetic radiation originating from an ESD event is that it is not necessary to know the exact location of the discharge. A typical process assessment flow using antennas and an oscilloscope is described in Section 7.6.

II. Equipment

For the detection of electromagnetic radiation, at least one antenna is required. Often it is useful to have two or more antennas to detect the radiation signal in different locations. Timing differences between the signals coming from antennas in different locations allow deriving additional information on where the electrostatic discharge occurs. There exists an antenna with different directional characteristics, sensitivities, and sizes. The directional behavior must be known, and the antenna must be placed accordingly with respect to the expected location of the electrostatic discharge to gain most of the use of the antenna.

ESD events, particularly discharges according to CDM, are very fast with a rise time of around 100 ps and a pulse width of less than 1 ns. The electromagnetic radiation caused by this ESD event is at least as fast as the discharge. Therefore, a high-bandwidth oscilloscope is required with an appropriate sampling rate. Experiences and published results recommend a minimum bandwidth of 1 GHz and a minimum sampling rate of 10 gigasamples/second, with several channels according to the number of antennas used in process assessment. If a quantitative analysis is required, it is important to follow step 2 of Section III “Measurement Technique”.

III. Measurement Technique

1. Connect the antenna(s) to the channel(s) of the oscilloscope.
2. It is recommended to record a signal of an ESD event with known discharge voltage, for example, the CDM event of a CDM qualification tester or a discharge of a metal object charged to a known voltage by contacting it with a short, grounded wire if CDM is a concern. With this experiment, the oscilloscope setting for a certain expected CDM discharge (for example, signal range, timing, and trigger level) can be derived. Additionally, the signal strength can be assessed as a function of the distance of the discharge location to the antenna and the antenna's orientation. This “verification” data can be used to get a very rough correlation between the recorded antenna signal of a real CDM event in the process and the pre-charge voltage of the discharged object.
3. Place the antenna in a location close to where the ESD event is suspected to happen; consider the antenna's directional characteristic.
4. Set the signal range at the oscilloscope (y-axis) and the trigger value as low as possible. If “non-ESD” noise is picked up, the trigger level must be increased step-by-step until the non-ESD-related electromagnetic noise does not trigger the oscilloscope. A time base (x-axis) of not more than 10 ns/division is recommended.
5. Run the process and start the oscilloscope. If the oscilloscope is in single-shot mode, every single event can be recorded, stored, and analyzed. The timing information of the recorded electromagnetic radiation (time consumed from start to the occurrence of the event) allows correlating the event to the process step. If the oscilloscope is running in continuous mode, the number of events during the process is recorded, correlation can often be achieved by manual observation of the process and the occurrence of the events.

IV. Measurement Limitations

Using antennas and an oscilloscope often allows for the detection of ESD events. However, correlation to a process step and even more the correlation to the magnitude (discharge current or pre-charge voltage) of the ESD event requires significant experience and is often impossible. Only if the ESD discharge location is known, a correlation to the discharge current can be established by comparing the electromagnetic signal amplitude with the signal from a known ESD event with the antenna in the same distance.

Often the measurements are obstructed by electromagnetic noise, which is not ESD related. In process equipment, many electromagnetic radiation sources exist, for example, motors, actuators, switches. Depending on the amplitude of the electromagnetic noise, the electromagnetic signals caused by ESD events are hidden by the electromagnetic noise.

NOTE: It is necessary to filter out any electromagnetic background noise. Therefore, a dry run without an ESDS item should be conducted to record the electromagnetic signals coming from the environment. Removing the signals caused by this dry run without the ESDS item from the run with the ESDS item can indicate the electromagnetic signals caused by ESD.

