

DETERMINATION OF FLUORIDE ANIONS BY ION-SELECTIVE ELECTRODE

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1. Theory

1.1. Potentiometry

Potentiometry is an electrochemical method, in which the potential difference (electromotive force, ΔE) of a cell composed of indicator and reference electrode. The potential of the indicator (measurement) electrode depends on the activity of the analyte present in the investigated solution, while the potential of the reference (comparative) electrode remains constant and independent of the composition of the measured solution. The voltage between the two electrodes is measured using a digital voltmeter with high input impedance at practically zero current.¹

In practical applications, there are two variants of potentiometry:

- a) **direct potentiometry** determines the analyte's concentration directly from the measured voltage. In this case, it is a comparative method because the determination is carried out using a calibration curve to compare the voltage of the cell in the analysed solution to that measured under identical conditions in solutions of known analyte composition.
- b) **potentiometric titration** determines the analyte's concentration based on the consumption of a titrant. In this method, the equilibrium voltage of the cell is measured as a function of the amount of added titrant, allowing for the determination of the titration endpoint.

1.2. Indicator electrodes: Ion-selective electrodes

In potentiometry, ion-selective membrane electrodes (ISEs) are commonly used as indicator electrodes to determine specific ions. A typical representative of ISEs is the calcium electrode (selective for Ca^{2+} ions), cyanide electrode (selective for CN^- ions), fluoride electrode (selective for F^- ions), and so on. The selective membrane of the electrode, which is crucial for ion determination, is influenced by its composition. Ion-selective membranes separate the internal electrode system from the measured solution and can be made from various materials.

The membrane of a Ca-ISE consists of a polyvinyl chloride membrane with a selective ionophore for calcium ions. The membrane of an F-ISE is composed of a single crystal of lanthanum fluoride (LaF_3) with a europium fluoride (EuF_2) impurity. By incorporating EuF_2 into the crystal lattice of LaF_3 , vacant sites are created due to the missing fluoride anion, which can be filled by neighboring fluoride anions (**Fig. 1**). As a result of this phenomenon, the membrane exhibits high selectivity for fluoride anions.

¹ There is a negligible current (in the order of magnitude of 10^{-14} A) in the electrochemical cell.

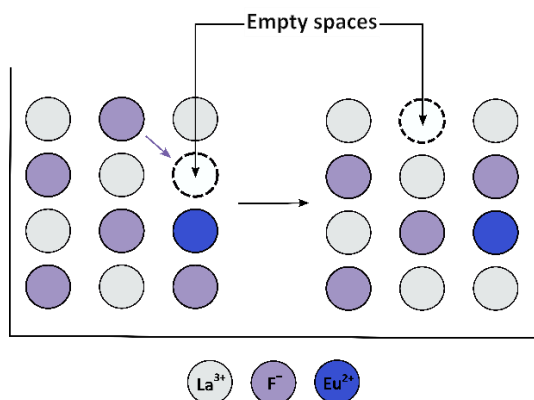
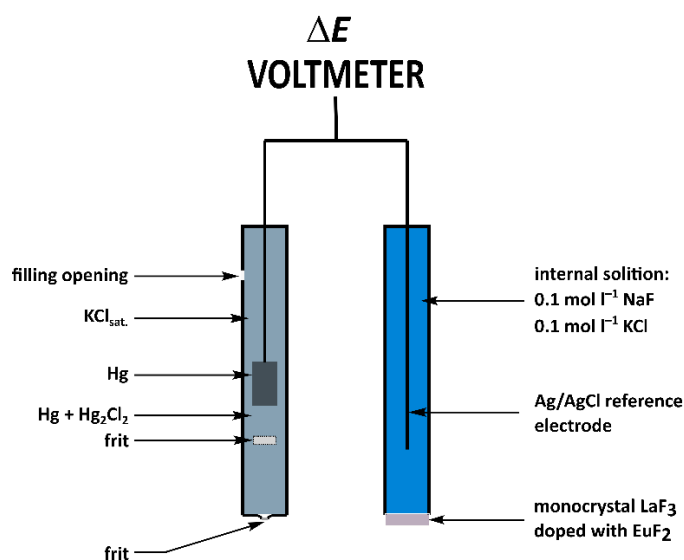


Fig. 1. The mechanism of the potentiometric response of a fluoride ion-selective electrode involves the migration of fluoride anions through the lattice of europium-doped lanthanum fluoride.

In the laboratory, both traditional standalone and combined fluoride ion-selective electrodes (F-ISEs) are employed. The standalone F-ISE necessitates the use of an external reference electrode. In the case of the combined F-ISE, the electrode is equipped with an integrated reference system (**Fig. 2**).

A)



B)

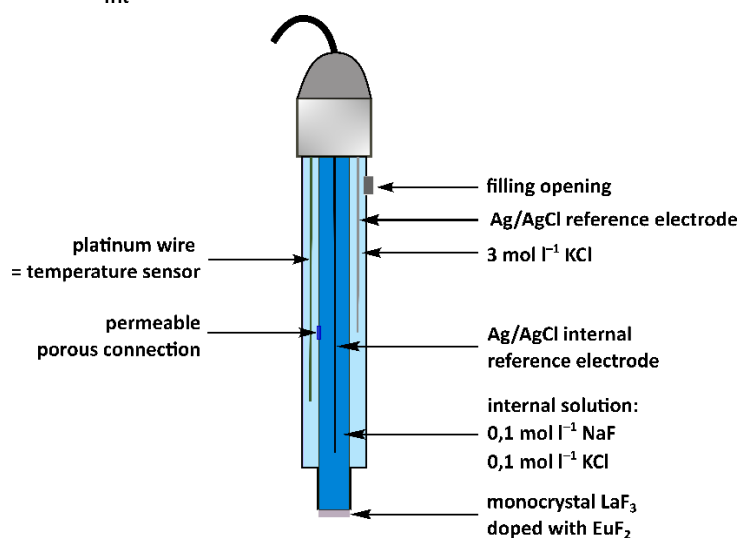


Fig. 2: Photograph and schematic representation of standalone (A) and combined (B) fluoride ion-selective electrodes. The electrode arrangements in the photographs correspond to the schematics.

1.3. Key Characteristics of Ion-Selective Electrodes

The characteristic properties of ISEs, including sensitivity (mV per decade), concentration range (mol L⁻¹), and practical detection limit ($c_{\min}$, mol L⁻¹), are determined from the calibration curve (**Scheme 1**). The calibration curve is obtained by systematically measuring the dependence of the electromotive force of the cell on the decimal logarithm of the activity of the specific substance ($\Delta E = f(\log a)$ ²). Measurements are conducted from the lowest ion concentration to the highest concentration. Prior to measurement, the ISE electrode is activated by overnight immersion in a solution containing the ion at a concentration of 10⁻³ mol L⁻¹ to which it is selective.

