Novel Potentiometric Sensors Based on Calixarenes

by

Aodhmar M. Cadogan B Sc

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Aodhmar Cadogan

Aodhmar M. Cadogan

Dermot Diamond

Dr. Dermot Diamond

For my parents
Thomas and Maureen

and to the memory of
a friend and colleague
Francis Regan

"The Universe is full of magical things just waiting for our wits to grow sharper"

Eden Phillpots

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Abstract

This thesis represents a study of the performance of potentiometric ion sensors incorporating modified calixarene compounds as the ionophores Three different groups of modified calixarenes were studied, namely tetrameric, hexameric and oxa calixarenes and formed the basis of Na$^+$, Cs$^+$ and K$^+$ sensors respectively

Tetrameric calix[4]arenes containing ketone functionalities methyl ketone (If), *t*-butyl ketone (Ig) and adamantyl ketone (Ih) and ester functionalities methyl ester (Ic), ethyl ester (Id) and *n*-butyl ester (Ie) were incorporated into mini electrode and macro electrode sensors with a conventional liquid filling solution A further two derivatives containing the monoacid trimethylester (Ij) and the monoacid triethylester (Ik) were also assessed for their ionophoric potential and compared to their tetra methylester and tetra ethylester counterparts All of the ester compounds and the methyl ketone derivative were found to exhibit excellent selectivities for sodium ions over the alkali and alkaline earth metals An effort was made throughout the research to identify the functionalities in these new class of complexing ligands which are most likely to induce and enhance selective ion-binding

The caesium selective electrodes were based on hexameric calix[6]arenes ligands (IIa) and (IIb) Both ligands contained an ethylester moiety in the substituted lower rim position with an unsubstituted (IIa) and *p-t*-butyl substituted (IIb) para position

The potassium selective electrodes are based on some monooxa and dioxa calix[4]arenes and on the ethylester *p-t*-butyl calix[5]arene The oxa calixarenes contain an additional methoxy spacer unit in the macrocyclic ring and hence have cavity sizes intermediate between that of the tetrameric and hexameric structures The electrodes based on these ligands showed varying degrees of selectivity and stability but are unlikely to provide viable individual ion sensors for potassium

The final section of the thesis is devoted to solid state sensors Electrodes were constructed by contacting the PVC liquid membrane either directly onto a platinum substrate or indirectly where the contact between the PVC and the platinum was provided by a layer of conducting polymer polypyrrole (PPy) The calix[4]arene involved was the tetrameric ethylester derivative (Id) Good functioning electrodes were produced and the PPy layer was found to enhance the stability of the contact

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Chapter 1

Theory

1 1 Galvanic cells

The simplest electrochemical cell consists of two electrical conductors immersed in an electrolyte solution In a galvanic cell, electrochemical reactions occur spontaneously at the electrolyte/electrode interfaces when the two electrodes are connected by a conductor Potentiometry is the measurement of the electromotive force which arises when the reversible electrode processes have reached equilibrium and there is no current flow through the cell A typical galvanic cell is the Daniell cell[1] which consists of two metal rods, copper and zinc, in contact with solutions of their electrolyte salts as shown in fig 1 1 The porous barrier allows a flow of ions within and between the two phases without bulk mixing of the phases When the two electrodes are immersed the following cell reaction proceeds spontaneously with the electrons flowing from the negative zinc electrode to the positive copper electrode

$$Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s) \qquad (1\ 1)$$

The cell notation to describe the electrochemical reactions occurring at the two half cells is

$$-\quad Zn(s)\,|\,Zn^{2+}(aq)\,||\,Cu^{2+}(aq)\,|\,Cu(s)\quad +$$

By convention, the single or double vertical bars represent a phase boundary, the single bar a solid/liquid boundary and the double vertical bar a salt bridge i e a liquid/liquid interface The cell with the more negative standard potential is written on the left hand side The overall cell potential or electromotive force (emf) is then given by

$$E_{cell} = E_{right} - E_{left} \qquad (1\ 2)$$

where E_{right} is the standard potential at the right hand electrode and E_{left} is the standard potential of the left hand electrode A list of standard electrode potentials can be found in ref 2

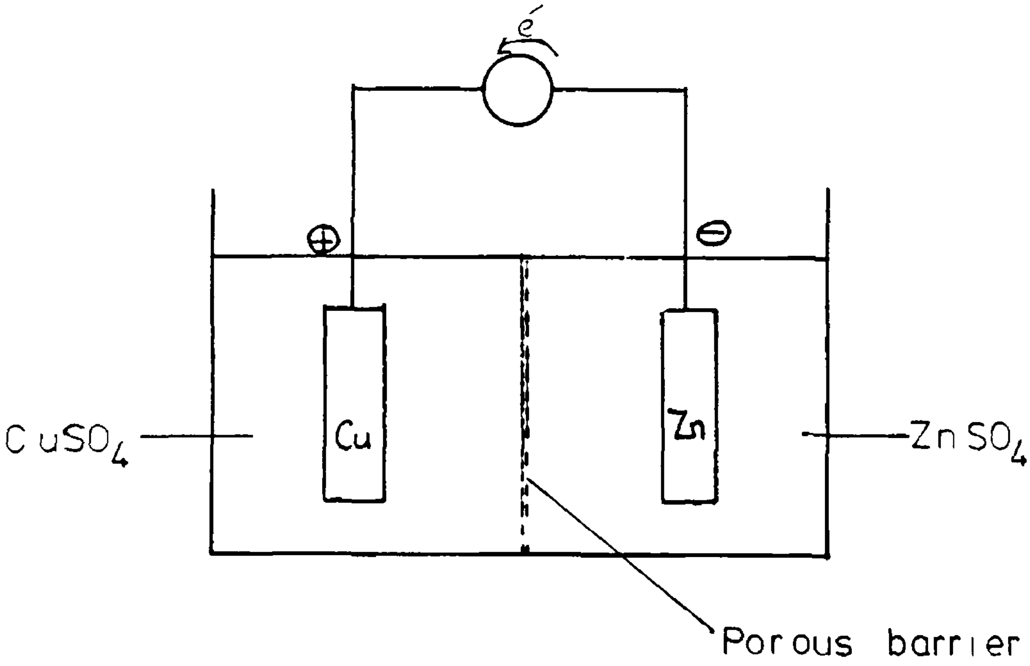


Figure 1 1 Schematic diagram of the Daniell cell

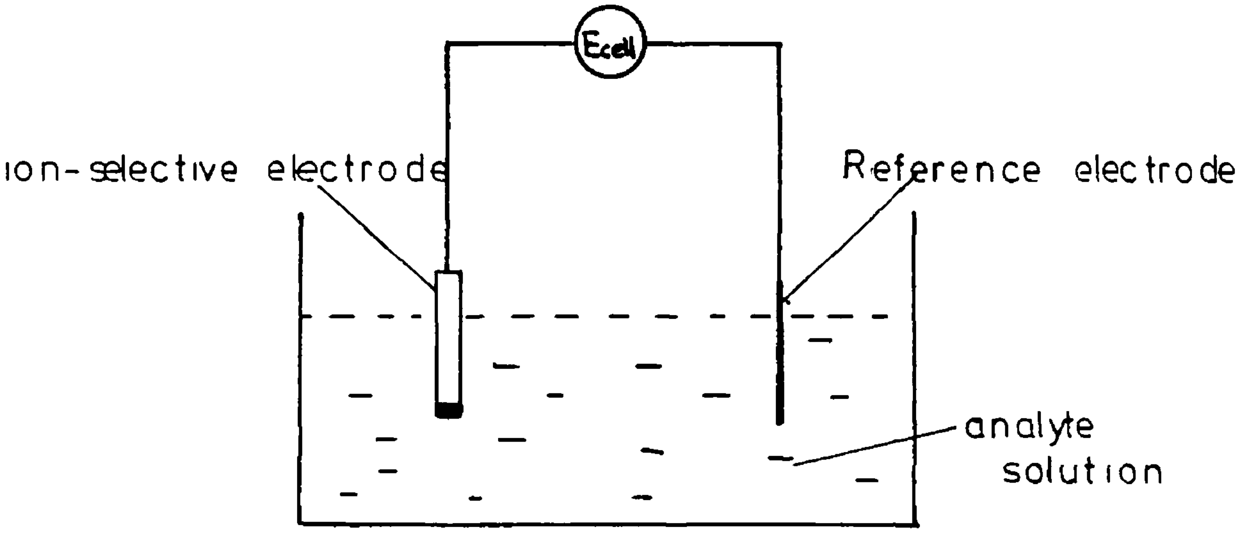


Figure 1.2. Schematic diagram of a simple potentiometric cell.

1 2 Analytical potentiometry

The object of analytical potentiometry is to operate the cell under conditions such that the spontaneous processes are maintained at dynamic equilibrium and zero current conditions are in operation Ideally changes in the measured cell potential can be related or interpreted in terms of changes in the concentration of one of the components present in the cell solution A typical potentiometric cell without a liquid junction is shown in fig 1 2 The cell potential is given by

$$E_{cell} = E_{ISE} - E_{ref} \qquad (1\ 3)$$

The potential of an ideally performing electrode is given by the well known Nernst equation

$$E_{ISE} = E^{o} + (RT/z_iF) \ln a_i \qquad (1\ 4)$$

where i is the analyte of interest, of charge z_i and activity a_i , R, T and F are the gas constant, the absolute temperature and the Faraday constant respectively and E^o is the standard electrode potential The type of reference electrode used in a simple configuration such as illustrated in fig 1 2 could be a silver wire chemically or electrochemically coated with AgCl The half-cell reaction and potential against the hydrogen electrode are

$$Ag(s), AgCl(s) | Cl^-$$

$$AgCl(s) + e \rightleftharpoons Ag(s) + Cl^-(aq) \quad E^o = +0\ 222V \qquad (1\ 5)$$

If the reference potential is constant i e independent of the sample composition then we can combine equation (1 3) and (1 4) above and write

$$E_{cell} = \text{constant} + (RT/z_iF) \ln a_i \qquad (1\ 6)$$

Hence the whole electrochemical cell responds in a Nernstian manner to changes in a_i The generated cell potential is measured by a high impedance voltmeter connected across the terminals of the two electrodes This could be a pH meter where the input impedance is typically ($>10^{12}$ Ω) This high impedance ensures that the current drawn from the cell by the measuring circuit is virtually zero The E_{cell} values can then be read from the meter display in millivolts (mV) Impedance values for ISE's typically range from 10^8 - 10^9 Ω for glass to 10^6 - 10^7 Ω for PVC membrane electrodes[3]

1 3 Liquid junction potential

The potential of the reference electrode should be constant irrespective of its environment But simple Ag/AgCl contacts, such as the one used above are often affected by the sample composition and hence must be physically separated from the solution whilst maintaining electrical conductivity via a salt bridge Such a junction between the sample and the bridge electrolyte creates its own potential, as one electrolyte diffuses into the other The differences in mobilities of the positively and negatively charged ions in the bridge electrolyte causes a charge separation, for example if the positively charged ions of the electrolyte migrate faster they form a band or group of positively charged species separated from the negatively charged counterions by a very small but finite distance which is responsible for the charge separation The size of the generated junction potential depends on the type of bridge ions, the composition of the sample solution, the geometry of the bridge and the temperature It is important that the liquid junction potential (E_j) is kept as small as possible or at least constant over the period of use As the mobility of K^+ and Cl^- ions are similar, saturated KCl is often chosen for the preparation of the salt bridge[4]

1 4 Membranes and membrane potentials

Membranes are fundamental to the transport of ions and molecules in highly complex living systems like human cells or in simpler systems like the membranes in electrochemical sensors The membrane separates two (usually liquid) phases in such a way that material transport can occur across the membrane Material transport can take the form of neutral or charged complex species or simple ions and electrons Sensing sites embedded in the membrane (they can be mobile or fixed) facilitate the selective entrapment of the required ion into the membrane In potentiometry the species transported are in general ions and an electrode incorporating such a permselective membrane is then called an ion-selective electrode (ISE) The selective transport of one ion into a membrane and the rejection of the counterion leads to the generation of charge separation and a potential develops at the membrane/electrolyte interface

The membrane potential has three contributions[5-7] As there are two interfaces in the ion sensing membrane of an ISE, two boundary potentials arise, (E_B') at the internal boundary and (E_B'') at the sample boundary (fig 1 3) A third potential, the diffusion potential (E_D) arises from the spontaneous transport of charged species across the membrane so that a potential gradient is formed Hence the full membrane potential is then given by

$$E_M = E_B'' - E_B' + E_D \qquad (1\ 7)$$

1 4 1 Boundary potential

The phase boundary potential arises from the non-uniform distribution of electrically charged species between the two phases Both chemical and electrical potential contributions must be taken into account in descriptions of ion transport or ion distribution For an ion i of charge z_i exchanging reversibly across an aquo-liquid membrane boundary, the work done in establishing equilibrium can be described by

$$-\Delta G = z_i F E_B \qquad (1\ 8)$$

where ΔG is the change in Gibbs free energy, F is the Faraday constant and E_B is the electrical potential established over the boundary The decrease in Gibbs free energy is given by the difference in the partial molar Gibbs free energy (μ) for the ion i in the membrane(m) and the aqueous(aq) phases

