

Determination of Fluoride in Toothpaste Using an Ion-Selective Electrode

Facility with ion-selective electrodes has become an important addition to the skills of the modern chemist. A recent paper in *this Journal* noted that because of increasing use of ion-selective electrodes for analysis and for process and control measurements, it is important that undergraduates receive some instruction in their usage (1). This paper presents a brief review of potentiometry and ion-selective electrode theory and gives an experiment employing the fluoride ion activity electrode (2). This laboratory determination uses a total ionic strength adjustment buffer (3) to measure the fluoride content of toothpaste by direct potentiometry in high ionic strength medium. The educational goals of this experiment are multiple and may be listed as follows

to introduce the student to the theoretical and practical aspects of direct potentiometric analysis including its strengths and weaknesses (4)

to emphasize and illustrate the relationship between concentration and activity as well as to present a method of measuring concentration with an electrode that fundamentally is an activity responding measurement device

to present some of the theory of ion-selective electrodes and provide a direct application of their use in a procedure that permits the analysis of low levels of fluoride in complex industrial and naturally occurring materials

to provide a simple and practical laboratory analysis of a key component in a familiar consumer product such as toothpaste and tap water

to stimulate further investigative thought through a series of discussion questions

Theory

Chemical Potentiometry

An ion-selective electrode may be defined as an indicator or measuring electrode with a relatively high degree of specificity for a single ion or a class of ions. It is used in conjunction with a reference electrode which is defined as an electrode with a potential independent of the composition of the solution. A potentiometer, which is a special high impedance voltmeter that draws virtually no electrical current, is used to complete the measuring circuit as shown in Figure 1. Typically, the potentiometers employed are commercially available pH-millivoltmeter combination instruments, and these are required because of the high resistance of most measuring electrodes. More extensive treatments of the theory and practice of ion-selective electrodes are available (5, 6).

If a measuring electrode, M, and a reference electrode, R, are placed in a solution with ion activity a_i (to which the measuring electrode is sensitive), the resulting electrochemical cell is written as



The emf, E , of cell (1) as observed in the measuring circuit of Figure 1 is given by the Nernst equation

$$E = E^\circ + (2.3RT/nF) \log a_i \quad (2)$$

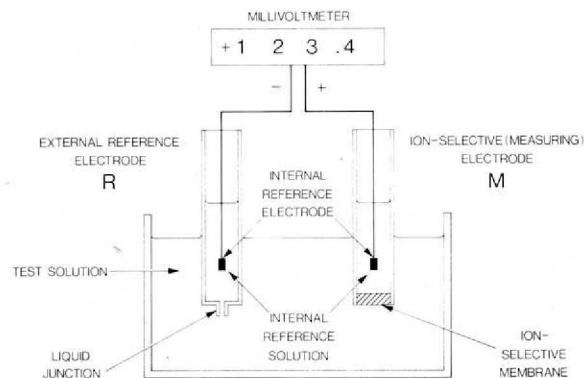


Figure 1. Potentiometric measuring circuit showing measuring (M) and reference (R) electrodes and potentiometer.

where E° is a constant (called the standard potential) for the particular cell at a standard temperature of 25°C and is dependent upon the type and construction of the measuring and reference electrodes, R is the gas constant, T is the absolute temperature, F is the Faraday constant, a_i is the activity of the ion being measured. The integer, " n ", is related to the number of electrons gained or lost in the electrode reaction and therefore has a sign associated with it. In many cases, n may simply be described as the valence of the ion being measured.

The most widely used ion-selective measuring electrode is the glass electrode for the determination of pH. Recalling that pH may be defined as

$$pH = -\log a_{H^+} \quad (3)$$

the Nernst equation (eqn. (2)) may be simply expressed in millivolts, mV, at 25°C as

$$E = E^\circ - 59.16 \text{ pH} \quad (4)$$

Fluoride Electrode

For the fluoride ion-selective electrode, which is the subject of this paper and is illustrated in Figure 2, the

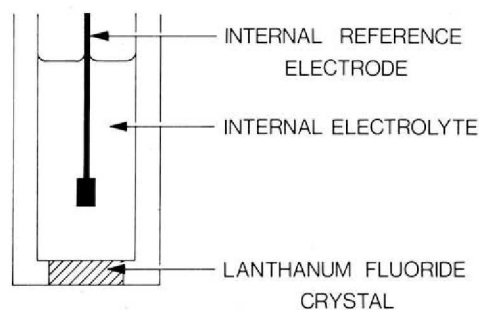


Figure 2. Fluoride ion-selective electrode showing lanthanum fluoride membrane and internal electrode construction.