The concentration range is the linear region of the calibration curve ($R^2 = 0.999$) for the respective ion (**Scheme 1**), where Nernstian response applies, and the slope is determined. Deviations from linear behavior (the nonlinear part of the calibration curve) are caused by: a) at high analyte concentrations, it becomes challenging to maintain a constant ionic strength of the analyzed solution; b) at very low analyte concentrations, specific interactions occur at the membrane-solution interface, such as adsorption on the membrane's surface or its dissolution. The fluoride ISE is applicable in the concentration range from 10⁻⁶ to 10⁻¹ mol L⁻¹.

The practical detection limit ($c_{\min}$, mol L⁻¹) is defined by the intersection of two lines, namely the extrapolated linear portion of the calibration line where the Nernstian response holds, with a line parallel to the x-axis, and its position on the y-axis corresponds to the potential at zero concentration of fluoride ions (TISAB solution without fluoride ions) (**Scheme 1**).

The slope (sensitivity) of an ISE ($S = 2,303 \frac{RT}{zF}$) is the change in electromotive force of the cell when the concentration changes by one order of magnitude in the linear portion of the calibration curve (i.e., within the concentration range). The slope (theoretical Nernstian response) for monovalent ions ($z = \pm 1$) has a theoretical value of ± 59.2 mV per decade (± 59.2 mV dec⁻¹), and for divalent ions ($z = \pm 2$), it is ± 29.6 mV per decade (± 29.6 mV dec⁻¹) (**Scheme 2**). The positive sign applies to cations, where an increase in the concentration of the specific ion leads to an increase in the ISE potential. Conversely, the negative sign applies to anion response, where an increase in the ion concentration results in a decrease in the ISE potential.

The calibration dependence $\Delta E = f(\log[F^-])$ is obtained using linear regression in MS Excel (in the form $y = ax + b$) (where 'y' is the measured electromotive force of the cell (ΔE), 'a' is the experimental slope of the ISE (S), 'x' is the logarithm of ion concentrations in the measured solution ($\log [F^-]$)).

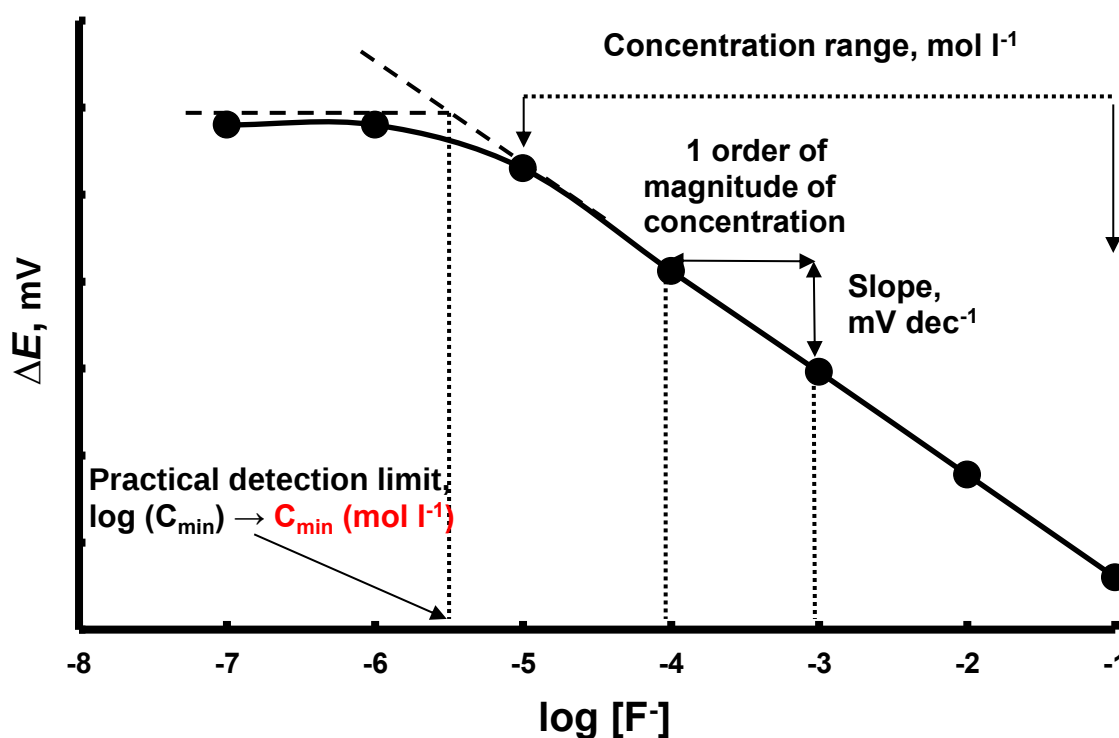
Selectivity is most commonly expressed using **the decimal logarithm of the selectivity coefficient** ($\log K_{F^-,J}^{pot}$), where F⁻ is the primary ion and J is the interfering ion. The value of $\log K_{F^-,J}^{pot}$ can be either negative or positive. The more negative the value of $\log K_{F^-,J}^{pot}$, the less the interfering ion affects the potentiometric determination of the primary ion. Conversely, the higher the value of $\log K_{F^-,J}^{pot}$, the more the interfering ion influences the potentiometric determination of

² a represents the activity (effective concentration) of the monitored ion. Activity is expressed as the product of the relative equilibrium concentration [X] and the activity coefficient $\gamma(X)$: $a(X) = \gamma(X) \cdot [X]$. In diluted solutions, where we assume that activity coefficients are close to unity, we can, therefore, replace activity with concentration.

