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Charge conditioning of aerosol particles for particle characterization and the generation of calibration and test aerosols

Conditionnement de la charge (électrique) des particules d'aérosols pour la caractérisation de particules et la génération d'aérosols pour calibration et essais

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Foreword

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This document was prepared by Technical Committee ISO/TC 24, *Particle characterization including sieving*, Subcommittee SC 4, *Particle characterization*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Charge conditioning of aerosol particles is the crucial process of establishing a known, size-dependent charge distribution on aerosol particles. Different designs for charge conditioners exist. In charge conditioners, aerosol particles are exposed to a cloud of ions of either both positive and negative polarities (bipolar charge conditioners) or a single polarity (unipolar charge conditioners).

The transport of the ions to the aerosol particles can either be driven by Brownian motion of the ions (diffusion charging) or by an electrical field (field charging). Since field charging is strongly biased by a particle's electrical properties (namely the relative permittivity), diffusion charging is generally used to condition aerosol particles:

— for particle size distribution measurement with the differential mobility analysing system (DMAS);

— for particle size classification with the differential electrical mobility classifier (DEMC).

Several parameters determine whether or not charge conditioning achieves its goal of either generating a mathematically describable bipolar steady-state charge distribution or a quantifiable unipolar mean charge. Examples for such parameters are the ion concentration, the particle concentration, the residence time of the particles in the ion cloud, the ion mass distribution or the ion mobility distribution. However, there is no standard methodology to specify the performance of charge conditioners.

The electrical mobility of aerosol particles is a physical particle property which is widely used for particle characterization (e.g. size distribution measurement with DMAS) and for particle classification (e.g. by DEMC). For a given particle size, the particles' electrical mobility is proportional to the net number of elementary charges on the particle. Therefore, the knowledge of particle charge distribution is an essential requirement for particle size distribution measurements with the DMAS and for particle size classification with the DEMC.

The purpose of this document is to provide a methodology to specify the performance of charge conditioners and for adequate quality control when charge conditioners are used in particle size and number concentration measurement or in particle size classification.

Other typical uses of charge conditioners which are not covered in this document are:

— conditioning of test aerosols for filter testing where particle charge has an influence on the test results;

— particle charge reduction during the droplet evaporation in an electrospray aerosol generator, where the very high unipolar charge of the sprayed solution or dispersion droplets can lead to the unwanted disintegration of the droplets due to exceeding the Rayleigh limit during droplet evaporation;[34]-[36]

— diffusion chargers (DC) in particle number devices (PND) that are typically used as robust, compact systems to measure particle number concertation in the exhaust emission of passenger cars, light and heavy duty cars under real driving emissions (RDE) as well as under periodical technical inspections (PTI) in Europe. The charging process in such a device is provided by a diffusion charger, which is charging the aerosol in a positive unipolar diffusion state. Typically, a thin wire is used as a high voltage electrode to generate positive ions. The ions are injected through a grounded grid into buffer volume where they are mixed with the particles. Afterwards, the charged aerosols will be counted in a two stage procedure by an pulsed precipitator and in an Faraday cup aerosol electrometer (FCAE);[37,38]

— large-scale ionizers combined with electrostatic precipitators (ESP) for cleaning flue gases of waste incinerators or power plants fired with solid fuels. In the ESP, a corona discharge generates ions which charge the flue gas particles (usually fly ash) by diffusion and field charging (depending on the particle size). Subsequently, the particles are deflected by electrophoresis in the ESP's electrostatic field and deposited on grounded collection electrodes. Industrial ESP are usually several tens of meters high and consist of a multi-stage configuration to optimize the overall collection and gas cleaning efficiency.

Charge conditioning of aerosol particles for particle characterization and the generation of calibration and test aerosols

1 Scope

This document specifies requirements and provides guidance for the use of charge conditioners for aerosol particles, especially for particle characterization and for the generation of calibration and test aerosols.

This document provides a methodology to specify the performance of charge conditioners and for adequate quality control, with respect to their application in:

— particle size and concentration measurement with differential mobility analysing systems (DMAS);

—particle size classification with differential electrical mobility classifiers (DEMC).

For these applications, this document covers particle charge conditioning for particle sizes ranging from approximately 1 nm to 1 µm and for particle number concentrations at the inlet of the charge conditioner up to approximately 10^7 cm^{-3}.

This document does not address specific charge conditioner designs or other applications besides those specified in Clause 1.

Radiation safety for charge conditioners with radioactive sources or x-ray tubes is not covered by this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 15900, *Determination of particle size distribution — Differential electrical mobility analysis for aerosol particles*

ISO 27891, *Aerosol particle number concentration — Calibration of condensation particle counters*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 15900, ISO 27891 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
charging probability
$f_p(d)$
ratio of the number concentration of particles exiting a charge conditioner with p charges to that of particles exiting the charge conditioner at all charge states, at particle size d

Note 1 to entry: p charges are 0, ±1, ±2, etc.

Note 2 to entry: The charging probability with respect to the number concentration entering (instead of exiting) the charge conditioner is called "extrinsic charging probability".

3.2
charge distribution function
either mathematical or empirical, or both, description of a conditioned distribution of particle size dependent *charging probability* (3.1)

3.3
electrostatic precipitator
ESP
device for removing charged particles from an airflow by electrophoresis to generate an uncharged aerosol

Note 1 to entry: More information on ESPs is given in Annex C.

3.4
ion mobility distribution
number density distribution with respect to the electrical mobility of the ionic molecular clusters that are responsible for the charging of aerosol particles in a charge conditioner

4 Symbols and abbreviated terms

For the purpose of this document, the following symbols and abbreviated terms apply.

CPC	condensation particle counter	
DEMC	differential electrical mobility classifier	
DMAS	differential mobility analysing system	
ESP	electrostatic precipitator	
d	particle diameter	m
$f_p(d)$	charging probability	dimensionless
N	number concentration of aerosol particles	m^{-3}
N_I	number concentration of ions	m^{-3}
p	number of net elementary charges on a particle	dimensionless
t	residence time of an ion in charge conditioner	s

5 General principle

5.1 General

The function of the charge conditioner in this document is to establish a known size-dependent, steady-state charge distribution on the sampled aerosol prior to the size classification process in electrical mobility classifiers like the DEMC. The charge distribution on the particles can either be bipolar or unipolar.

All charge conditioners can be regarded as ionization sources because they generate ions of either one polarity or both polarities in the carrier gas. These ions interact with the particles to generate a charge distribution. The characteristics of ionization sources frequently used for charge conditioning are outlined in 5.2.

Since charge conditioners are used to achieve steady state charge distribution in the aerosol sample flow, the charge conditioner shall, by design or by measurement, perform correctly and not produce artefact particles.

In its simplest form, a charge conditioner, such as that used in a DMAS, consists of an aerosol inlet, aerosol outlet, ionizing source, charging zone and enclosure.

5.2 Ionization sources

5.2.1 General

There are three common types of ionization sources for charge conditioning.

— Radioisotopes.

— Soft X-rays.

—Corona-discharges.

Other, less common ionization sources are included in Table 1.

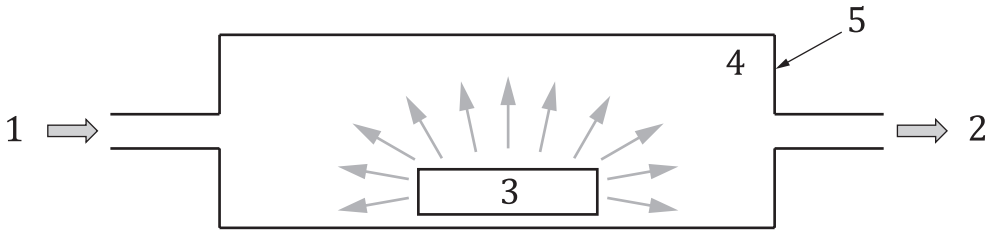
5.2.2 Sources with radioisotopes

5.2.2.1 General

Radioisotope charge conditioners generally contain a sealed radioactive source. This device acts as a bipolar diffusion charge conditioner. It produces both negative and positive ions in the carrier gas. The radiation generates, so called, primary ions like N_2^+ and O_2^+ and free electrons in the carrier gas. These ions are short-lived. Some of them attach themselves to neutral molecules, which then coagulate into relatively stable ion clusters. Diffusion (Brownian movement) leads to collisions between these ions and the aerosol particles and thus to charge transfer to the particles.

Either alpha or beta radiation can be applied for air ionization. Alpha radiation with its very high linear energy transfer is able to produce high ion concentrations in a small charging volume. This is an advantage over beta radiation, where the charging volume must be bigger. As a result, the particle residence time in a radioactive charge conditioner with beta radiation is typically longer, which is a disadvantage with respect to diffusion losses. On the other hand, alpha radiation sources can easily be shielded, e.g. by a very thin layer of dust. Surface contamination can reduce the resulting ion concentration in charge conditioners with alpha sources.

Figure 1 shows a schematic example of the design of a radioisotope charge conditioner.



Key

1	aerosol inlet	4	charging zone
2	aerosol outlet	5	enclosure
3	radioisotope source		

Figure 1 — Schematic example of a radioisotope charge conditioner

The most commonly used radioactive isotopes are:

— Krypton 85 (^{85}Kr).

— Americium 241 (^{241}Am).

— Polonium 210 (^{210}Po).

— Nickel 63 (^{63}Ni).

Their properties are explained in 5.2.2.2 to 5.2.2.5.

NOTE Sealed radioactive sources are classified based on ISO 2919,[71] which provides tests and a classification system, e.g. for ranges of temperature, pressure, puncture, impact and vibration.

5.2.2.2 Krypton 85 (^{85}Kr)

^{85}Kr is a beta emitter (with 0,43 % gamma radiation probability of 514 keV) with a half-life of 10,78 years. The maximum beta energy is 687 keV. Krypton is a noble gas, substantially reducing the health risk in case of leakage or damage to the source. In nearly all sources, the ^{85}Kr gas is contained in a small-diameter, sealed, stainless steel tube. This tube is contained inside a larger-diameter stainless steel or aluminium housing. Aerosol passes axially through the housing that contains the ^{85}Kr tube. Part of the beta radiation is absorbed in the steel or aluminium that makes up the tube and the housing, thus producing Bremsstrahlung that also contributes to ion production. It is recommended to use lead shielding if possible.

5.2.2.3 Americium 241 (^{241}Am)

^{241}Am is an alpha emitter (with negligible additional beta and gamma radiation) with a half-life of 433 years. Sealed sources of this metal are available as strips covered with a very thin gold, palladium, or gold and palladium alloy film. The alpha energy is 5,5 MeV.

5.2.2.4 Polonium 210 (^{210}Po)

^{210}Po is an alpha emitter with a half-life of 138 days. Due to their short half-life, ^{210}Po sources should be replaced annually or more often. The metalloid ^{210}Po is available in the form of gold-coated, typically embedded in a protective housing. Its alpha energy is in the range between 4 MeV and 5,3 MeV.

5.2.2.5 Nickel 63 (^{63}Ni)

^{63}Ni is a beta emitter (100 %) with a half-life of 100,1 years. Its beta energy is 67 keV; the decay product is stable ^{63}Cu. ^{63}Ni foils are also used, as ionisation source in GC-MS for example. Unsealed as well as sealed (inactive Ni overplating) foils, with up to 100 MBq, are commercially available.

NOTE 100 MBq is the free limit in the EU.

5.2.2.6 Licensing and precautions for radioisotope sources

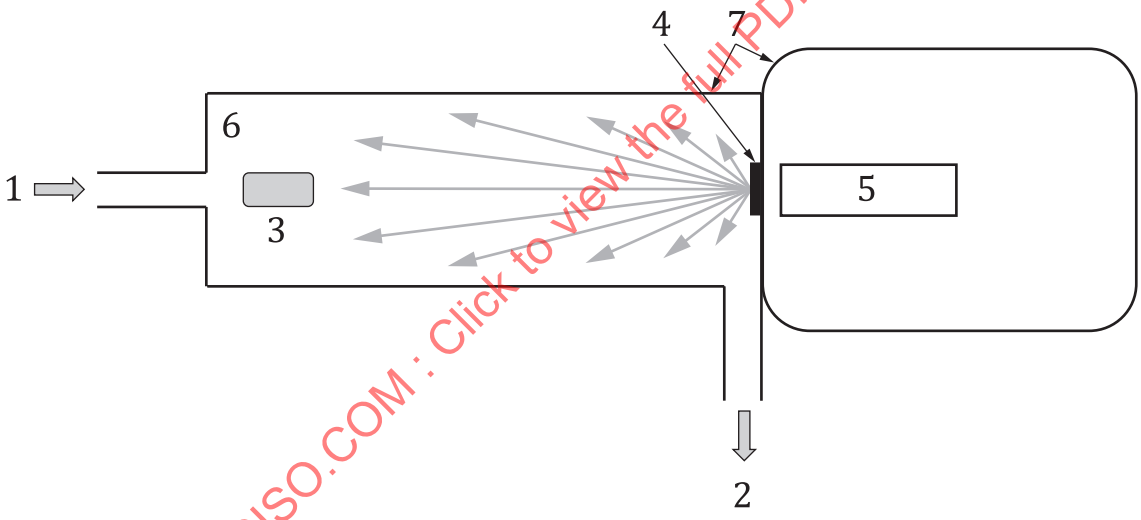
The use, transportation and disposal of radioisotopes is regulated by government authorities. Basic international standards and guidelines are, for example, set by commissions of the United Nations, such as IAEA, ICRP, ADR, etc. The licensing, shipping and disposal regulations that govern radioactive sources vary from nation to nation.

5.2.3 Soft X-ray sources

5.2.3.1 General

Soft X-ray sources emit X-rays in the energy range below 10 keV. Soft X-rays are a very efficient source for charge conditioning because they have energies that are much higher than the ionization threshold of all molecules, thus creating an abundance of active ions. This device acts as a bipolar diffusion charge conditioner, comparable to sources with radioisotopes. A stainless steel or aluminium housing is irradiated with X-rays from a source. The aerosol flows through the housing from an inlet to an exit port. A radiation window (e.g. beryllium) protects the X-ray source from particle impact and also attenuates the radiant flux and radiation energy to adjust the ion concentration. X-ray blockers can prevent X-rays from exiting through the aerosol ports. While radioisotope sources emit radiation continuously, X-ray sources can be turned on and off.

Figure 2 shows a schematic example of the design of a soft X-ray charge conditioner. While in this example, the aerosol flow is directed towards the attenuation window, other designs exist where the flow is reversed.



Key

1	aerosol inlet	5	x-ray source
2	aerosol outlet	6	charging zone
3	x-ray blocker (optional)	7	enclosure
4	attenuation window		

Figure 2 — Schematic example for a soft X-ray charge conditioner

5.2.3.2 Licensing and precautions for soft X-ray sources

The use of soft X-ray sources can be regulated by international, national or local government authorities, or all. Regulations can vary from nation to nation.

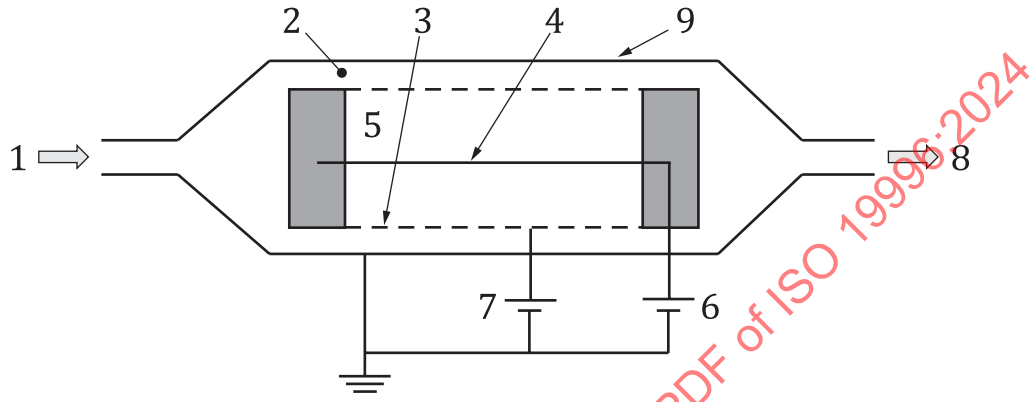
Users shall conform to manufacturers' instructions.

5.2.4 Corona discharge

Corona discharge can function as a source for both negative and positive ions in the carrier gas. Either a single corona electrode operated with DC-high voltage (for ions of one polarity) or with AC-high voltage (for two ion polarities), or two separate corona electrodes (one for each ion polarity) can be used.

NOTE If an aerosol electrometer is used as a particle detector immediately downstream of the charge conditioner (without the DEMC), an ion trap is possibly necessary as an additional element to eliminate any remaining free ions from the charge-conditioned aerosol. Otherwise an aerosol electrometer will measure these free ions as an additional current.