Nernst equation may be expressed, in mV at 25°C, as

$$E = E^\circ - 59.16 \log a_{F^-} \quad (5)$$

The construction of the fluoride ion sensitive electrode, Figure 2, is seen to consist of a fluoride ion-sensitive membrane sealed over the end of an inert and usually opaque plastic tube which contains an internal electrode and filling solution. The membrane consists of a single crystal of a rare earth fluoride, such as lanthanum fluoride, doped with a divalent ion such as Eu^{2+} (2). The internal electrode would be a silver-silver chloride electrode immersed in a sealed internal filling solution containing both chloride and fluoride ions.

Activity and Concentration

Analytical composition information may be desired either in terms of the ionic activity, a_i , of eqn. (2) or in terms of the analytical concentration, C_i , as determined by many classically used analytical chemistry procedures. Even though electrodes and chemical potentiometry inherently yield information concerning activity, either activity or concentration results may be obtained from properly planned and calibrated ion-selective measurements. The relationship between activity and concentration is given by

$$a_i = \gamma_i C_i \quad (6)$$

where the single ion activity coefficient, γ_i , may be derived both theoretically and empirically. In dilute solutions, γ_i is frequently close to unity thus leading to the approximation from eqn. (6) that activity and concentration may be used interchangeably. In the chemical solutions encountered in most analytical problems, γ_i differs significantly from unity. It is principally a function of the ionic strength of the solution, I

$$I = (1/2) \sum_i C_i z_i^2 \quad (7)$$

where z_i is the charge on an ion.

Correlation of the single ion activity coefficient with the ionic strength of a solution has been provided by the Debye-Hückel equation applicable to dilute solutions

$$-\log \gamma_i = \frac{A z_i^2 \sqrt{I}}{1 + B \sqrt{I}} \quad (8)$$

where A and B are constants.

Tabulated data for estimated single ion and mean ion activity coefficients in solutions of various ionic strengths are available (7).

Free and Total Ion Concentration

Another factor, in addition to the activity coefficient, which may make the observed ion activity less than the total ion concentration, is the tendency for ions in solution to associate with other ions to form undissociated molecules. Examples of this are the formation of weak acids, weak bases, insoluble precipitates, and complex molecules or ions. For example, hydrofluoric acid, HF , is a weak acid and is slightly dissociated



and obeys the following equilibrium expression

$$K_a = \frac{a_{\text{H}^+} a_{\text{F}^-}}{a_{\text{HF}}} \quad (10)$$

where K_a is the dissociation constant for hydrofluoric acid.

Using the activity coefficient concept introduced in eqn. (6), the equilibrium expressions may be written in terms

of the concentrations and activity coefficients

$$K_a = \frac{a_{\text{H}^+} \gamma_{\text{F}^-} C_{\text{F}^-}}{\gamma_{\text{HF}} C_{\text{HF}}} \quad (11)$$

and solved for the concentration of the fluoride ion, C_{F^-}

$$C_{\text{F}^-} = \frac{a_{\text{F}^-}}{\gamma_{\text{F}^-}} = \left(\frac{1}{a_{\text{H}^+}} \right) \left(\frac{\gamma_{\text{HF}}}{\gamma_{\text{F}^-}} \right) (C_{\text{HF}})(K_a) \quad (12)$$

Equation (12) teaches that the fluoride ion concentration may be interpreted from measurements of fluoride ion activity if the pH and the activity coefficients are adjusted to optimum and constant values.

High Ionic Strength Medium

A concept called TISAB (Total Ionic Strength Adjustment Buffer) has been introduced (3a) precisely for the purpose of adjusting the conditions of fluoride analysis, as defined in eqn. (12) so that fluoride ion concentration may be deduced from measurement of fluoride ion activity. The composition of TISAB is not critical when the same solution is used for standardization and unknowns. A typical composition is given in Table 1.

Table 1. Composition of "TISAB," a High Ionic Strength Buffered Complexing Medium for Measuring Fluoride ion Concentration (3)

Sodium chloride	1.0 M
Acetate acid	0.25 M
Sodium acetate	0.75 M
Sodium citrate	0.001 M
pH	5.0
Ionic strength	1.75 M

In use, equal volumes of the sample and TISAB are mixed thus fixing the ionic strength high enough to make the activity coefficients of unknowns and standards virtually identical. The optimum pH range for the fluoride electrode is at pH 5 and this is provided by the sodium acetate-acetic acid buffer. Some citrate ion is added to preferentially complex metal ions such as iron and aluminum and ensure that the fluoride ion is displaced into the solution as "free" fluoride.