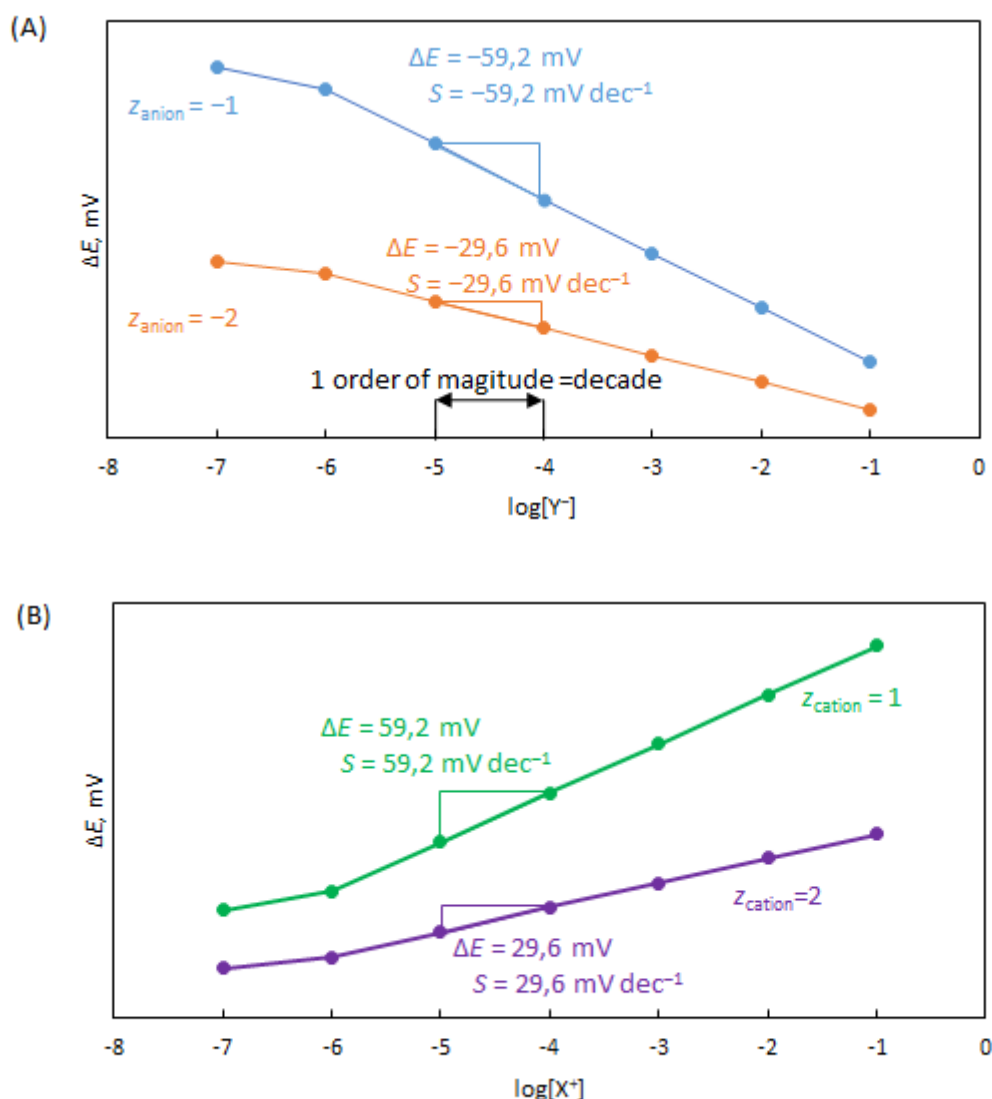
the primary ion. The values of $\log K_{F^-,j}^{pot}$ are determined experimentally. Knowledge of selectivity coefficients is crucial for the practical use of ISE.

Interfering anions for F-ISE include OH^- ions, and interfering cations for F-ISE include cations that form complexes with fluorides (Fe^{3+} , Al^{3+} , and others). Therefore, the potentiometric determination of fluorides is conducted in the 'Total Ionic Strength Adjustment Buffer' (TISAB) solution, which maintains a pH range of 5 to 6, thus eliminating interference from OH^- ions.

The hysteresis (memory effect) of an electrode is related to adsorption and desorption processes. This phenomenon can be observed when transitioning from more concentrated solutions to more diluted ones (for example, the transition from 10^{-3} to 10^{-4} mol L $^{-1}$) during measurements of real samples, especially on unrenewed surfaces.



Scheme 1. Evaluation of the characteristic properties of anion-selective ISE from the calibration curve.



Scheme 2. Calibration curves corresponding to anion (A) and cation (B) responses of ion-selective electrode.

2. Measurement with Ion-Selective Electrodes

2.1. Regeneration

To obtain reproducible results, ISEs must undergo regeneration before potentiometric measurements. Regeneration is typically accomplished by immersing the electrodes into a regenerating solution that closely mimics the composition of calibration solutions, especially in terms of pH, ionic strength, and the presence of interferents. Regeneration of F-ISEs involves immersing the electrodes into a stirred solution of a buffer, such as 0.01 mol L⁻¹ TISAB.

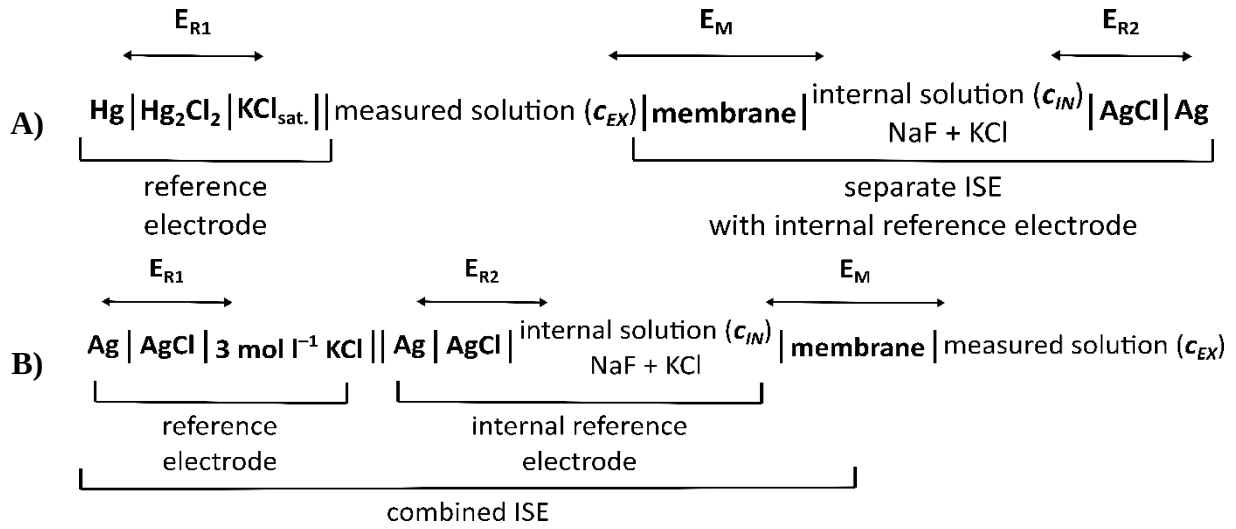
Regeneration of the electrode pair or combined electrode must be performed before each calibration curve measurement and before sample measurement. **Fresh regenerating solution is required for each regeneration.** The duration of regeneration is related to the memory effect of the individual ion-selective membrane.

2.2. Stirring

In potentiometric analysis, it is advantageous to measure in stirred solutions because the total response time (the time required to reach a stable potential value) of the electrode is determined by the thickness of the hydrodynamic layer on the electrode surface. Stirring reduces the thickness of the hydrodynamic layer at the electrode, shortening the response time of the electrode and improving the reproducibility of results. It's important that **the rate of solution movement and the geometry of the working space remain constant**.

2.3. Potentiometric signal

In potentiometry with ISEs, the electromotive force (ΔE) of the cell is measured, which is the difference in potentials between the ISE and the reference electrode. The cells for both standalone and combined F-ISEs can be described by **Scheme 3**.



Scheme 3. Electrochemical cell describing measurements with standalone (A) and combined (B) ion-selective electrode. E_{R1} represents the potential of the standalone calomel reference electrode or the internal reference silver chloride electrode, E_M is the membrane potential at the interface between the measured solution (EX) and the internal solution (IN), E_{R2} is the potential of the internal reference silver chloride electrode.