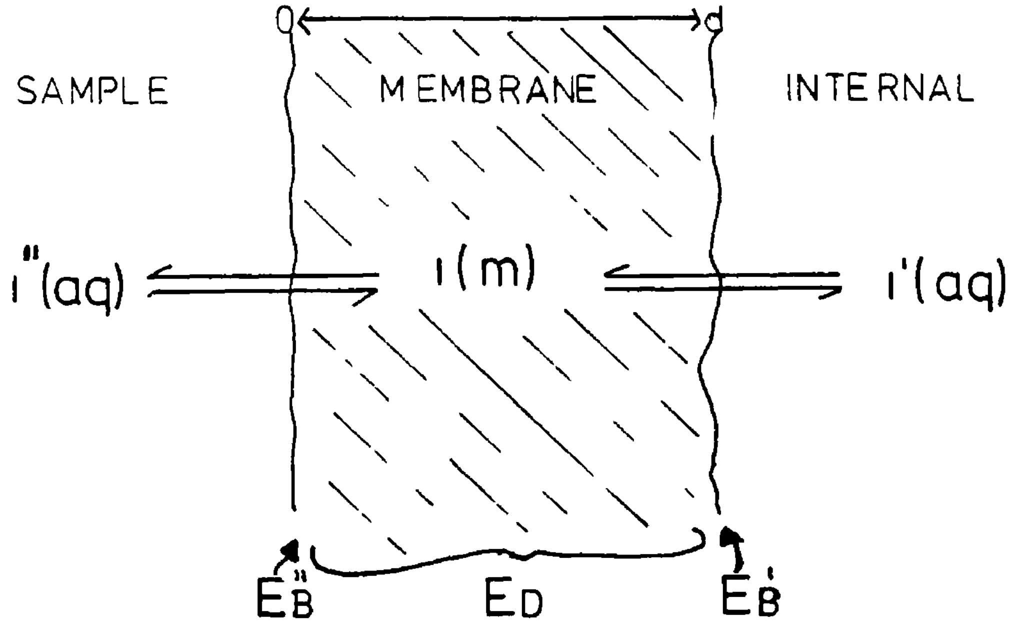


Figure 1.3. Boundary and diffusion potentials of ion-selective liquid membranes.

$$-\Delta G = \mu_{i(aq)} - \mu_{i(m)} \qquad (1\ 9)$$

While measurements are usually carried out under a wide variety of conditions, these are conventionally related to the work done to bring about the same charge under standard conditions by

$$-\Delta G^{o} = \mu^{o}_{i(aq)} - \mu^{o}_{i(m)} = z_i F E^{o}_{B} \qquad (1\ 10)$$

and the standard state ^{o} is related to other states by

$$\mu_i = \mu^{o}_{i} + RT\ln a_i \qquad (1\ 11)$$

where R, T and a_i are the gas constant , the absolute temperature and the activity of ion (i) in the particular phase respectively So substituting into equation (1 9) above

$$-\Delta G = \mu^{o}_{i(aq)} - \mu^{o}_{i(m)} + RT\ln\left[\frac{a_{i(aq)}}{a_{i(m)}}\right] \qquad (1\ 12)$$

The electrical potential at the interface is thus

$$E_B = \left[\frac{\mu^{o}_{i(aq)} - \mu^{o}_{i(m)}}{z_i F}\right] + \frac{RT}{z_i F}\ln\left[\frac{a_{i(aq)}}{a_{i(m)}}\right] \qquad (1\ 13)$$

If E^{o}_{B} the standard potential = $[\mu^{o}_{i(aq)} - \mu^{o}_{i(m)}]/z_i F$ Then the boundary potential at any particular membrane interface is

$$E_B = E^{o}_{B} + \frac{RT}{z_i F}\ln\left[\frac{a_{i(aq)}}{a_{i(m)}}\right] \qquad (1\ 14)$$

As there are two membrane interfaces, (') the internal interface and ('') the external interface Two equations can be written for the boundary potentials $E_B^{'}$ and $E_B^{''}$ from (1 14) above

$$E_B^{'} = E_B^{o'} + \frac{RT}{z_iF} \ln \left[\frac{a^{'}_{i(aq)}}{a^{'}_{i(m)}}\right] \tag{1 15}$$

$$E_B^{''} = E_B^{o''} + \frac{RT}{z_iF} \ln \left[\frac{a^{''}_{i(aq)}}{a^{''}_{i(m)}}\right] \tag{1 16}$$

Combining (1 15) and (1 16) the net boundary potential across the membrane is

$$E_B^{''} - E_B^{'} = E_B^{o''} - E_B^{o'} + \frac{RT}{z_iF} \ln \left[\frac{a^{''}_{i(aq)}\, a^{'}_{i(m)}}{a^{''}_{i(m)}\, a^{'}_{i(aq)}}\right] \tag{1 17}$$

Assuming the activity of the ion a_i is the same at both interfaces in the membrane i e $a^{'}_{i(m)} = a^{''}_{i(m)}$ then

$$E_B^{''} - E_B^{'} = E_B^{o''} - E_B^{o'} + \frac{RT}{z_iF} \ln \left[\frac{a^{''}_{i(aq)}}{a^{'}_{i(aq)}}\right] \tag{1 18}$$

1 4 2 Diffusion potential

Although the membrane is considered to be a uniform phase, the free energies of the membrane components undergo variation with time and this gives rise to diffusional fluxes of ions within the membrane Although more commonly used for the estimation of junction potentials, the Henderson approximation[5] can be used to describe the diffusion potential across the membrane This allows easy and rather close characterisation of the diffusion potential in terms of boundary concentrations and mobilities of diffusing ions

$$E_D = \frac{\Sigma z_i u_i a_i(o) - \Sigma z_i u_i a_i(d)}{\Sigma z^2_i u_i a_i(o) - \Sigma z^2_i u_i a_i(d)} \times \frac{2\ 303RT}{F} \times \log \frac{\Sigma z^2_i u_i a_i(o)}{\Sigma z^2_i u_i a_i(d)} \qquad (1\ 19)$$

Where x=0 for the sample boundary(''), x = d at the internal boundary(') and the thickness of the membrane is d The summation terms include contributions by all the ionic species (i) that are present within the membrane, the absolute value of the charge numbers z_i, mobilities u_i and activities a_i If we assume there is a negligible drop in primary ion activity across the membrane i e

$$a_{i(o)} \approx a_{i(d)} \qquad (1\ 20)$$

and that there is virtually no penetration of the membrane by interfering ions (j)

$$a_{j(o)} \approx a_{j(d)} \approx 0 \qquad (1\ 21)$$

then substitution into the Henderson equation leads to the approximation

$$E_D \approx 0 \qquad (1\ 22)$$

1 4 3 The complete membrane potential

Since E_D can be approximated to zero or is at least constant, variations in the overall membrane potential will be determined by the values of the boundary potentials As the internal electrolyte activity a'_i is constant, the overall membrane potential will be given by

$$E_M = E^o_M + (RT/z_iF)\ln(a''_i) \qquad (1\ 23)$$

where E^o_M is a standard membrane potential and includes contributions from E_D, $E^{o''}_B$ and $E^{'}_B$ Provided that the junction potential (E_{jn}) and the reference potential

(E_{ref}) remain constant the overall cell potential will depend on the activity of the primary ion a_i in solution and can be defined by

$$E_{cell} = \text{constant} + S\log a_i \qquad (1.24)$$

For a ten-fold change in primary ion activity (a_i) the ideal slope (S) is $2.303RT/z_iF$. This is 59.2 mV for a monovalent ion and 29.6 mV for a divalent ion at 25°C. A schematic diagram of an electrochemical cell is shown in fig. 1.4. The response function of an ISE is shown in fig. 1.5. The analytical useful range of these sensors is generally from 10^{-1}M to 10^{-5}M although some may be useful at even lower concentrations. The glass electrode (sensitive to H^+ ions) is perhaps the most well known and used potentiometric system. The advantages of a potentiometric measuring system are speed, sensitivity, cost, simplicity, reliability and the non-destructive nature of the process. ISE's are finding many applications in biological and environmental areas and particularly in clinical chemistry where a large number of samples and the need for a rapid method of analysis, rule out many slower, more complex methods.

1.5 The Nikolskii equation

Thus far in our discussion we have assumed negligible influence of other ions (j) on the electrode response other than the primary ion of interest (i) i.e. ideal selectivity. In practice the response will be affected by the presence of other ions, particularly when the analyte concentration is low. An extension of the Nernst equation called the Nikolskii or Nikolskii-Eisenman equation takes account of the additional contribution of interfering ions a_j of charge z_j on the response to the primary ion a_i of charge z_i[8].

$$E_{cell} = \text{constant} + RT/z_iF \ln\left[a_i + \Sigma K_{ij}^{pot}(a_j)^{\frac{zi}{zj}}\right] \qquad (1.25)$$

The parameter K_{ij}^{pot}, the selectivity coefficient, is a measure of the preference by the sensor for the primary ion (i) relative to the interfering ion (j). In an ideally

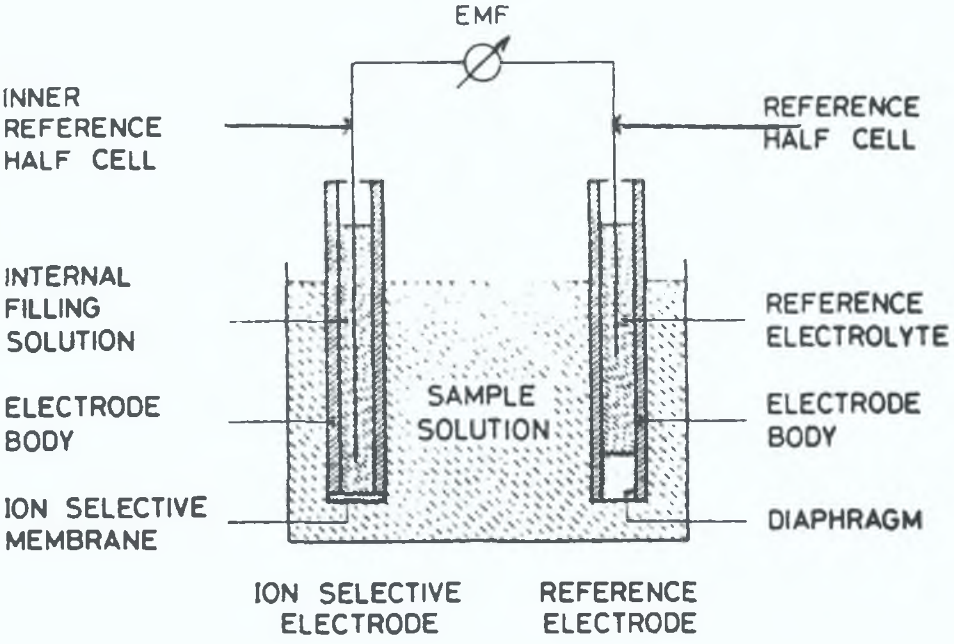


Figure 1.4. Schematic diagram of a membrane electrode measuring circuit and cell assembly.

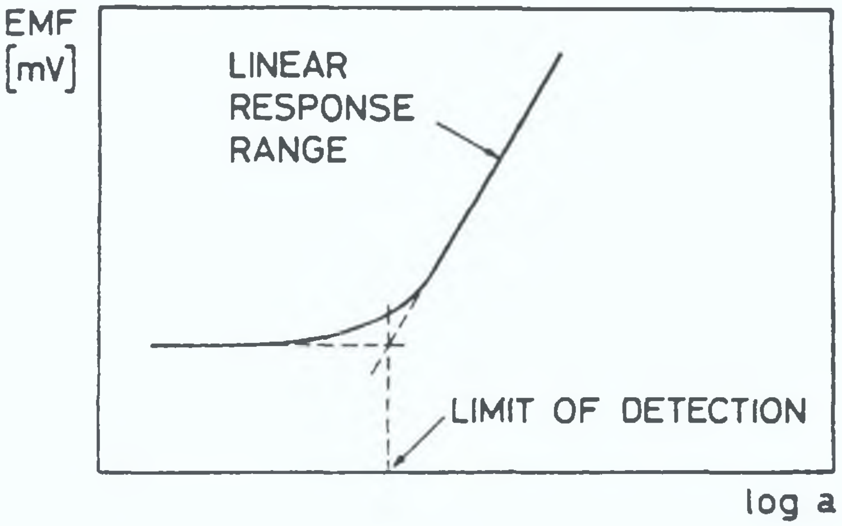


Figure 1.5. Schematic diagram of the response function of an ion selective electrode.

selective membrane electrode K_{ij}^{pot} should tend towards zero for all interfering ions and the equation reduces to the Nernstian form K_{ij}^{pot} is sometimes referred to as the selectivity constant which is misleading as strictly speaking it is not constant For a further discussion of the use of selectivity co-efficients see section 2 7

1 6 Reference electrodes

The potential of a reference electrode must remain constant during the calibration and subsequent use of the cell The international standard reference electrode is the Standard Hydrogen Electrode (SHE), the standard potential of which is defined arbitrarily to be zero at all temperatures and all other standard potentials are reported relative to it[9] However it is very cumbersome to operate and is seldom used in practice nowadays The most frequently used reference electrodes are the saturated calomel electrode (SCE) (mercury covered by calomel Hg_2Cl_2 paste) and the silver/ silver chloride electrode (Ag/AgCl) (silver covered by silverchloride)

The half reaction for the Ag/AgCl electrode is

$$AgCl_{(s)} + e \rightleftharpoons Ag_{(s)} + Cl^-_{(aq)} \qquad (1\ 26)$$

$$E_{Ag/AgCl} = E^o_{Ag/AgCl} + S \log a_{Cl} \qquad (1\ 27)$$

The silver/silver chloride electrode consists of silver covered with a layer of sparingly soluble silver chloride As long as the concentration of chloride in the surrounding electrolyte is high and constant the potential will remain constant In practice chloride concentrations well above 10^{-3}M are adopted KCl is often chosen as the electrolyte in reference electrodes in order to minimise the liquid junction potential as the mobilities of the Cl^- and K^+ ions are nearly equal Other reasonably suitable equitransferent salts are KNO_3, NH_4NO_3, RbCl or NH_4Cl[4]