A.6.2 ESD Event Detectors

I. Background Information and Application to Process Assessment

Every electrostatic discharge is accompanied by electromagnetic radiation, which can be detected by ESD event detectors. The advantage of using ESD event detectors is that it is not required to know where the discharge happens, and the process does not need to be interrupted. But significant experience is required when using the ESD event detectors because these are also detecting many other "noise" events in the environment, such as switching relays. ESD event detectors might be used in the process assessment flow of Section 7.6 when assessing whether a discharge occurs in a process.

II. Equipment

ESD event detectors are available as very simple detectors like an AM radio (a crackling noise during discharge can be heard) as well as more complex tools. Some detectors claim to determine the voltage of the object where the discharge came from. Other tools are complete systems monitoring discharges in an assembly or test line.

III. Measurement Technique

The ESD event detectors are not really doing any measurement but are rather a tool for indication. Typically, the antenna of the detector is directed towards the suspected location of the ESD event.

For more detailed evaluations, a measurement without the ESDS should be made before the actual process with the ESDS so that both processes can be compared for additional events.

IV. Measurement Limitations

As mentioned above, the user needs to be very experienced when using an ESD event detector since it detects all kinds of radiation events. Additionally, the directional property of the radiation makes it more difficult to get reliable results.

NOTE: It is necessary to filter out any electromagnetic background noise. Therefore, a dry run without an ESDS item should be conducted to record the electromagnetic signals coming from the environment. Removing the signals caused by this dry run without the ESDS item from the run with the ESDS item can indicate the electromagnetic signals caused by ESD.

A.7 Measurements of Discharge Currents

I. Background Information and Application to Process Assessment

I(t) is the most direct way to assess the risk of an ESD event to a device when measuring the discharge current waveform. In addition to the peak current, discharge parameters such as charge, parasitic resistance, inductance, and capacitance can be deduced from the current waveform.

In general, discharge currents of real-world ESD events can hardly be measured directly because the discharge location must be known in advance. This is also the reason why it is not described in the process flows of this document.

If the discharge location is known, the measurement of the discharge might be implemented and would give the real threat of a device.

It is easy to measure the discharge current for a charged person or a charged conductor, as shown a couple of times [8].

It is more complex to measure the discharge current of a charged board in the production/field, but sometimes it is possible to reproduce a field event under laboratory conditions. For example, a discharge of a charged printed-circuit board through a metal pin during board assembly or testing can be reproduced rather easily in a laboratory. In the field, the physical effect causing charging of the board is primarily triboelectricity or induction. In a lab experiment, the PCB can be directly charged by a high-voltage source. Contacting the charged PCB by a grounded pogo pin would result in the same discharge event as in the field. This is valid as long as the geometries of the metal pin in the equipment, the pogo pin, and the probes' capacitance to the PCB are similar.

II. Equipment

The discharge current from the charged object can be measured either by a current probe, a Pellegrini target, or a CDM test head, which measures a voltage drop in the path to ground. The equipment is described below.

III. Measurement Technique

The measurement technique is described below.

IV. Measurement Limitations

The limitations are described below.

A.7.1 Current Probe

I. Background Information and Application to Process Assessment

A current probe surrounds a conductor to measure the current through the conductor without physically contacting the conductor. The current through the conductor causes a magnetic field that induces a current in the current probe. Figure 7 shows two designs of current probes.