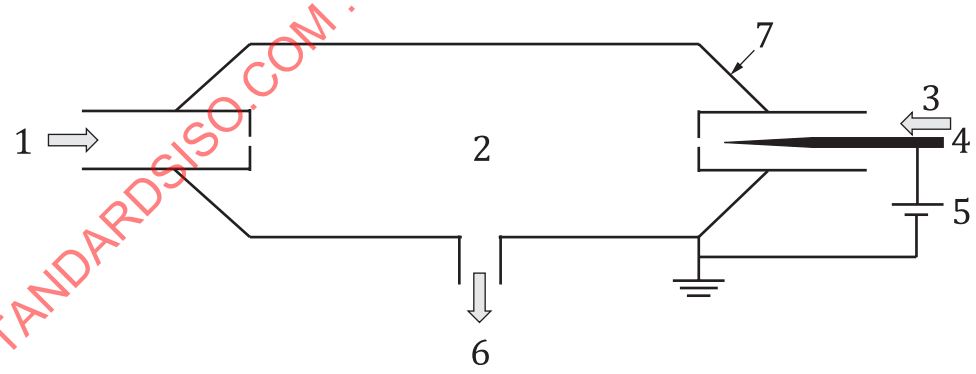
Figures 3 and 4 show schematic examples of the design of corona discharge charge conditioners.



Key

1 aerosol inlet
2 charging zone
3 mesh electrode
4 corona wire
5 ion generation zone
6 high voltage
7 mesh electrode voltage
8 aerosol outlet
9 enclosure

Figure 3 — Schematic example for a mesh corona discharge charge conditioner



Key

1 aerosol inlet
2 turbulent charging zone
3 sheath air inlet
4 corona needle
5 high voltage
6 aerosol outlet
7 enclosure

Figure 4 — Schematic example for a counter-flow corona discharge charge conditioner

5.3 Charge conditioning

5.3.1 General

In order to calculate the particle size distribution from the measured electrical mobility distribution, a known particle size-dependent distribution of electrical charges shall be generated on the aerosol particles, described by the charge distribution function, $f_p(d)$. Charge conditioners upstream of a DEMC are used for this purpose.

In a gaseous medium containing aerosol particles and a sufficient concentration of unipolar ions or ions of both polarities, a charge distribution will develop on the particles. As the dominant driving forces are the random thermal diffusion of the ions and the collision between ions and aerosol particles, the terms bipolar or unipolar diffusion charging are frequently used for these types of charge conditioning. The main advantage of diffusion charging over other methods is that it depends only weakly upon aerosol particle material.[16] Subclauses 5.3.2 and 5.3.3 describe the characteristics of bipolar and unipolar diffusion charging.

In some charge conditioner designs, the ion transport is deliberately influenced by AC- or DC-electric fields and sheath air flows.

The particle charging efficiency depends mainly on the so called $N_I{\cdot}t$ product, which is the concentration of either positive or negative ions, N_I, multiplied by their residence time, t, which is the interaction time of aerosol particles with the ions.

The $N_I{\cdot}t$ product reached in a radioactive charge conditioner depends on the type and energy of the radiation of the isotope, on the activity and geometry of the sealed source, on the geometry of the housing, on the flow rate and concentration of the aerosol through the housing and also on the composition of the carrier gas. Similarly, the $N_I{\cdot}t$ product reached in a soft X-ray charge conditioner depends on the X-ray energy and the radiant flux, the radiation field geometry, the flow rate and concentration of the aerosol flow through the housing and on the composition of the carrier gas (see Clause 6).

Table 1 gives an overview on charge conditioners. There is a list of literature provided at the end of the document.

Table 1 — Overview on charge conditioners and selected references

Category	Type	Reference
Bipolar charge conditioners	Radioactive charge conditioner (RC)[a]	[1], [7], [49], [50]
	Soft-X-ray charge conditioner (SXRC)	[1], [31], [32], [49] – [53]
	Bipolar corona ionizer (BCI)	[54] – [59]
	Surface-discharge microplasma aerosol charger (SMAC)[a]	[3], [60] – [64]
Unipolar charge conditioners	Positive unipolar corona discharge (PCD) charge conditioner	[5], [12], [49], [50], [65] – [67]
	Negative unipolar corona discharge (NCD) charge conditioner	

[a] Can also be applied for unipolar charge conditioning.

5.3.2 Bipolar charge conditioners

Bipolar charge conditioners (also traditionally called aerosol neutralizers) produce ions of both polarities (i.e. positive and negative ions). Neutral particles can acquire charge while highly charged particles can discharge themselves by capturing ions of the opposite polarity. Bipolar charge conditioners differ by the way the ions are generated.

— Radioactive bipolar diffusion charge conditioners generate ions in the carrier gas by α- or β-radiation from a radioactive isotope.

— X-ray bipolar diffusion charge conditioners use soft-X-rays (< 10 keV) for ion generation in the carrier gas.

In these two charge conditioner types, the ions are produced directly in the carrier gas and diffuse to the aerosol particles by Brownian motion.

— Bipolar corona ionizers (BCI) use an arrangement of two DC-corona ionizer stages (one for each polarity). Ions of opposite charge are produced in separate sections and are subsequently mixed with the aerosol. In another variant, bipolar ions are produced by AC-corona discharging.

5.3.3 Unipolar charge conditioners

Besides the widely used bipolar steady-state charge distribution, unipolar charge conditioning can also be used to achieve a defined charge distribution. In a unipolar charge conditioner, ions of either positive or negative polarity are produced (e.g., by a corona discharge process or separation of one ion polarity in an electric field). Like in bipolar charging, diffusion charging is advantageous because variations caused by the composition of the particles can be neglected for diffusion charging.

Unipolar charging can achieve higher charging probabilities than bipolar charging. This is an advantage if small particles (d < 20 nm) are to be measured. Due to the higher charging probability, more particles are classified by the DEMC. This leads to better counting statistics in a DMAS. On the other hand, larger particles (d > 100 nm) carry significantly more multiple charges compared to bipolar charge conditioning. This makes the data inversion more complex and reduces the size resolution of large particles. A variety of unipolar charge conditioners for aerosol particles have been described and built; see, for example, References [44], [45], [46], [47] and [48].

Corona discharge is produced by a strong nonuniform electrostatic field, such as that between a needle and plate or a concentric thin wire and a tube. The electric field and space charge effects result in repulsion of ions of polarity opposite to that of the wire which can lead to positively or negatively charged particles. There are two designs for corona discharge charge conditioners:

— Negative corona discharge charge conditioner.

  The discharge electrode is held at high negative potential. The free electrons are repelled from the electrode and can attach to air molecules to form negative ions. Ozone is generated as a by-product which makes this design not favourable for aerosol charging.

— Positive corona discharge charge conditioner.

  In positive corona discharge charge conditioners, the discharge electrode (wire or tip) is held at high positive potential. In this case the free electrons from the corona discharge are attracted to the electrode and do not need to be absorbed. Most commercially available charge conditioners use positive ions due to the fact that the process is stable by controlling the corona current and the emission of ozone can be avoided.

  Among the group of positive corona charge conditioners are indirect corona charge conditioners and turbulent jet charge conditioners. Indirect corona charge conditioners shield the particle charging zone from the corona discharging zone in order to reduce particle losses. A grounded electrode in the aerosol flow can be applied as a trap for excess ions. Turbulent jet charge conditioners completely separate the ion generation from the particle charging zone. This leaves the charging zone free of electrical fields and reduces particle losses to a minimum. Ions are transported into the particle charging zone by an additional flow, which dilutes the aerosol flow at the exit.

NOTE Corona charge conditioners that apply field charging, in contrast to diffusion charging, are not considered for measurement purposes here because of their increased particle material dependence.

Other charge conditioning processes such as static electrification, photoionization, thermionic emission, self-charging of radioactive particles and agglomeration are not considered because of their very restricted controllability and usability to charge conditioning in measuring devices. However, some of these processes should be taken into account as disturbances.

5.4 The charge distribution function

5.4.1 General

The particle size-dependent charge distribution function, $f_p(d)$, shall be known in order to calculate the size distribution of airborne particles classified in a DEMC. A charge conditioner is used at the entrance of a DEMC to achieve a conditioned charge distribution which is independent of the initial charge state of the aerosol particles. The conditioned charge distribution is, at least for typical aerosol residence times in a DEMC, in a steady state or stable.

$f_p(d)$ may then be given by a set of equations or tabulated data, approximating the size-dependent charge distribution by either theoretical models or empirical data, or both.

5.4.2 Charge distribution function for radioactive bipolar charge conditioners

For commercially available radioactive bipolar charge conditioners, the charge distribution function under standard conditions (spherical particles in air: 293,15 K, 101,3 kPa) is given by Formulae (A.10) and (A.11) which are derived from an approximation to the theoretical models (see Reference [17] in combination with the result from Reference [18]). Table 2 shows some numerical results. Unless explicitly specified differently in the measurement report, Formulae (A.10) and (A.11) or values in Table 2 shall be used for the determination of $f_p(d)$ for radioactive bipolar charge conditioners.

Table 2 shows the bipolar charge distribution $f_p(d)$ for spherical particles in air (293,15 K, 101,3 kPa), produced by radioactive charge conditioners (see Formulae (A.10) and (A.11)).

Table 2 — Bipolar charge distribution $f_p(d)$ produced by radioactive charge conditioners

d (nm)	Charge distribution												
	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6
1	0	0	0	0	0	0,004 8	0,999 3	0,004 5	0	0	0	0	0
2	0	0	0	0	0	0,008 3	0,974 2	0,007 5	0	0	0	0	0
5	0	0	0	0	0	0,022 5	0,969 3	0,018 9	0	0	0	0	0
10	0	0	0	0	0	0,051 4	0,912 4	0,041 1	0	0	0	0	0
20	0	0	0	0	0,000 2	0,109 6	0,793 1	0,084 6	0,000 1	0	0	0	0
50	0	0	0	0	0,011 4	0,222 9	0,581 4	0,169 6	0,006 6	0	0	0	0
100	0	0	0,000 1	0,003 7	0,056 1	0,279 3	0,425 9	0,213 8	0,031 7	0,001 7	0	0	0
200	0	0,000 5	0,005 3	0,034 0	0,121 1	0,264 1	0,299 1	0,204 3	0,071 9	0,015 3	0,001 8	0,000 1	0
500	0,006 7	0,020 7	0,050 4	0,098 0	0,149 0	0,181 6	0,181 8	0,140 3	0,089 1	0,044 0	0,017 3	0,005 4	0,001 4
1 000	0,035 7	0,058 4	0,085 4	0,111 3	0,126 1	0,138 5	0,123 5	0,103 9	0,075 4	0,050 0	0,029 3	0,015 4	0,007 2

5.4.3 Charge distribution functions for other bipolar and unipolar charge conditioners

Calculations of the respective charge distribution functions for non-radioactive bipolar and unipolar charge conditioners are complicated and require careful experimental verification before usage in data inversion routines for the analysis of measured data.

The theoretical concepts described in Annex A can be helpful for the experienced user to calculate a charge distribution function for a given bipolar charge conditioner. Annex A also shows an example of the charge distribution function for a charge conditioner based on an X-ray ionization source.

The charging of particles in unipolar charge conditioners depends on individual designs and operating parameters. Therefore, no general approximation for the charge distribution function can be given for the variety of unipolar charge conditioners.

6 Factors influencing the resulting charge distribution

6.1 General

The purpose of operating a charge conditioner, as described in this document, is to achieve either:

—a steady state;

— equilibrium charge distribution (bipolar charge conditioners);

—a well characterized and repeatable charge distribution (unipolar charge conditioners).

If charge conditioning is done for particle measurement purposes (e.g. for measurements with the DMAS), any changes in the aerosol properties during the charging process must be negligible with respect to the result of the measurement.

All charge conditioners described have individual permissible upper particle concentration limits and particle size dependent charging efficiencies. Their respective charge distribution functions, $f_p(d)$, depend on ion concentrations, ion mass and ion mobility, as well as on residence time and concentration of particles. Situational factors such as carrier gas composition, purity, humidity and temperature can also influence the performance. Charge conditioner manufacturers should provide the respective charge distribution function and describe the conditions under which the device performs in a predictable way and does not produce artefacts.

Considering the influence of operating conditions, there is a major difference between bipolar and unipolar charge conditioners.

— In bipolar charge conditioners, the resulting charge distribution depends on the ion mass distribution and the ion mobility distribution. Since the necessary time to reach steady state conditions is very small compared to the residence time of the particles in the charging zone, the steady state charge distribution will be reached and remain unchanged as long as the particle concentration, in combination with the particle size distribution, does not exceed the design-based ($N_I \cdot t$-product based) limit of the charge conditioner.

— In unipolar charge conditioners, the achieved mean charge per particle and the charge distribution depend on the $N_I \cdot t$ product. Therefore, besides the ion properties (mass and mobility), the ion concentration profile within the charging region as well as the aerosol flow rate through the charge conditioner must be maintained within narrow tolerances to guarantee reproducible operation achieving the expected charge distribution.

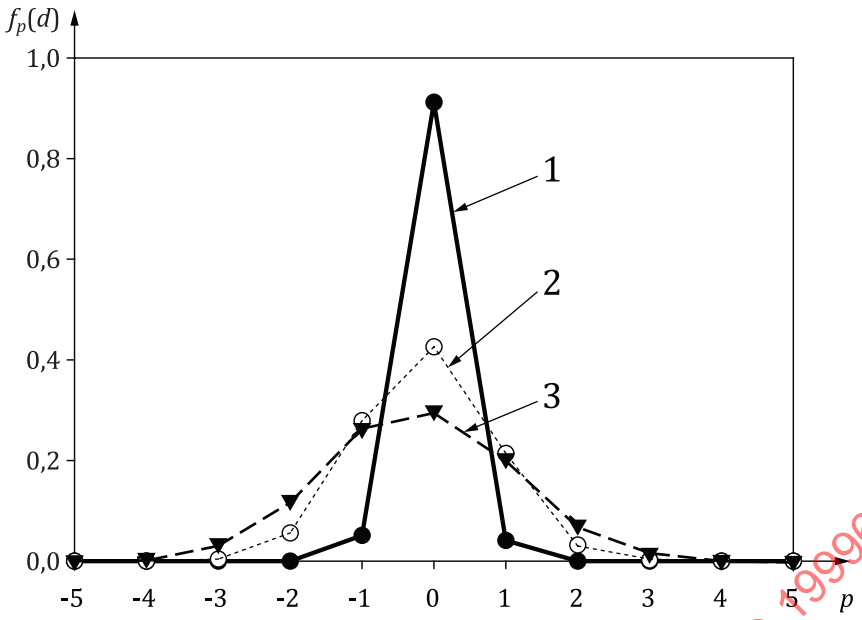
Clause 6 covers the influence of aerosol particle and carrier gas characteristics as well as the influence of charge conditioner operating parameters (and others) on the resulting charge distribution and eventual changes in aerosol properties. Sub-clauses 6.2 to 6.5 cover topics under the assumption that all other conditions do not change.

6.2 Aerosol particle characteristics influencing the charge distribution

6.2.1 Particle size and surface area

The mean number of elementary charges per particle increases and the charge distribution widens with increasing particle size.

Figure 5 shows a comparison of the steady state, equilibrium charge distribution for spherical particles with a diameter of 10 nm, 100 nm and 200 nm, calculated with the approximation for radioactive ionization sources in a bipolar diffusion charge conditioner as described in Reference [17], see A.4.