The SCE is also based on the reversible solubility of chloride ion in the reaction

$$Hg_2Cl_{2(s)} + 2e \rightleftharpoons 2Hg_{(l)} + 2Cl \qquad (1\ 28)$$

$$E_{SCE} = E^o{}_{SCE} + S \log a_{Cl} \qquad (1\ 29)$$

In this case the surrounding electrolyte is usually 3 0 - 3 5M KCl

The internal bridging electrolyte provides a medium of fixed activity of chloride ion in order to maintain the electrode at a fixed potential It also provides a conducting pathway from the reference cell through the sample solution and thus to the indicator electrode Normally one electrolyte solution fulfils these two requirements but sometimes two bridging solutions are required - a double junction - in order to provide complete isolation of the reference cell from the external sample solution This may be necessary where leakage of the reference electrolyte has an adverse affect on the sample solution or the indicator electrode e g leakage of KCl may affect the sample solution in K^+ or Cl measurements or may cause precipitation in Ag^+ or Pb^{2+} measurements The magnitude of the liquid junction potential depends on the geometry of the interface and it is of great practical importance[10] A free diffusion junction such as a flowing junction gives a high stability and reproducibility and is most suitable for samples of high concentrations or complex matrices with a high protein content where the open nature of the junction prevents clogging For extremely dilute or low volume samples slower impeded flow type junctions are more stable such as a fibre wick or a ceramic frit For accurate work the composition of the standards must be carefully matched to that of the sample Failure to do so can result in fluctuations in the junction potentials on switching from standard to sample Temperature variations may also lead to large potential variations due to variations in the solubility of KCl at different temperatures Temperature changes will also affect the standard potentials which are different at different temperatures Many of the errors associated with potentiometric measurements are caused by insufficient attention to the preparation and maintenance of the reference electrodes rather a malfunction of the sensing electrode In view of the above discussion the importance of a well-functioning reference electrode cannot be over stressed and proper care and attention should always be addressed to reference electrode storage and use

1 7 Activity concentration relationships

The theoretical equations quoted so far have used activities rather than stoichiometric concentrations The activity (a_i) of an ion is not identical to its concentration (c_i), the two quantities are related by an activity coefficient (f_i)

$$a_i = f_i c_i \qquad (1\ 30)$$

as the concentration of a species tends to zero, the activity coefficient tends to unity and so the activity and concentration become identical at infinitely dilute solutions The main deviation occurs at high concentrations where ion-solvent interactions and electrostatic interactions prevent the ions from generating their full effect and thus decreases the activity of the solute Several equations have been proposed for the calculation of activity coefficients One of the simplest is the Davies model[11], for solutions of ionic strength less than 0 1M, and allows the calculation of activity coefficients from the ionic strength of the electrolyte ions

$$\log f_i = -Az_i^2 \left\{ \frac{I^{1/2}}{1+I^{1/2}} - 0\ 2I \right\} \qquad (1\ 31)$$

where A is a constant which depends on the temperature and the solvent (0 511 for water at 25°C) The ionic strength I is calculated by summing the concentration of each ion(c_i) multiplied by its valence(z_i) squared and dividing the summation by two

$$I = 0\ 5\ \Sigma\, c_i z_i^2 \qquad (1\ 32)$$

This equation is only suitable up to concentrations of around I = 0 1 For higher concentrations approaches such as that based on hydration theory must be adopted This is still a contentious issue (i e which model to adopt) as recent debate testifies [12-14]. However for the purposes of this research, the conventional ionic strength based approach has been used.

1.8 Temperature effects

Equations such as (1.23) contain a temperature variable and so temperature variations of the cell assembly will affect the overall emf response. The slope factor ($2.303RT/z_iF$) predicts a change in response slope of an electrode of up to 2 mV dec^{-1} for every 5°C rise in temperature. Unfortunately such simple equations do not describe the temperature variation completely as the standard electrode potential E^o and the ion activity a_i of the free determined ion in solution are also temperature dependent. As outlined already the reference electrode(SCE or Ag/AgCl) is particularly suceptible to changes in temperature due to solubility changes of the KCl. Temperature control may be achieved by the use of a thermostatically controlled bath with facilities to pump the water into the jacket surrounding the electrochemical cell.

1.9 Dynamic response characteristics

A very important characteristic of an ISE is the speed at which it follows variations in analyte concentration. Some electrodes respond slowly (minutes and hours) while others almost instantaneously (ms). If the time constant is 100 ms or less the response is said to be instantaneous. If the time constant runs to several thousands of seconds then the practical value of the electrode is limited.

The theoretical treatment of the response time is far from simple and extensive studies have been undertaken to formulate theories[15-18]. The different theories have been more or less successful in describing the variation in electrode potential $E(t)$ with time t after a step change in analyte solution activity from an initial value $a_{i(o)}$ to a final steady state value a_i.

when $t = 0$

$$E_{(o)} = E_i^o + S\log a_{i(o)} \qquad (1\ 33)$$

to a final value t = *

$$E_{(*)} = E_i^o + S\log a_i \qquad (1\ 34)$$

The particular theories differ widely in their description of intermediate values of potential $E_{(t)}$, depending on the model assumption made in respect to the rate determining process They focus on the various time dependent processes occurring at or in the membrane and the time constants associated with the processes One of the simplest theories was proposed by Shatkay[15] and it takes the form of a simple semi-empirical sum to represent the potential time response following a change of activity $a_{i(o)}$ to a_i

$$E_{(t)} \approx E_{(o)} + \sum_n \Delta En(1 - e^{-t/\tau}) \qquad (1\ 35)$$

where ΔEn is the contribution by the n^{th} process to the final emf change However some of the slower processes occurring in the membrane cannot be represented by this model adequately Morf and Simon[16] outlined four rate determining processes each one having an associated value of $E_{(t)}$ and time constant τ The time constant τ is normally defined as the time taken to reach 63% of $E_{(*)}$

1 The electrical circuit of the measuring cell

$$E_{(t)} \approx E^* - [E^* - E_{(o)}]e^{-t/\tau_1} \qquad (1\ 36)$$

In this case the time constant is

$$\tau_1 = RC \qquad (1\ 37)$$

where R is the internal resistance of the electrochemical cell and C is the total capacitance of the cell and amplifier input

2 Kinetics of ion-transfer reactions across the membrane sample boundary of the measuring cell

$$E_{(t)} = E^{*} + S\log\left[1 - \left(1 - \frac{a_{i(o)}}{a_i}\right) e^{-kt}\right] \qquad (1\ 38)$$

where k is the rate constant for the ion transfer process, $\tau_2 = k^{\ 1}$

3 Diffusion through the stagnant layer

Perhaps the most important rate determining step is the diffusion of sample ions through the un-stirred boundary layer adjacent to the membrane In this case

$$E_{(t)} = E^{*} + S\log\left[1 - \left(1 - \frac{a_{i(o)}}{a_i}\right) \frac{4}{\pi} e^{-t/\tau_3}\right] \qquad (1\ 39)$$

This time the rate constant(τ_3) depends on the thickness of the diffusion layer (δ) and the ionic diffusion coefficient (D)

$$\tau_3 = \frac{4\delta^2}{\pi^2 D} \approx \frac{\delta^2}{2D} \qquad (1\ 40)$$

This formulation has been applied to describe electrodes based on charged sites (as long as no interfering species are present), the sluggish response of glass electrodes, dynamic response responses of gas sensing electrodes and enzyme electrodes [16]

4 Diffusion within the ion-sensing membrane

This is determined by the dynamic behaviour of the membrane itself Some time-dependent variations in the membrane composition due to the presence of cations and anions (either as primary ions or interfering ions) in the membrane phase give rise to the potential time response

$$E_{(t)} = E^{*} + S\log\left[1 - \left(1 - \frac{a_{i(o)}}{a_i}\right) \frac{1}{(t/\tau_4)^{1/2} + 1}\right] \qquad (1\ 41)$$

with a time constant

$$\tau_4 = \frac{D'K^2\delta^2}{\pi D^2} \qquad (1\ 42)$$

This expression for $E_{(t)}$ is strikingly different as it contains a square root relationship and no exponential term The time constant contains the parameter δ and D as before but it is also depends on the salt distribution parameter K and the salt diffusion coefficient D'

5 Other factors such as inhomogenities in the membrane phase and changes in the liquid junction potential may have severe effects causing response delays, potential drifts or transient response phenomena

The limitations to response time caused by membrane resistance (1) some kinetic limitations (2) and some of the other factors (5) can be excluded for most analytical useful membranes Therefore the dynamic behaviour of an ion-sensor will tend to be dominated by the two diffusional processes (3) and (4) occurring adjacent to and in the membrane respectively Further developments of the diffusional theory have dealt in more detail with the salt diffusion and ionic partition in terms of flux equations [16 p 251] The following assumptions were drawn

1 9 1 Ion sensors based on mobile ionic sites

These include solid state, glass, classical ion-exchanger and neutral carrier membranes with incorporated anion exchange e g tetraphenylborate In the absence of interfering anions the ionic diffusion within the membrane becomes negligible and realistic results are obtained from a modified form of (1 39)

$$E_{(t)} = E^* + S\log\left[a_i - (a_i - a_{i(o)})\frac{4}{\pi}e^{-t/\tau_2}\right] \qquad (1\ 43)$$

$$\tau_3 = \frac{4\delta^2}{\pi^2 D} \approx \frac{\delta^2}{2D} \qquad (1\ 40)$$

In this case the dynamic response can be improved by the following modifications The thickness of the aqueous diffusion layer (δ) can be drastically reduced by stirring and by minimisation of the membrane surface by better design (fig 1 6) The rate of stirring should be high enough to produce adequate mixing and yet not so vigorous that it induces vortex effects One other major factor affecting the dynamic response of the membrane is the direction of the activity change in the sample solution The response time may be expected to increase considerably when changing from a high activity to a low activity solution as opposed to a change in the opposite direction (fig 1 7)

1 9 2 Ion sensors based on neutral carrier membranes (with no incorporated ion-exchangers)

If ionic diffusion into the membrane cannot be excluded (as in the case here) then the diffusion of ions within the membrane cannot be ignored, (4) above As the membrane internal steady state is attained more slowly compared to the external equilibration the response time will be expected to increase as it now depends on the slowest equilibration process (equations 1 41 and 1 42) The dynamic response will be more dependent on the membrane properties such as the extraction capacity and the resistance to diffusion In order to decrease the time constant the following membrane modifications should be adopted [16 p 259]

(a) Reduction of K the salt distribution parameter
The membrane solvent and matrix should be as non-polar as possible The concentration of the ion-selective ligand should be kept at a moderate concentration and the sample solution should contain no lipophilic anions
(b) Reduction of D' the ionic diffusion coefficient
Reducing diffusion (D') within the membrane by keeping the membrane viscosity high and reducing the permeability of the membrane for sample anions
(c) Reduction of the thickness of the stagnant layer δ by stirring or by using a flow through cell

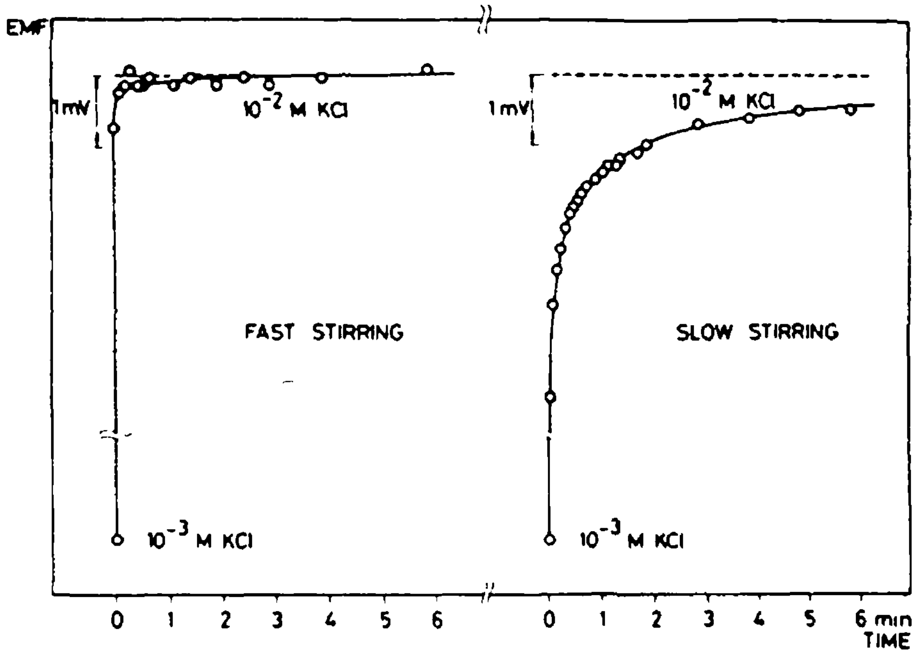


Figure 1 6 Effect of stirring on the response profile of a valinomycin based PVC membrane electrode following a sudden change in the concentration of the sample solution from 10^{-3}M KCl to 10^{-2}M KCl.

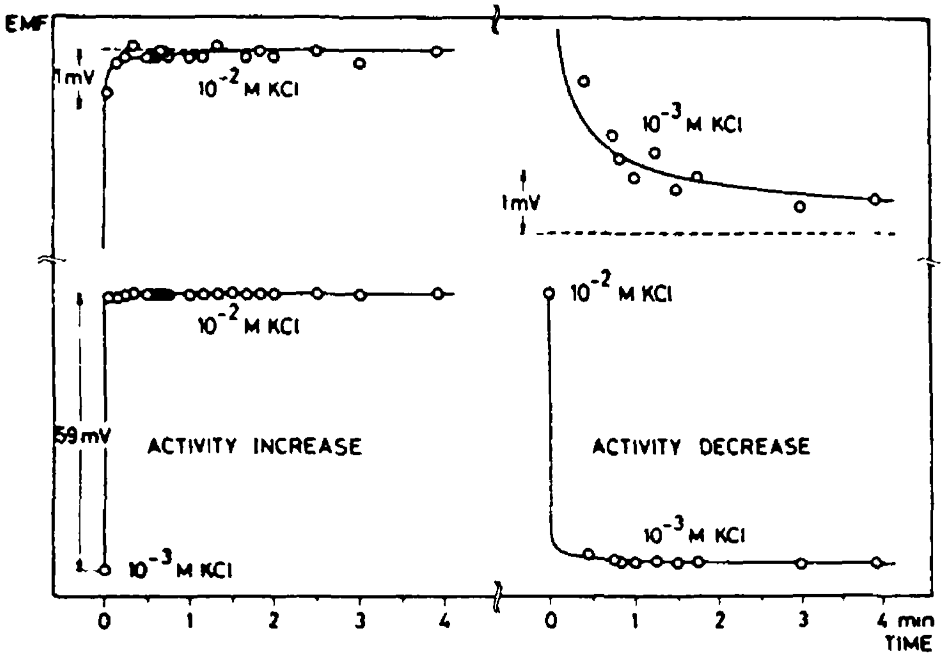


Figure 1 7 Effect of the direction of the sample concentration change on the response time of a valinomycin based PVC membrane electrode following a change 10^{-3}M KCl ->10^{-2}M KCl and 10^{-2}M->10^{-3}M KCl. Note slower response on going from the higher concentration to lower concentration.

