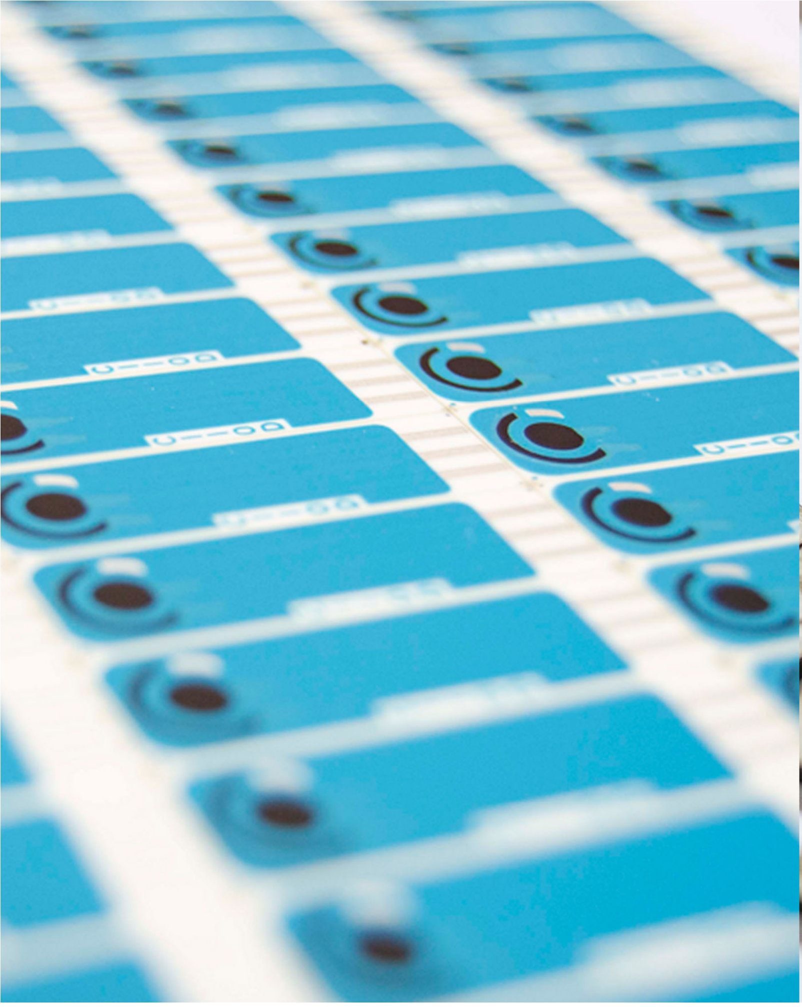

DS APPLICATION NOTE AN-EC-034

Ion-selective electrodes based on screen-printed technology

Fundamentals and tips when using ion-selective solid-contact potentiometric sensors based on screen-printing electrodes

Potentiometry has had a long historical development, from the studies of Galvani and Volta in the late 18th century to the first potentiometric titration developed in 1893 by Robert Behrend. However, it was not until the 1960s when so-called modern potentiometry was born. In just a decade, the first membrane electrodes based on either liquid ion-exchanger or solvent polymers were developed based on the works of Ross [1] and Bloch [2], respectively. Nowadays, potentiometry is a standard analytical technique for detecting relevant ions which are commonly employed in clinical laboratories.

The use of solvent polymeric membranes favors the development of sensor arrays capable of detecting a large variety of ions compared to glass membranes. Taking advantage of this, screen-printed technology offers miniaturization and portability, two essential characteristics in «point-of-care» analysis.

MEASUREMENT PRINCIPLE

Potentiometry is an electrochemical method that measures the electrical potential, or voltage, of an electrochemical cell made of two electrodes: a working and a reference electrode. The potential of the reference electrode remains constant while the potential in the working electrode varies in proportion to the analyte concentration in the sample. The relative potential between the two electrodes is measured under the zero-current condition, so the electroanalytical technique employed with these sensors is known as open circuit potentiometry (OCP).