The electromotive **force** (ΔE) of the cell is:

$$\Delta E = E_{R2} + E_M - E_{R1} \quad (1)$$

$$E_{ISE} = E_{R2} + E_M \quad (2)$$

$$E_M = \frac{RT}{zF} \ln \frac{a(F^-)_{EX}}{a(F^-)_{IN}} = 2,303 \frac{RT}{zF} \log \frac{\gamma(F^-)_{EX} \cdot [F^-]_{EX}}{\gamma(F^-)_{IN} \cdot [F^-]_{IN}} \quad (3)$$

where $[F^-]_{EX}$ is the unknown concentration. When using a constant ionic strength of the solution (as further discussed), the activity coefficient $\gamma(F^-)$ can also be considered constant and it is incorporated into the constant K . For the potential of the F-ISE at 25 °C (298.15 K), the following equation applies:

$$E_{F-ISE} = K - 0,0592 \cdot \log[F^-]. \quad (4)$$

The potential of an ISE, which generally depends not only on the concentration of the ion of interest but also on other ions present in the solution (interferents), is described by the Nikolsky-Eisenmann equation. For F-ISE, it takes the form:

$$E_{F-ISE} = K - S \cdot \log \left([F^-] + \sum_J K_{F^-,J}^{pot} \cdot c[J]^{z_F/z_J} \right), \quad (5)$$

where S is the slope, $[F^-]$ and $[J]$ are the respective concentrations of fluorides and interfering ions, z_F and z_J are the charges of fluorides and interferents, and $K_{F^-,J}^{pot}$ is the selectivity coefficient (commonly expressed in logarithmic form) for practical purposes. Interferents for F-ISE include OH^- , Al^{3+} , and Fe^{3+} ions.

2.4. Potentiometric selectivity

The selectivity of the electrode to the analyte against various interferents is described by the potentiometric selectivity coefficient ($\log K_{F^-,J}^{pot}$) (see 'Key Characteristics of Ion-Selective Electrodes' [1]). There are three methods for determining potentiometric selectivity coefficients:

- The Fixed Interference Method (FIM).
- The Separate Solution Method (SSM).
- The Matched Potential Method (MPM).

Appendix 1 schematically illustrates the methods for determining potentiometric selectivity coefficients. The most commonly used methods are the Separate Solution Method (SSM) and the

3. Measurement techniques

3.1. Calibration Curve Method

This method is generally suitable when determining ion content in a simple matrix (e.g., drinking water or mineral water). The composition of samples and standard solutions must be as similar as possible, especially in terms of pH, ionic strength, and the presence of interferents, for the determination to be done with acceptable accuracy. The precision of the determination is not generally very high. With a precision of potential measurement (± 1 mV) at laboratory temperature, the relative error of determination is ± 4 % for monovalent ions and ± 8 % for bivalent ions.

It is desirable for the concentration of the target ion in the samples to fall within the linear range of the calibration curve (concentration range). The concentration of the target ion is calculated directly from the modified Nernst equation evaluated from the experimentally obtained calibration curve.

In the case of F-ISE the equation takes the form:

$$\Delta E_x = K' - S \cdot \log[F^-], \quad (6)$$

- ΔE_x is the voltage of the potentiometric cell measured in the sample solution,
 K' is an additive constant determined from the experimental equation (6) after calibrating the ISE electrode,
 S is the experimental value of the slope determined from the experimental equation (6) after calibrating the ISE electrode,
 $[F^-]$ is the unknown concentration of fluoride anions being determined in the sample.

3.2. Standard addition method

This method is more suitable for determining ion concentrations in a complex matrix (such as blood serum or blood). The main advantage is that the entire measurement is performed in the presence of the sample matrix, which allows for results with better precision and accuracy. The basis of this method is the measurement of the cell voltage in the sample before addition (ΔE_x , Equation (6)) and after the addition ($\Delta E_1, \Delta E_2, \Delta E_3, \dots \Delta E_n$) of the standard solution (c_s) with a volume of V_s to the sample with a volume of V_x :

$$\Delta E_1 = K' - S \cdot \log \frac{c_x V_x + c_s V_{s1}}{V_x + V_{s1}} \quad (7)^3$$

$$\Delta E_n = K' - S \cdot \log \frac{c_x V_x + c_s V_{sn}}{V_x + V_{sn}} \quad (8)$$

$$c_x = \frac{c_s V_{sn}}{(V_x + V_{sn}) \cdot 10^{\frac{\Delta E}{S}} - V_x} \quad (9)$$

- ΔE_x is the voltage of the cell in the sample solution without the addition of the standard,
 $\Delta E_1 \dots \Delta E_n$ are the voltages of the cell in the sample solution with the addition of the standard,
 ΔE is the difference in voltage of the cell with and without the addition of the standard,
 c_x and c_s are the unknown concentration in the sample solution and the known concentration of fluorides in the added standard,
 V_x and V_{sn} are the added volumes of the unknown sample and the standard,

³ The argument of the logarithm should be dimensionless (we should use relative equilibrium concentrations).

- V_x is the volume of the sample prepared for measurement,
 $V_{S1} \dots V_{Sn}$ are the volumes of the standard solution added to the sample,
 K' is the additive constant, which depends on the construction of the ISE electrode,
 S is the experimental slope value, which is determined during the electrode calibration process.

4. Fluoride Presence in Real Samples

Fluorides are present in mineral waters. Mattoni contains 0.55–1.80 mg L⁻¹ (currently unreported), Ondrášovka contains 1.08 mg L⁻¹, Dobrá voda contains 0.46 mg L⁻¹, and Vincentka contains 2.54 mg L⁻¹. Higher fluoride content is found in tea (green tea: 71–180 mg kg⁻¹; black tea: 30–441 mg kg⁻¹), Coca-Cola (0.82–0.98 mg L⁻¹), and grapefruit juice (6.80 mg L⁻¹). It is well known that fluoride intake is particularly beneficial for the development of healthy teeth. Therefore, some toothpaste products intentionally contain elevated levels of fluoride compounds such as sodium fluoride, aminofluorides, and fluorophosphates. The concentration of fluoride varies among different types of toothpaste, with the highest levels found in so-called therapeutic toothpaste.

For adults, an acceptable concentration is reported to be in the range of 1,000 to 1,500 mg kg⁻¹, while for children up to 4–5 years of age, the content is lower, around 250–400 mg kg⁻¹. This is due to the repeated observation that young children occasionally swallow toothpaste. The task at hand involves determining the fluoride content in various samples of toothpaste.