It can be seen from the preceding discussion of the various theories that the definition of a universal theory for the dynamic response is difficult The speed of the response is not only dependent on the membrane type but also on the sample solution There is also some confusion over the definition of the final potential E* because the potential increases exponentially towards its final value after an activity step[19] IUPAC has recommended that response time should be defined as the time required to undergo 90% of its total change ($t_{90\%}$) However several different definitions t_α (α =50%, 90%, 95%, 99%) are still in use by some workers Ambiguities also arise due to differences in laboratory practices or procedures which are most troublesome to standardise e g

1 The level of activity being measured, the response is lower at lower activities

2 The rate of sample stirring, quoted values of "fast" of "slow" have great uncertainty

3 The membrane composition

4 The measuring circuit time-response characteristics which are dependent on the equipment available in a particular laboratory

1 10 Liquid membrane electrodes

The key to successful design of a potentiometric sensor is to select a membrane that exhibits a selective and reproducible change in the presence of the desired species Sensors are classified by the nature of the membrane and one of the largest groups of such sensors contain liquid membranes The membrane material can be a nonpolar liquid or polymer/liquid system with mobile ion-exchange sites that can move throughout the membrane but which are trapped within the boundaries of the membrane because of their lipophilic nature This generates a membrane potential via ion transfer from the aqueous to the membrane phase at the aquo/liquid boundary and forms the basis of the potentiometric measurement of ions adjacent to the liquid membrane The mobile ion-exchanger sites used in these sensors are of two types

(i) Organic ion-exchangers which interact with solution anions or cations by mainly electrostatic forces

(ii) Neutral ion carriers (ionophores) which can selectively complex ions from the analyte solution

1 10 1 Ion-exchange liquid membrane electrodes

The ion-exchangers used in liquid membranes are usually a salt of the type R^+X^- incorporated into a non-aqueous solvent The R^+ is usually a high molecular weight cationic complex such as a long chain tetraalkylammonia cation This can enter into an ion-exchange with the anion A to be detected For measurement of cations e g B^+ a lipophilic salt such as M^+R^- may be used

$$R^+X^-_{(m)} + A_{(aq)} \rightleftharpoons R^+A^-_{(m)} + X_{(aq)} \qquad (1\ 44)$$

$$M^+R_{(m)} + B^+_{(aq)} \rightleftharpoons B^+R^-_{(m)} + M^-_{(aq)} \qquad (1\ 45)$$

Examples of cation exchangers (M^+R^-) are the long chain dialkylesters of phosphoric acid for detection of Ca^{2+}[20] or tetraphenylborate complexes Examples of common solvents used are o-dichlorobenzene, p-nitrocymene and diphenyl ether Often the membrane salts and solvent are fixed in a polymer matrix, e g PVC, to improve the robustness and mechanical properties of the sensors The types of matrices are similar to those described below for neutral carrier membranes

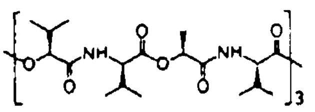
1 10 2 Neutral carrier liquid membrane electrodes

This classification of liquid membrane is based on electrically neutral ion-carriers (ionophores) which are dissolved in an organic solution The carrier is mobile within the membrane and the analyte species are mainly cations The ionophore is a neutral lipophilic ion-complexing molecule which will form a complex with the ion of interest and facilitate the transport of the ion from the aqueous solution into the organic layer The charge separation leads to the generation of the membrane potential The membrane can be composed of the ionophore dissolved in an organic liquid or the ionophore can be part of a polymer supported liquid membrane

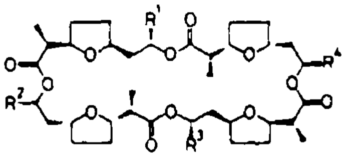
1 11 Historical perspectives

The first reference to neutral carriers was by Moore and Pressman in 1964[21], they reported the potassium ion binding ability of the naturally occurring antibiotic valinomycin The analytical potential of the molecule as a highly selective potassium complexing agent was realised a few years later by Stefanac and Simon[22] The valinomycin based electrode has since become the most successful electrode for K^+ determination The early work on neutral carriers was based on natural systems such as valinomycin and similar naturally occurring macrotetrolides which are NH_4^+ specific fig 1 8, **2-6** More recently work focused on macrocyclic synthetic compounds such as the polyethers (crown compounds) developed by Pederson[23] Simon's group in Zurich have developed several hundred non-macrocyclic carrier molecules the most successful of which led to ion-selective electrodes for Ca^{2+}, Mg^{2+}, Na^+, K^+, Li^+, Ba^{2+}, H^+ and UO_2^{2+}[24] Some of the most notable ionophoric compounds are outlined below and shown in fig 1 8

Apart from the highly successful valinomycin compound (**1**) potassium selective electrodes based on crown compounds (**7**)[25] or bis crown compounds (**8**)[26], where two crown rings are linked by a bridge, have been developed Sodium selective ionophores include non-macrocyclic structures (**9**, **10** and **11**)[27] and cyclic crown structures (**12**)[28] NH_4^+ selective neutral carriers are almost exclusively based on the macrotetrolides antibiotics (**2-6**) There has been an interest in the development of lithium selective ionophores based on modifications of natural systems[29], crown compounds[30,31] and non-macrocylic molecules[32] Successful divalent sensors have been developed for calcium (**13**)[33] ETH 1001 and magnesium (**14**)[34] These are just a few of the available ligands, for an extensive list of neutral carrier based ISE's and their current applications see the excellent reviews [5,35-39]


VALINOMYCIN

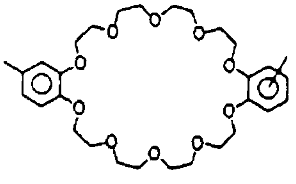
1 K^+

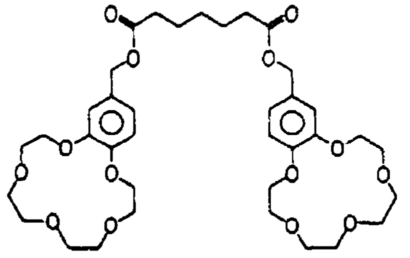


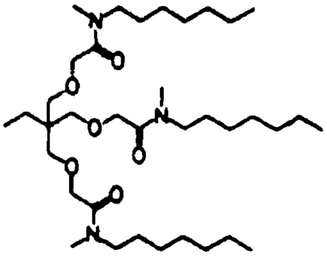
$R^1 = R^2 = R^3 = R^4 = CH_3$		NONACTIN	2
$R^1 = R^2 = R^3 = CH_3$	$R^4 = C_2H_5$	MONACTIN	3
$R^1 = R^3 = CH_3$	$R^2 = R^4 = C_2H_5$	DINACTIN	4
$R^1 = CH_3$	$R^2 = R^3 = R^4 = C_2H_5$	TRINACTIN	5
$R^1 = R^2 = R^3 = R^4 = C_2H_5$		TETRANACTIN	6

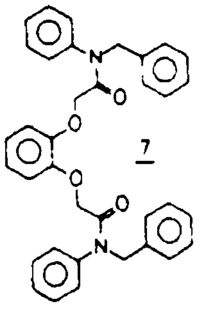
MACROTETROLIDES

NH_4

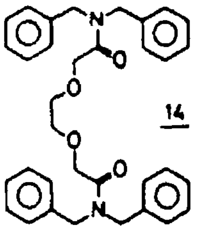

K^+ 7


K^+ 8

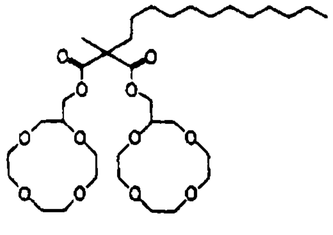

Na^+ 10

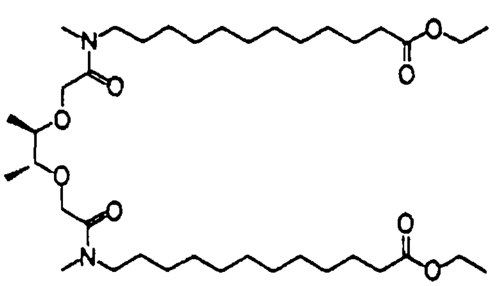


Na^+ 9



Na^+ 11


Na^+ 12


Ca^{2+} 13

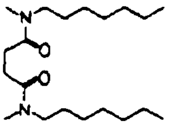

Mg^{2+} 14

Figure 1.8 Structures of some of the neutral carrier ligands discussed

1.12 Mode of action of neutral carrier based ISE's

The fundamental processes occurring in the membrane can be broken down into several steps which are shown schematically in fig 1.9. The first step is the transfer of free ligands from the membrane into the aqueous boundary phase. The cation is also transferred into the aqueous boundary phase where it loses its water of hydration and is complexed by the ligand. This is followed by transfer of the cationic complex into the bulk membrane. The ionophore or ion carrier usually complexes the ion by inducing the ion into a preformed cavity (in the case of macrocyclic compounds) or by forming a cavity around the ion (non-macrocyclic structures).

1.12.1 General properties of suitable neutral carriers[40-42]

(a) The ligand should be overall electrically neutral with a high lipophilicity to ensure it stays in the organic phase but not so high that it limits mobility. A high lipophilicity is also necessary to ensure an adequate lifetime. For this purpose it is recommended that the partition coefficient (K) of the carrier (S) between the aqueous sample solution and the organic membrane is larger than $10^{5.5}$ [43]

$$S(aq) \rightleftharpoons S(m) \qquad K = \frac{[S_{(m)}]}{[S_{(aq)}]} \qquad (1.46)$$

The partition coefficient may be estimated by calculating the partition coefficient of the ionophore between water and octan-1-ol (P) by TLC (thin layer chromatography)[40]

(b) The free energy of activation of the ligand exchange reaction

$$IS + S' \rightleftharpoons IS' + S \qquad (1.48)$$

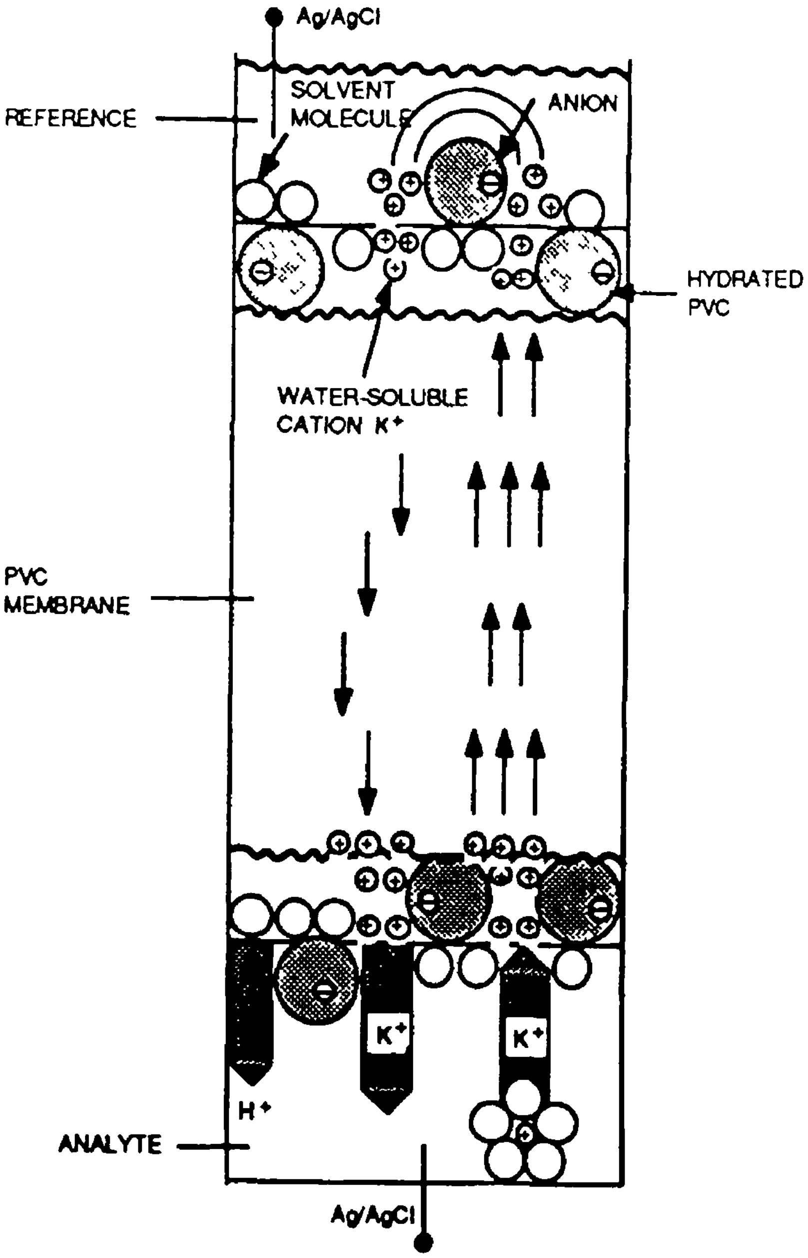


Figure 1 9. Schematic diagram of the fundamental processes occuring in a PVC membrane should be relatively low so that the processes of ion uptake (complexation) and ion release at the membrane/solution interface take place quickly and are sufficiently reversible Related to this is the concentration of uncomplexed species in the membrane The concentration of free ligand should be much higher and relatively constant compared to the concentration of complexed ligands in the membrane