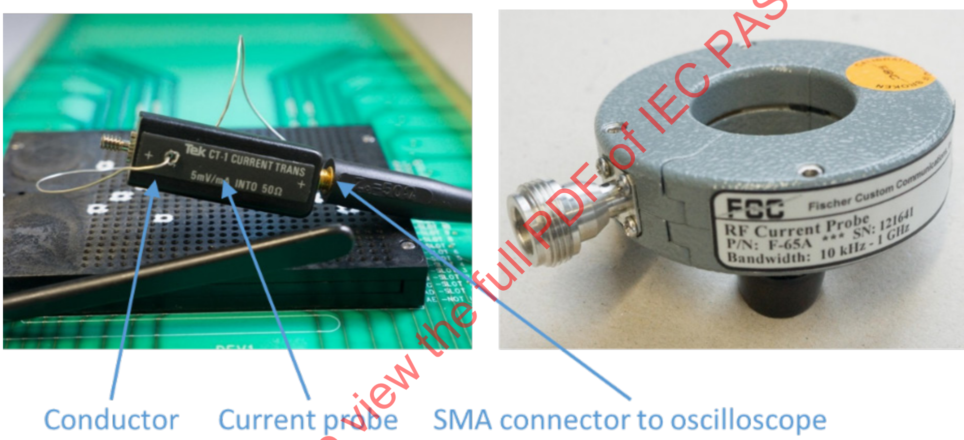

Figure 7 – Examples of Current Probes

NOTE: To avoid inductive effects, the cable through the current probe should be as short as possible.

Often current probes are called “current clamps”, indicating that the current probe comprises a split ring that can be opened to surround the conductor. Depending on size and design, current clamps can measure alternating (AC) currents up to several 100 amperes.

Several parameters influence the measurements significantly:

- Frequency response – limits the applicable range of the current probe. Typically, current probes are available in a range from low frequency to 1–2 GHz. As typical CDM discharge events may require a bandwidth of 6 GHz and higher, the bandwidth limitation of the peak current must be considered in the assessment.
- Maximum peak current/saturation current – should be as high as possible. As a rule of thumb, 10 amperes should be the minimum saturation current value.
- Sensitivity to 50 ohms, typically given in millivolts, output voltage per milliamperes current through the conductor. If the sensitivity is too high, attenuators with appropriate bandwidth must be inserted to protect the oscilloscope and avoid clipping of the signal.
- Insertion impedance at a given frequency (typically at the highest applicable frequency) – should be as low as possible to avoid distortion of the input signal.
- For practical applications, the maximum wire diameter should be considered.

For a quantitative analysis of the measurements, verification, and characterization of the current probe are mandatory. This can be done using a fast pulse source, for example, transmission line pulsing (TLP) systems or solid-state pulse generators. The pulse parameters (rise time, pulse width, pulse amplitude) ideally should be in the range of the expected waveform to be analyzed in the application.

II. Measurement Technique

- Connect the current probe to the oscilloscope using the 50-ohm input.
- Select the right voltage to current conversion factor to determine the current amplitude in the right way.
- Feed wire through the hole of the current probe.
- Connect one end of the wire to ground.
- Touch the object that the discharge current will be measured from to the other end of the wire and record the current waveform.

III. Measurement Limitations

Since using a current probe requires a wire to be touching the object under investigation, a quantitative measurement outside a lab environment is exceedingly difficult.

Although current probes might have a bandwidth of up to 1 to 2 GHz, this bandwidth might still be too low to capture a metal-to-metal contact as, for example, in a CDM event or a discharge event of a human being through a metal tool. For a risk assessment, this must be considered.

A.7.2 Pellegrini Target

I. Background Information and Application to Process Assessment

Pellegrini targets (see Figure 8) are primarily used to calibrate ESD simulators ("ESD guns"), according to IEC 61000-4-2 Ed. 2.0 [15]. The pulse parameters are measured as a voltage drop across a coaxial shunt with a nominal impedance of 2 ohms. The design of the Pellegrini target is optimized for high currents and high bandwidth.

The ESD simulator discharges into the contact area of the Pellegrini target. The Pellegrini target is fitted into a metal plate with a size of at least 1.2 meters x 1.2 meters. The bandwidth of the Pellegrini target is typically 1–4 GHz. It is capable of measuring currents of more than 100 amperes.