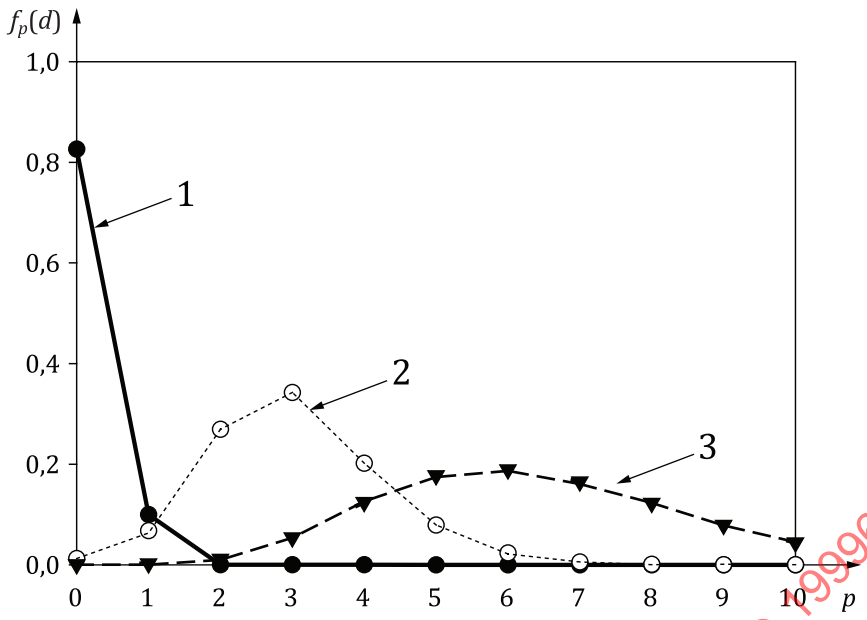


Key

p	number of net elementary charges on a particle	1	d = 10 nm
$f_p(d)$	charging probability	2	d = 100 nm
		3	d = 200 nm

Figure 5 — Bipolar charge distribution for spherical particles with a diameter of 10 nm, 100 nm and 200 nm

Similar behaviour is found for unipolar diffusion charge conditioners. Figure 6 shows a comparison of the unipolar charge distribution for spherical particles with a diameter of 10 nm, 100 nm and 200 nm, in a mixing type charge conditioner, calculated with the approximation for a unipolar charge conditioner (that is, ion jet and turbulent mixing) described in Reference [12].



Key

p	number of net elementary charges on a particle	1	d = 10 nm
$f_p(d)$	charging probability	2	d = 100 nm
		3	d = 200 nm

Figure 6 — Unipolar charge distribution for spherical particles with a diameter of 10 nm, 100 nm and 200 nm

Classical particle charging models as discussed in Annex A assume spherical particles and hence apply the sphere's geometrical diameter and surface area to determine ion attachment. For irregularly shaped, non-spherical particles, the ion attachment equivalent surface area must be used to determine the ion attachment when calculating the average charge per particle and the charge distribution.[39]

6.2.2 Particle number and surface area size distribution and concentration

The particle concentration to be charged shall be limited in such a way that the depletion of ions due to ion attachment to the particles does not lead to significantly reduced charges on the particles.

Whether or not the expected charge distribution is achieved in a charge conditioner due to ion depletion depends on the total ion attachment surface area concentration. While steady state conditions are reached (e.g. for a certain particle number concentration of monodisperse particles of a given size), it can eventually not be reached when a wide particle size distribution with the same number concentration is present. The presence of larger particles in the size distribution increases the ion depletion.

6.2.3 Particle pre-charge

In bipolar charge conditioners, the ion concentration can be insufficient to compensate high pre-charge while the same aerosol, if uncharged, reaches steady state conditions.

Unipolar charge conditioning is also affected by the pre-charge (also known as a primary charge) on the particles. Unipolar charge conditioning will fail if the particles entering the device already carry a charge level of the same polarity as the ions which is higher than the expected steady state charge level. Such higher pre-charge cannot be reduced by ions of the same polarity. Some unipolar charge conditioners minimize this effect by a two-stage design, where the first charge conditioner stage operates at the opposite polarity.

6.3 Aerosol carrier gas characteristics influencing the charge distribution

6.3.1 Carrier gas composition

In a different carrier gas than air (e.g. pure nitrogen or argon), the ratio of the electrical mobility of positive and negative ions will change. This will lead to a different steady state (equilibrium) charge distribution for bipolar charge conditioners (see Reference [9]).

Furthermore, particle formation from precursor gases (e.g. SO_2 or pinenes) can increase in the presence of the high ion concentration in the charge conditioner. Ozone produced by the corona plasma in unipolar chargers can also serve as a particle precursor. It should be checked prior to measurements, e.g. with a DMAS that particle generation in the charge conditioner is insignificant compared to the measured particle concentration. A system zero test (refer to ISO 15900:2020, 8.2.3) with the aerosol to be measured is helpful to uncover particle generation in the charge conditioner.

6.3.2 Carrier gas pressure and temperature

A change in either temperature or pressure, or both, changes the ion electrical mobility distribution but does not change the ratio of the electrical mobility of positive and negative ions, because electrical mobilities are directly proportional to temperature or inversely proportional to pressure. The steady state (equilibrium) charge distribution for bipolar charge conditioners, thus, will not change (see Reference [40]).

The charge distribution for unipolar conditioners, however, will change with carrier gas pressure and temperature since the ion mobility distribution is changed.

6.3.3 Carrier gas humidity

Depending on the relative humidity (RH) of the carrier gas, the ion mobility distribution will change. With increasing RH, the mobility of negative ions, especially, increases. The mobility of positive ions remains unchanged. See Reference [32] for further information. This changes the steady state (equilibrium) charge distribution for bipolar chargers as well as the charge distribution for negative unipolar chargers under otherwise unchanged conditions.

6.4 Charge conditioner operating parameters influencing the charge distribution

6.4.1 Aerosol flow rate

6.4.1.1 Particle residence time in the charging volume

The particle residence time in the charging volume of a charge conditioner depends on the aerosol flow rate through the charging volume.

For typical designs of bipolar charge conditioners, the residence time of the particles in the charging volume (seconds) is not a significant parameter since it is much longer than the time required to achieve the steady state charge distribution (milliseconds), see Reference [33].

For unipolar charge conditioners, the achieved charge distribution (for otherwise unchanged conditions) depends on the residence time in the charging volume. The mean charge per particle increases with increasing residence time.

The residence time cannot be assumed to be simply proportional to the flow rate, since the particle velocity field can change with changing flow rate; for example, stagnation zones can develop under certain flow conditions. Therefore, the geometric design of the charge conditioner has a strong influence on the residence time.

6.4.1.2 Particle concentration profile (mixing state) in the charging volume

The particle concentration profile and the mixing state of the aerosol in the charging volume can change depending on the following:

— aerosol flow rate;

— geometric design of the charge conditioner;

— spatial particle and ion concentration profiles.

Extreme cases are laminar particle stream lines directly from the inlet to the outlet of the charging chamber presenting a high particle concentration to the ion cloud versus a homogeneously mixed aerosol inside the whole chamber presenting a much lower concentration. Obviously, these two cases can lead to very different particle concentration to ion concentration ratios.

Poor mixing conditions in the charging chamber can significantly reduce the maximum allowed particle concentration to reach steady state conditions in a bipolar charge conditioner.

For unipolar charge conditioners, the average $N_I \cdot t$ product will be very different for the extreme cases covered in 6.4.1.2, therefore the resulting particle charge will also be significantly different.

6.4.2 Ion production rate

The ion concentration in the charging volume (and therefore the charging capacity of a charge conditioner) is directly linked to its ion production rate.

In charge conditioners with radioactive sources, the ion production rate decreases over time due to the decay of the radionuclide. After one half-life of the used radionuclide, the activity (decays per second) and hence the ion production rate is reduced to 50 %. Depending on the radiation type and energy of the radiation emitted by the radioactive source, surface contamination can also influence the ion production rate. This reduction can become significant especially for alpha radiation, which is easily shielded by a thin layer of solid or liquid contamination.

The ion production rate from electrically controlled ion sources (e.g. corona discharge or x-ray tubes) can be user-controllable by design; it can also vary due to malfunction of the control circuit.

The performance of the corona needle or wire in a charge conditioner can degrade either due to erosion or due to the build-up of deposited materials. The latter was, for example, reported if the gas flow around the corona needle contains traces of out-gassings from silicone tubing.[41] Because of performance degradation, the ion production rate at unchanged corona voltage is reduced.

In a bipolar charge conditioner, a decrease in ion production rate will result in a proportional decrease in allowed particle concentration at a given size distribution. In a unipolar charge conditioner, decreasing ion production rate will also change the charging efficiency and, therefore, the mean charge per particle and the charge distribution.

6.5 Others

6.5.1 Surplus ions downstream of device

Depending on the charge conditioner's design, ions can leave the charging chamber through its exit port. In instruments which detect the electrical charge of the particles (e.g. charger and electrometer combinations for total Fuchs surface area concentration or lung-deposited surface area concentration measurement), these ions can bias the measurement. An electrostatic ion trap (precipitator) is used in such cases to separate surplus ions from the aerosol.

6.5.2 Particle losses to the chamber wall

Particle losses to the walls of the charging chamber are mainly due to diffusion (Brownian and eventually turbulent). If charged particles pass through an electrical field in a corona charger, electrophoretic losses can also occur.

Internal losses are already included in the (measured) extrinsic charge distribution of a charge conditioner. However, charge distribution measurements are typically made at a nominal flow rate through the device.

Since the losses also depend on the flow rate through a given charge conditioner, corrections to compensate flow rate effects on the losses and, hence, the extrinsic charging efficiency can become necessary when the flow rate deviates from its nominal value.

6.5.3 Aerosol dilution in the charge conditioner

When a charge conditioner is used in a measurement system like a DMAS, aerosol dilution (by design) in the charge conditioner must be compensated in the measurement system's data inversion. The stability of the flow control in a charge conditioner with internal aerosol dilution directly influences the measurement uncertainty of the measurement system.

6.5.4 Generation of artefact particles

If corona discharge methods are used, the instrument manufacturer and the user should, by design or by measurement, ensure that the method performs correctly and does not produce artefact particles.

7 Operational parameters for device specification

The following parameters shall be listed in the specifications that accompany the charge conditioner.

— Type of charge conditioning: bipolar or unipolar.

— Information for the ion source, including:

  — Type of ion source (radioactive, soft x-ray, discharge, others).

  — For radioactive ion sources: the isotope used, half-life, initial activity in Bq.

  — For soft x-ray ion sources: x-ray tube voltage, maximum x-ray energy.

  — For corona discharge ion sources: voltage, current.

— Material of the enclosure.

— Maximum particle generation rate and concentration.

— Charge distribution function (if available).

— Flow rate range.

— Type of carrier gas permitted (in addition, type of ion transport gas for some devices).

— Maximum particle number concentration.

— The pressure, temperature, and RH ranges permitted.

— Recommended particle size range (if available).

— Equivalent length for calculation of particle transmission efficiency (if available).

8 Test procedures for determining the suitability of charge conditioners

8.1 Guidance to test procedures in the annexes

A thorough characterization of the properties of charge conditioners allow informed decisions on the suitability of a specific charge conditioner for an intended application. Further, the proper performance of charge conditioners when used in particle generation or in DMAS measurements should be periodically verified. Table 3 summarises the information included in the annexes listed, which describe test procedures for important performance parameters of charge conditioners.

Table 3 — Annexes with test procedures

Annex	Performance parameter	Test procedure in subclause	Notes
Annex B	Particle generation rate	B.2	Suitable for unipolar and bipolar charge conditioners
	Particle transmission efficiency	B.3	Suitable for unipolar and bipolar charge conditioners
	Charging probability f_0	B.4	
	Charging probabilities f_i ($i \neq 0$)	B.5	Refer to Annex E for a simplified version for f_{+1} (or f_{-1})
Annex D	Maximum permissible particle number concentration	D.2	Quantitative performance assessment
Annex E	Ratio of +1 charged particles to -1 charged particles	E.2.4	Especially suitable for electrical discharge bipolar charge conditioners
	Charging probability f_{+1} (or f_{-1})	E.2.5	Simplified version of B.5
Annex F	Adequate performance of charge conditioner	F.3	Qualitative performance check for bipolar charge conditioners

Additionally, ISO 27891:2015 Annex K describes a test procedure to determine if the charge conditioner is performing adequately for the purpose of CPC calibration.

8.2 Charge conditioner performance verification

Annex D describes a test method to determine the breakdown of steady state conditions in a charge conditioner by increasing the aerosol test concentration. By this, the maximum particle number concentration the charge conditioner can handle is identified. While this test is primarily intended to be performed by the manufacturers of the charge conditioners to establish a performance index, it can also be applied by the user, e.g. before a measurement campaign, to characterize the maximum permissible concentration range in a given scenario. This test makes use of a lot of equipment and takes significant time to run and evaluate.

Annex F utilizes ambient air as test aerosol to check whether a bipolar charge conditioner is suitable for use in ambient monitoring. It requires stable ambient aerosol overnight and a known good reference charge conditioner but is otherwise straightforward to use.

8.3 Particle losses in a charge conditioner

B.3 describes a method to determine the transmission efficiency in a charge conditioner in case this specification is not given in the manufacturer's datasheet.

8.4 Particle generation rate

Depending on the type of bipolar charge conditioner, particles can be generated inside the charge conditioner, for example by excess ions from electrical discharge (see 6.5.4). B.2 describes a test to quantify the particle generation in a charge conditioner.

8.5 Charge distribution of bipolar charge conditioners

For a given particle size, the particles' electrical mobility is proportional to the net number of elementary charges on the particle. Therefore, the particle charge distribution must be known for particle size classification with differential electrical mobility analysing systems (DMAS), as it is used in the data inversion routines for the analysis of the measured data.

B.4 describes a method to test for the charging probability f_0, generated from singly charged particles in a charge conditioner. B.5 describes how to determine other charging probabilities f_i ($i \neq 0$). E.2.5 describes a simplified test if one is only interested in the charging probabilities f_{+1} (or f_{-1}).

Annex A provides the theoretical concepts behind calculating the charge distribution function for a given charge conditioner.

9 Cleaning and maintenance including safety issues

Charge conditioners should be checked regularly to ensure operation as expected, for example by following the guidelines in Annexes D and F. Cleaning charge conditioners can be hazardous and should only be performed by a trained professional if manufacturer's instructions exist.

The use, transportation and disposal of radioisotopes are regulated by government authorities. Basic international standards and guidelines are provided, for example, by commissions of the United Nations like IAEA, ICRP, ADR, etc. The licensing, shipping and disposal regulations that govern radioactive sources vary from nation to nation.

The use of soft X-ray sources is regulated by national and/or local government authorities. The regulations vary from nation to nation.

Annex A
(informative)

Implementation of bipolar steady-state charge conditioning

A.1 General

If the aerosol interacts long enough with a sufficient concentration of bipolar ions in a gaseous medium, a steady-state bipolar charge distribution will develop on the particles (see A.3). By bipolar diffusion charging, particles less than 30 nm acquire one charge at most, which is a major requirement for application to the production of monodisperse nanoparticles. Nonetheless, single charging efficiencies are rather low.

A.2 Charge distribution function of particles

Under the steady-state conditions in the case of bipolar charging, the charge distribution function $f_p(d)$ can be expressed as:

$$f_p(d) = \frac{N_p}{N} = \frac{\prod_{j=+1}^{p} \left(\frac{\beta_{j-1}^{+}}{\beta_j^{-}} \right)}{\Sigma} \qquad \text{if } p \geq +1 \qquad \text{(A.1)}$$

$$f_p(d) = \frac{N_p}{N} = \frac{\prod_{j=-1}^{p} \left(\frac{\beta_{j+1}^{-}}{\beta_j^{+}} \right)}{\Sigma} \qquad \text{if } p \leq -1 \qquad \text{(A.2)}$$

$$f_p(d) = \frac{N_0}{N} = \frac{1}{\Sigma} \qquad \text{if } p = 0 \qquad \text{(A.3)}$$

where

$$\Sigma = \sum_{p=+1}^{+\infty} \left\{ \prod_{j=+1}^{p} \left(\beta_{j-1}^{+} / \beta_j^{-} \right) \right\} + \sum_{p=-1}^{-\infty} \left\{ \prod_{j=-1}^{p} \left(\beta_{j+1}^{-} / \beta_j^{+} \right) \right\} + 1$$

$f_p(d)$ is the charge distribution as a function of particle size d;

N is the number concentration of aerosol particles of size d;

N_p is the number concentration of charged particles of particle size d;

N_0 is the number concentration of uncharged particles of size d;

$\beta_p^{\pm}$ is the ion-aerosol attachment coefficient of particles of size d with p charges, with positive or negative ions;

p is the number of elementary units of charge.

The charge distribution function $f_p(d)$ can be calculated from Formulae (A.1), (A.2), (A.3), if the ion-aerosol attachment coefficients (combination charging constants) β are known.