(c) The ionophore has to induce permselectivity in the membrane The selectivity of the membrane depends to a large extent on the selectivity determining structure of the ligand itself This has been fully characterised by the relative values of the stability constants of the complex with the primary ion (β_{is}) in comparison to the interfering ion(s) The selectivity of the membrane will also be affected, to a lesser extent, by the extraction properties of the membrane solvent and other membrane additives, the concentration of free ligands in the membrane and by the concentration of ionic sites in the membrane

1 12 2 Molecular aspects of ionophore design

The most important molecular parameters of an ionophore are as follows

(a) Coordination sites

In order to attract the cation into the cavity the ligand should contain some polar groups These are usually carbonyl or ether oxygen atoms (as in crown ethers and calixarenes) but nitrogen or sulphur atoms have also been used

(b) Cavity/coordination number

The carrier molecule should assume a stable conformation containing a cavity The polar coordinating sites are generally arranged on the inside of the cavity, shielded by the outer non-polar shell, and should be arranged in an ordered manner around the cavity to provide the optimum number and spatial arrangement of coordinating sites for the ion of interest

(c) Cavity size

The shape and size of the cavity should be complementary to the target ion Cations larger than the cavity will deform it while smaller cations will not fill the available space To ensure the rigidity of the ligand structure the coordinating sites are often locked into a fixed position by the presence of intra-molecular bonds such as the hydrogen bonds in valinomycin

1 13 The role of other membrane additives

1 13 1 Plasticizer

The organic solvent used to dissolve the ionophore often has the dual function of acting as the plasticizer for the polymeric support as well as being a non-volatile solvent for the ligand In general, the function of a plasticizer is to lower the glass transition temperature of the polymer (Tg) below ambient temperature However the extraction properties of the plasticizer can have an important influence on the overall membrane characteristics A variety of plasticizers have been tried in electrode membrane systems in monovalent and divalent ion sensors The polarity of the organic phase or plasticizer is an important property For example if the polarity of the membrane is increased a preference for divalent ions relative to monovalent ions is exhibited [44] Hence a plasticizer with a higher dielectric constant such as 2-NPOE (see table 1 1) is generally used for divalent ion sensors Since most membranes contain 60-70% by weight plasticizer the dielectric constant of the membrane would be similar or largely dependent on the plasticizer polarity[45] Some examples of suitable membrane solvents are shown in table 1 1 Apart from 1-decanol they all possess plasticizing properties can be divided into three categories, diester of carboxylic acids, organophosphates and nitroaromatics Smaller molecules (e g nitrobenzene) plasticize PVC but they are lost from the membrane in aqueous solution

Table 1.1 Some examples of commonly used membrane solvents.

dibutyl sebacate
bis(2-ethyl hexyl)sebacate
di-n-decyl phthalate(DDP)
bis(2-ethyl hexyl) phthalate
dioctylphenyl phosphate(DOPP)
tris-(2-ethylhexyl)-phosphonate
1-decanol
2-nitrophenyl octylether(2-NPOE)
2-nitrophenyl phenylether

1.13.2 Fixed ion-exchange sites

The organic membrane phase may contain substances other than the ionophore, these may be introduced deliberately or they may be unintentional. Anions such as tetraphenyl borate(TPB$^-$) in the form of potassium or sodium salts may be added to the membrane during its preparation and act in a beneficial way. TPB$^-$ anions are highly lipophilic and so are trapped within the organic phase by virtue of their poor water solubility. In order to maintain electroneutrality in the bulk membrane the presence of anionic sites (such as TPB$^-$) help to compensate for the positively charged neutral carrier-ion complexes. The presence of permanent anionic charges tends to repel sample anions from the membrane phase and improve the anion selectivity. They also boost the cation selectivity, especially for divalent ions over monovalent ions by increasing the membrane polarity, without affecting the selectivity among ions of the same charge. Finally the incorporation of TPB$^-$ lowers the membrane resistance which is also desirable. Other additives such as potassium tetra-kis-*p*-chlorophenyl borate (KTpClPB) or tetrabutyl ammonium tetraphenyl borate salts may be used. Variation in the amount and type of ion-exchanger also has a significant effect on the membrane selectivity pattern. Ammann et al. showed the effect of concentration of KTpClPB in the neutral carrier membrane containing the carrier ETH 1692[5].

At very high concentrations of anion excluder there is a danger of the exchanger dominating the overall cation extraction behaviour of the membrane Cations will then be drawn into the membrane in reverse order of their hydration energies In order to avert this affect the additive concentration should be kept below that of the carrier A 50% by mole ratio of ion-exchanger to ligand is recommended by some authors[46]

Under certain conditions lipophilic anions may enter the membrane and cause a distortion of the Nernstian response due to a partition process between the lipophilic ions and the membrane solvent For example thiocyanate or perchlorate anions may become soluble in the organic phase and lead to increased membrane conductance of the interfering species and a subsequent reduction in the concentration of free carriers at the membrane/sample interface The greater the lipophilicity of an interfering anion the greater its possible interfering effect The Hoffmeister series is a series of anions in the order of increasing lipophilicity[47]

$$\mathrm{Cl} < \mathrm{Br}^- < \mathrm{NO_3} < \mathrm{SCN} < \mathrm{ClO_4} < \mathrm{R}$$

1 13 3 Matrix materials

The introduction of poly(vinylchloride) (PVC) as a support matrix for liquid membranes boosted the development of liquid ion-exchanger and neutral carrier ion-selective electrodes[48-50] PVC based membranes are fabricated by dissolving the electroactive component (ion-exchanger and/or ionophore), the plasticizing solvent mediator and the PVC in THF followed by slow evaporation of the THF at room temperature Early work showed that approximately 30 m/m% of PVC was suitable, since smaller proportions led to fragile membranes while larger amounts led to sluggish responses[51] There have been suggestions that impurities present as fixed negative charged sites in the PVC may be responsible for some of the charge compensation for the cation/carrier complexes but the nature of these sites remains undefined[52]

The operative lifetimes of the PVC based systems are considerably shorter than the lifetimes of their solid-state counterparts e g the lanthanum fluoride model The principle cause is the loss of active component(s) from the polymer matrix, especially at the membrane/solution interface and the deleterious effect of anionic surfactants and biochemical components Some investigations have centered on the prospect of alternative matrix materials Silicone rubber has been used as an alternative matrix to PVC[49,52] This material has a low Tg and so requires no plasticizer however it has been found to exhibit higher membrane resistance (by a factor of 10 to 100) than PVC based membranes[53] Polyacrylate polymers, Urushi (a lacquer of Japanese origin), polyurethane, cellulose acetate, ethyl cellulose and grafting of the electroactive groups to the support have all been attempted[49] with varying degrees of success although little improvement in electrode lifetime was achieved to warrant the synthetic effort Despite drawbacks, PVC remains the most popular and frequently used inert support

1 14 Coated wire electrodes (Asymmetric design)

The demand to simplify and miniaturise electrode devices brought about a new configuration of sensors, namely coated wire electrodes(CWE's) The main feature of a coated wire electrode is the elimination of the aqueous reference electrolyte found in conventional polymer membrane electrodes The electroactive agent is incorporated into a polymeric film, most commonly PVC and coated directly onto a metallic substrate (usually platinum but copper, silver and graphite have also been used) The first report was by Hirate and Date who coated a copper(I) sulphide impregnated silicone rubber membrane directly onto a platinum wire and obtained Nernstian responses to copper(II) ions[54] The electroactive component is usually embedded in PVC or PMM (poly methyl methacrylate) and the wire dip coated until a bead is formed[55] Sensors for calcium[56,57], nitrate[58], potassium[59,60] and halides[61] have been developed Although equal and even superior selectivities have been claimed for the devices compared to their conventional counterparts[62], comparisons of selectivity coefficient data for different electrodes can be unreliable (see section 2 7) The standard potential of CWE's is often unstable varying for one electrode during its lifetime as well as differing between electrodes of the same type and hence they require frequent re-calibration The success of CWE systems raised some fundamental questions concerning the charge conduction mechanism occurring in the membrane phase and at the polymer substrate interface In a conventional ISE the reversibility and equilibrium of transition from ionic to electronic conductivity is ensured by the reversible half cell at the silver wire in the internal filling solution Buck[63] classified coated wire electrodes as being "completely blocked" as the interface between the membrane i e an ionic conductor and the internal contact i e an electronic conductor is somehow blocked to a reversible electron or ion transfer The coupling between the metal and the coating in CWE's can be described as capacitive and the contact potential is distributed between the capacitors of the two surfaces In theory these systems cannot provide very reproducible potentials Some attempts have been made to rationalize the charge transfer system in CWE's Cattrall et al [55] have suggested the presence of an oxygen half cell at the interface caused by the permeation of oxygen gas from the working solution

Further modifications have been made to solve the blocked interface problem Dispersion of a redox couple in the membrane phase[62] or layering of phases containing redox species have been tried The use of a hydrogel layer in ISFETs[64], an epoxy layer loaded with metal[65-67] have overcome some of the potential stability problems, and in some cases, are an improvement on their conventional counterparts Despite the theoretical limitations there has been great interest in CWE's due to advantages such as greater mechanical flexibility (as there is no internal liquid) simpler manufacturing and easier miniaturisation

1 15 Calixarenes

1 15 1 Introduction

Pederson, Lehn and Cram were awarded the 1987 Nobel Chemistry Prize for their contribution to macrocyclic chemistry Their award was an acknowledgement of the substantial contributions they made to host-guest chemistry or supramolecular chemistry in the fields of crown ethers, cryptands and spherands respectively[68] Not only a remarkable feat itself, it also raised the status of this whole area of supramolecular chemistry Their molecules were characterised by a cyclic structure with an electron rich cavity to provide binding sites for the cation and a cavity size that matched the desired cation (see fig 1 10) Of all the structures the spherands are most rigid and have the highest binding for alkali metal ions This is followed by the cryptands and then the crown compounds

In 1978 C D Gutsche introduced the term "Calixarene" to describe another class of macrocyclic compounds which had been the subject of his research since the early 1970's Calixarenes are cyclic oligomers produced by the condensation of *p*-substituted phenols with formaldehyde An appropriate nomenclature for the compounds yielded some concern with different names being suggested by different groups such as novalaks, the schematic but cumbersome chemical abstract terminology or the metacylophanes of Cram and Steinberg[69] However it was C D Gutsche who introduced the more pictorially and descriptively appealing term "Calixarenes" based on the similarity of the basket shapes to a *calix* (Greek vase or chalice) and the *arene* which denotes the presence of the aryl groups This is the convention which has been generally adopted by researchers in the area (albeit not by IUPAC)

There has followed a remarkable burst of attention and interest in the area due in part to the ready accessibility of the compounds and the talents of the chemists involved The outcome of all this is the publication very recently of two books[70,71], a conference dedicated solely to the topic[72] not to mention a plethora of journal publications The number aryl groups is indicated by the insertion of the number between the calix and the arene e g calix[4]arene Then

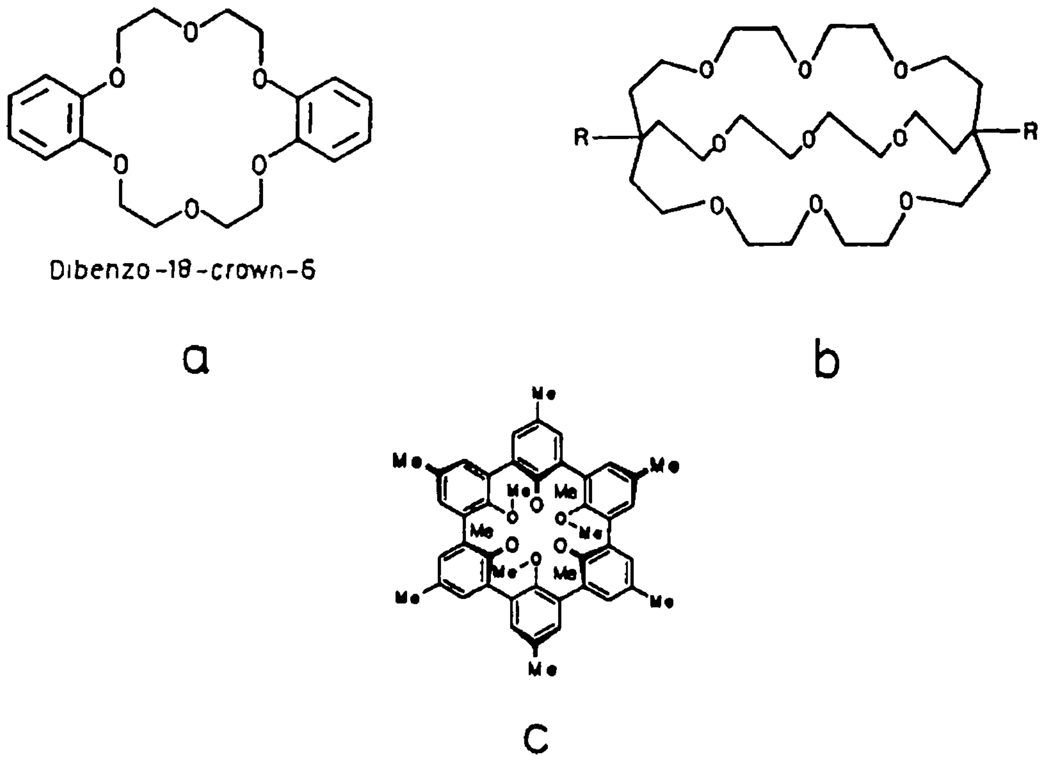


Figure 1 10 Structure of typical (a) crown (b) cryptand and (c) spherand

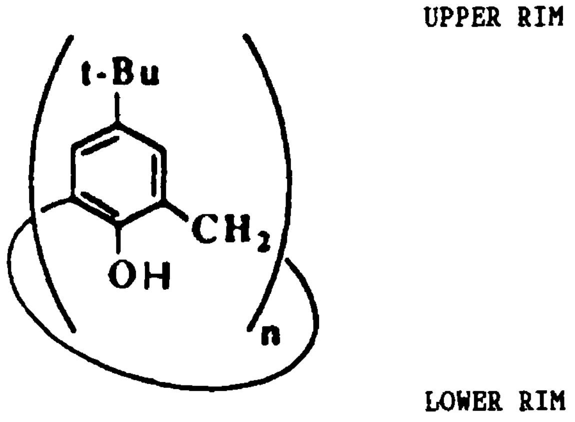
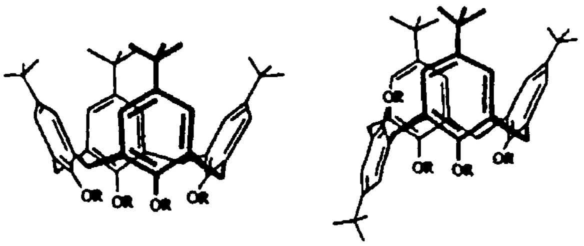