Classical ion-selective electrodes (ISEs) developed in the early 20th century were made of a membrane (as the sensing phase) in contact with an internal solution to form a liquid-contact interface. It was not until 1971 that the first ISE without the internal solution was proposed by Hirata and Dato [3], followed by Cattrall and Freiser [4] the year after. These novel sensors are based on a solid-contact layer between the membrane and the conducting substrate (**Figure 1**), which Cadogan et al. [5] in 1992 named the «ion-to-electron transducer layer».

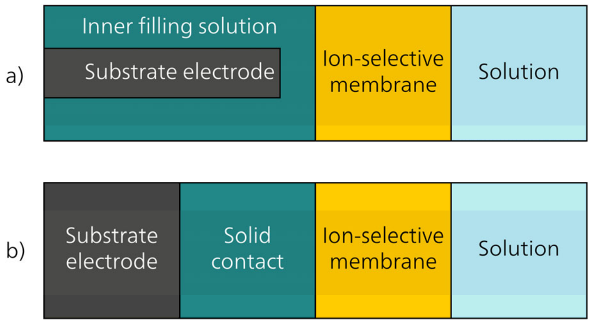

Figure 1. Illustrated graphic of an ISE with a) a liquid-contact interface and b) a solid-contact interface. Both versions show the most common setup employed when developing ion-selective electrodes.

The full response mechanism has been described elsewhere in depth [6], but the analytical signal is the same in both types of ISEs (i.e., liquid- or solid-contact) – the sum of the phase interfacial potentials. In practical terms, depending on the type of ion measured, the analytical signal follows the Nernst equation, which when simplified at 25 °C and applying a common logarithm results in the following equation:

Equation 1. $$E_{meas} = K + \frac{0.05916}{z_A}\log(a_A)$$

where K is a constant, z_A is the charge of the analyte ion A and can be either positive (cation) or negative (anion), and a_A is the activity of the ion in the solution. This measured potential (E_{meas}) is the analytical signal that can be observed when measuring with ISEs in OCP where the potential is monitored over time.

Figure 2 shows a typical OCP signal where E_{meas} is the plateau achieved after several seconds when the ISE reaches equilibrium. This potential remains constant, and its value is linearly proportional with the common logarithm of the concentration of the analyte ion in **Equation 1** (i.e., log [a_A]).

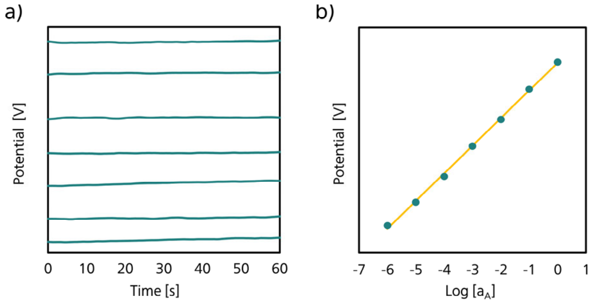

Figure 2. a) Experimental data observed in OCP and b) a calibration plot obtained when representing the measured potential vs logarithm of the analyte ion activity.

Although the Nernst equation has no limits and correlates well with the linear part of the calibration plot (**Figure 2b**), real sensors have two practical limits. Electrodes reach their lower limit at a low analyte concentration and stop responding as no potential changes are observed. The upper limit can be reached when electrodes become insensitive to high ionic activities, resulting in a plateau.

To calculate both limits, IUPAC recommends that the lower limit (defined as the limit of detection) and the upper limit are the points of intersection of the extrapolated midrange linear segment and the limiting lower or higher activity response, respectively [7]. Considering that the sign of the slope can change depending on the type of ion measured, **Figure 3** shows both types of experimental calibration curves typically observed with cationic- or anionic-selective electrodes and their corresponding limits.

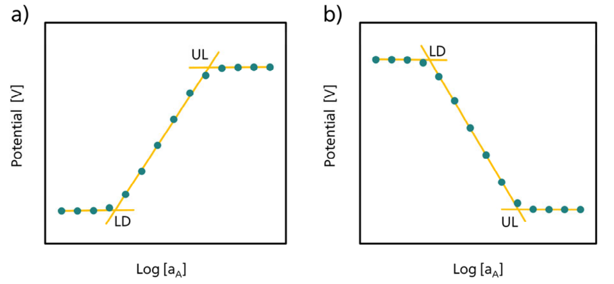

Figure 3. Whole calibration plots obtained with a) cations and b) anions along with the respective lower limit (denoted as detection limit, LD) and upper limit (UL) marked on each plot.