A.3 Ion-aerosol attachment coefficient

A.3.1 Fuchs' Theory

Under the steady-state charging processes, there is a well-known theory describing the ion-aerosol attachment coefficients, β, which is the so-called Fuchs' attachment theory. β can be expressed as:

$$\beta_p^{\pm} = \frac{\pi \cdot c^{\pm} \cdot \alpha^{\pm} \cdot \delta^{\pm 2} \cdot \exp\left\{-\varphi_p\left(\delta^{\pm}\right)/kT\right\}}{1+\exp\left\{-\varphi_p\left(\delta^{\pm}\right)/kT\right\} \cdot \frac{c^{\pm} \cdot \alpha^{\pm} \cdot \delta^{\pm 2}}{4D^{\pm} \cdot a} \cdot \int_0^{a/\delta^{\pm}} \exp\left\{-\varphi_p\left(a/x\right)/kT\right\} \mathrm{d}x} \tag{A.4}$$

where

$$x = a/r$$

$$\varphi_p(r) = \frac{p \cdot e^2}{4\pi \cdot \varepsilon_0 \cdot r} - \frac{\varepsilon_1 - 1}{\varepsilon_1 + 1} \cdot \frac{e^2}{8\pi \cdot \varepsilon_0} \cdot \frac{a^3}{r^2\left(r^2 - a^2\right)}$$

$$\delta^{\pm} = \frac{a^3}{\lambda^{\pm 2}} \left\{ \frac{1}{5}\left(1+\frac{\lambda^{\pm}}{a}\right)^5 - \frac{1}{3}\left(1+\frac{\lambda^{\pm 2}}{a^2}\right)\left(1+\frac{\lambda^{\pm}}{a}\right)^3 + \frac{2}{15}\left(1+\frac{\lambda^{\pm}}{a}\right)^{5/2} \right\}$$

$$\alpha^{\pm} = \left(\frac{a}{\delta^{\pm}}\right)^2$$

a is the aerosol particle radius ($d = 2a$);

e elementary charge;

r is the distance between the particle and the ion;

$c^{\pm}$ is the thermal velocity of positive or negative small ions;

$\alpha^{\pm}$ is called Fuchs'α parameter, corresponding to the square of the ratio of the particle radius to the limiting sphere;

$\delta^{\pm}$ is the radius of a sphere that divides the free molecular regime near the particle and the continuum regime far from the particle (this imaginary sphere is often called Fuchs' limiting sphere);

k is the Boltzmann constant;

T is the absolute temperature;

$D^{\pm}$ is the thermal diffusion coefficient of positive or negative small ions;

ε_0 is the dielectric constant;

ε_1 is the specific dielectric constant;

$\lambda^{\pm}$ is the mean free path of positive or negative small ions.

If the values of dynamic properties $c^{\pm}$, $D^{\pm}$, $\lambda^{\pm}$ of the small ion, and aerosol particle diameter ($d = 2a$) are known, the ion-aerosol attachment coefficients, β, can be calculated.

NOTE Above equation for $\alpha^{\pm}$ is only valid when the particle is electrically uncharged ($p = 0$). When the particle is charged ($p \neq 0$), the equation for $\alpha^{\pm}$ becomes rather complicated, see Reference [25].

A.3.2 Properties of the ion

The values of dynamic properties $c^{\pm}$, $D^{\pm}$, $\lambda^{\pm}$ of small ions can be defined from fundamental gas kinetic theories. The relationship between the diffusion coefficient and mobility is given in Reference [14], and can be expressed as:

$$D^{\pm} = kTZ^{\pm}/e \tag{A.5}$$

where $Z^{\pm}$ is the electrical mobility of small ions. The thermal velocity of small ions was derived by Reference [15], and can be expressed as:

$$c^{\pm} = \sqrt{\frac{8kT}{\pi \cdot m^{\pm}}} \tag{A.6}$$

where $m^{\pm}$ is the mass of a small ion. There are several approximation methods for the mean free path of small ions. The representative example of these can respectively be expressed as:

$$\lambda^{\pm} = \frac{16\sqrt{2}}{3\pi} \cdot \frac{D^{\pm}}{c^{\pm}} \cdot \left(\frac{M}{M + m^{\pm}} \right)^{1/2}, \quad \text{as described by Reference [21]} \tag{A.7}$$

$$\lambda^{\pm} = \frac{32}{3\pi} \cdot \frac{D^{\pm}}{c^{\pm}} \cdot \left(\frac{M}{M + m^{\pm}} \right)^{1/2}, \quad \text{a first-order Chapman-Enskog approximation, explained in Reference [22]} \tag{A.8}$$

$$\lambda^{\pm} = \frac{1}{1+\sigma} \cdot \frac{16\sqrt{2}}{3\pi} \cdot \frac{D^{\pm}}{c^{\pm}} \cdot \left(\frac{M}{M + m^{\pm}} \right)^{1/2}, \quad \text{as described by References [23],[24] and [25]} \tag{A.9}$$

where

M is the average molecular mass of air;

σ is a correction factor: $\sigma = 0{,}132$.

If the ion properties $Z^{\pm}$ and $m^{\pm}$ are known, the charge distribution function, $f_p(d)$ can be calculated. As the ion properties are strongly dependent on the chemical composition (e.g. impurities) of the carrier gas,[42] values of several ion properties are shown in Table A.1.

Table A.1 — Values of ion properties used by various authors

Mobility of ion		Mass of ion		Reference
$Z^{+}\ (\times 10^{-4}\ \mathrm{m^2 V^{-1} s^{-1}})$	$Z^{-}\ (\times 10^{-4}\ \mathrm{m^2 V^{-1} s^{-1}})$	m^{+} (Da)	m^{-} (Da)	
1,15	1,425	290	140	[26]
1,40	1,90	109	50	[27]
1,40	1,90	130	100	[27]
1,15	1,39	140	101	[28]
1,20	1,35	150	90	[25]
1,15	1,39	140	101	[13]
1,35	1,60	148	130	[8]
1,33	1,84	200	100	[30]
1,40	1,60	140	101	[9]

A.4 Approximation of the bipolar charge distribution for aerosol particles charge-conditioned by a bipolar radioactive ion source

As described in A.1 to A.3, an expert user of DMAS should be able to calculate the charge distribution function, $f_p(d)$. However, as those calculation methods necessitate laborious numerical calculations, a more convenient empirical expression to approximate the charge distribution function, $f_p(d)$, in the size range from 1 nm to 1 000 nm is presented in A.4. This approximation permits a useful and rapid calculation of the bipolar charge distribution function.

Situational factors such as carrier gas composition, purity, humidity and temperature can limit the validity of the approximation.

For an aerosol particle carrying up to two elementary charges, in steady state charge conditions, the charge distribution function, $f_p(d)$, can be expressed using the approximation given in Formula (A.10), derived from the Fuchs model.

$$\log\left[f_p(d)\right] = \sum_{i=0}^{5} a_i(p) \cdot (\log d)^i \tag{A.10}$$

Formula (A.10) is valid for the size range:

$1\ \text{nm} \le d \le 1\ 000\ \text{nm}$ for $p = \{-2, -1, 0, +1, +2\}$

NOTE In Formula (A.10), d is given in nanometres.

To develop this approximation, specific values of ion properties are taken, and their sources are:

a) ion mobilities from Reference [8] (see Table A.1);

b) ion masses from Reference [13] (see Table A.1);

c) the Fuchs' α parameters from Reference [25].

The coefficients $a_i(p)$ were derived for a charge conditioner with a radioactive ion source (^{241}Am) and air as carrier gas (at ambient conditions) using a least-square regression analysis; they are listed in Table A.2.

Corrections for other carrier gas conditions are described, e.g. in Reference [8], while data for other gas compositions can be found in Reference [9].

The charge distribution function, $f_p(d)$, with three or more elementary charge units can be calculated using Formula (A.11), which is based on Gunn's model:

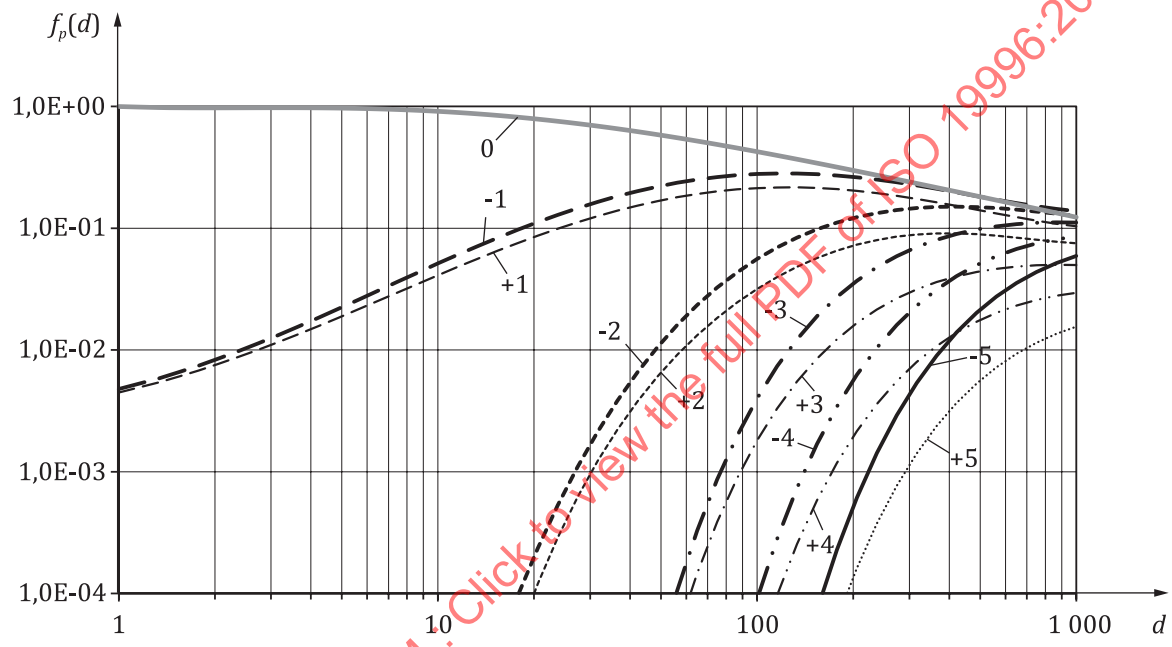
$$f_p(d) = \frac{e}{\sqrt{4\pi^2 \varepsilon_0 dkT}} \cdot \exp \frac{-\left[p - \frac{2\pi\varepsilon_0 dkT}{e^2} \cdot \ln\left(\frac{N_I^+}{N_I^-} \cdot \frac{Z^+}{Z^-}\right)\right]^2}{2\frac{2\pi\varepsilon_0 dkT}{e^2}} \tag{A.11}$$

where $N_I^{\pm}$ is the concentration of positive or negative small ions.

For this calculation, the concentration of positive and negative ions is assumed to be equal, and the ratio of ion mobilities Z^+ / Z^- was taken from Reference [8] to be 0,875. The results of this calculation are given in Figure A.1 and Table 2.

Table A.2 — Coefficients $a_i(p)$ for Formula (A.10) for radioactive ion sources

i	$a_i(p)$				
	$p = -2$	$p = -1$	$p = 0$	$p = +1$	$p = +2$
0	−26,332 8	−2,319 7	−0,000 3	−2,348 4	−44,475 6
1	35,904 4	0,617 5	−0,101 4	0,604 4	79,377 2
2	−21,460 8	0,620 1	0,307 3	0,480 0	−62,890 0
3	7,086 7	−0,110 5	−0,337 2	0,001 3	26,449 2
4	−1,308 8	−0,126 0	0,102 3	−0,155 3	−5,748 0
5	0,105 1	0,029 7	−0,010 5	0,032 0	0,504 9
NOTE Two coefficients in Reference [17] were later corrected. The coefficients in Table A.2 contain this correction.					



Key

d particle diameter, expressed in nanometres

$f_p(d)$ charge distribution function (–)

NOTE Figure A.1 shows the charge distribution function for particles in the size range between 1 nm and 1 000 nm calculated from Formulae (A.10) and (A.11) for a bipolar radioactive ion source.

Figure A.1 — Charge distribution function for a bipolar radioactive ion source

A.5 Approximation of the bipolar charge distribution for aerosol particles charge-conditioned by a bipolar X-ray ion source

While the coefficients in Table A.2 generally apply for bipolar charge conditioners with radioactive ion sources, they cannot be used for other types of bipolar charge conditioners. In fact, experimental results[43] have yielded significant deviations of soft X-ray charge conditioners from charge conditioners with radioactive ion sources in the charge distributions and moreover, available models and designs differ considerably in their charging characteristics. The reason for the differences has not yet been fully understood. Therefore, the empirical coefficients for other designs of bipolar charge conditioners must be determined individually for each device design. This can be accomplished by following the method outlined in Annex B.

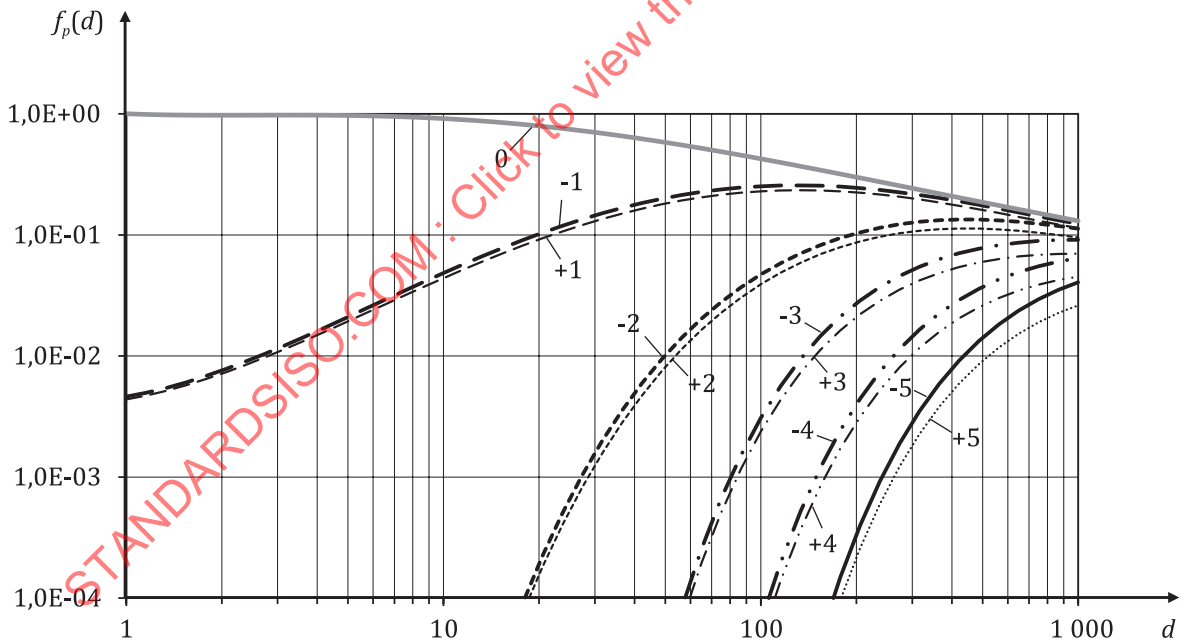
Table A.3 is an example of a specific type of soft X-ray charge conditioner as determined within Reference [10] and should not be used in general for soft-X ray charge conditioners. Compared to Table A.2, Table A.3 describes a different set of empirical coefficients $a_i(p)$ which apply for two types of charge conditioners with a soft X-ray source with an X-ray tube voltage of 9,5 kV.

Table A.3 shows an example of coefficients $a_i(p)$ for Formula (A.10) for a bipolar charge conditioner with a 9,5 kV X-ray ion source.[10]

Table A.3 — Coefficients $a_i(p)$ for Formula (A.10)

i	$a_i(p)$				
	$p = -2$	$p = -1$	$p = 0$	$p = +1$	$p = +2$
0	−30,615 58	−2,335 09	0,001 63	−2,358 89	−27,253 20
1	46,338 85	0,436 35	−0,113 84	0,451 69	38,479 63
2	−31,181 91	1,086 54	0,333 93	0,997 98	−24,271 28
3	11,390 70	−0,556 79	−0,357 14	−0,481 73	8,441 62
4	−2,220 28	0,049 81	0,107 70	0,026 31	−1,605 89
5	0,179 35	0,005 51	−0,010 82	0,008 04	0,129 17

Figure A.2 shows a charge distribution function for particles within the size range between 1 nm and 1 000 nm calculated from Formulae (A.10) and (A.11) for a bipolar 9,5 kV X-ray ion source. In accordance with the recommendation in Reference [10], ion mobilities used for the calculation of charge levels beyond $p = \pm 2$ (Formula A.11) were 1,4 $cm^2/(V{\cdot}s)$ for negative and 1,34 $cm^2/(V{\cdot}s)$ for positive ions, respectively, while the ion concentrations of positive and negative ions were again assumed to be equal.



Key

d particle diameter, expressed in nanometres

$f_p(d)$ charge distribution function (−)

Figure A.2 — Charge distribution function for particles for a bipolar 9,5 kV X-ray ion source

Annex B
(informative)

Performance test procedures for charge conditioners

B.1 General

B.1.1 Tested performance parameters

This annex describes a set of performance tests for charge conditioners. For the use of charge conditioners in DMAS, the evaluation of the below listed key metrics is a prerequisite and the tests may serve to characterize existing or newly developed charge conditioner designs.

The tests evaluate the following physical quantities:

— number concentration of particles generated in a charge conditioner;

— transmission efficiency for singly charged particles;

— charging probability f_0 ; and

— charging probabilities f_i (i ≠ 0) for positively and negatively charged particles.