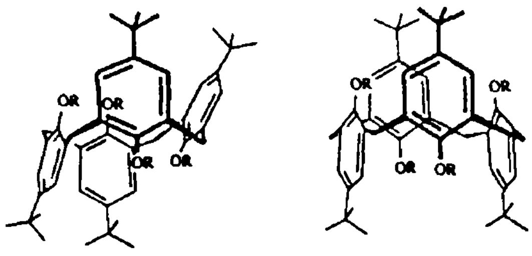
Figure 1.11. Structure of the parent *p*-t-butyl-calix[n]arene

to indicate from which phenol the calixarene is derived the *p*-substituent is designated by name e g the cyclic tetramer from *p-tert*-butylphenol is called *p-tert*-butylcalix[4]arene (fig 1 11)

There are five members of the series ranging from the relatively rigid calix[4]arene to the much larger and more flexible octomeric calix[8]arene, although the odd numbered pentamers and heptamers are much less accessible than the other three The parent *p-tert*-butyl calix[n]arenes are white crystalline materials characterised by high melting points e g *p-tert*-butylcalix[4]arene mp 342-344^{o}C and low solubility in organic solvents They possess a high degree of conformational mobility and one or two of the aryl rings can rotate about the C2-C4 axis (a process called conformational inversion) to form three possible conformations of the calixarene These are described as the cone, partial cone or 1-3 alternate conformation (fig 1 12) The 1-2 alternate conformation is encountered much less frequently [73]



Cone Partial Cone



1 2 Alternate 1,3-Alternate

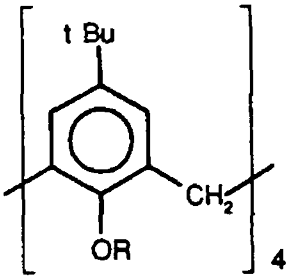
Figure 1 12 Schematic drawings of the four conformations of a calix[4]arene.

1 15 2 Modified calixarenes

These structures may be used as a base or platform onto which groups of ion-binding substructures may be assembled The "lower rims" of phenol derived calixarenes are already functionalised with hydroxyl groups which provide excellent sites for the introduction of other moieties For example in the presence of excess acylating agent the hydroxyl groups are easily converted to ester groups, thus lowering the conformational mobility and freezing the molecule into one of the three conformations Substituents have also been introduced onto the "upper rim" of calixarenes via modification of the *p*-alkyl group by several methods [74] The substituent in the lower rim can greatly influence the melting point, in some cases lowering it significantly e g the tetramethyl and tetrabenzyl ethers of *p-tert*-butyl calix[4]arene have mp 226-228°C and 230-231°C respectively compared to mp 342-344°C for the unsubstituted *p-tert*-butyl calix[4]arene Modification of the *p*-substituents generally increases the solubility in a variety of organic solvents and in extreme cases render them soluble in water e g sulphonated calixarenes[75,76]

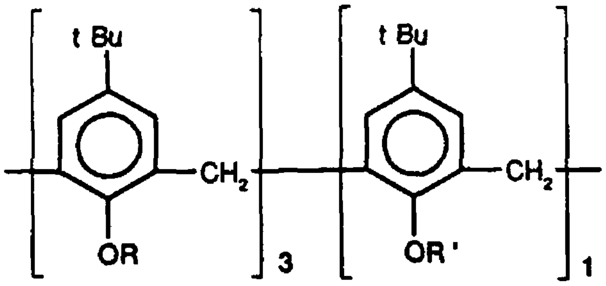
All the calixarenes used in this study are part of a larger group of modified calixarenes synthesised by Dr Stephen J Harris at Dublin City University, Ireland (formerly at Loctite Irl) and Prof M A McKervey, Queens University Belfast, Northern Ireland (formerly at University College Cork, Ireland)[77-83] Carbonyl groups in the form of ketones and esters have been introduced into the parent calixarene structures in the hope that they might act as ligating groups in the much the same way that esters participate in ion-binding in the natural receptors such as valinomycin Similar work has been undertaken independently by Chang and Cho in South Korea [84-86] Three ring sizes are available with n = 4,5 and 6, although much of the work concentrates on the more readily accessible tetrameric structure

Fig 1 13 shows the structures of the modified tetramers, pentamer and hexamers In the structures shown, modified groups at the lower rim are all identical The tetrameric structures exist in a very rigid cone structure with the polar substituents mutually *syn* with respect to the macro ring i e grouped together at one end of the

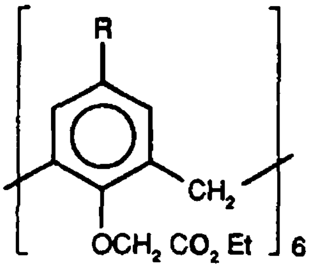


R = H Ia
R = $CH_2CH_2OC_2H_5$ Ib
R = $CH_2CO_2CH_3$ Ic
R = $CH_2CO_2C_2H_5$ Id
R = $CH_2CO_2(CH_2)_3CH_3$ Ie
R = CH_2COCH_3 If
R = $CH_2COt\text{-}Bu$ Ig
R = $CH_2COAdamantyl$ Ih

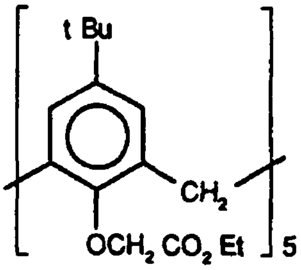
Adamantyl =



R' = CH_2CO_2H R = $CH_2CO_2CH_3$ Ij
R' = CH_2CO_2H R = $CH_2CO_2C_2H_5$ Ik
R' = CH_2CO_2Me R = $CH_2CO_2C_2H_5$ Im



R = H IIa
R = t-Bu IIb

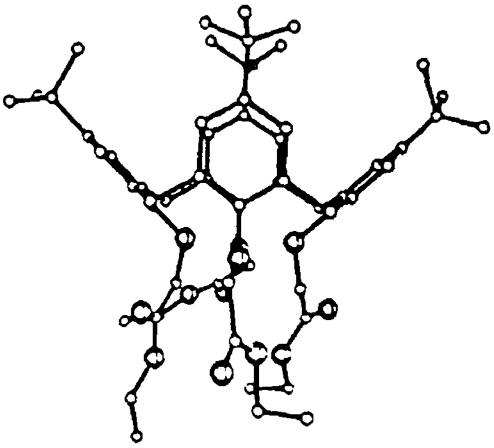


IIIa

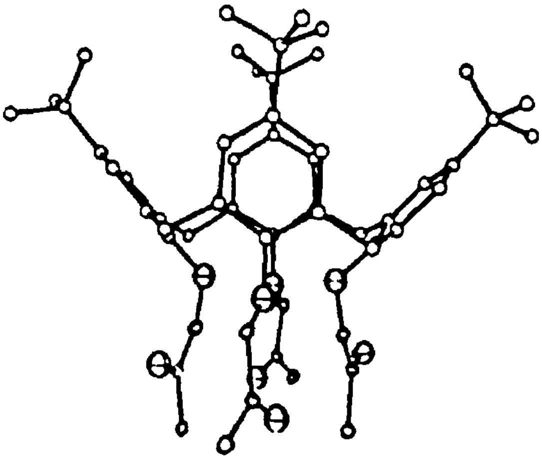
Figure 1 13 **Structures of the tetrameric, pentameric and hexameric** calixarenes cavity and the hydrophobic moieties directed towards the upper rim The molecules are frozen into the cone conformation during synthesis X-ray crystal structures for two of the tetramers (**Id**) and (**If**) are shown in fig 1 14[78] The tetra ethylester (**Id**) exhibits a distorted cone structure with two of the opposing aromatic rings essentially parallel, while the other two rings are almost normal to one another The same type of distorted cone shape is seen in the tetramethylketone (**If**) Conformational analysis of the hexameric and octomeric structures is more difficult due to the increased size of the macrocycle which leads to greater flexibility of the ring The x-ray crystal structure for the ethylester hexamer (**IIa**) (fig 4 2) clearly demonstrates the more open less organised nature of the larger calixarenes

In recent times the problem of synthesising mixed ligating groups i e where the derivatives are not all identical has been overcome for some of the tetrameric structures The tetra ethylester (**Id**) was found to undergo partial hydrolysis with tetrafluoroacetic acid or methylsulphonic acid in a non-random fashion to yield a product in which one and only one of the ester groups was cleaved[81] The product of the reaction monoacid triethylester (**Ik**), is not only interesting in itself but is a useful precursor for preparing chemically modified calixarenes with a 1 3 arrangement of mixed ligating functional groups The structures of (**Ik**) and the monoacid trimethylester (**Ij**) are shown in fig 1 13

Another group of related structures are the so-called oxa calixarenes in which an extra methoxy group has been introduced at one or two of the methylene bridges In the absence of any simple term to describe these substances, the term oxa calixarene was proposed as a general trivial name with the prefix mono-, di- or tri- depending on the number of modified methylene bridges They possess polar cavities intermediate in dimensions between the tetramers and the hexamers mentioned above The structures of some ethyl and butyl esters and a methoxyester derivatives monooxa calixarenes (**IVa-IVc**) and dioxa calixarenes (**Va-Vc**) are outlined in fig 1 15

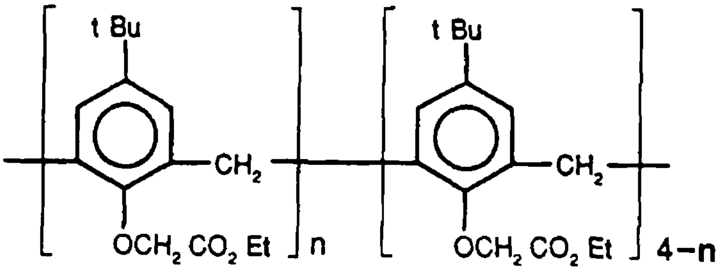


(Id)

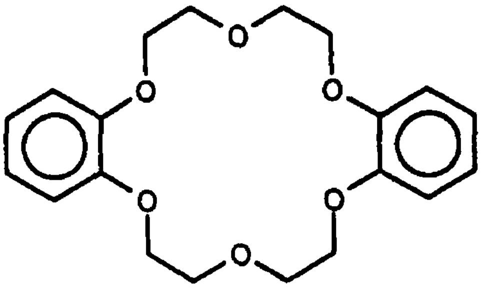


(If)

Figure 1 14 X-ray crystal structures of the tetra ethylester Id and the tetra methylketone If. Carbon and oxygen atoms are shown as spheres of arbitry radius, oxygen atoms are larger and marker with a cross.



n	R	Name	Code
1	C_2H_5	monooxa ethylester	IVa
1	t-Bu	monooxa t-butylester	IVb
1	$CH_2CH_2OCH_3$	monooxa methoxy	IVc
2	C_2H_5	dixa ethylester	Va
2	t-Bu	dioxa t-butylester	Vb
2	$CH_2CH_2OCH_3$	dioxa methoxy	Vc



Dibenzo-18-crown-6

Figure 1 15 Structures of the monoxa, dioxa and other ligands discussed

1 15 3 Complexation of alkali cations phase transfer and stability constants

1 15 3 1 Phase transfer studies

Phase transfer (extraction) of alkali metal cations from aqueous solution into dichloromethane can be investigated using a method of alkali picrate extraction devised by Pederson[23] Phase transfer data have been obtained for most of the tetrameric and hexameric calixarenes studied The available data are presented in table 1 2 as %E (percentage cation extracted) Most of the experiments were carried out using a basic metal picrate solution except for the experiments with the *n*-butyl ester (**Ie**) and dioxaethylester (**Va**) which were obtained in neutral metal picrate The data reveals a wide range in the phase transfer ability for both the esters and ketones and suggest it is a size related phenomenon Several factors are immediately obvious

(a) The phenolic OH group of the parent *p-tert*-butyl calix[4]arene (**Ia**) on its own is not sufficient to extract any response Neither is the addition of an ether oxygen group (**Ib**) in the derivative chain

(b) The smallest of the series, the tetramers, show peak selectivity for Na$^+$ irrespective of the derived group (ester or ketone)

(c) The nature of the alkyl group attached to the ester group in the tetramers (**Ic**), (**Id**) and (**Ie**) is relatively unimportant

(d) The tetraketones (**If**), (**Ig**) and (**Ih**) show a much broader extraction pattern with larger amounts of K$^+$/Cs$^+$/Li$^+$ being transported compared to the tetramer esters

(e) The larger hexamer esters show a distinct shift in preference towards the larger cations with less affinity for Na$^+$ than K$^+$ and a maximum affinity for, but with little preference between Rb$^+$ and Cs$^+$

1 15 3 2 Stability constants

Phase transfer studies are used as a semiquantitative assessment of ion-transport ability, however the affinity of a receptor for a cation is more correctly described

Table 1.2. % Extraction of alkali metal picrate into CH_2Cl_2 at 20^oC. Metal picrate ($2.5x10^{-4}M$) in CH_2Cl_2; $2.5x10^{-4}M$ picric acid in 0.1M aqueous metal hydroxide (MOH). Receptor solution (5 ml) was shaken (3 min) with picrate solution 5 ml) and % extraction was measured from absorbance of resulting CH_2Cl_2 solution at ca. 378nm; values are +/-5%. No picrate extraction in absence of receptor, * values obtained using neutral metal picrate, na - not available