Laboratory manual

DETERMINATION OF FLUORIDE ANIONS IN A TOOTHPASTE

Tasks:

1. Preparation of Solutions and Samples
2. Determination of Basic Properties of F-ISE:
 - Slope (S, mV dec⁻¹)
 - Concentration Range (mol L⁻¹)
3. Determination of Fluoride Anion Content in Toothpaste using the following methods:
 - Calibration Curve
 - Standard Addition

Required Solutions and Equipment:

- 2 mol L⁻¹ stock solution of TISAB (available in the fume hood)
- Laboratory standard of fluorides (ρ_{std} , g L⁻¹, concentration is indicated on the label)
- Portable 913 pH meter Lab (Metrohm, Czech Republic)
- Magnetic stirrer
- Electrode holder
- Combined F-ISE (Metrohm, Czech Republic) (fluoride ISE type 600500600, price 35,360 CZK)
- ROW-automatic micropipette 100–1000 μ L (5,499 CZK) with tips
- "Kartell" rubber bulb
- Manuals
- Notebook (shared by 3 students, price 8,290 CZK) (*or/it is possible to use private notebook*)

Technical equipment: 913 pH meter

The laboratory instrument 913 pH Meter allows for the measurement of direct current voltage, pH, and temperature. The device is powered by a built-in battery (3.7 V) or a network adapter. Technical specifications are provided in **Table 1**. The instrument is equipped with an LCD monitor and a control panel. Individual connectors and control elements are described in **Figure 3**.

Table 1 Technical Specifications of the Device 913 pH Meter

Measured quantity	Voltage	pH
Range	From –1,200 to +1,200 mV	From –13 to 20
Resolution	0.1 mV	0.001 pH
Accuracy	± 0.2 mV	± 0.003 pH

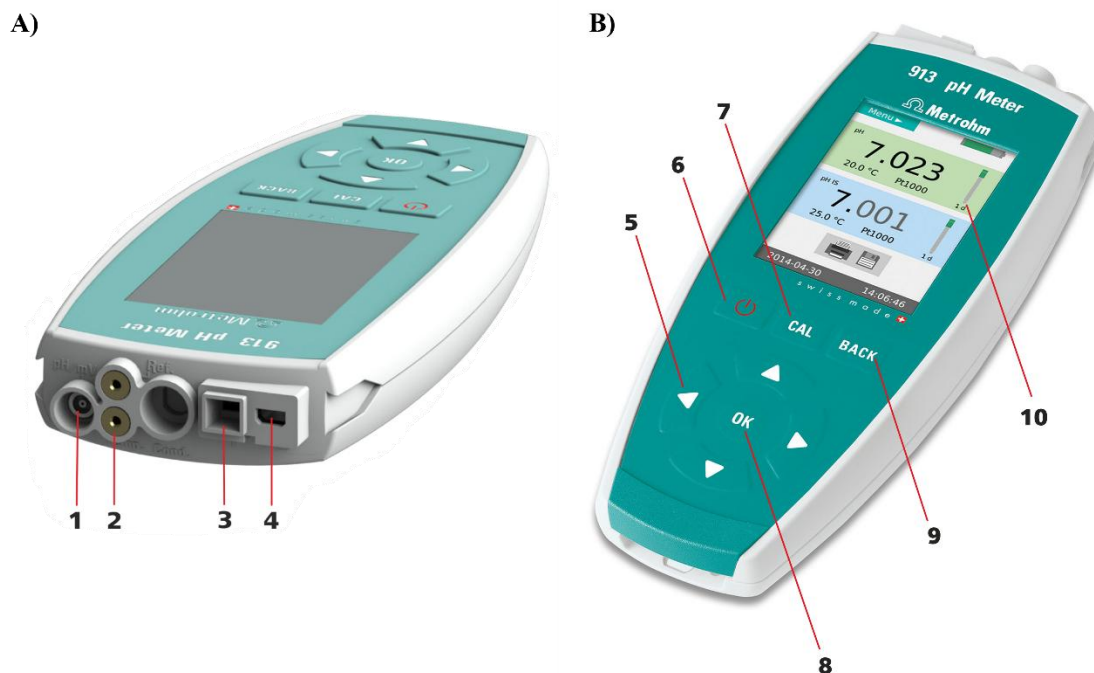


Figure 3: 913 pH meter:

- A) Connectors: 1 - connection socket for analogue measuring electrode 2 - connectors for temperature sensor/reference electrode (up – blue, down – red), 3 – connection socket for special chip (not available in the laboratory), 4 – connection socket for energy supply/data transmission
- B) Front panel: 5 – arrow keys 6 – power on/off button, 7 – button for recording calibration points (not used), 8 – confirmation button, 9 – back button, 10 – LCD monitor

Operation

- 1) When the device is powered from the mains, it is always in "Standby" mode. To turn it on, press button 6 (**Figure 3B**). The home screen will appear (**Figure 4A**). If the voltage value stabilizes, the individual digits on the screen are displayed in gray. After the signal stabilizes, the individual digits turn black.
- 2) First, it is necessary to enter the user's name without diacritics into the device. To enter the name into the device, use the arrow buttons (5) and OK (8) as follows: Menu → User → User (**Figure 4A–C**, red frames), where you can enter the name using the on-screen keyboard (**Figure 4D**). To return to the home screen, use the "back" button (9).

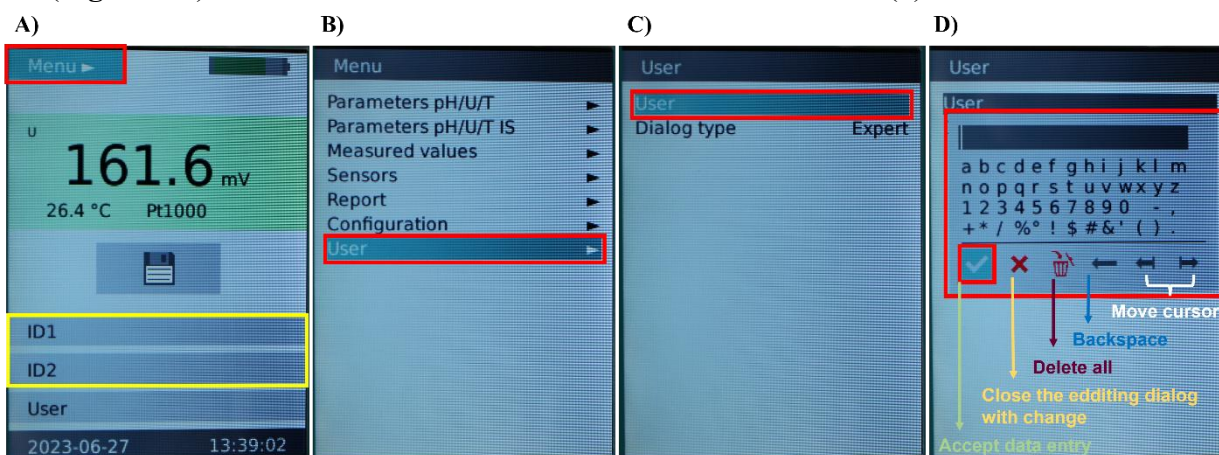


Figure 4: Home Screen (A) and the process of entering a name into the device (B-D).

- 3) When measuring individual solutions, you can enter information about the solution to be measured (e.g., the calibration solution or standard addition) into the device. You can enter this information on the home screen under ID1 and ID2 (**Figure 4A**, yellow box). Under ID1, enter the following for each measurement:
- Calibration: CAL 1 to 3
 - Determination of fluorides in paste: STD

You won't change ID1 within one measurement. You will change ID2 before each addition. In this column, simply record the addition number. Before each addition, change ID2, add the respective addition, and start the timer for 1 minute. After one minute, save the voltage value (see point 4).