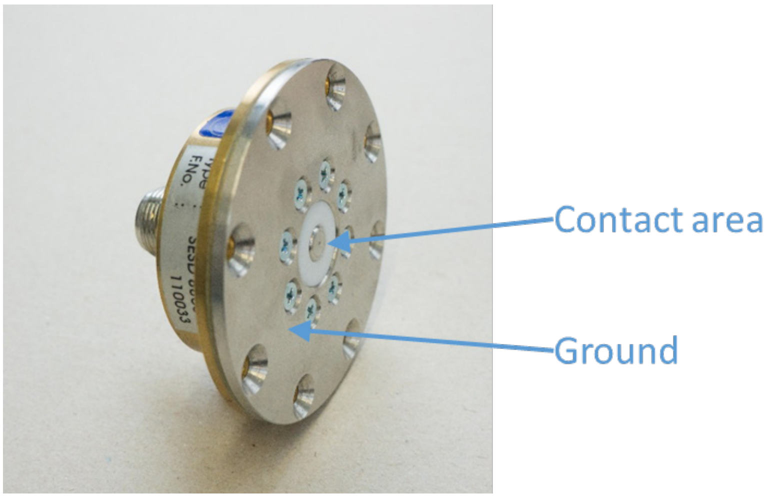

Figure 8 – Example of a 4-GHz Pellegrini Target

There are two typical applications in ESD process risk assessments in which Pellegrini targets can be used. First, discharges of human beings can be simulated by charging the personnel and then touching ("contacting") the Pellegrini target's contact area. There are several examples for such studies available; see, for example, [16] and [8]. The discharge current waveform of the human being depends on the speed of approach. Thus, a "reasonable" speed of approach must be chosen, which reflects a realistic scenario. In contrast, to measure only the personnel's charging, the discharge current waveform allows a risk scenario under real conditions, for example, with gloves on, under a certain relative humidity, with a tool in hand, etc.

The Pellegrini target can also be used to measure discharge currents of charged devices. There are several possible scenarios. Typically, the Pellegrini target is used in a laboratory environment. The charged device can be brought into contact with the contact area by approaching the device to the target or the target moving towards the charged device. For special applications, the Pellegrini target could be modified, for example, with a pogo pin soldered to the contact area; the target is then similarly used to a CDM test head (see Section A.7.3).

II. Measurement Technique

- Connect the Pellegrini target to the 50-ohm input of the oscilloscope.
- Touch the contact area of the Pellegrini target with the charged object under investigation.
- Record the discharge current waveform.

III. Measurement Limitations

There are factors limiting the application of the Pellegrini target in ESD process risk assessment besides some practical restrictions that apply to all current probes. First, although the Pellegrini targets have a bandwidth of up to 4 GHz, this bandwidth might still be too low to capture a metal-to-metal contact as, for example, in a CDM event or a discharge event of a human being through a metal tool. For a risk assessment, this must be considered. Secondly, the capacitance in the experiment with the relatively large ground plane of the Pellegrini target around the contact area may not necessarily reproduce the situation in the real-world well.

A.7.3 CDM Test Head

I. Background Information and Application to Process Assessment

Commercially available CDM test heads, as used in today's CDM test system, typically comprise of a pogo pin with a defined shape (length, radius), connected via a 1-ohm resistor to ground. This test head can be used for manually contacting any charged item by the pogo pin. An example of a commercially available CDM test head is shown in Figure 9.