Ligand	Ref.	Li^+	Na^+	K^+	Rb^+	Cs^+
Ia	85	<1	<1	<1	<1	<1
Ib	85	<1	4	<1	<1	<1
Ic	78	7	86	22	10	26
Id	78	15	95	49	24	49
Id*	87	7	29	5	4	6
Ie*	87	na	25	2	na	na
If	78	31	99	84	54	83
Ig	78	47	93	81	44	32
Ih	78	50	94	73	23	17
Ik	88	1	6	4	1	4
IIa	78	5	10	51	94	95
IIb	78	11	50	86	89	100
Va*	89	3	2	16	15	14

by the stability constant β of the complex in water, where β is the concentration ratio $[ML^+]/[M^+][L]$ corresponding to the equilibrium

$$M^+_{(aq)} + L_{(aq)} \rightleftharpoons ML^+_{(aq)} \qquad (1.48)$$

where L is the complexing ligand and M is the cation. Solubility limitations of the calixarene derivatives precluded stability constant measurements in water and the available data was obtained by UV spectrophotometry in methanol (MeOH) or acetonitrile (MeCN). The data are shown in table 1.3[83] together with the literature values for dibenzo 18-crown-6 (DB18C6)[90]. The stability constants of the alkali cation complexes lie in the general range 2 to 5.5 log units in methanol and between 2 and 6 5 log units in acetonitrile There is a clear maximum for Na$^+$ in most tetramers and a maximum for K$^+$ with the hexamer (**IIb**) The values are about the same order of magnitude as for DB18C6 The increase in stability of the Li$^+$ complex in acetonitrile from methanol is due to a solvent effect of MeCN rather than a specific effect of the receptor Although the stability constant data (table 1 3) should ideally be calculated in water in order to compare the data with the phase transfer data of table 1 2, methanol can be regarded as a protic solvent and hence allow some comparisons The tetramers (**Id**) and (**Ie**) display a peak selectivity for Na$^+$, as is found in the phase transfer for the tetramers The tetramethylketone (**If**) binds and extracts all alkali cations more strongly than the tetra ethylester (**Id**) Despite the difficulty in comparing the two data sets because of differing solvent systems they support each other with regard to the selectivity of the derivatives for the various alkali metal cations Studies of ion transport rates for the calixarenes, although less extensive, have confirmed the extraction studies and stability constant data[83]

Table 1 3 Logarithms of the stability constants β of the complexes of alkali cations with some modified calixarenes at 25°C SD 0 2 to 0 3 log units, ionic strength = 10^{-2} M(Et_4NCl in MeOH and Et_4NClO_4 in MeCN [83]

		logβ					
Solvent	cation	**Id**	**Ie***	**IIb****	**If**	**Ig**	**DB18C6**$^\$$
MeOH	Li$^+$	2 6			2 7	1 8	
	Na$^+$	5 0	5 6		5 1	4 3	4 4
	K$^+$	2 4	2 7		3 1	5 0	5 0
	Rb$^+$	3 1			3 6	1 6	4 2
	Cs$^+$	2 7			3 1	<1	3 5
MeCN	Li$^+$	6 4		3 7	5 8		
	Na$^+$	5 8		3 5	5 6		4 8
	K$^+$	4 5		5 1	4 4		4 8
	Rb$^+$	1 9		4 8	1 7		3 7$^{\$\$}$
	Cs$^+$	2 8		4 3	3 7		3 5$^{\$\$}$

* ref 87, ** insoluble in MeOH, \$ ref 90, \$\$ ref 91

1 16 Conducting Polymers

1 16 1 Introduction

The idea that plastics could conduct electricity would have appeared ludicrous twenty years ago, such was the preconceived vision of plastics and polymers But a new class of conducting polymers have been developed since the 1970's and they have aroused a great deal of interest in the semiconductor, electrochemical and scientific community Ordinary polymers are made conducting by the incorporation of certain chemicals into the polymer by a process called doping The most important polymers are acetylene, polythiophene, polypyrrole, poly-3-alkyl thiophene and polyaniline A common feature of the polymers is the presence of long strands of conjugated double bonds (fig 1 16) The first experiments were performed with polyacetylene with various groups of workers competing to increase the conductivity of the polymer B A S F have reported a conductivity of 147,000 S cm^{1} (siemens per centimeter) for acetylene [92] Good insulators such as teflon and polystyrene have conductivity close to 10^{-18} S cm^{1} and good conductors such as copper and silver have conductivities close to 10^{6} S cm^{1}

1 16 2 Charge conduction in metals and semiconductors

Metals conduct because they have partially filled conduction bands The highest occupied band in a material is called the valence band and the empty band above it is called the conduction band Insulators and semiconductors are materials whose conduction band is completely or almost completely empty respectively and there is a large energy gap between the valence and conduction band in an insulator and a smaller gap in a semiconductor An ordinary polymer is similar to an insulator in that there is a large energy gap between the valence band and the conduction band Doping of the polymer changes that profile by taking electrons from the valence band (p-doping or positive doping as the molecule acquires a positive charge) or by adding electrons to the conduction band (n-doping or

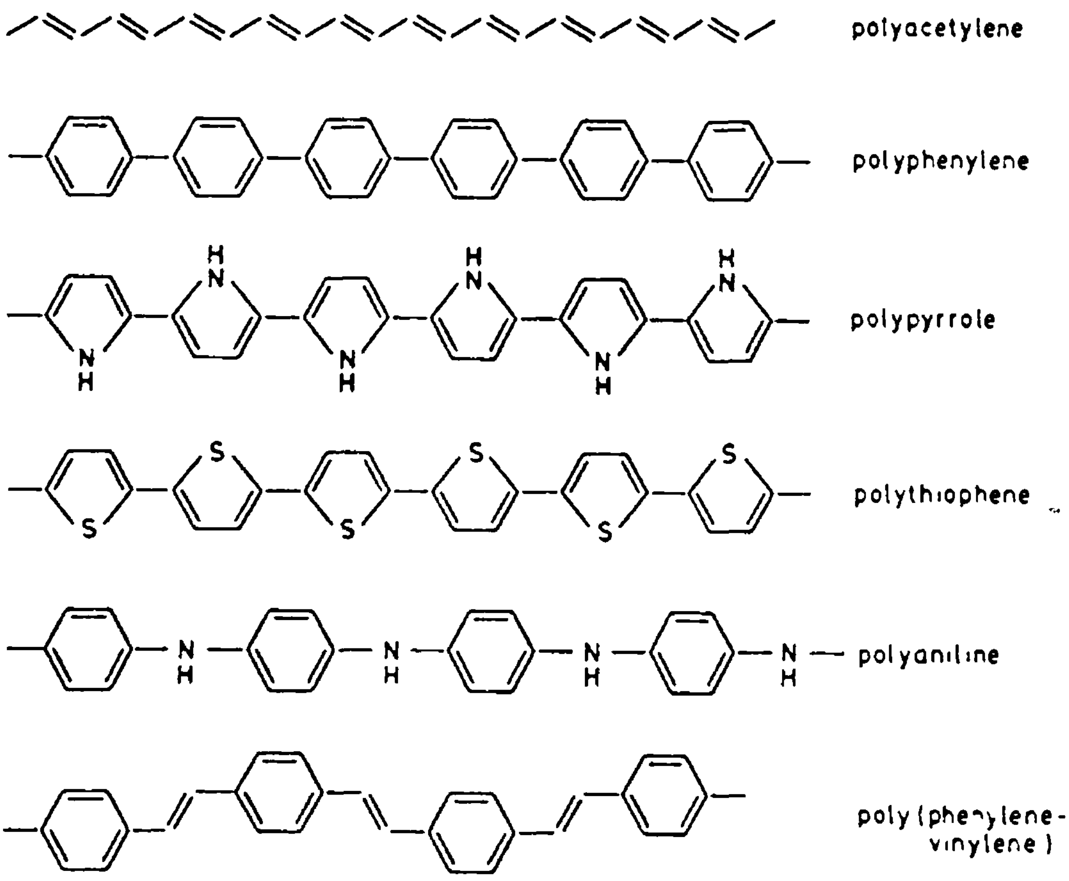


Figure 1 16 Chemical structure of the most important conducting polymers with conjugated double bonds negative doping as the molecule acquires a negative charge) Doping of the polymer creates new bands in the energy gap, making it possible for electrons to move into these new bands and increasing the conductivity of the material Although the actual formation of energy bands is more complex than this[93,94], the current discussion will merely focus on the broad principles involved Recent interest in conducting polymers has developed in part from their relatively straight forward synthesis from readily available materials and also because they can be formed as thick stable films in air The conducting polymer is composed of linear chains of aromatic rings which are bundled into intertwined fibres which may be orientated in several directions The chains themselves are not perfect and contain defects due to impurities, doped and undoped regions The conductivity mechanism along the chain via the conjugated strand is called "intrinsic conduction" and from fibre to fibre is called "non-intrinsic"[95] The mechanism of the latter is still not yet fully understood

Conducting polymers may be prepared by either chemical or electrochemical polymerisation from a monomer solution In chemical synthesis the film is formed, washed and then treated with a reducing or oxidising agent e g iodine, bromine, ferric chloride or arsenic pentafluoride (p-doped) or alkali metals e g sodium (n-doped) In electrochemical polymerisation both processes occur simultaneously A three electrode voltammetric cell is normally used The working electrode on which the polymer membrane is formed is usually made of platinum, glassy carbon or ITO glass (indium tin oxide) Electrochemical polymerisation can be performed in three ways with the material being formed in the oxidised state in each case In galvanostatic methods, a fixed amount of current is drawn through the cell and polymer is formed as a film on the working electrode In potentiostatic methods the working electrode is held at a potential at which polymerisation takes place The third method is by cyclic voltammetry where the electrode potential is scanned over the range at which polymerisation takes place New polymer material is formed during each scan During the reverse scan the new material formed will be reduced and on the next scan the earlier layers will be reoxidised simultaneously with the formation of new polymer layers

1 16 3 Electrochemical polymerisation of polypyrrole[96-99]

The first step is the loss of one electron from the monomer adjacent to the positively charged electrode due to the applied potential This prompts polymerisation of monomers on the surface of the electrode During polymerisation electrons are still being pulled from the polymer so it is still positively charged It has been found that polypyrrole has one positive charge per four pyrrole units in acetonitrile To counterbalance the positive charge of the polymer backbone, negative ions (the doping ions) enter the polymer membrane from the solution When the polymer is reduced to its neutral state the doping ion is repelled from the polymer The doping/undoping mechanism is still not yet clear and it is also possible that a cation enters the membrane during the reduction and balances the charge It is perhaps more likely that the entire mechanism involves both the cation and the anion [100] The proposed reaction for the formation of polypyrrole is shown in fig 1 17[101-102] After an initial oxidation step there is a coupling reaction of two pyrrole monomers to produce a dimeric intermediate The second stage is the reaction between the pyrrole monomer and the polymeric intermediates Polypyrrole has a high stability (stable up to 130^{o}C in air) and conductivity (1-100S cm ^{1}) [103] The potential at which the monomer starts to polymerise is normally more positive than the oxidation potential of the polymer film

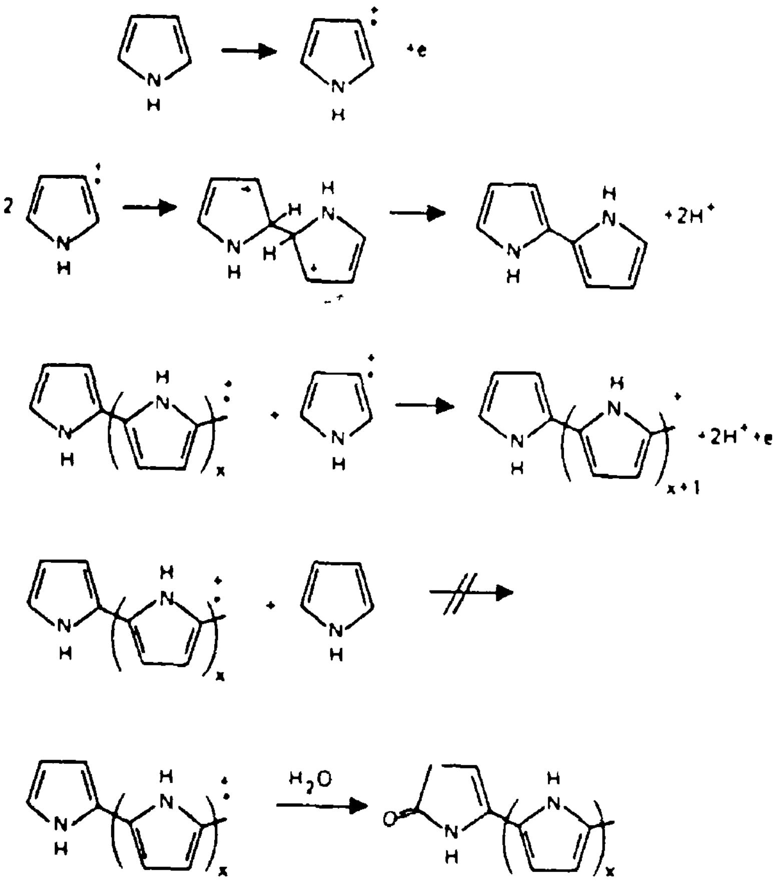


Figure 1 17 Electropolymerisation of polypyrrole

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Chapter 2

Methods and Materials

2.1 Materials

The reagents and materials were obtained from the following sources. The membrane components poly(vinyl chloride)(PVC), potassium tetrakis-(*p*-chlorophenyl)-borate (KTpClPB), 2-nitrophenyl octyl ether(2-NPOE) and tetrahydrofuran(THF) were obtained from Fluka Chemicals. AnalaR grade chlorides of sodium, potassium, lithium, caesium, rubidium, magnesium and calcium were supplied by Riedel-de-Haen, sodium and lithium salts of perchlorate, cyanate, nitrate and tetrafluoroborate were obtained from Merck or Fluka and used without purification. Pyrrole, obtained from Merck, was purified by double distillation and stored at low temperature, protected from light. Distiled, deionized (Millipore grade) water was used throughout.