- 4) The measured voltage values can be saved in the device's memory by pressing the floppy disk icon (**Figure 5A**, purple box) on the home screen. Saved values can be viewed at any time by going to: Menu → Measured values → Values → view (**Figure 5A–D**, red boxes). The last saved value and all the associated information are automatically displayed. You can navigate between the stored values using the up/down and left/right arrows (5). This way, you can save up to 10,000 values.

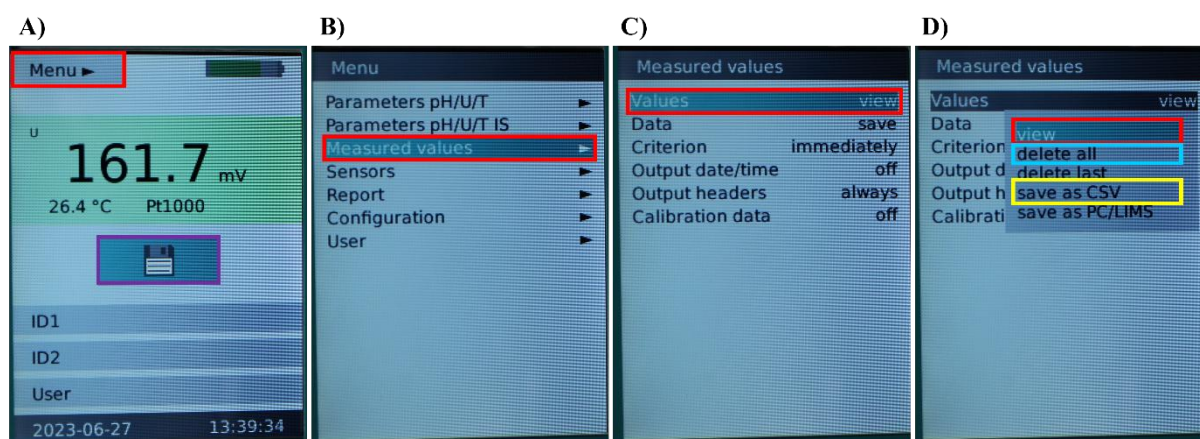


Figure 5: Procedure for saving measured values, their subsequent display (red boxes), data export to a computer (yellow box), and data deletion at the end of the task (turquoise box).

- 5) You can export the measured and saved values from the device to your computer in CSV format. Before connecting the computer, you need to enter the export command as follows: Menu → Measured values → Values → save as CSV (Figure 5D, yellow box). After connecting the device to the computer using a USB cable, the device will connect similarly to a flash drive, and you will find the measured values in the MEASREPORT.csv file.
- 6) At the end of the laboratory day, delete all measured values from the device as follows: Menu → Measured values → Values → delete all (Figure 5D, turquoise box).

1. Preparation of Solutions and Samples

1.1 Preparation of working solution of TISAB ($c = 0.01 \text{ mol L}^{-1}$)

TISAB is an aqueous solution composed of NaCl, CH_3COONa , CH_3COOH , and *trans*-1,2-diaminocyclohexane-*N,N,N',N'*-tetraacetic acid. The high concentration of NaCl ensures a constant ionic strength of the solution. The mixture of acetic acid and its sodium salt (acetic acid pH buffer) guarantees pH adjustment to the range of 5–6. The chelating agent (*trans*-1,2-diaminocyclohexane-*N,N,N',N'*-tetraacetic acid) forms stable complexes with multivalent cations (Fe^{3+} , Al^{3+}), preventing their complexation with fluorides.

1. Transfer 5 ml of the TISAB stock solution ($c = 2.0 \text{ mol L}^{-1}$) into a 1000 ml volumetric flask using a pipette.
2. Fill with distilled water up to the mark and mix thoroughly.

1.2 Preparation of Toothpaste Sample

- Weigh the sample with toothpaste on an analytical balance with a precision of 0.1 mg.
- Transfer **1.5–2.0 g of the sample** from the weigh boat **using a dry glass rod into a dry beaker with a volume of 400 ml**. Perform this transfer quickly due to the volatile nature of toothpaste samples. Seal the weigh boat after each transfer. The difference in weight before and after transferring the sample will provide precise information about the exact amount of toothpaste sample being analyzed. Record the precise weight of the toothpaste in your notebook. **Leave the glass rod in the beaker, and do not wipe it under any circumstances.**
- Add approximately 100 ml of distilled water and a boiling chip (glass marble) to the 400 ml beaker containing the toothpaste sample. **The resulting toothpaste sample should be a finely mixed suspension without foam.** Cover the beaker with a watch glass and place it on a heated hot plate with a stirring rod inserted.
- Heat the prepared toothpaste sample for about 5 minutes. In case the sample starts foaming and there is a risk of overflowing from the beaker, remove the beaker from the hot plate, cool it with tap water, and return it to the hot plate after the foam subsides.

Caution! Do not leave the suspension in the beaker unattended - there is a risk of boiling over and sudden boiling of the heated solution, which can lead to the loss of part of the sample. In this case, the solution should be discarded, and a new sample should be prepared.

- Cool the beaker with the toothpaste suspension in a water bath located in the fume hood.
- Rinse the watch glass and glass rod with a small amount of distilled water into the beaker.
- Quantitatively transfer the suspension to a 250 ml volumetric flask, cool to room temperature.
- Add **1.5 ml of stock TISAB solution ($c = 2 \text{ mol L}^{-1}$)** to the 250 ml volumetric flask. Choose the correct pipette for taking 1.5 ml of liquid (pipette the entire volume at once).
- Fill with distilled water up to the mark and mix thoroughly.

Caution! Some toothpaste solutions can produce a lot of foam. To achieve good results, be patient and follow the assistant's instructions.

2 Determining the key properties of F-ISE

2.1. Regeneration of F-ISE

1. Add 100 ml of the working solution of TISAB ($c = 0.01 \text{ mol L}^{-1}$) into a 150 ml beaker.
2. Place the 150 ml beaker with the TISAB solution ($c = 0.01 \text{ mol L}^{-1}$) in the center of the magnetic stirrer.
3. Submerge the F-ISE electrode 1 cm below the surface, near the wall of the beaker (follow the assistant's instructions) into the TISAB solution. Ensure that the surface of the magnetic stirrer and the bottom of the beaker are dry.
4. Start the stirring carefully. **CAUTION!** The stirring bar may damage the electrodes, so do not let them touch!!!
5. Regenerate the electrode for 10 minutes.
6. Turn off the stirring, remove the electrode from the solution, rinse it with distilled water, dry the electrode's surface with cellulose wadding, and proceed with the assigned tasks according to the assistant's instructions.