An improved version of the TISAB solution, sometimes known as "TISAB II," uses a more effective complexing agent, CDTA, (1,2-cyclohexylene dinitrilo) tetraacetic acid, and its formula has been described (3b). Recently an eight-fold concentrate of this latter TISAB, now called "TISAB III," has been made available (3c) and has been used satisfactorily in one of the analyses reported in Table 4, as indicated. TISAB III is more sensitive and economical to use since only one volume of TISAB III is added to nine volumes of the sample as opposed to the equivolume requirements of TISAB's I and II.

Accuracy

The accuracy for the analysis of fluoride in toothpaste, as in all analytical procedures, is a composite of all contributing variables. The usual analytical chemistry procedural errors of weighing, volumetric measurements, purity of reagents, and so on will not be considered here. However, it is instructive to mention possible sources of error in ion-selective electrode measurements. These include the measuring electrode, the reference electrode and its liquid-junction potential, the potentiometer, temperature, solution errors, and the Nernst equation relationship.

The relationship between overall emf errors, ΔE , and the activity of the fluoride ion (or concentration, if activity coefficients are assumed to be unity for the sake of mathematical simplicity) may be derived from the Nernst eqn. (2) by taking the derivative with respect to concentration

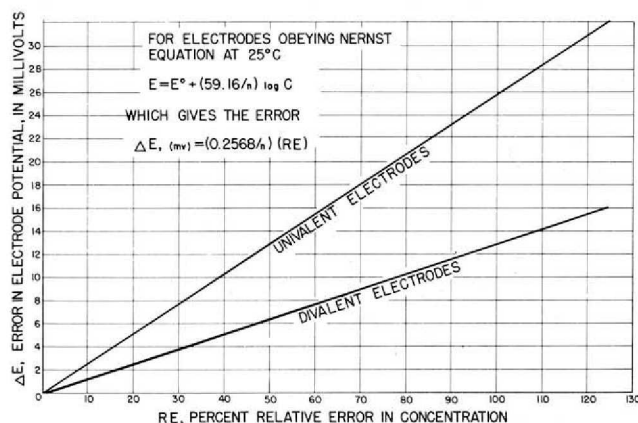


Figure 3. Theoretical error in potential as a function of relative error in concentration for potentiometric cells obeying Nernst equation.

$$dE = (59.16/2.303)(dC/C) \quad (\text{mV at } 25^\circ\text{C}) \quad (13)$$

and if the percent relative error in concentration, RE , is defined as $100\Delta C/C$, then

$$\Delta E = (0.2568/n)(RE) \quad (14)$$

A plot of eqn. (14) is given in Figure 3. The relative error in concentration is dependent only on the error in the emf and is independent of the concentration range and of the size of the sample. For an electrode system responding to the univalent fluoride anion, an overall error of 1 mV corresponds to 3.9% relative error in the fluoride ion concentration. Commercially available pH-millivolt meters are available with measuring accuracy of ± 0.1 mV. Used in conjunction with good quality measuring and reference electrodes and temperature control within $\pm 1^\circ\text{C}$, experimental errors may be held within a few tenths of a millivolt.

Fluoride in Toothpaste

Shane and Miele (8) have reviewed some of the difficulties of the earlier methods of analysis including the distillation separation step and the determination of fluoride by spectrophotometric methods. These authors also report a direct potentiometric method for determination of fluoride ion in toothpaste using a fluoride ion electrode. Their method involves preparation of a calibration curve by the standard addition of known fluoride salt to an unfluoridated toothpaste as a background media. Various limitations discussed by the authors include the possible oxidation of stannous fluoride and the interference of calcium both of which may be present in fluoridated toothpaste. There is also no assurance that the standards and the unknowns have the same ionic strength or that the unknowns are free from other ions which may prevent the fluoride from being completely available in the ionic form in solution.

Bushee, Grissom, and Smith (9) have described a method for free fluoride determination in toothpaste and other dental products. Their procedure, by not utilizing complexing agents and constant ionic medium, was intended to measure free fluoride rather than total fluoride. They found up to 96% loss of free fluoride in toothpastes within four months.