The tests can be performed with different particle sizes, particle number concentrations and flow rates. The tolerance of the tests is not given in this document and should be set according to the purpose of performing these tests.

B.1.2 Test equipment

CPCs and DEMCs used in the tests should be appropriately calibrated and verified in accordance with ISO 27891 and ISO 15900.

A CPC function check is strongly recommended. For this purpose, connect the CPC inlet to a HEPA filter and record the particle number concentration displayed on the CPC at 1 s reading intervals for 1 min. Calculate the arithmetic mean, $N_{\text{CPC-check}}$, of the number concentration for the last 30 s. Only proceed with the test if $N_{\text{CPC-check}}$ is equal to or less than 0,1 cm^{-3}.

Flowmeters and voltmeters used for controlling the test settings should have a reputable calibration certificate.

The assurance of functionality of other equipment such as ESPs (see Annex C), flow splitters, aerosol generators and diluters is strongly recommended, but not covered in this annex.

A primary aerosol generator used in B.3, B.4 and B.5 should be provided with passive overflow in order to adapt to the aerosol flow rate at the inlet of the bipolar charge conditioner.

B.1.3 Test aerosol

The test aerosol used in the tests should meet the following conditions:

— the mode diameter and particle number concentration should be sufficiently stable during the tests;

— the vapor content from water or other dispersing medium or solvent should be low in order to prevent particle growth in the test setup and the influence on the performance of the test charge conditioner.

The use of monodisperse particles (e.g., polystyrene latex particles) is required for the tests in B.3 and is recommended for all other tests in this Annex, with the exception of B.2.

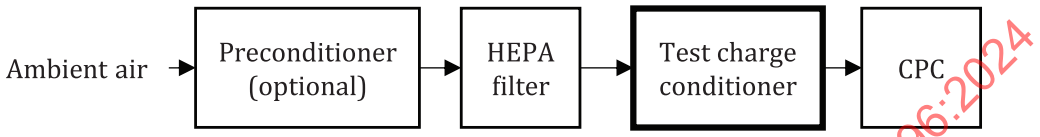
B.2 Test of the number concentration of particles generated in a charge conditioner

B.2.1 General

This test quantifies the number concentration of particles generated in a test charge conditioner when particle free air is passed through. It is preconditioned that the test charge conditioner is separable from the DMAS and can be turned on and off.

B.2.2 Test setup

The test setup is shown in Figure B.1. Ambient air, filtered through a HEPA-filter, should be used for the test. A preconditioner (diffusion dryer) is required if the relative humidity in the air exceeds 80 %.



NOTE Figure B.1 shows the setup for a particle generation test for a charge conditioner separable from the DEMC.

Figure B.1 — Particle generation test setup

B.2.3 Test procedure

a) Turn off the charge conditioner. After the system reaches a steady condition, i.e. with a stable CPC reading, record the particle number concentration with the CPC at 1 s reading intervals for 1 min. Calculate the arithmetic mean N_{off} of the number concentration for the last 30 s of the 1-min measurement.

   If the test charge conditioner cannot be turned off, replace it with a shortcut tube. The shortcut tube should consist of a straight metal pipe or piece of conductive silicone hose with maximum length of 10 cm and the same diameter as used for the tubing in the setup.

b) Turn on the charge conditioner. After the system reaches a steady condition, record the particle number concentration with the CPC at 1 s reading intervals for 1 min. Calculate the arithmetic mean of the number concentrations measured by the CPC for the last 30 s as N_{on}.

c) Repeat a) to b) four more times. Calculate the averages $\overline{N_{\mathrm{on}}}$ and $\overline{N_{\mathrm{off}}}$ from the five measurements. The number concentration of particles generated in the test charge conditioner is calculated by Formula (B.1):

$$N_{\mathrm{G}} = \left| \overline{N_{\mathrm{on}}} - \overline{N_{\mathrm{off}}} \right| \tag{B.1}$$

d) Report N_{G} with the test charge conditioner flow rate q_{TCC}.

B.3 Test of the transmission efficiency

B.3.1 General

This test quantifies the transmission efficiency for singly charged particles in a charge conditioner.[29]

B.3.2 Test setup

The test setup is shown in Figure B.2.

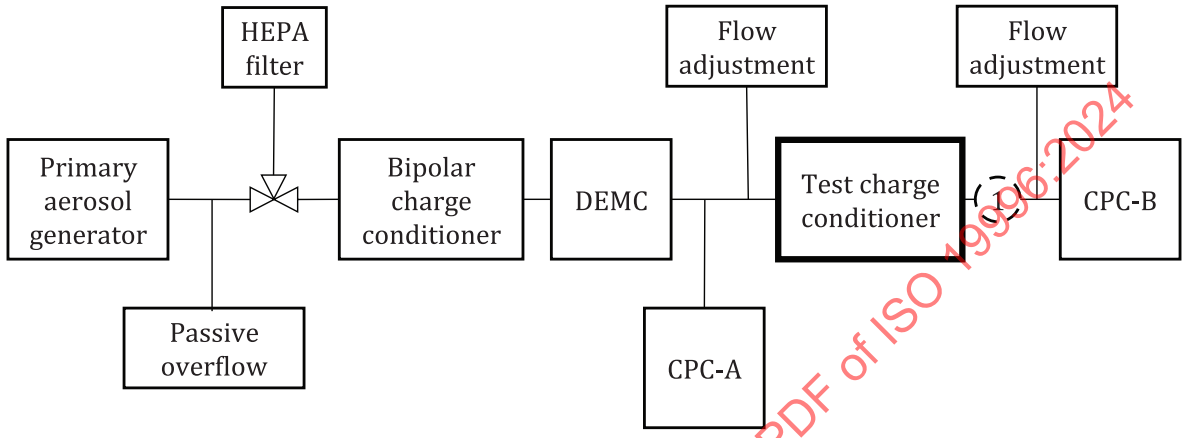
The CPC clocks should be synchronized to the second, in order to identify the data sets belonging to the measuring intervals during steps B.3.3 d) and e).

The test charge conditioner will be replaced by a shortcut (not shown in Figure B.2) as described in step B.3.3 e) of the test. The shortcut should consist of a straight metal pipe or piece of conductive silicone hose with maximum length of 10 cm and the same diameter as used for the tubing in the setup.

The CPCs should work preferentially in single count mode, i.e. at moderate particle number concentrations.

NOTE 1 The flow adjustments before and after the test charge conditioner are optional and allow testing the charge conditioner at varied flow rates.

NOTE 2 The test can be performed with uncharged particles by adding a bipolar charge conditioner and an ESP immediately after the outlet of the DEMC.



NOTE Figure B.2 shows the setup for evaluation of the transmission efficiency of singly charged particles in a charge conditioner.

Figure B.2 — Setup for evaluation of transmission efficiency

B.3.3 Test procedure

a) This step is optional and is to be applied if the flow rate through the test charge conditioner is intended to differ from that of CPC-B:

Install the flow adjustments as indicated in Figure B.2 and connect a flowmeter downstream of the test charge conditioner outlet at position (1). Switch the three-way-valve to input through the HEPA filter. Turn on the DEMC, the bipolar charge conditioner upstream of the DEMC, both CPCs and the test charge conditioner. Wait for the system to stabilize. Adjust the flow q_{TCC} through the test charge conditioner to the desired value. Ensure that all flows through the setup are stable. Remove the flowmeter.

b) Turn on both CPCs if not yet powered. Switch the three-way-valve to input from the particle generator. Generate a test aerosol by turning on the primary aerosol generator, bipolar charge conditioner and DEMC. Adjust the DEMC to the desired particle size. Turn on the test charge conditioner. Wait for the system to stabilize.

c) Check the particle number concentration readings from both CPCs. If these are not in the desired range, readjust the particle generator setting, add a diluter, or both.

d) Record the particle concentrations of CPC-A ($N_{A,1}$) and CPC-B ($N_{B,1}$) at 1 s reading intervals for at least 1 min. Calculate the arithmetic means of the number concentrations measured by the CPCs for the last 30 s as $\overline{N_{A,1}}$ and $\overline{N_{B,1}}$ respectively.

e) Turn off the test charge conditioner, remove it from the setup and replace it by a shortcut. Record the particle concentrations of CPC-A ($N_{A,0}$) and CPC-B ($N_{B,0}$) at 1 s reading intervals for at least 1 min. Calculate the arithmetic means of the number concentrations measured by the CPCs for the last 30 s as $\overline{N_{A,0}}$ and $\overline{N_{B,0}}$ respectively.

f) Repeat steps b) to e) at least four more times. Calculate the transmission efficiency Tr using Formula (B.2):

$$Tr_k = \frac{\overline{N_{\mathrm{B},1,k}}}{\overline{N_{\mathrm{A},1,k}}} \cdot \frac{\overline{N_{\mathrm{A},0,k}}}{\overline{N_{\mathrm{B},0,k}}} \tag{B.2}$$

where k is the test round index.

g) Calculate the arithmetic mean from the five measurements.

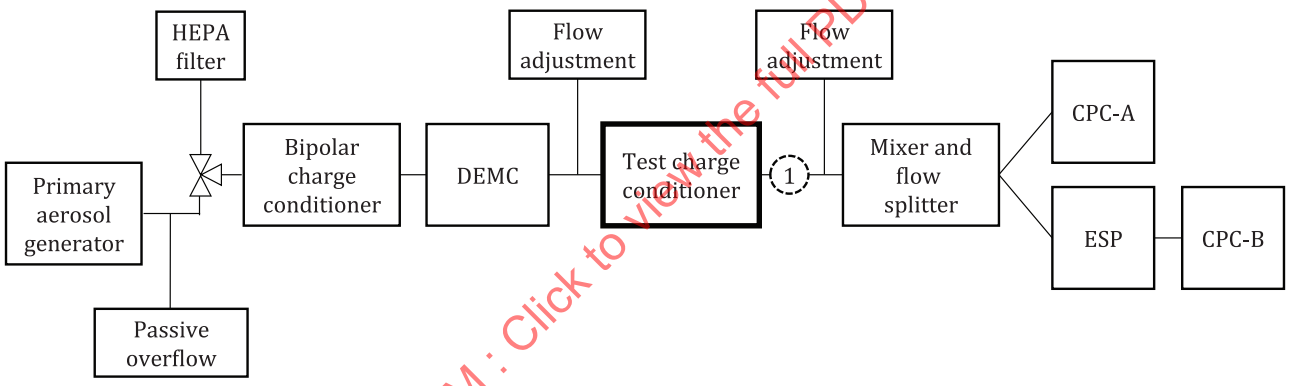
Report the result as $Tr(d, q_{\mathrm{TCC}})$ with particle diameter d and test charge conditioner flow rate q_{TCC}. The measurement uncertainty in Tr can be estimated from the sample standard deviation.

For each variation of the particle size, B.3.3 b) to g) shall be performed. Each variation of the flow rate requires starting the test with B.3.3 a).

B.4 Test for the charging probability, f_0, generated from singly charged particles in the test charge conditioner

B.4.1 Test setup

The test setup is shown in Figure B.3.



NOTE Figure B.3 shows the setup for evaluation of the charging probability f_0 from a charge conditioner acting on singly charged particles.

Figure B.3 — Setup for evaluation of the charging probability f_0

NOTE 1 The flow adjustments before and after the test charge conditioner are optional and allow testing the charge conditioner at varied flow rates.

NOTE 2 The test can be performed with uncharged particles by adding a bipolar charge conditioner and an ESP immediately after the outlet of the DEMC.

If the primary aerosol source is generated by an atomizer from an aqueous suspension or solution, a diffusion dryer is required.

If an ESP is not available, a cylindrical DEMC may be modified to serve as an ESP in the above setup. For this purpose, the DEMC is run without sheath air and held at a constant voltage, high enough to collect on the two electrodes all positively or negatively charged particles which enter the device through either the sheath flow (q_1)or sample aerosol flow (q_2) inlets, or both. The sample aerosol flow outlet (q_3) is blocked. The uncharged particle fraction leaves the DEMC through the excess air flow outlet (q_4) at a flow rate established by the downstream CPC-B (the q_i designations of the flows in a DEMC refer to ISO 15900:2020, Figure 1).

A reputable flowmeter should be available in order to measure and adjust the actual flow through the test charge conditioner at position (1) indicated in Figure B.3.

The flow controls of the two CPCs after a flow splitter can affect each other. In that case, makeup air between test charge conditioner and mixer can be provided.

The CPC clocks should be synchronized to the second in order to identify the data sets belonging to the measuring intervals during B.4.2 d) and e) below.

The CPCs should work preferentially in single count mode, i.e., at moderate particle concentrations. This can be achieved either by adjustment of the aerosol generator or by dilution, or both.

To evaluate f_0 for particles in the opposite polarity, the polarity of the voltage on DEMC must be reversed.

B.4.2 Test procedure

a) This step is optional and is to be applied if the flow rate through the test charge conditioner is intended to differ from the sum of flow rates of CPC-A and CPC-B. Install the flow adjustments as indicated in Figure B.3 and connect a flowmeter downstream of the test charge conditioner outlet at position (1). Switch the three-way-valve to input through the HEPA filter. Turn on the DEMC, the bipolar charge conditioner upstream of the DEMC, both CPCs and the test charge conditioner. Wait for the system to stabilize. Adjust the flow q_{TCC} through the test charge conditioner to the desired value. Ensure that all flows through the setup are stable. Remove the flowmeter.

b) Ensure that both CPCs are running, and the ESP is off. Switch the three-way-valve to input from the particle generator. Generate a test aerosol by turning on the primary aerosol generator, bipolar charge conditioner and DEMC. Adjust the DEMC to the desired particle size *d*. Turn on the test charge conditioner. Wait for the system to stabilize.

c) Check the particle number concentration readings from both CPCs. If these are not in the desired range, readjust the particle generator setting, add a diluter, or both.

d) Turn on the ESP. Record the particle concentrations of CPC-A ($N_{\mathrm{A,on}}$) and CPC-B ($N_{\mathrm{B,on}}$) at 1 s reading intervals for at least 3 min. Only proceed if the CPC-B reading reaches a stable plateau, i.e. if it does not fluctuate by more than 10 %. Calculate the arithmetic means of the number concentrations measured by the CPCs for the last 60 s in the plateau range as $\overline{N_{\mathrm{A,on}}}$ and $\overline{N_{\mathrm{B,on}}}$ respectively.

e) Turn off the ESP. Record the particle number concentrations of CPC-A ($N_{\mathrm{A,off}}$) and CPC-B ($N_{\mathrm{B,off}}$) at 1 s reading intervals for at least 3 min. Only proceed if the CPC-B reading reaches a stable plateau, i.e. it does not fluctuate by more than 10 %. Calculate the arithmetic means of the number concentrations measured by the CPCs for the last 60 s in the plateau range as $\overline{N_{\mathrm{A,off}}}$ and $\overline{N_{\mathrm{B,off}}}$ respectively.

f) Repeat steps b) to e) at least four more times. Calculate the charging probability f_0 using Formula (B.3):

$$f_{0,k} = \frac{\overline{N_{\mathrm{B,on},k}}}{\overline{N_{\mathrm{B,off},k}}} \cdot \frac{\overline{N_{\mathrm{A,off},k}}}{\overline{N_{\mathrm{A,on},k}}} \tag{B.3}$$

where *k* is the test round index.

g) Calculate the arithmetic mean from the five measurements. Report the result as $f_0\left(d^+, q_{\mathrm{TCC}}\right)$ or $f_0\left(d^-, q_{\mathrm{TCC}}\right)$ with positively (d^+) or negatively (d^-) charged particles of diameter *d* entering the test charge conditioner with flow rate q_{TCC}.

The measurement uncertainty in f_0 can be estimated from the sample standard deviation.

For each variation of the particle size, B.4.2 b) to g) shall be performed. Each variation of the flow rate requires starting the test with B.4.2 a).