PRINCIPLE OF SELECTIVITY

The analytical performance of ion-selective electrodes is determined by their membrane properties. As their name suggests, the main advantage of these electrodes is that they have a high degree of selectivity. Therefore, the membrane composition ideally must only respond to one specific ion—either cation or anion.

Although the glass pH electrode was invented in 1906 by Cremer [8], it took another 60 years before Frant and Ross [9] invented the most successful solid-contact ISE—the fluoride ISE—made of a single crystal of LaF_3. In the same year, Stefanac and Simon [10] developed the potassium ISE using valinomycin as a neutral ionophore incorporated in a plasticized membrane. Both approaches rapidly became the standard of solid-contact ISE development, expanding the possibilities to other new successful developments based on these setups.

In general, the prepared plasticized membrane must have reversible ion/electron transfer and be highly stable in aqueous media to avoid leaching the components of the membrane [11]. In solid-contact ISEs, the membrane is commonly a PVC-based polymer, usually prepared by evaporating a cocktail of several components mixed in well-known proportions. A typical recipe is comprised of the polymer matrix (with or without a plasticizer), an ionophore, and a lipophilic ionic additive to lower electrical resistance.

Table 1. Components commonly found in classical recipes of potentiometric solid-contact electrodes. **Acronyms**: BPA: bis(1-butylpentyl) adipate, CHA: cyclohexanone, DBS: dibutyl sebacate, DOS: dioctyl sebacate, KTCPB: potassium tetrakis(4-chlorophenyl)borate, NaTPB: sodium tetraphenylborate, NaTFPB: sodium tetrakis(4-fluorophenyl)borate dihydrate, O-NPOE: 2-nitrophenyl octyl ether, PVC: polyvinyl chloride, THF: tetrahydrofuran

Component	Examples
Solvent	CHA, THF
Polymer matrix	PVC
Plasticizer	BPA, DOS, O-NPOE
Lipophilic ionic additive	KTCPB, NaTPB, NaTFPB
Ionophore	See refs. [12–14]

Apart from the physical and chemical properties related to structural considerations of the polymer matrix itself, the most important component of the «cocktail» (**Table 1**) is the ionophore that lends selectivity to the finished electrode. The nature of the ionophore depends on the type of cation or anion that is to be quantified. Initially, ion-exchangers were usually employed to develop these sensors, but they suffer from a lack of ion-recognition function as their selectivity follows the Hofmeister series. A classical successful example of this is the calcium ion electrode developed by Ross in 1967 [1]. Based on an ion-exchange process, the cation-exchanger is an aliphatic diester of phosphoric acid where the phosphate group has a strong affinity for calcium ions.

The term «ionophore» was born later in the 1960s and defines chemical compounds that reversibly bind and transport ions. Ionophores can be natural or synthetic, and usually contain a hydrophilic center that interacts with the ions and a hydrophobic portion that interacts with the membrane. An example of a successful natural ionophore is valinomycin, a neutral carrier molecule that selectively binds potassium ions due to its cavity with very similar dimensions to K^+. Many synthetic ionophores are developed to mimic behavior similar to valinomycin. After years of development, a plethora of different structures have been produced varying from macrocyclic species (e.g., crown ethers, cryptands and calixarenes) to chelating agents based on organometallic molecules, or even simple organic compounds that also exhibit ionophoric properties (e.g., phenols). Selectivity and stability are the main considerations when selecting one ionophore over another.

EVALUATING SELECTIVITY

Despite being known for their good selectivity, ion-selective electrodes are not ideal – there can be interferences introduced by the sensor responding to the presence of other ions. The Nernst equation (**Equation 1**) assumed that E_{meas} is only related to the electrode's response to one specific ion. If we consider the existence of other ions that can also be present in the same sample, it is necessary to use a new equation.