The use of TISAB in the method described below demonstrates a procedure that appears to be applicable to the determination of total fluoride in all toothpastes. The form in which the fluoride is added to the toothpaste need not be known. Interference from alkaline toothpaste or ions which complex or precipitate fluoride is eliminated.

Experimental

Reagents

Total ionic strength adjustment buffer ("TISAB"—See Table 1 and associated comments).

Standard Fluoride Solutions

A stock solution of 1000 mg F/l is prepared from reagent grade sodium fluoride which has been dried for 2 hr at 110°C . Calibration solutions containing 1.00 mg F/l and 10.00 mg F/l each in a 1:1 solution of TISAB and water are prepared by dilution from the stock solution and stored in plastic bottles. These solutions are stable for several months.

Apparatus

The fluoride ion activity electrode (Orion Model 94-09) was used with an Orion Model 404 Specific Ion Meter or a Corning Model 12 pH Meter each of which have logarithmic scales permitting direct concentration readings. Other expanded scale pH-millivoltmeters, such as the Orion Model 801, have also been used. A sleeve type reference electrode, such as Orion Model 94-01, was used as was a pressurized ceramic tip reference electrode. It should be noted that because of the suspended matter present during the measurements, the reference electrode should have a readily renewable junction interface and this should be cleaned for each series of measurements.

Procedure

A weighed sample of toothpaste of approximately 200 mg is placed in a 250-ml beaker containing 50 ml of TISAB. The mixture is then boiled for 2 min. After cooling, the solution is quantitatively transferred to a 100-ml volumetric flask and diluted to the mark with distilled water.

The measuring system, consisting of the fluoride and reference electrodes and the specific ion meter, is standardized with the 10 mg F/l standard. Using the "calibrate" or "standardize" control, the highest point on the logarithmic scaled dial becomes direct reading as "1.00 mg F/100 ml." The measuring system should be verified with the 1 mg F/l standard which should be directly read as " 0.100 ± 0.005 mg F/100 ml." The samples are then measured and directly recorded as "mg F/100 ml." The electrodes are rinsed with distilled water and dried with a tissue after each measurement. After flushing the reference electrode tip, one of the standards is rechecked immediately after each series of measurements and should be verified within $\pm 5\%$ relative error.

Alternatively, depending on the measuring instrument used, a calibration curve may be prepared by plotting the observed emf in mV versus concentration of fluoride in mg/l on two or three cycle semi-logarithmic paper.

Calculations

The fluoride content may be calculated directly from the observed Specific Ion Meter or calibration curve reading, M , in mg F/100 ml and the sample weight, S , in milligrams. If the fluoride is known to have been added as sodium fluoride, NaF, or stannous fluoride, SnF_2 , then these may also be calculated. The following relations hold

$$\% \text{ F} = (M/S)100 \quad (15)$$

$$\% \text{ NaF} = (M/S)221.0 \quad (16)$$

$$\% \text{ SnF}_2 = (M/S)412.4 \quad (17)$$

Results and Discussion

Toothpaste is a complex mixture with a typical formulation shown in Table 2. (This brand was selected because it contains added fluoride, as stannous fluoride, and its

Table 2. Composition of Brand "J" Toothpaste (10)

Constituent	Percentage
Calcium pyrophosphate	39.00
Water	24.97
Sorbitol (70% solution)	20.00
Glycerin	10.00
Miscellaneous formulating agents	4.63
Stannous pyrophosphate	1.00
Stannous fluoride	0.40

quantitative composition has been documented in the literature (10.) By adding a large amount of the TISAB buffer compared to the toothpaste, all toothpastes may be made to fit the same fluoride calibration curve since the pH is adjusted to five and the ionic strength is essentially constant. By keeping the total fluoride concentration very low, below 10 mg F/l, there is little danger of losing fluoride by association or formation of insoluble fluorides. Most fluorides are virtually 100% dissociated or soluble at this level. Those that are not, such as iron or aluminum fluorides, will have their metal nucleus strongly complexed by the added citrate thus freeing the fluoride ions. In the presence of a large excess of TISAB, the fluoride ion electrode truly becomes a specific ion electrode for its only known interference, hydroxide ion (2), is incompatible with the media.

The toothpaste listed in Table 2 with its known 0.4% SnF₂ content was analyzed four times in succession as shown in Table 3. The expected value of 0.40% SnF₂ was obtained with a relative standard deviation of 2% which is well within the expected accuracy of this direct potentiometric method of analysis.