2.2 Calibration of F-ISE

1. Pipette 50 ml of the working solution TISAB ($c = 0.01 \text{ mol L}^{-1}$) into a 100 ml beaker.
2. Place the 100 ml beaker with the prepared solution in the center of the stirrer. Submerge the F-ISE electrode 1 cm below the surface, close to the beaker's wall. Ensure that both the surface of the stirrer and the bottom of the beaker are dry.
3. Submerge the F-ISE electrode into 50 ml of 0.01 mol L^{-1} TISAB. Start the stirrer. **CAUTION!** Do not touch the electrodes as the stirrer may damage them!
4. Add 100 μl of the laboratory standard fluoride solution (using an automatic pipette) and record the voltage after one minute for solution 1 (c_1). The concentration of the laboratory standard fluoride solution is indicated on the label ($\rho_{\text{std}}, \text{g L}^{-1}$).
5. Add 200 μl of standard fluoride solution ($\rho_{\text{std}}, \text{g L}^{-1}$), start the timer, and record the voltage after one minute for solution 2 (c_2).
6. Add 300 μl of standard fluoride solution ($\rho_{\text{std}}, \text{g L}^{-1}$), start the timer, and record the voltage after one minute for solution 3 (c_3).
7. Add 400 μl of standard fluoride solution ($\rho_{\text{std}}, \text{g L}^{-1}$), start the timer, and record the voltage after one minute for solution 4 (c_4).
8. Add 800 μl of standard fluoride solution ($\rho_{\text{std}}, \text{g L}^{-1}$), start the timer, and record the voltage after one minute for solution 5 (c_5).
9. Add 1000 μl of standard fluoride solution ($\rho_{\text{std}}, \text{g L}^{-1}$), start the timer, and record the voltage after one minute for solution 6 (c_6).
10. Turn off the stirrer, remove the electrode from the solution, rinse it with distilled water, dry the electrode's surface with cellulose wadding, and replace the measured solution.
11. Replace the measured solution with 100 ml of working solution TISAB ($c = 0.01 \text{ mol L}^{-1}$). Regenerate the electrode for 10 minutes.
12. Repeat the calibration three times.
13. Complete Table 2.
14. Calculate the concentration of fluoride anions ($c_1, c_2, c_3, c_4, c_5, c_6$) (mol L^{-1}).

15. Construct the dependence of the electromotive force of the cell (ΔE) on the logarithm of fluoride ion concentration in the prepared calibration solutions ($\log [F^-]$) ($R^2 = 0.999$).
16. Evaluate the experimental calibration equation using linear regression in MS Excel.

Discuss the results with the assistant.

17. Determine the basic properties from the experimental calibration curve.
18. Calculate the average slope value (sensitivity).

Table 2. Parameters used and obtained during the calibration of the fluoride ion-selective electrode ($M_F = 18.9984 \text{ g mol}^{-1}$)

Addition of standard fluoride solution, μL	100	200	300	400	800	1000
Volume 0,01 mol L⁻¹ TISAB, mL	50	50	50	50	50	50
Total volume, mL						
[F⁻], mol L⁻¹						
ΔE, mV (1st measurement)						
ΔE, mV (2nd measurement)						
ΔE, mV (3rd measurement)						

3. Determination of fluoride anion content in toothpaste samples

3.1. Calibration Curve Method

1. Regenerate the electrode in fresh 0.01 mol L^{-1} TISAB solution (10 minutes).
2. Mix the toothpaste sample in a volumetric flask and transfer a portion of the mixed sample into a 150 ml beaker.
3. Pipette 50 ml of the toothpaste sample into a 100 ml beaker.
4. Measure the voltage after 1 minute for the sample.
5. Insert the measured voltage into your experimental calibration equation and determine the fluoride concentration (mol L^{-1}).
6. Determine the mass percentage of fluorides $\% (m/m)_{\text{F}^-}$ corresponding to the calculated concentration of fluoride ions in the toothpaste sample.

3.2. Method of standard addition

1. Regenerate the electrode in fresh 0.01 mol L^{-1} TISAB solution (10 minutes).
2. Mix the toothpaste sample in a volumetric flask and transfer a portion of the mixed sample into a 150 ml beaker.
3. Pipette 50 ml of the toothpaste sample into a 100 ml beaker.
4. Add laboratory standard fluoride solution: $100 \mu\text{l} \rightarrow 200 \mu\text{l} \rightarrow 400 \mu\text{l} \rightarrow 800 \mu\text{l} \rightarrow 1000 \mu\text{l}$.
5. Record the voltage after 1 minute for each addition: $\Delta E_1 \rightarrow \Delta E_2 \rightarrow \Delta E_3 \rightarrow \Delta E_4 \rightarrow \Delta E_5$.
6. Determine the mass percentage of fluorides $\% (m/m)_{\text{F}^-}$ in the toothpaste sample for each addition.
7. Fill in table 3.
8. Calculate the average mass percentage of fluorides $\% (m/m)_{\text{F}^-}$ in the toothpaste sample (see Appendix 2).

Table 3. Parameters Used and Obtained During the Analysis of Toothpaste Sample Using the Standard Addition Method

Addition of standard fluoride solution, μl	0	100	200	400	800	1000
Volume of analysed toothpaste sample, ml	50	50	50	50	50	50
Total volume, ml						
ΔE_n , mV						
$[\text{F}^-]_n$, mol l^{-1}						
$\% (m/m)$						

Compare the results of toothpaste analysis obtained using the calibration curve method and the multiple standard addition method. Try to interpret any differences if present.

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Control Questions

1. Describe the principle of direct potentiometry.
2. List factors (at least 3) that influence the accuracy of potentiometric fluoride determination. How do these factors contribute to the accuracy of potentiometric fluoride determination?
3. Define the role of NaCl, CH₃COOH, CH₃COONa in potentiometric fluoride determination.
4. Draw the theoretical course of the potentiometric calibration curve for systems (label the axes):
 - a. Indicator F-ISE in solutions of 10^{-6} to 10^{-1} mol L⁻¹ NaF,
 - b. Indicator Na-ISE in solutions of 10^{-6} to 10^{-1} mol L⁻¹ NaF,
 - c. Indicator F-ISE in solutions of 10^{-6} to 10^{-1} mol L⁻¹ NaOH.
5. Which equation is applied when calculating the fluoride content in potentiometric determination using the calibration curve in the absence and presence of interfering ions?
6. Which of the listed cations interfere with potentiometric fluoride determination: a) Na⁺, b) Fe³⁺, c) K⁺? How is their interfering influence eliminated?
7. What phenomenon will you observe when transitioning from concentrated to diluted solutions? How can this phenomenon be suppressed during potentiometric measurements?
8. What is the measured variable (i.e., dependent variable) in measurements with F-ISE? What are its units?
9. List and characterize the basic properties of F-ISE.
10. What is the chemical composition of the membrane in F-ISE? What is the significance of EuF₂ in the F-ISE membrane?
11. Draw a schematic electrochemical cell diagram for the determination of fluorides using standalone and combined F-ISE.
12. What is the relationship between the electromotive force (EMF) of the cell with F-ISE and the concentration of F⁻ in the solution? Write the equation. Is this relationship linear?
13. Write the equation obtained during the calibration of pH combined glass ISE, CN-ISE, Na-ISE.
14. Which anions and cations interfere with F-ISE work? How can this phenomenon be prevented?
15. What is the selectivity coefficient? In what units is the selectivity coefficient expressed? In what range of values are selectivity coefficients found?
16. In which cases is the method of calibration curves and standard addition method used?
17. Write equations for calculating the unknown concentration of fluoride ions using the calibration curve method.
18. Describe the procedure and write equations for calculating the unknown concentration of fluoride ions using the standard addition method.