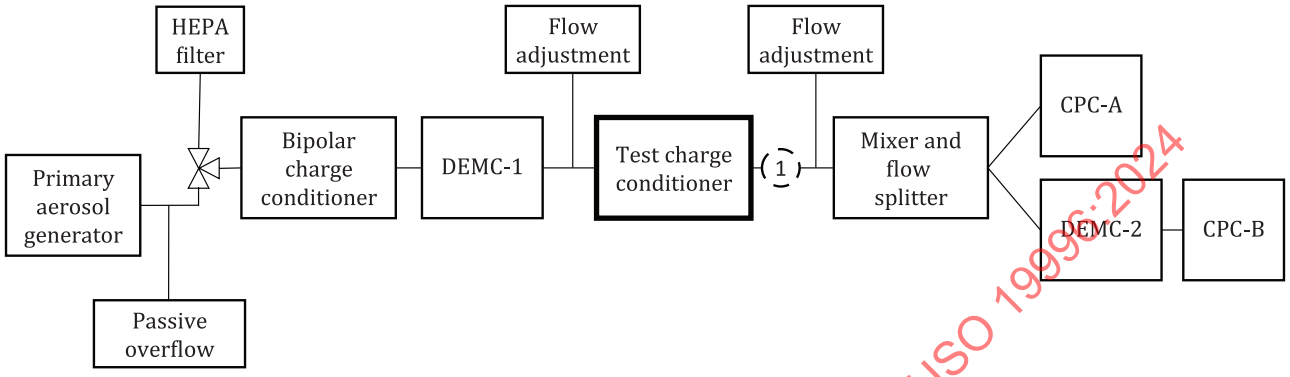
The recovery time, i.e., the time period after turning on or off the ESP to revert the CPC-B number concentration reading to a plateau value, can depend on the ESP design. A longer recovery time can occur

especially when a DEMC is used as an ESP. In such cases, the measuring periods in B.4.2 d) and e) should be prolongated accordingly.

B.5 Test of the charging probability f_i

B.5.1 Test setup

The test setup is shown in Figure B.4.



NOTE Figure B.4 shows the setup for evaluation of the charging probability f_i of a charge conditioner acting on singly charged particles.

Figure B.4 — Setup for evaluation of the charging probability f_i

NOTE 1 The flow adjustments before and after the test charge conditioner are optional and allow testing the charge conditioner at varied flow rates.

In this test, a monodisperse test aerosol is generated and charge-conditioned in the test charge conditioner. A size scan with DEMC-2 downstream reveals to what extent the test charge conditioner is able to produce singly and multiply charged fractions in the test aerosol.

In a cylindrical DEMC with positive polarity of the voltage, the inner electrode attracts negatively charged particles. This test can be run with four options for the settings of the DEMC voltage polarities.

— Both DEMCs have the same polarity: Monodisperse particles of either positive or negative charge exit DEMC-1 and are recharged by the test charge conditioner. This test evaluates the charging probabilities for the chosen polarity.

— The polarity of DEMC-2 is opposite to that of DEMC-1. Monodisperse particles of either positive or negative charge exit DEMC-1 and are recharged by the test charge conditioner. The charging probabilities according to the polarity set for DEMC-2 are evaluated.

NOTE 2 The test procedure as described in B.5.2 is applicable only for charged test particles. For uncharged test particles, the setup in Figure B.4 necessitates the addition of a bipolar charge conditioner and an ESP immediately after the outlet of the DEMC. Additionally, the procedure in B.5.2 must be modified accordingly, which is not covered in this document.

Prior to testing, the CPC clocks and the DEMC-2-controller should be synchronized to the second in order to timewise correlate CPC-A number concentration records as well as start and stop of DEMC-2 size scans.

The CPCs should work preferentially in single count mode, i.e. at moderate particle concentrations.

Depending on the aim of using this test to determine the charging probability, CPC-B and CPC-A may be outside of the traceably calibrated concentration ranges, i.e. at lower concentrations. CPCs are shown by theory (see ISO 27891:2015, A.2) to be linear below the traceable calibration range. As such, the important criteria can be the standard uncertainty calculated with Formula (B.10).

DEMC-2 should be set to at least 64 size bins per decade. It should be operated at the best size resolution, for example sheath to sample flow ratio larger than 15:1, in order to avoid overlap in peaks representing the different charges of the size distribution density function (see left diagram of Figure B.5).

As described in detail in B.5.2, the test procedure requires calculation of the raw number size distribution density function $\mathrm{d}N_{\mathrm{raw}}/\mathrm{dlog}(d)$ by the DEMC-2 manufacturer's software based on a simplified DEMC response function $R\left(U^*\right)$ (see ISO 15900:2020, Formula D.1). The simplifications are:

— no multiple charge correction;

— no correction for diffusion losses, i.e., $P(d)=1$;

— no correction for CPC detection efficiency $\eta_{\mathrm{CPC}}(d)$ in the detector response $W(d,p)$;

— the CPC detection flow rate q_{CPC} in $W(d,p)$ is equal to the DEMC sample aerosol flow rate q_2.

NOTE 3 If the correction for CPC detection efficiency cannot be inactivated by the software, it can cause some error in the size range where the CPC detection efficiency drops.

With these assumptions, ISO 15900:2020 Formula (D.1) can be written as:

$$\left.\frac{\mathrm{d}N_{\mathrm{uncorr}}}{\mathrm{dlog}(d)}\right|_{d_1^*} = \frac{N_{\mathrm{CPC}}^*}{f_1\left(d_1^*\right)\int_{d=0}^{\infty}\Omega\left(Z(d,1),\Delta\Phi\left(U^*\right)\right)\mathrm{d}d}\cdot\frac{1}{d_1^*\cdot\ln 10} \tag{B.4}$$

where

U^* is the voltage supplied to DEMC-2;

d_1^* is the diameter of singly charged particles with the central electrical mobility of the transfer function of DEMC-2 set at voltage U^*;

$\left.\frac{\mathrm{d}N_{\mathrm{uncorr}}}{\mathrm{dlog}(d)}\right|_{d_1^*}$ is the uncorrected number size distribution function at d_1^*;

N_{CPC}^* is the number concentration displayed by CPC-B when DEMC-2 voltage is U^*;

$f_1\left(d_1^*\right)$ is the charging probability for $p=1$ at d_1^* used in the DEMC-2 software;

$\Omega\left(Z(d,1),\Delta\Phi\left(U^*\right)\right)$ is the transfer function of DEMC-2 for $p=1$ when voltage U^* is applied.

Formula (B.4) can be converted to the raw number size distribution density function:

$$\left.\frac{\mathrm{d}N_{\mathrm{raw}}}{\mathrm{dlog}(d)}\right|_{d_1^*} = \left.\frac{\mathrm{d}N_{\mathrm{uncorr}}}{\mathrm{dlog}(d)}\right|_{d_1^*}\cdot f_1\left(d_1^*\right) \tag{B.5}$$

where the charging probabilities for all particles are set to unity.

B.5.2 Test procedure

a) This step is optional, and is to be applied if the flow rate through the test charge conditioner is intended to differ from the sum of flow rates of CPC-A and CPC-B. Install the flow adjustments as indicated in Figure B.4 and connect a flowmeter downstream of the test charge conditioner outlet at position (1). Switch the three-way-valve to input through the HEPA filter. Turn on DEMC-1 and its bipolar charge conditioner, both CPCs and the test charge conditioner. Wait for the system to stabilize. Adjust the flow q_{TCC} through the test charge conditioner to the desired value. Ensure that all flows through the setup are stable. Remove the flowmeter.

b) Ensure that both CPCs are running, and DEMC-2 is off. Switch the three-way-valve to input from the particle generator. Generate a test aerosol by turning on the primary aerosol generator, bipolar

charge conditioner and DEMC-1. Adjust DEMC-1 to the desired particle size, *d*. Turn on the test charge conditioner. Wait for the system to stabilize.

c) Turn on DEMC-2 and perform a particle number size spectrum measurement. While scanning, observe the particle number concentration readings from both CPCs. If these are not in the desired range, readjust the particle generator setting, add a diluter, or both, and wait for the system to stabilize.

d) Perform a particle number size scan with DEMC-2 using CPC-B as particle counter. Record the raw size distribution density function as $\mathrm{d}N_{\mathrm{raw,on}}/\mathrm{dlog}(d)$ and the number concentration measured by CPC-A as $N_{\mathrm{A,on}}(t)$ at 1 s reading intervals. Note the start and stop time of the size scan.

e) Turn off the test charge conditioner. Perform a particle number size scan with DEMC-2, using CPC-B as particle counter. Record the raw number size distribution density function as $\mathrm{d}N_{\mathrm{raw,off}}/\mathrm{dlog}(d)$ and the number concentration measured by CPC-A as $N_{\mathrm{A,off}}(t)$ at 1 s reading intervals. Note the start and stop time of the size scan.

If the test charge conditioner cannot be turned off, replace it with a shortcut tube. The shortcut tube should consist of a straight metal pipe or piece of conductive silicone hose with the length from the aerosol inlet to the aerosol outlet of the test charge conditioner and the same diameter as used for the tubing in the setup.

f) Calculate the arithmetic means of $N_{\mathrm{A}}(t)$ over the respective scan time periods in B.5.2 d) and e) as $\overline{N_{\mathrm{A,on}}}$ and $\overline{N_{\mathrm{A,off}}}$ respectively.

g) Plot $\mathrm{d}N_{\mathrm{raw,on}}/\mathrm{dlog}(d)$ according to the left diagram in Figure B.5. Label the apparent peaks representing singly (i = ±1) and multiply (i = ±2, ±3 …) charged particles from right to left. For each peak, calculate the integral using Formula (B.6).

$$N_{i,\mathrm{raw,on}} = \int\left[\mathrm{d}N_{i,\mathrm{raw,on}}/\mathrm{dlog}(d)\right]\mathrm{dlog}(d) \tag{B.6}$$

h) Plot $\mathrm{d}N_{\mathrm{raw,off}}/\mathrm{dlog}(d)$ according to the right diagram in Figure B.5. Label the apparent peak representing singly charged particles (i = ±1). Calculate the integral for the peak using Formula (B.7).

$$N_{\mathrm{raw,off}} = \int\left[\mathrm{d}N_{\mathrm{raw,off}}/\mathrm{dlog}(d)\right]\mathrm{dlog}(d) \tag{B.7}$$

If the raw size distribution density function $dN_{\mathrm{raw,on}}/\mathrm{dlog}(d)$ in g) (left diagram of Figure B.5) reveals peaks above d(i = +1 or -1), the sum of integrals over these peaks shall not exceed 5 % of the integral $N_{\mathrm{raw,off}}$. The test shall only be continued if this criterion can be met.

i) Repeat B.5.2 b) to h) at least four more times. Calculate the charging probabilities f_i using Formula (B.8) for each of the apparent singly (i = ±1) and multiply (i = ±2, ±3 …) charged fractions.

$$f_{i,k}(d) = \frac{N_{i,k,\mathrm{raw,on}}}{N_{k,\mathrm{A,on}}} \Big/ \frac{N_{k,\mathrm{raw,off}}}{N_{k,\mathrm{A,off}}} \tag{B.8}$$

where the index k assigns the test round.

j) Calculate the arithmetic means for each of the apparent singly and multiply charged fractions with Formula (B.9), where n is the total number of test rounds.

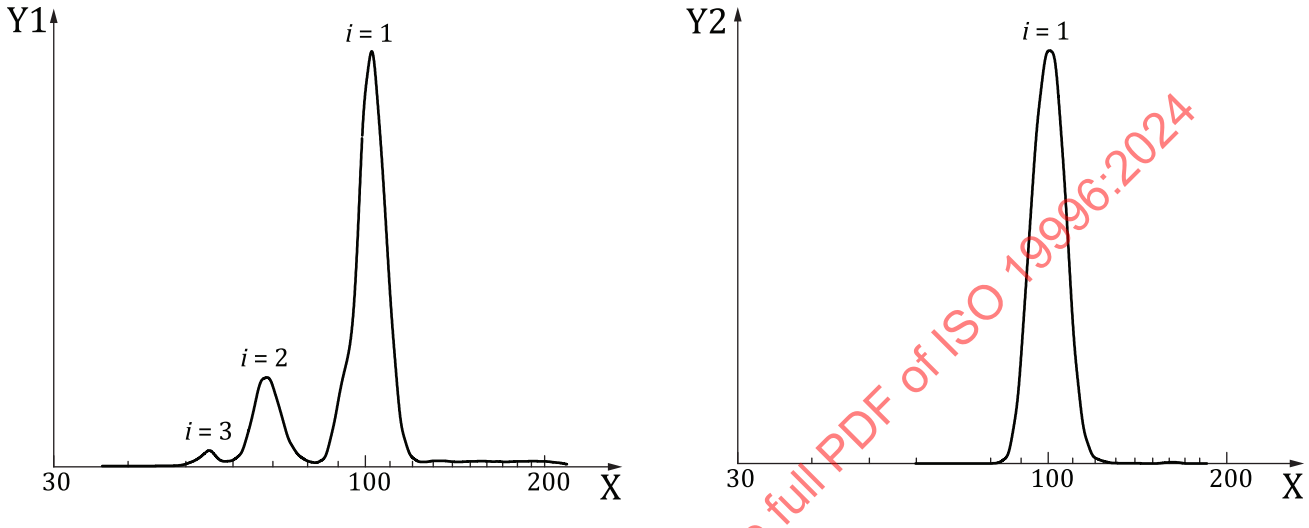
$$f_i(d) = \sum_k^n f_{i,k}(d)/n \tag{B.9}$$

The standard uncertainty in $f_i(d)$ is given by Formula (B.10):

$$u(f_i(d)) = \frac{1}{\sqrt{n(n-1)}} \sqrt{\sum_{k=1}^{n} \left[f_{i,k}(d) - f_i(d) \right]^2} \quad \text{(B.10)}$$

For each variation of the particle size, B.5.2 b) to j) shall be performed. Each variation of the flow rate requires starting the test with B.5.2 a).

Test results on charging probabilities should be unambiguously assigned, e.g. $f_{i,+}(d)$ for positively charged particles of diameter *d*, with the number of charges, *i*. The DEMC polarities in the test should also be noted in the report.



Key

X electrical mobility diameter (nm)

Y1 raw size distribution density function $\mathrm{d}N_{\mathrm{raw,on}} / \mathrm{dlog}(d)$ with the test charge conditioner on

Y2 raw size distribution density function $\mathrm{d}N_{\mathrm{raw,off}} / \mathrm{dlog}(d)$ with the test charge conditioner off

NOTE Figure B.5 shows examples of raw size distribution density functions with a test charge conditioner that is on (left) and off (right).

Figure B.5 — Raw size distribution density functions with on and off test charge conditioner

NOTE The measurement and calculation of $N_{i,\mathrm{raw,on}}$ and $N_{\mathrm{raw,off}}$ can also be made by recording the DEMC voltage (U) and particle concentrations of CPC-B at voltage U with the test charge conditioner on and off, $N_{B,\mathrm{on}}(U)$ and $N_{B,\mathrm{off}}(U)$, respectively, and using Formulae (B.11) to (B.13) instead of (B.6) to (B.8):

$$N_{i,\mathrm{B,on}} = \int \left[N_{i,\mathrm{B,on}} / U \right] \mathrm{d}U \quad \text{(B.11)}$$

$$N_{\mathrm{B,off}} = \int \left[N_{\mathrm{B,off}} / U \right] \mathrm{d}U \quad \text{(B.12)}$$

$$f_{i,k}(d) = \frac{N_{i,k,\mathrm{B,on}}}{N_{k,\mathrm{A,on}}} / \frac{N_{k,\mathrm{B,off}}}{N_{k,\mathrm{A,off}}} \quad \text{(B.13)}$$

B.6 Charge conditioner test report template

Test report number and date of issue:

Name and address of testing institution:

Name and address of Customer: **Order number:**

Charge conditioner model:
Charge conditioner manufacturer:
Identification / serial number:

Signed: (authorized signatory)

Performed test(s) according to ISO 19996, Annex B (check appropriate boxes)**:**

- ☐ **Test of the number concentration of particles generated in a charge conditioner, Section B.2**
- ☐ **Test of the transmission efficiency, Section B.3**
- ☐ **Test for the charging probability f_0 generated from singly charged particles in the test charge conditioner, Section B.4**
- ☐ **Test of the charging probability f_i, Section B.5**

Test results overview:

B.2			
date	parameter	value	uncertainty (optional)
	N_G		
	q_{TCC} (L/min)		

B.3			
date	parameter	value	uncertainty
	$T_r(d, q_{TCC})$		
	d (nm)		
	DEMC polarity		
	q_{TCC} (L/min)		
	test aerosol		

B.4			
date	parameter	value	uncertainty
	$f_0(d^+, q_{TCC})$		
	$f_0(d^-, q_{TCC})$		
	d (nm)		
	DEMC polarity		
	q_{TCC} (L/min)		
	test aerosol		

B.5			
date	parameter	value	uncertainty
	$f_{i,-}(d, q_{TCC})$		
	$f_{i,+}(d, q_{TCC})$		
	d (nm)		
	DEMC-1 polarity		
	DEMC-2 polarity		
	q_{TCC} (L/min)		
	test aerosol		

(extend above tables accordingly for each repeated test and/or tested variation in parameters)

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Condition of test device

Date of test device receipt:

Result of initial visual inspection:

- ☐ undamaged
- ☐ security seals unbroken
- ☐ date and result of leak test, if applicable:
- ☐ activity, if applicable:
- ☐ unused
- ☐ used; if applicable, operating time counter reading:
- ☐ other (specify):