Considering the interfering ion as *B*, its corresponding activity as a_B, and its charge as z_B, we can incorporate a selectivity coefficient ($K_{A,B}$), extending the Nernst equation to the empirical Nicolsky-Eisenman equation (**Equation 2**):

Equation 2.

$$E_{meas} = K + \frac{0.05916}{z_A} \log \{a_A + K_{A,B}^{pot} (a_B)^{z_A/z_B}\}$$

where $$K_{A,B}^{pot} = \frac{a_A}{(a_B)^{z_A/z_B}}$$

The selectivity coefficient of a particular ISE can be defined as a numerical value that reflects how well the sensing membrane can discriminate against a certain interfering ion in comparison to the analyte ion. It is denoted as $K_{A,B}^{pot}$, where *A* is the analyte ion and *B* is the interferent ion. If a sensor exhibits a similar response to both ions, then $K_{A,B}^{pot}$ = 1, meaning no selectivity is achieved. If the selectivity constant is <1, then the membrane is more selective to the analyte ion. However, if this value is >1, the ISE is more selective to the interfering ion. The smaller the $K_{A,B}^{pot}$ value is, the less impact the interfering ion has on the measured potential, E_{meas}. For example, if $K_{A,B}^{pot}$ = 10^{-3}, then the ISE is 1000 times more responsive to ion *A* (analyte) than ion *B* (interferent).

Experimental data when an interfering ion is present is shown in **Figure 4**, with three different situations provided depending on the strength of the interferent. The stronger the interferent is considered against the membrane, then the higher the detection limit (LD) is, so the analytical range that can be measured shortens.

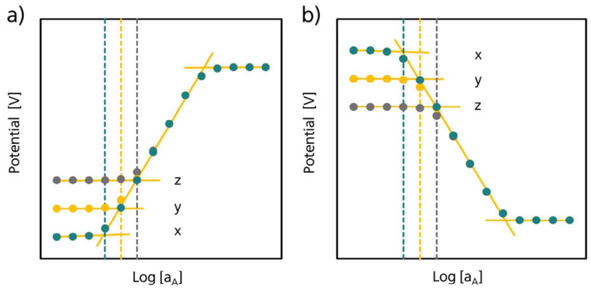

Figure 4. Experimental data for a) cations and b) anions where interferences are absent (x), weak (y), or strong (z).

There are several protocols to calculate selectivity coefficients according to IUPAC recommendations that also work with sensors where no Nernstian but linear response is obtained [15]. Discussion about the selectivity and limit of detection is covered in depth elsewhere [16] and their values must be considered carefully when analyzing real samples as interfering ions are usually present, so linear range can be compromised depending on the sample matrix.

MINIATURIZATION AND PORTABILITY

All-solid-state ISEs are internal solution-free and employ a conducting polymer or nanostructures (e.g., nanowires, nanoparticles, or nanotubes) as a solid contact beneath the ion-selective or reference membrane. This enables the miniaturization of ISEs, facilitating portability and making the development of handheld setups possible (**Figure 5**). Working with portable potentiostats allows on-site measurements, while working with ion-selective screen-printed electrodes makes ion quantification possible in complicated scenarios or in circumstances where conventional probes cannot be adequately cleaned so they must be discharged.

Sensors developed with screen-printing technology offer new possibilities for in-situ measurements where only a very small sample volume is required, as samples can be expensive or scarce. Several examples of such requirements can be found in the environmental, biotechnology, quality control, or industrial fields, and especially in biomedical research.

Moreover, these sensors do not require maintenance or complex pretreatments such as those needed when using non-portable optical devices.

Figure 5. Example of a novel handheld setup where a miniaturized ion-selective screen-printed electrode is utilized with a portable potentiostat to make on-site measurements.

Screen-printed ion-selective sensors do not require cleaning and can be discarded when the assay is complete, facilitating their use for myriad purposes. They are especially practical for analyzing hazardous samples.

GENERAL TIPS FOR WORKING WITH ION-SELECTIVE SCREEN-PRINTED ELECTRODES

To work with ion-selective SPEs from Metrohm DropSens, below are several tips that users can follow to achieve good results. Some advice may seem obvious, but it is still important to consider for good laboratory practices. Typical ions detected by these sensors are employed as examples in each section.