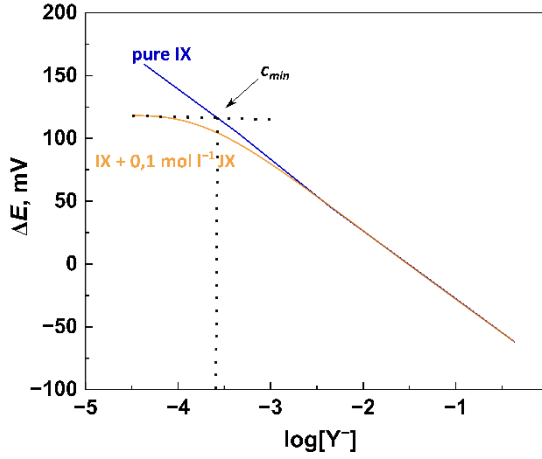
19. What will be the substance concentration of fluoride when:
- You add 100 μl of fluoride solution ($[\text{F}^-] = 10^{-3} \text{ mol L}^{-1}$) to 50 ml of water,
 - You mix 100 μl ($\rho_{\text{fluorides}} = 8.5451 \text{ g L}^{-1}$) and 50 μl ($\rho_{\text{fluorides}} = 8.5451 \text{ g L}^{-1}$) with 50 ml of 0.01 mol L^{-1} TISAB ($\text{MF} = 18.9984 \text{ g mol}^{-1}$, $\text{MCl} = 35.453 \text{ g mol}^{-1}$),
 - You add 400 μl of fluoride solution ($\rho_{\text{fluorides}} = 8.5451 \text{ g L}^{-1}$) to 50 ml of 0.01 mol L^{-1} TISAB? ($\text{MF} = 18.9984 \text{ g mol}^{-1}$)
20. Write equations for reactions that may occur in acidic solutions during fluoride determination.
21. Write the equation obtained during the calibration of Na-ISE, Ca-ISE, CN-ISE.
22. F-ISE regeneration can be performed in:
- 0.01 mol L^{-1} TISAB solution
 - Solutions of $10^{-6} \text{ mol L}^{-1}$ NaF
 - Solutions of $10^{-1} \text{ mol L}^{-1}$ NaF.
23. What is the sensitivity of ISE? In what units is the sensitivity of F-ISE expressed? What sensitivity does ISE exhibit towards divalent anions and cations?
24. What is $\log K_{\text{F}^-, \text{J}}^{\text{pot}}$? What do the symbols F^- and J represent? In what range of values do they vary? What does it mean if the value of $\log K_{\text{F}^-, \text{J}}^{\text{pot}}$ is negative?

Appendix

Appendix 1

Methods for determining potentiometric selectivity coefficients for anionic ion-selective electrodes.

A)



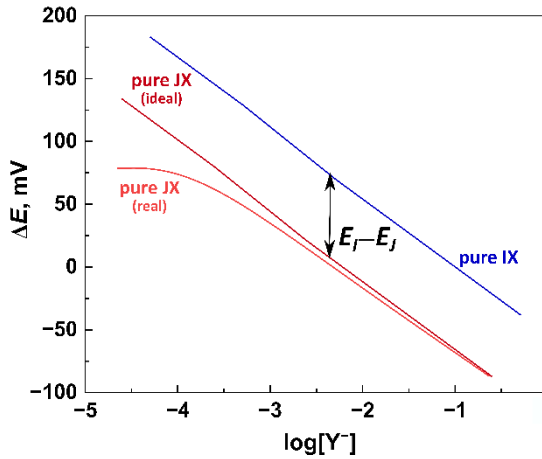
FIM method

$$\log K_{I,J}^{pot} = \log \left(\frac{c_{min_I}}{c_J^{z_I/z_J}} \right)$$

c_{min_I} is the detection limit for the primary ion, which was determined during the calibration curve measurement in the presence of interferent J.

c_J is the concentration of interfering ion

B)



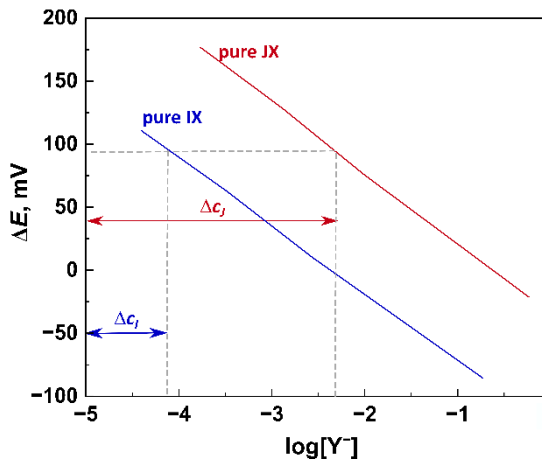
SSM method

$$\log K_{I,J}^{pot} = \frac{(\Delta E_I - \Delta E_J)}{S} + \log \left(\frac{c_I}{c_J^{z_I/z_J}} \right)$$

S is the electrode sensitivity,

ΔE_I and ΔE_J are the values of electromotive force (EMF) at the same concentration of the primary ion (c_I) and interfering ion (c_J).

C)



MPM method

$$k_{I,J}^{MPM} = \frac{\Delta c_I}{\Delta c_J}$$

Δc_I represents the change in concentration of the primary ion that causes a change in electromotive force,

Δc_J represents the change in concentration of the interfering ion that causes the same change in electromotive force as Δc_I .

Appendix 2

Based on the calculated weight percentages of fluorides in the toothpaste sample, determine a confidence interval at the 95% confidence level. The upper and lower bounds of the interval (confidence limits) are obtained from the equation:

$$L_{1,2} = \bar{x} \pm t_{n-1} \cdot \frac{s_{n-1}}{\sqrt{n}}, \quad (2-1)$$

L_1 a L_2 are the lower and upper bounds of the confidence interval,
 $\bar{x}$ is the average weight percentage of fluorides in the toothpaste % (m/m),
 t_{n-1} is the critical value of the Student's t-distribution for n-1 degrees of freedom (n is the number of determinations),
 s_{n-1} is the sample standard deviation.

In MS Excel, the function =TINV(0.05;n-1)⁴ is used to calculate t_{n-1} and the function =SMODCH.VÝBĚR (or STDEV) is used for s_{n-1} .

⁴ The value 0.05 corresponds to a significance level of 5%, which means a confidence level of 95%.