Result of initial power on function test (if applicable):

- ☐ indicator lights signaling functional readiness
- ☐ other (specify):

Test equipment

	Type	Serial number	Calibration date
B.2			
Preconditioner			
CPC			
B.3			
Bipolar charge conditioner			
DEMC			
Flow meter			
CPC-A			
CPC-B			
B.4			
Bipolar charge conditioner			
DEMC			
Flow meter			
Flow splitter			
CPC-A			
CPC-B			
ESP			
B.5			
Bipolar charge conditioner			
DEMC-1			
DEMC-2			
Flow meter			
Flow splitter			
CPC-A			
CPC-B			
ESP			

Test conditions

Laboratory temperature, humidity, and pressure:

Aerosol carrier gas temperature and humidity:

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Test results

B.2

Test round index	N_{on}	N_{off}
1		
2		
3		
4		
5		
arithmetic mean		

B.3

Particle material and carrier gas:
Method of particle generation:
Particle diameter d (nm) at DEMC outlet:
Particle polarity at DEMC outlet:
DEMC voltage (V):
DEMC sample flow rate (L/min):
DEMC sheath flow rate (L/min):
q_{TCC} (L/min):
$q_{CPC\text{-}A}$ (L/min):
$q_{CPC\text{-}B}$ (L/min):

Test round index, k	$\overline{N_{B,0_k}}$	$\overline{N_{B,1_k}}$	$\overline{N_{A,0_k}}$	$\overline{N_{A,1_k}}$	$T_{r,k}$
1					
2					
3					
4					
5					

arithmetic mean of sample parameter T_r	
standard deviation of sample parameter T_r	

(add parameter values and tables accordingly for each repeated test and/or tested variation in parameters)

B.4

Particle material and carrier gas:
Method of particle generation:
Particle diameter d (nm) at DEMC outlet:
Particle polarity at DEMC outlet:
DEMC sample flow rate (L/min):
DEMC sheath flow rate (L/min):
q_{TCC} (L/min):
$q_{CPC\text{-}A}$ (L/min):
$q_{CPC\text{-}B}$ (L/min):

Test round index, k	$\overline{N_{A,on_k}}$	$\overline{N_{A,off_k}}$	$\overline{N_{B,on_k}}$	$\overline{N_{B,off_k}}$	$f_{0_k}(d)$
1					
2					
3					
4					
5					

arithmetic mean of sample parameter f_0	
standard deviation of sample parameter f_0	

(add parameter values and tables accordingly for each repeated test and/or tested variation in parameters)

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B.5

Particle material and carrier gas:
Method of particle generation:
Particle diameter d (nm) at DEMC-1 outlet:
Particle polarity at DEMC-1 outlet:
DEMC-1 sample flow rate (L/min):
DEMC-1 sheath flow rate (L/min):
Particle polarity at DEMC-2 outlet:
DEMC-2 sample flow rate (L/min):
DEMC-2 sheath flow rate (L/min):
q_{TCC} (L/min):
$q_{CPC\text{-}A}$ (L/min):
$q_{CPC\text{-}B}$ (L/min):

Charge fraction, i	±1, ±2, ±3 … *)				
Test round index, k	$\overline{N_{k,A,on}}$	$\overline{N_{k,A,off}}$	$\overline{N_{i,k,raw\,on}}$	$\overline{N_{k,raw,off}}$	$f_{i,k}$
1					
2					
3					
4					
5					
arithmetic mean of sample parameter f_i					
standard deviation of sample parameter f_i					

*) Note here the measured charge fraction and polarity

(add tables accordingly for each of the apparent singly (i = ±1) and multiply (i = ±2, ±3 …) charging probabilities)
(add parameter values and tables accordingly for each repeated test and/or tested variation in parameters)

Observations and comments

E. g., intentional changes in suggested setups and procedures….

Data repository

This report as well as metadata of all settings and instruments, and raw and processed data sets from all measurements have been stored in the following repository:

(web address or storage location…)

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Annex C
(informative)

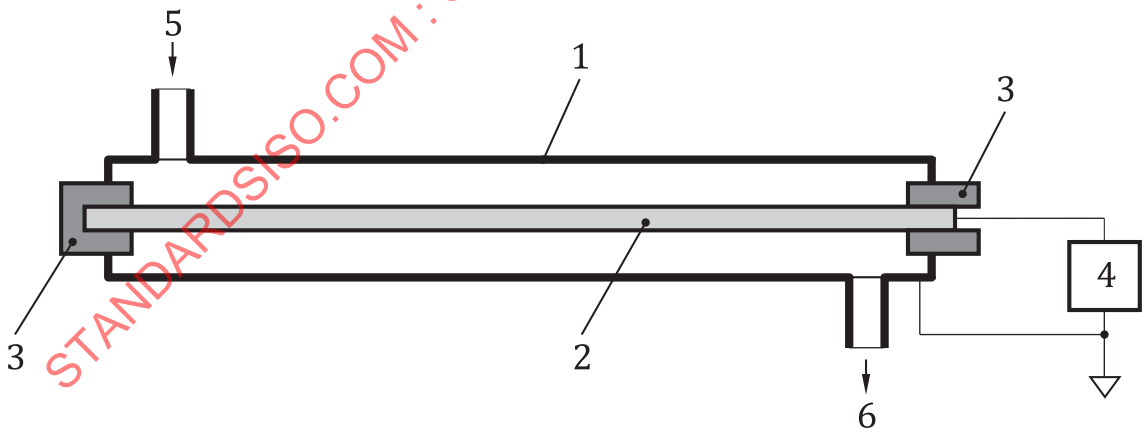
Electrostatic precipitator to provide uncharged aerosol particles

C.1 General

A device called an ESP or an aerosol condenser (AC) is used in tests of aerosol charge conditioners for generating test aerosols that only consist of uncharged particles. The ESP for this application consists of a pair of electrodes, an aerosol inlet and aerosol outlet, and a high voltage power supply. As an example, a schematic of a typical cylindrical ESP is shown in Figure C.1. The outer electrode is electrically grounded, while a high voltage is applied to the inner electrode by the high voltage power supply. Charged aerosol particles that entered into the ESP through the aerosol inlet flow through the annular gap between the outer and inner electrodes while they feel an electrostatic force inward or outward depending on the combination of the polarities of the particle charge and of the voltage applied to the inner electrode. For a given flow rate and the strength of the electric field of the ESP, charged particles of a certain electrical mobility or greater collide with the inner surface of the ESP and trapped. Losses of uncharged particles in the ESP occurs only due to Brownian diffusion and inertial impaction. By optimizing the flow rate and voltage, the ESP can pass uncharged particles at nearly 100 % efficiency while it eliminates all charged particles. To trap charged particles of a lower electrical mobility for a given ESP, either the flow rate must be reduced or the voltage must be increased.

NOTE 1 There are types of ESPs that are equipped with a unipolar charge conditioner. Those ESPs are used for removing particles, both charged and uncharged, from air in a stack, etc. The ESP, described in this annex, for generating test aerosols made of uncharged particles does not have a charge conditioner.

NOTE 2 If the voltage of a DEMC is set high enough to separate the largest particles entering the device, the excess air flow of a DEMC can also serve as a source of uncharged aerosol particles. In this case, all charged particles are either collected on the two electrodes of the DEMC or leave the DEMC with the monomobile (also known as "monodisperse") aerosol outlet flow.



Key

1	outer electrode	4	high voltage power supply
2	inner electrode	5	aerosol inlet
3	insulators	6	aerosol outlet

Figure C.1 — Typical cylindrical electrostatic precipitator

C.2 Implementation of an ESP

For a cylindrical ESP as shown in Figure C.1 with the dimensions of:

— the outer radius of the inner electrode r_1;

— the inner radius of the outer electrode r_2;

— and the effective length (i.e. the distance along the cylinder axis) between the inlet and outlet L,

the smallest electrical mobility of charged particles trapped in the ESP is approximately calculated with the aerosol flow rate q and the voltage applied across the electrodes U using Formula C.1:

$$Z_{\min} = \frac{q \ln (r_2 / r_1)}{2\pi L U} \quad \text{(C.1)}$$

For example, for an ESP of $r_1 = 5$ mm, $r_2 = 15$ mm, and $L = 500$ mm which is operating with the aerosol flow rate at 1 L/min, to trap particles of electrical mobility of $2{,}5 \times 10^{-9}$ $\mathrm{m^2/(V\,s)}$ or greater, which correspond to singly charged particles of about 500 nm or smaller in diameter, the voltage U must be 2 400 V or greater.

Annex D
(informative)

Concentration series test for charge conditioners

D.1 General

This annex describes a test method to check that the performance of a charge conditioner stays within allowed tolerances by testing the device under standardized, reproducible conditions as described in D.2. While this test is primarily intended to be performed by the manufacturers of the charge conditioners, it can also be applied for quality control purposes by users and test institutes. To perform the test, a particle generator capable of producing uncharged particles at concentrations of up to nominally 10^7 cm^{-3} will be needed. This test can also serve to establish a charge conditioner performance index.

An example measurement is described in D.3.

D.2 Test method

The test setup is shown in Figure D.1. The setup consists of a section for the generation of a test aerosol, a test charge conditioner, a section for the measurement of the charging probability f_0 at a chosen particle size d_{test}, and instruments for measuring the test condition, i.e. the particle number concentration and size distribution at the inlet of the test charge conditioner. The test is performed with an uncharged polydisperse aerosol. The use of an uncharged and polydisperse aerosol is to let the test charge conditioner challenge with an aerosol in an extreme charge state and of a large ion sink. With an uncharged test aerosol, as the particle load increases and exceeds the charge conditioning capability of the test charge conditioner, the f_0 value deviates and increase from the values at low loads.

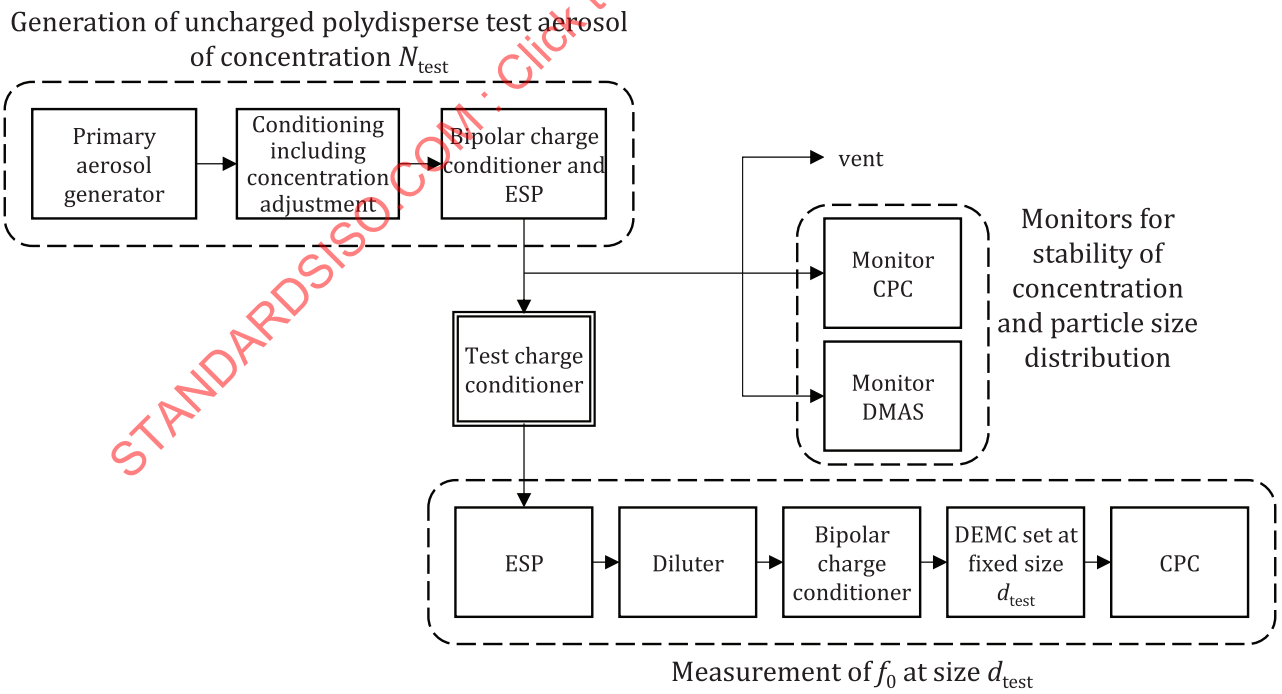


Figure D.1 — Schematic setup of the charge conditioner test

The test method is as follows.

a) Generate an uncharged polydisperse test aerosol.

b) Challenge a test charge conditioner with a concentration N_{test} of the test aerosol.

c) Set the classification size of the DEMC at d_{test}.

d) With the ESP after the test charge conditioner is off, record the concentration by the CPC, N_{off}.

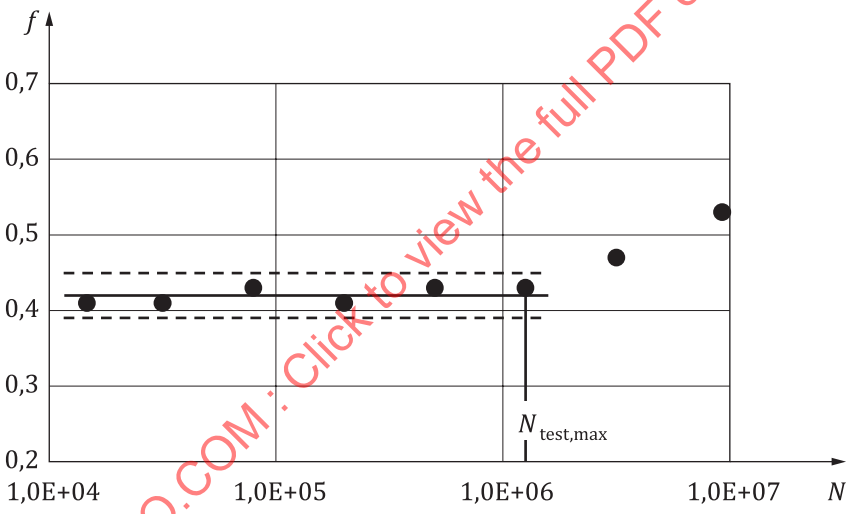
e) With the ESP after the test charge conditioner is on, record the concentration by the CPC, N_{on}.

f) Calculate f_0 as:

$$f_0 = N_{on} / N_{off} \quad \text{(D.1)}$$

g) Run the measurement given in Steps b) to f) for a series of at least 5 different concentrations N_{test} of the test aerosol. The concentration range should cover approximately 2 orders of magnitude. Calculate f_0 for each measured concentration. Ideally, the highest concentration(s) is (are) already in a region where the test charge conditioner does not reach steady state conditions anymore. This is indicated by f_0 starting to increase.

h) Determine the plateau region for f_0 (see Figure D.2). Within the plateau region, f_0 should not differ by more than ±3 % from the average of f_0. If the N_{test} within the plateau region covers less than 1 order of magnitude or if there are less than 3 measurements within the plateau region, the test is not valid.



Key

N particle number concentration of the test aerosol N_{test} [cm^{-3}]

f charging probability f_0

Figure D.2 — Plateau region of f_0 and $N_{test,max}$ of the test charge conditioner

i) Determine the coefficient of variation (CV) of f_0 within the plateau region. A test is valid if CV is less than 3 %.

j) The concentration $N_{test,max}$ is the highest value of N_{test} within the plateau region.

k) If the test is performed with spherical test particles, calculate the theoretical ratio $f_{0,theo}$. Within the plateau region found in the test, $f_{0,theo}$ and f_0 should not differ by more than 10 %.

l) Report all test conditions and the test results.

The results of the test in this annex (namely f_0 and $N_{test,max}$) are intended to be comparable from lab to lab. To achieve such comparability, the test aerosol fed into the test charge conditioner and the test itself should fulfil several requisites. Table D.1 shows a set of suggested requirements for test aerosol characteristics, DEMC settings, and the stability during test.

Table D.1 — Requisites for a standardized test

Polydisperse test aerosol — d_{mode} of dN/dlog$d$	60 nm ≤ d_{mode} ≤ 80 nm
Polydisperse test aerosol — GSD	1,5 ≤ GSD ≤ 2,2
Polydisperse test aerosol — particle material (examples)	Thermally conditioned flame soot. Dried, atomized aqueous NaCl solution. Atomized di(2-ethylhexyl) sebacate (DEHS) or poly-alpha-orefin (PAO).
Polydisperse test aerosol — charge	Uncharged
Polydisperse test aerosol — stability of particle size distribution	Monitored by DMAS
Polydisperse test aerosol — stability of particle number concentration	Monitored by CPC
DEMC settings — classification size	30 nm to 100 nm
DEMC settings — q_1/q_2	$7 \leq q_1/q_2 \leq 20$
Allowed deviation of f_0 from $f_{0,theo}$ when the test particles are spherical	$\lvert(f_0 - f_{0,theo})/f_{0,theo}\rvert \leq 0{,}1$
Tolerance band for f_0	Average f_0 ±3 %

D.3 Example test measurement

D.3.1 Test setup and procedure

The test setup for the example test measurement is shown in Figure D.3.