Use solutions with a known amount of analyte to obtain the calibration plot. This can be achieved by weighing the correct amount of analyte and dissolving it in a known volume of ultrapure water or by purchasing the correct standard for the desired sensor. In the case of, e.g., Na^+ and K^+ ion-selective SPEs, use standard solutions of NaCl or KCl, respectively. Good calibration data can be easily obtained by using standards prepared based on these reagents. Other sensors in the Metrohm DropSens catalog also use chloride as the counter ion in the salt to study their analytical performance.

Prepare standard solutions with a concentration of the analyte inside the linear range of the sensors. For each application developed, consider the linear range of the sensor employed. This information is given in the brochure included with each sensor made by Metrohm DropSens. In the case of K^+ ion-selective SPEs, the linear range spans from 10^{-6} to 1 mol/L, and the linear range spans from 10^{-4} to 1 mol/L for Na^+ sensors. Linearity with potentiometric sensors can only be achieved by representing the potential obtained as an analytical response versus the logarithm of the analyte concentration assayed. A typical representation plots the potential against the exponent of the concentration tested, as previously shown.

It is recommended to measure each solution in triplicate to obtain enough data to evaluate the precision of the electrodes. This is a general recommendation when employing any purchased sensor, not only for ion-selective SPEs. Metrohm DropSens electrodes assure a precision of 10% with Na^+ and K^+ ion-selective SPEs.

As a general matter, accuracy and precision always depend on the solutions tested. If the target solution presents matrix effects, the accuracy and precision of the electrodes could change due to the nature of the solution itself. Sensor response must always be tested with the target solution because sometimes a correction factor or a sample pretreatment must be done. This is a common behavior not only for potentiometric but also for voltamperometric sensing devices.

The calibration curve belongs to each batch of electrodes, so it is not necessary to recalibrate the electrode. However, if the target solution evolves or changes, it is recommended to test the sensor again as its response could be altered due to matrix changes.

Understanding selectivity coefficient values is important to estimate how sensors will work on actual samples. The values usually afforded to users by the manufacturers or represented in the bibliography below are either the logarithm of the selectivity constant ($logK_{A,B}^{pot}$) or the ratio between primary and interfering ions ($1/K_{A,B}^{pot}$). In the previous example where $K_{A,B}^{pot}$ = 10^{-3}, then $logK_{A,B}^{pot}$ = -3 and $1/K_{A,B}^{pot}$ = 1000. In the case where the logarithm is used, the lower the value, the better the selectivity of the ISE. In the case with the inverted selectivity constant, the higher the value, the better selectivity the ISE has.

CONCLUSION

In contrast to larger traditional liquid-contact probes, the development of solid-contact potentiometric sensors based on screen-printing technology makes miniaturization possible, which is a crucial advantage in many industrial or research fields. Due to their low energy consumption, low cost, and user-friendly operability, ion-selective screen-printed electrodes are not only capable of detecting both positively and negatively charged ions but are also very suitable for practical applications in point-of-care testing.

Considering the importance that potentiometric sensors have nowadays (reflected by common examples of potassium, calcium, or fluoride ISEs), it is interesting to understand how these kinds of electrodes work, how their analytical performances rate, and what can they offer to users. In this way, a broader understanding of these sensors is presented with several practical tips that make these electrodes more accessible to analysts, helping them to develop their own applications.

REFERENCES

[1] Ross, J. W. Calcium-Selective Electrode with Liquid Ion Exchanger. *Science* **1967**, *156* (3780), 1378–1379. https://doi.org/10.1126/science.156.3780.1378.

[2] Bloch, R.; Shatkay, A.; Saroff, H. A. Fabrication and Evaluation of Membranes as Specific Electrodes for Calcium Ions. *Biophysical Journal* **1967**, *7* (6), 865–877. https://doi.org/10.1016/S0006-3495(67)86626-8.

[3] Hirata, H.; Dato, K. Copper(I) Sulphide-Impregnated Silicone Rubber Membranes as Selective Electrodes for Copper(II) Ions. *Talanta* **1970**, *17* (9), 883–887. https://doi.org/10.1016/0039-9140(70)80185-0.

[4] Cattrall, R. W.; Freiser, H. Coated Wire Ion-Selective Electrodes. *Anal. Chem.* **1971**, *43* (13), 1905–1906. https://doi.org/10.1021/ac60307a032.