Ten other brands of toothpaste were analyzed for their fluoride content by this method as shown in Table 4. These toothpastes could be classified into three groups—nonfluoridated, fluoridated with sodium fluoride, and fluoridated with stannous fluoride—but there was no independent indication of their quantitative composition. Five of these samples which were nonfluoridated all showed 0.002% fluoride. Although small, this value was still above the lower limit of detectability of fluoride in toothpaste which is about 10⁻⁴%. In all probability, the 0.002% is the naturally occurring fluoride impurity level in the components of the toothpaste.

Three of the samples of Table 4 were identified on their packaging as containing fluoride added as sodium fluoride. Three other samples were marked as having had stannous fluoride added. Except for brand "F", which analyzed low in fluoride, all of this group had a fluoride content between 0.075 and 0.1% and were analyzed reproducibly and rapidly. It should be emphasized, however, that the procedures reported in this paper are not as refined as those used to maintain quality control in at least some of the laboratories that manufacture such toothpastes. It should be emphasized also that the total fluoride content is but one of many factors contributing to the clinical evaluation of dentifrices and no judgment as to the efficacy of dentifrices should be implied solely on the basis of the total fluoride analysis.

Appendix: Questions for Discussion, Investigation, or Thought

Fluoride may be determined in water supplies by using a 50-ml water sample in place of the toothpaste sample. Derive an equation for the fluoride content of water in the units of mg F/l (these units are sometimes called "parts per million") in terms of the meter reading *M*. What is the typical fluoride content of natural water in your locality?

Describe one of the accepted APHA (American Public Health Association) standard methods for the determination of fluoride in public water supplies prior to the introduction of the fluoride ion electrode (11).

Fluoridation of public water supplies as a means of substantially improving dental health of children is now required by many states and countries. What are the requirements of the U.S. Public Health Service for the fluoride content of the fluoridated water supplies? How firmly founded in scientific fact is this requirement (12)?

How much error (quantitative estimate) is expected in a typical determination of the stannous fluoride content in toothpaste at the 0.4% level if the weighing error in the 200-mg sample is es-

Table 3. Determination of Fluoride in Brand "J" Toothpaste

Sample Wt (mg)	Specific Ion Meter Reading (mg F/100 ml)	%F	%SnF ₂
174.8	0.166	0.095	0.392
97.1	0.097	0.100	0.412
216.7	0.206	0.095	0.392
98.7	0.096	0.097	0.401
	Average	0.097	0.399
	Standard Deviation	±0.002	±0.009

Table 4. Determination of Fluoride in Various Brands of Toothpaste

Brand	Sample Wt (mg)	Specific Ion Meter Reading (mg F/100 ml)	%F	%NaF	%SnF ₂
A ^a	227.1	0.005	0.002		
	253.8	0.003	0.001		
B ^a	168.7	0.003	0.002		
	158.4	0.002	0.001		
C ^a	212.9	0.005	0.002		
	194.1	0.005	0.003		
D ^a	187.3	0.004	0.002		
	193.8	0.006	0.003		
E ^a	157.4	0.005	0.003		
	161.1	0.005	0.003		
F ^b	211.0	0.020	0.0095	0.021	
	244.6	0.023	0.0094	0.021	
G ^b	191.8	0.150	0.078	0.173	
	242.6	0.188	0.077	0.171	
H ^c	173.7	0.160	0.092		0.380
	190.7	0.162	0.085		0.350
I ^c	230.6	0.180	0.078		0.322
	180.0	0.144	0.080		0.330
J ^c	(See Table 3)		0.097		0.399
K ^d	203.7	0.206	0.101	0.223	
	210.3	0.195	0.093	0.205	

^a Nonfluoridated.

^b Fluoridated with sodium fluoride.

^c Fluoridated with stannous fluoride.

^d Fluoridated with sodium fluoride; analyzed with TISAB III (see text).

timated to be 1 mg, the error in the 100-ml volumetric flask is 0.5 ml, and the emf error totals 0.6 mV?

Derive an equation for the calculation of fluoride content based directly on the emf reading, *E* in mV, rather than indirectly on a meter or calibration curve reading.

Ion-selective electrodes are now grouped into several categories—glass, solid state, liquid ion-exchange, gas and enzyme electrodes. Give examples and briefly discuss the construction and theory of each of these classes.

How would temperature affect analyses made by potentiometry based on the Nernst equation?

Describe the pro's and con's of direct potentiometry versus potentiometric titration as an analytical technique.

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