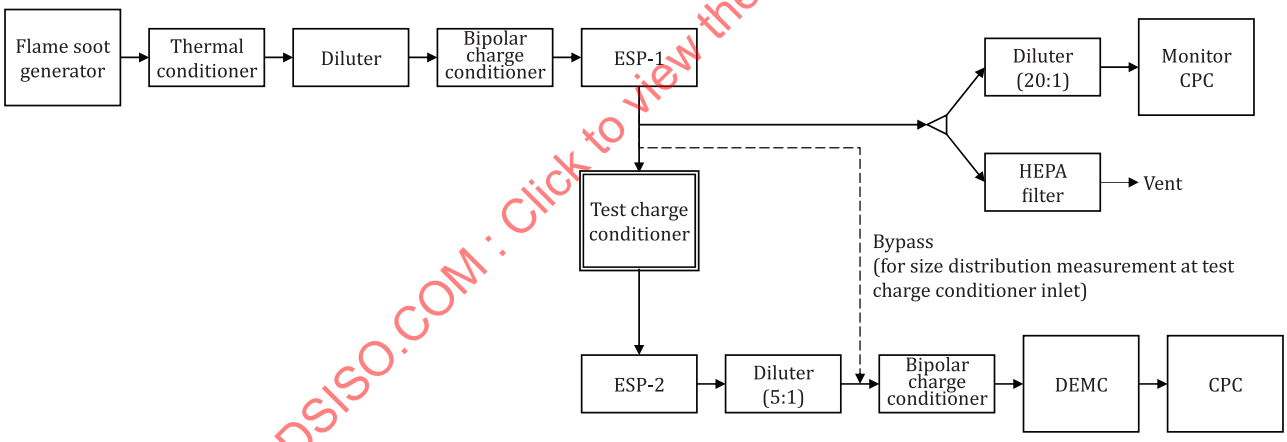
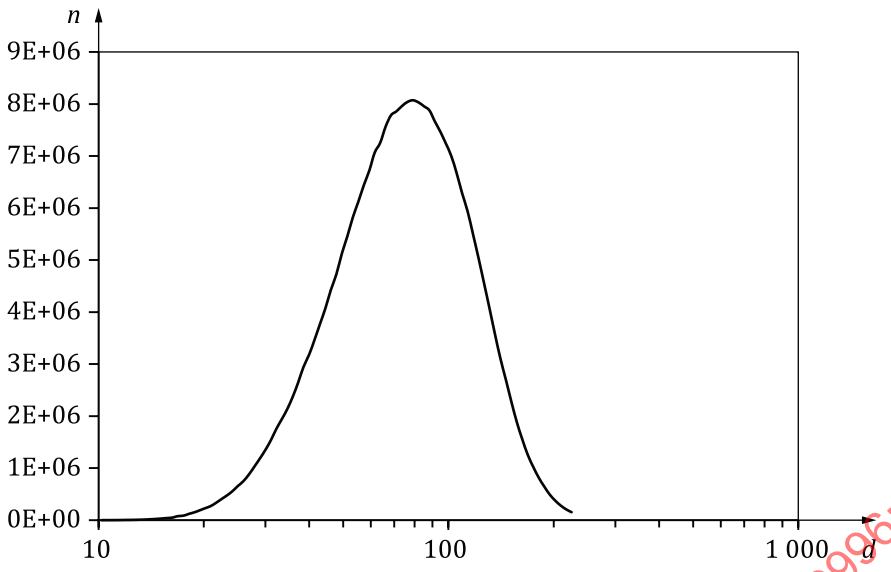


Figure D.3 — Schematic setup of the example test measurement

For the generation of an uncharged polydisperse test aerosol, the primary aerosol was generated with a flame soot generator and thermally conditioned at 350 °C in a catalytic stripper. A rotating disc diluter, with an approximate range of the dilution ratio from 10:1 to 1 000:1, was used to adjust the test aerosol concentration. The concentration-adjusted aerosol then passed through a bipolar charge conditioner with 3 MBq Am-241 and an ESP (ESP-1) to leave only uncharged particles, and entered the test charge conditioner. The number concentration (N_{test}) and size distribution of the test aerosol at the inlet of the test charge conditioner was measured with a monitor CPC (upper concentration limit of 3 x 10^5 cm^{-3}) with a diluter of the dilution ratio of 20:1 and a DMAS, which was composed of a bipolar charge conditioner, a DEMC and a CPC that were used for the measurement of f_0 (see below), through a bypass connection indicated with a dashed line, respectively. In this example measurement, an uncharged polydisperse test aerosol with the geometric mean diameter of 73 nm, the geometric standard deviation of 1,6, and the maximum number concentration of 4,0 x 10^6 cm^{-3} was generated (see Figure D.4).



Key

d particle size [nm]

n size distribution density function dN/dlog$d$ [cm^{-3}]

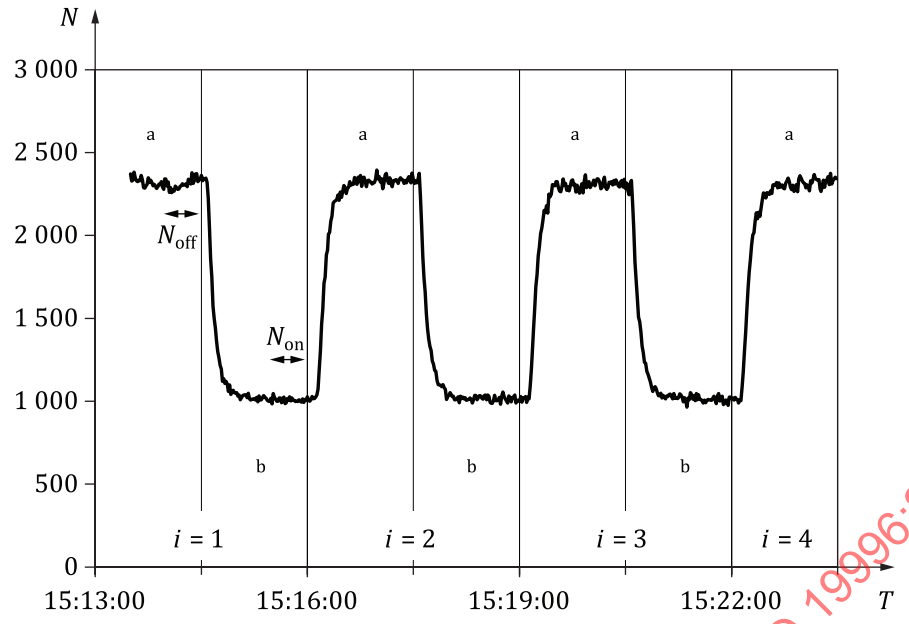
Figure D.4 — Particle size distribution of the test aerosol at the highest concentration level

The test aerosol after charge conditioning by the test charge conditioner then passed through another ESP (ESP-2). When ESP-2 was on, particles that got charged in the test charge conditioner were removed in ESP-2 while, when ESP-2 was off, all particles from the test charge conditioner passed through ESP-2. The output aerosol from ESP-2 was then diluted by 5:1, charge conditioned with a bipolar charge conditioner (3 MBq Am-241) and introduced into a DEMC. The dilution by 5:1 was added to reduce the particle load for the following bipolar charge conditioner. The DEMC was set at a fixed size d_{test} (e.g. 70 nm). The number concentration of the particles from the DEMC was continuously recorded with a CPC (upper concentration limit of 5 x 10^4 cm^{-3}). The voltage on ESP-2 was toggled on and off at 1,5 min intervals. The average of the CPC records for the last 30 s in each 1,5 min interval was calculated for the concentration N_{off} and N_{on} with ESP-2 off and on, respectively. The charging probability f_0 was calculated with Formula (D.1).

The measurement was carried out at five N_{test} levels of 3 x 10^4, 1 x 10^5, 4 x 10^5, 1 x 10^6 and 4 x 10^6 cm^{-3} by adjusting the dilution ratio of the rotating disc diluter.

D.3.2 Test result

An example concentration record is shown in Figure D.5. In this example, the DEMC classified at d_{test} = 70 nm and the concentration N_{test} was adjusted at 1 x 10^6 cm^{-3}. ESP-2 was toggled on and off six times, which gave four $N_{off,i}$ (i = 1 – 4) and three N_{on} (i = 1 – 3) averages (Table D.2).



Key

T time

N particle number concentration recorded by the CPC [cm^{-3}]

a Off.

b On.

NOTE Figure D.5 shows a concentration record with ESP-2 off and on at 1,5 min intervals at d_{test} = 70 nm and N_{test} = 1 x 10^6 cm^{-3}.

Figure D.5 — Concentration record example with ESP-2 off and on

Table D.2 shows 30 s average concentrations N_{off} and N_{on} and the charging probability f_0 in the example shown in Figure D.5.

Table D.2 — 30 s average concentrations

i	1	2	3	4	Average
$N_{off,i}$ [cm^{-3}]	2 311	2 332	2 313	2 312	
$N_{on,i}$ [cm^{-3}]	1 009	1 013	1 009		
$f_{0,i}$	0,435	0,436	0,436		0,436

The charging probability $f_{0,i}$ (i = 1 – 3) was calculated with Formula (D.2), which is a variation of Formula (D.1):

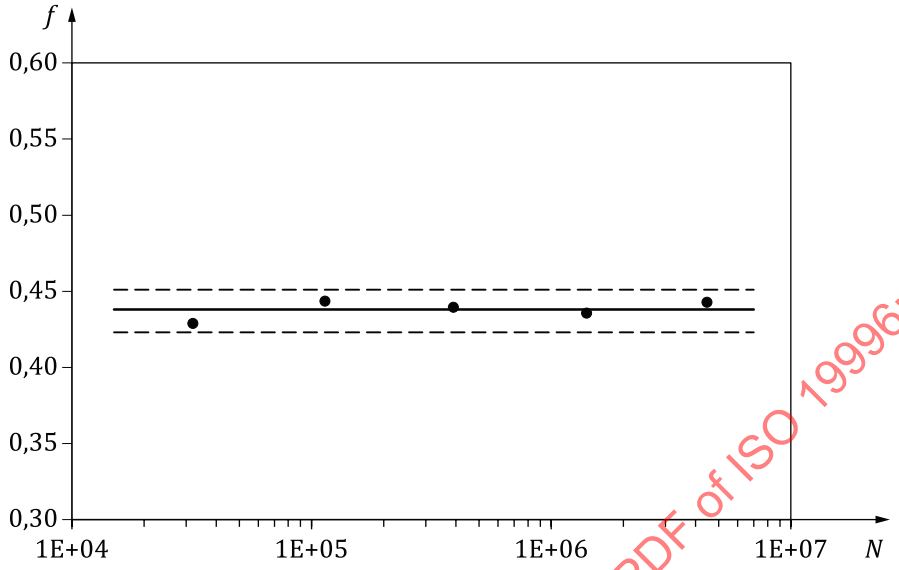
$$f_{0,i} = \frac{N_{on,i}}{(N_{off,i} + N_{off,i+1})/2} \quad \text{(D.2)}$$

The average of $f_{0,i}$ (i = 1 – 3) in this example was 0,436.

The results at the five concentration levels are summarized in Table D.3 and plotted in Figure D.6. The charging probability f_0 remained unchanged even at the highest concentration, which means that the test did not deliver high enough particle loads to exceed the charge conditioning capability of the test charge conditioner. All five f_0 values were within 3 % of the average 0,438 (i.e. between 0,423 and 0,451) and therefore in the plateau region. Since the plateau region covered about two orders of magnitude and contained five measurements, and since the CV in the plateau region was 1,4 %, the test was valid. The concentration $N_{test,max}$ obtained by this test was 4 x 10^6 cm^{-3}.

Table D.3 — The charging probability f_0 at the five tested concentration levels

N_{test} [cm^{-3}]	3 x 10^4	1 x 10^5	4 x 10^5	1 x 10^6	4 x 10^6
f_0	0,429	0,444	0,439	0,436	0,443



Key

N particle number concentration of the test aerosol N_{test} [cm^{-3}]

f charging probability f_0

Figure D.6 — The charging probability f_0 at the tested five concentration levels and ±3 % limits (dashed lines)

Annex E
(informative)

Example set of tests for bipolar charge conditioners

E.1 General

This annex describes a selected set of tests especially suitable for periodic inspection of bipolar charge conditioners that generate ions by electrical discharge, which can have performance issues such as:

— significant particle generation in the charge conditioner;

— lower particle penetration through the charge conditioner especially for charged particles;

— the positive-to-negative ion concentration ratio drifted from the designed optimum.

The tests may be applicable to bipolar charge conditioners of other ion sources.

The example set consists of the following four tests:

a) number concentration of generated particles (see B.2);

b) particle transmission efficiency (see B.3);

c) charging probability f_0 (see B.4);

d) the ratio of +1-charged particles to −1-charged particles, or the charging probability f_{+1} (or f_{-1}).

The tests specified in E.1 a) to c) should refer to Annex B. To simplify the tests in E.1 b) and c), the monitoring CPCs [i.e. CPC-A in test E.1 b) and CPC-A in test E.1 c)] may be omitted for the purpose of this annex.

The test specified in E.1 d) is intended as a simplified test compared to the evaluation of the charging probability f_i (see B.5). E.2 describes the test E.1 d).

The tests specified in E.1 b) to d) should be performed at least at one particle size, and the size can be different among the three tests.

The tolerance of the tests is not given in this document and should be set according to the purpose of performing these tests.

E.2 Tests for singly charged particles

E.2.1 General

The test E.1 d) can be either:

— the ratio of the number concentration of +1-charged particles to that of −1-charged particles described in E.2.4; or

— charging probability f_{+1} (or f_{-1}) described in E.2.5.

E.2.2 Test equipment

The equipment used in the tests should be appropriately calibrated and verified in accordance with ISO 15900, ISO 27891 and this document.

E.2.3 Test aerosol

The test aerosol used in the tests should meet the following conditions:

— the use of monodisperse particles (e.g. polystyrene latex particles) is required;

— the mode diameter and particle number concentration should be sufficiently stable during the tests;

— low vapor content from water or other dispersing medium or solvent to prevent particle growth in the test setup, which can influence the performance of the test charge conditioner.

E.2.4 Test for the ratio of the number concentration

E.2.4.1 General

This test quantifies the ratio of the number concentration of +1-charged particles to that of −1-charged particles at the outlet of the test charge conditioner under a given condition such as the flow rate and the size and charge state of particles. To determine the ratio, the number concentrations of +1-charged and −1-charged particles are measured with the CPC, with the DEMC classifying at the same absolute voltage but of opposite polarities.

E.2.4.2 Test setup

The test setup is shown in Figure E.1.

The DEMC should be able to apply both negative and positive voltages.

A pre-conditioning device for drying the test aerosol should be added if the humidity of the primary aerosol is too high.

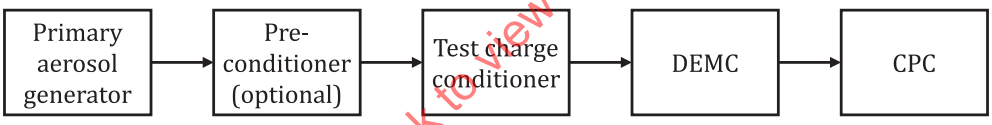


Figure E.1 — Setup for the determination of the ratio of the number concentration of +1-charged particles to that of −1-charged particles

E.2.4.3 Test procedure

The test procedure is as follows.

a) Start the primary aerosol generator.

b) Turn on the charge conditioner.

c) Set the DEMC at the voltage to classify +1-charged particles of the desired size. After the system reached a steady condition, record the number concentration with the CPC at 1 s reading interval for 1 min. Calculate the arithmetic mean of the number concentrations measured by the CPC for the last 30 s of the 1 min measurement, $N_{C,+1}$.

d) Set the DEMC at the voltage to classify −1-charged particles of the same size as in c). After the system reaches a steady condition, record the number concentration with the CPC at 1 s reading interval for 1 min. Calculate the arithmetic mean of the number concentrations measured by the CPC for the last 30 s of the 1-min measurement, $N_{C,-1}$.

e) Calculate the ratio of the number concentration of +1-charged particles to that of −1- charged particles $R_{C,+1/-1}$ with Formula (E.1):