[5] Cadogan, A.; Gao, Z.; Lewenstam, A.; et al. All-Solid-State Sodium-Selective Electrode Based on a Calixarene Ionophore in a Poly(Vinyl Chloride) Membrane with a Polypyrrole Solid Contact. *Anal. Chem.* **1992**, *64* (21), 2496–2501. https://doi.org/10.1021/ac00045a007.

[6] Lyu, Y.; Gan, S.; Bao, Y.; et al. Solid-Contact Ion-Selective Electrodes: Response Mechanisms, Transducer Materials and Wearable Sensors. *Membranes* **2020**, *10* (6), 128. https://doi.org/10.3390/membranes10060128.

[7] Buck, R. P.; Lindner, E. Recommendations for Nomenclature of Ionselective Electrodes (IUPAC Recommendations 1994). *Pure and Applied Chemistry* **1994**, *66* (12), 2527–2536. https://doi.org/10.1351/pac199466122527.

[8] Cremer, M. Über Die Ursache Der Elektromotorischen Eigenschaften Der Gewebe, Zugleich Ein Beitrag Zur Lehre von Den Polyphasischen Elektrolytketten. *Zeitschrift für Biologie* **1906**, *47*, 562–608.

[9] Frant, M. S.; Ross, J. W. Electrode for Sensing Fluoride Ion Activity in Solution. *Science* **1966**, *154* (3756), 1553–1555. https://doi.org/10.1126/science.154.3756.1553.

[10] Simon, W.; Štefanac, Z. In-Vitro Behavior of Macrotetrolides in Membranes as Basis Far High-Selective, Cation-Specific Electrode Systems. *Chimia* **1966**, *20*, 436–438.

[11] Maksymiuk, K.; Stelmach, E.; Michalska, A. Unintended Changes of Ion-Selective Membranes Composition—Origin and Effect on Analytical Performance. *Membranes* **2020**, *10* (10), 266. https://doi.org/10.3390/membranes10100266.

[12] Umezawa, Y.; Bühlmann, P.; Umezawa, K.; et al. Potentiometric Selectivity Coefficients of Ion-Selective Electrodes. Part I. Inorganic Cations (Technical Report). *Pure and Applied Chemistry* **2000**, *72* (10), 1851–2082. https://doi.org/10.1351/pac200072101851.

[13] Umezawa, Y.; Umezawa, K.; Bühlmann, P.; et al. Potentiometric Selectivity Coefficients of Ion-Selective Electrodes. Part II. Inorganic Anions (IUPAC Technical Report). *Pure and Applied Chemistry* **2002**, *74* (6), 923–994. https://doi.org/10.1351/pac200274060923.

[14] Umezawa, Y.; Bühlmann, P.; Umezawa, K.; et al. Potentiometric Selectivity Coefficients of Ion-Selective Electrodes Part III. Organic Ions: (IUPAC Technical Report). https://doi.org/10.1515/iupac.74.0092.

[15] Umezawa, Y.; Umezawa, K.; Sato, H. Selectivity Coefficients for Ion-Selective Electrodes: Recommended Methods for Reporting KA,Bpot Values (Technical Report). *Pure and Applied Chemistry* **1995**, *67* (3), 507–518. https://doi.org/10.1351/pac199567030507.

[16] Bakker, E.; Bühlmann, P.; Pretsch, E. Polymer Membrane Ion-Selective Electrodes-What Are the Limits? *Electroanalysis* **1999**, *11* (13), 915–933. https://doi.org/10.1002/(SICI)1521-4109(199909)11:13<915::AID-ELAN915>3.0.CO;2-J.

RELATED DOCUMENTS:

- Blog post: Ion-selective electrodes: General tips - Part 1
- Blog post: Ion-selective electrodes: Standard addition and direct measurement - Part 2
- WP-062EN Overcoming difficulties in ion measurement: Tips for standard addition and direct measurement

Analytes:	**Alkali metals – sodium, potassium; Alkaline earth metals – magnesium, calcium; Nitrogen – ammonia, ammonium, nitrate; pH value; Transition metals – copper, iron**
Matrix:	**Water – drinking water, tap water, others**
Method:	**Electrochemistry; Voltammetry, Polarography**
Industry:	**R&D (Academia)**

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