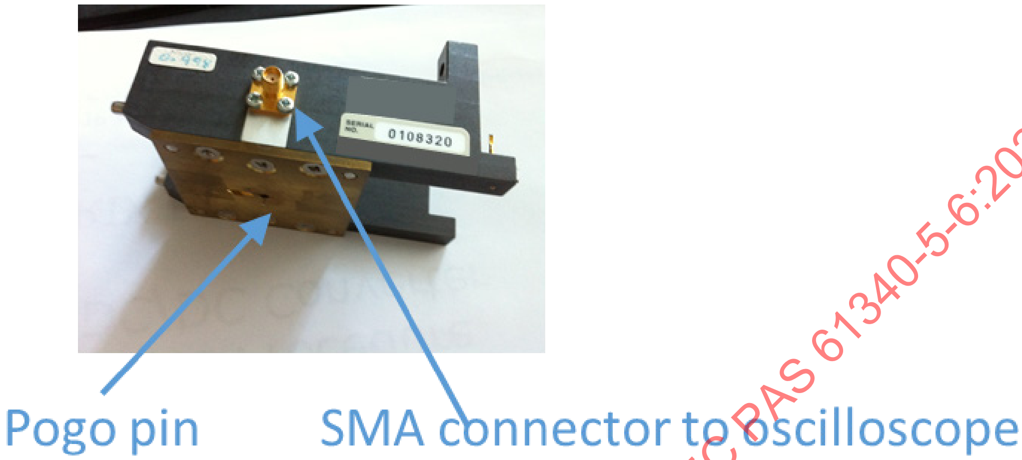

Figure 9 – Commercially Available CDM Test Head Used for Discharge Current Measurements

CDM test heads are designed for capturing CDM currents, which have a rise time of down to 100 ps. Thus, the CDM test head's bandwidth, including the measurement chain, must typically exceed 6 GHz as recommended in the current CDM standard ANSI/ESDA/JEDEC JS-002 [4].

NOTE: If only an oscilloscope with lower bandwidth is available, the captured peak current value must be scaled with a factor of 1.5 (worst-case) to estimate the real peak current [4].

Before using a CDM test head in an experimental set-up to assess discharge current, careful characterization of the entire measurement system is required. Typically, CDM tester verification modules can be used. Those verification modules are metal discs with a defined capacitance defined in ANSI/ESDA/JEDEC JS-002 [4]. The waveforms depend on the metrology chain's bandwidth; assuming an extremely high bandwidth of the CDM chain, the bandwidth is limited primarily by the oscilloscope. The attenuator in the measurement path must have an appropriate bandwidth, too. For precise measurements of CDM discharge events, an oscilloscope with a 3 dB bandwidth of at least 6 GHz and a sampling rate of ≥ 20 gigasamples/second is recommended. Lower bandwidth oscilloscopes can be used. However, the peak current measured might be significantly lower than the actual peak current. Typical peak current values for two charging voltages and a 1 GHz and a 6 GHz bandwidth oscilloscope are given in Table 2.

Table 2 – Peak Current Ranges of CDM Discharges of Small and Large Verification Modules for Oscilloscopes with a Bandwidth of 1 GHz and 6 GHz According to ANSI/ESDA/JEDEC JS-002

Test conditions	Peak current small module (amperes)		Peak current large module (amperes)	
	BW 1 GHz	BW 6 GHz	BW 1 GHz	BW 6 GHz
TC 125	1.0 – 1.6	1.4 – 2.3	1.9 – 3.2	2.3 – 3.8
TC 500	4.4 – 5.9	6.1 – 3.8	9.1 – 12.3	10.3 – 13.9

A CDM test head can be used not only in experimental environments, but it was also successfully applied in real applications, for example, in test handlers [17]. Experiments on PCBs using a “home-made” CDM test head, which allows current measurements with a current transducer Tektronix CT-1 and/or as a voltage drop across a 1-ohm resistor, are presented in [8]. With this, the discharge current can be directly compared to the discharge current received during device qualification, making an assessment much easier.

II. Measurement Technique

- Connect the CDM test head to the 50-ohm input of the oscilloscope.
- Touch the charged object under investigation with the pogo pin of the CDM test head.
- Record the discharge current waveform.

III. Measurement Limitations

If a discharge head is used, as shown in Figure 9, the big metal ground plate makes it difficult or impossible to hit the right discharge point on the IC or PCB. Therefore, a discharge head without this big metal plate might be easier to use. It is then easier to hit a defined location on the device or PCB, and the discharge scenario is more realistic (there aren´t many scenarios where the discharge goes into a big metal plate). But if the missing ground plate changes, of course, the waveform and the comparison with the CDM waveform received during device qualification is more difficult.