2.2 Apparatus

Electrode measurements were made relative to a silver/silver chloride (Ag/AgCl) (Metrohm) or saturated calomel electrode (SCE) using a Phillips PM9421 digital pH/millivoltmeter or an ORION Research Expandable Ion Analyser EA940. A Phillips PM8251 single pen recorder or an Perkin Elmer 56 pen recorder were used for the traces. The Ag/AgCl was a Metrohm capillary tip model(Ref 6.075.000) chosen for is stability and low rate of KCl leakage. This arrangement assured that errors arising from variations in the junction potentials and potassium contamination of the sample were minimised. An ORION Ag/AgCl reference electrode with a porous frit was also used according to availability. An EG&G Princetown Applied Research Corporation (PARC) model 273 potentiostat/galvanostat with software version 2.00 was used for the electrochemical polymerisations and cyclic voltammetry. The electrochemical cell was a conventional three electrode system. The working electrode was a platinum (Pt) or glassy carbon (GC) disc (Metrohm) (diameter 3 mm) set in teflon (o.d. 10 mm) with a platinum wire or carbon rod (Metrohm) counter electrode. The reference electrode was an Ag/AgCl satd KCl reference electrode (Metrohm). All solutions were degased by bubbling with high purity nitrogen for 6-10 min and all polymerisations were performed under nitrogen. Electrodes were polished to a mirror finish with 1 µm diamond paste followed by 0 3 µm Al_2O_3 using intermediate washing steps with distiled/deionized water

2 3 Electrode fabrication

All electrodes used in the research were based on the incorporation of a calix[n]arene as the neutral carrier in a PVC matrix membrane The electrodes were of two fundamental types The following three chapters deal with classical potentiometric sensors where there is an internal reference electrolyte and a sensing membrane incorporating a calixarene as the ion-sequestering molecule dissolved in a plasticizer (liquid membrane) and held in an inert PVC matrix The second type of sensor constructed is based on solid state configurations where there is no internal reference solution and the ion sensing membrane is placed either directly or indirectly in contact with the conducting metal

2 4 PVC membrane cocktail

The general composition of the liquid membranes was as follows, the exact composition for the different ligands are given in the relevant sections

Component	% w/w
Plasicizer	60-66%
PVC	30-33%
Ionophore	0 05-2 0%

(i) A PVC content of 30 to 33% was adopted as this amount is generally recommended to produce membranes of optimum mechanical characteristics[1]
(ii) The carrier concentration is usually kept at > 10^{-4} mol/l which for a tetramer calixarene would be a minimum of around 0 01% In practice, a higher weight% 0 05 to 2 0% of the ionophore was used
(iii) Evidence suggests [2,3] that the mole ratio of any membrane additives such as the ion-exchanger KTpClPB should be kept below a 1 1 mole ratio ligand ion-

exchanger and preferably 2 1 to ensure domination of the electrode selectivity by the carrier A mass ratio of 4 1 ligand ion-exchanger was generally adopted in this research which is equivalent to a 2 1 mole ratio for a tetrameric calixarene The whole cocktail was dissolved with THF (approximately 1-2 ml per 100 mg plasticizer) and stirred in a sealed container for at least 1hr to ensure a homogeneous mixture

2 5 Potentiometric devices

2 5 1 Mini electrodes

A schematic diagram of a mini electrodes is shown in fig 2 1 and a detailed description is outlined below A batch of 6-10 electrodes would normally be prepared simultaneously

1 The internal reference electrode was a trimel enamel coated silver wire (0 004") Johnson Mathey Ltd The ends (up to 3 cm) of an 18 cm piece of wire were emmersed in 50/50 conc H_2SO_4/conc HNO_3 for 10 seconds, rinsed in distiled water and the enamel coating stripped from the acid soaked portion by gently pinching the wire and pulling towards the ends Oxidation of the wire can occur if the wire is over-exposed to acid The bared section was then chloridised by soaking in a 40% sodium hypochlorite solution for 20 min

2 One end of the prepared silver wire was coiled around the tip of a fine hypodermic needle and the whole wire inserted into a 15 cm portion of PVC tube (i d 1 0 mm) (EMS Medical Group Ltd , Sloughouse, Gloucestershire) The uncoiled end was soldered to a 2 mm plug which was fixed over the PVC tubing with an epoxy glue

3 A porcelain tip (Morgon Matroc Products Ltd ,) of 4-5 mm length was turned on a small lathe to the required diameter and was inserted halfway into the PVC tube This was glued in place by a drop of THF and left to air dry

4 To coat the porcelain tip with PVC membrane the whole tip was "dipped" several times into the membrane cocktail and left at room temperature for several

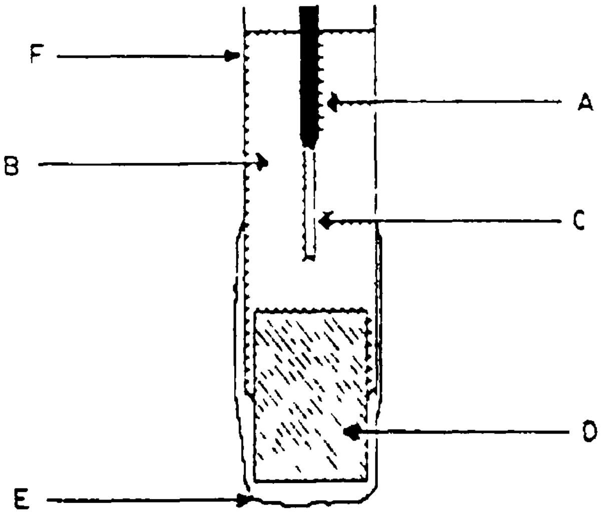


Figure 2 1 Mini electrode, (A) enamelled silver wire, (B) internal reference solution, (C) chloridised silver wire, (D) ceramic plug, (E) PVC ion-selective membrane, (F) main electrode body.

hours to allow the THF to evaporate Further coatings were sometimes required to build up a suitable thickness coating, depending on the consistency of the PVC membrane solution The tip was then left overnight to dry fully

5 The internal reference electrolyte (usually 10^{-1}M of the primary cation chloride solution) was then injected into the PVC tube by means of a fine syringe through a small hole pierced near the plug end

6 Fabricated electrodes were conditioned by soaking in 10^{-1}M solution of the primary chloride ion for at least 30 min and preferably overnight before use

2.5.2 Bench electrodes

The PVC membrane solution was poured into a 30 mm square glass mould and covered to prevent contamination in a manner similar to that described by Moody and Thomas[4]. Gradual evaporation at room temperature gave a transparent flexible PVC membrane of 0.1 - 0.4 mm thickness. A 9 mm diameter disc was then cut from the master membrane with a cork borer and inserted into the cap of a Russel Gas Sensing Electrode model ISE 98-7809 (the diameter of the exposed membrane is 7 mm). The PVC disc was mechanically clipped into place rather than being glued into the electrode tip. The internal reference electrolyte was a 10^{-1}M chloride solution of the primary ion. A schematic diagram of the casting technique and the final bench electrode is shown in fig. 2.2. Fabricated electrodes were conditioned as for the mini electrodes.

2.6 Solid state devices

2.6.1 Coated wire electrodes

An aliquot of the PVC membrane cocktail incorporating the tetra ethylester *p-t*-butylcalix[4]arene ligand (**Id**), was coated directly onto the surface of the 3 mm platinum disc electrode. The electrode was termed "coated wire electrode" type as it resembled the Pt/PVC contact in conventional coated wire electrodes[5]. During fabrication the platinum disc electrode was clamped in an upright position and a 100 µl portion of the PVC/THF solution pipetted on top (fig. 2.3a). The electrode was then protected from particulate contamination and allowed to dry overnight. This left a thin transparent PVC film on top of the conducting contact. SEM profile measurements of the PVC showed a dry film thickness of 0.23 mm. The membrane was soaked in 10^{-1}M chloride solution of primary ion for a minimum of 30 minutes prior to use.

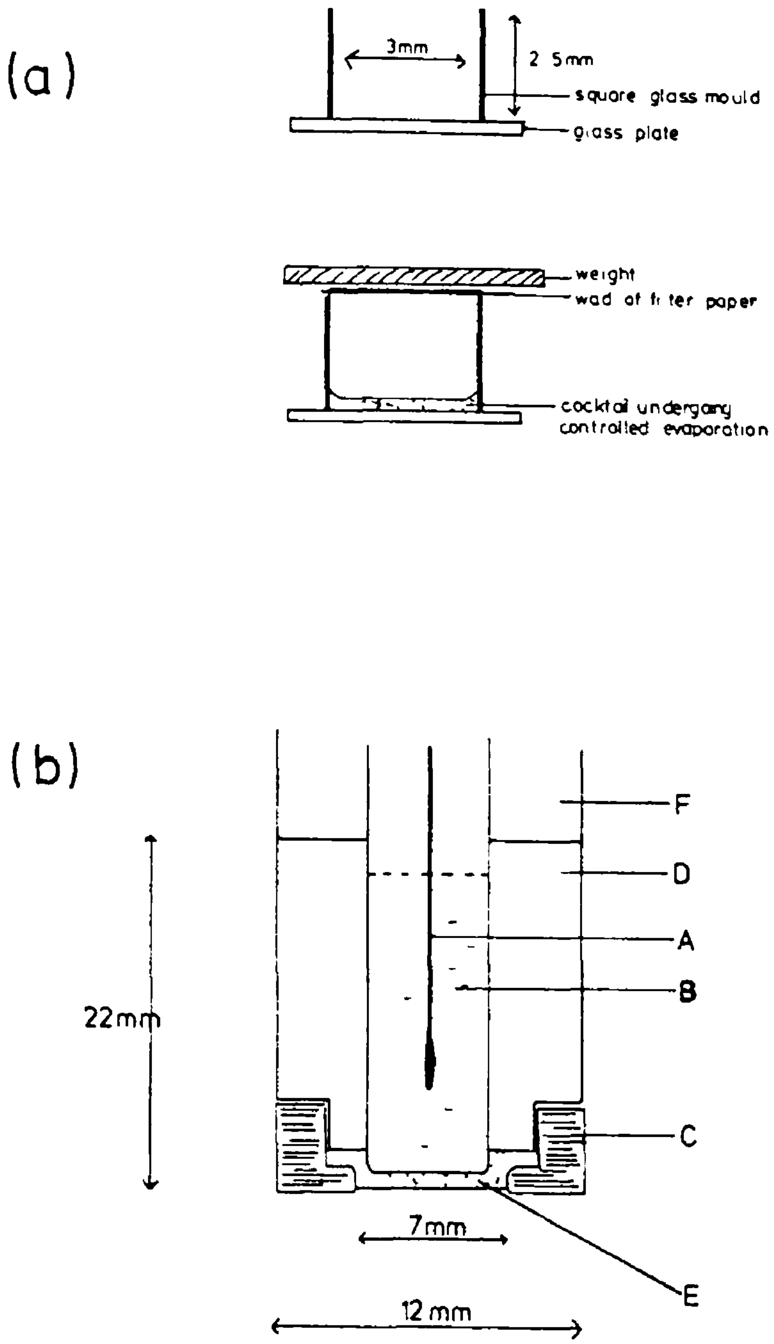


Figure 2 2 (a) Casting of a PVC master membrane, (b) PVC membrane bench electrode (A) chloridised silver wire, (B) internal reference solution, (C) clip-on tip, (D) screw-on electrode cap, (E) PVC ion-selective membrane, (F) main electrode body

2 6 2 Solid contact electrodes

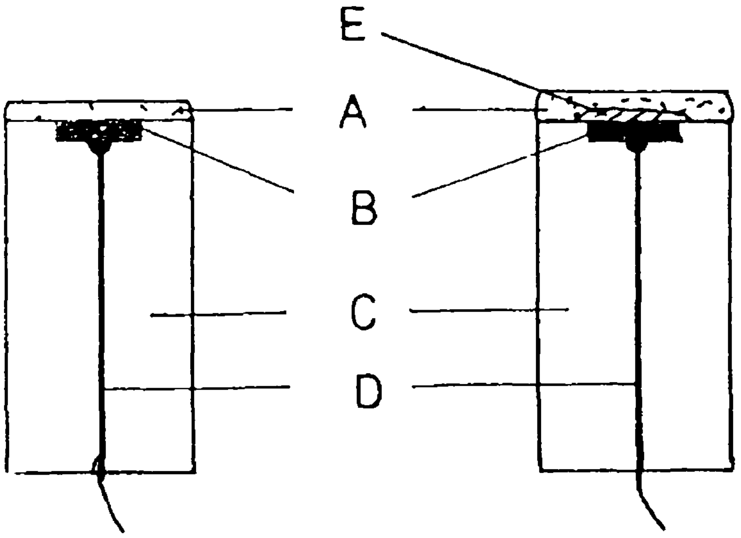
The second type of solid state electrode was based on the use of the conducting polymer polypyrrole doped with $NaBF_4$ as mediating layer between platinum and the same PVC membrane as above (fig 2 3b) The polypyrrole (PPy) films were prepared by three methods (a) constant current oxidation, (b) constant potential oxidation (c) continuous scanning cyclic voltammetry Films were prepared in aqueous and non aqueous solvents using LiCl, $LiBF_4$, $NaBF_4$ and KTpClPB as the doping salts

2 6 2 1 Constant current electropolymerisation

Two techniques were employed for electropolymerisation of polypyrrole by constant current oxidation The first was "drop polymerisation" where a 50 µl drop of monomer solution was placed between the working electrode (WE) and a second electrode of equal surface area (platinum or gold) A current was passed between the two electrodes for various time periods (fig 2 4) At long polymerisation times the pyrrole concentration in the droplet tends to be depleted and so constant current polymerisations were also performed in a three electrode electrochemical cell (fig 2 5) The terminals of the working and counter electrode (CE) (this time a platinum wire angled so that it lay close to the working electrode surface) were connected to the PARC 273 and a current passed between the two electrodes for fixed time periods A much larger volume of monomer solution could then be employed (12 to 25 ml)

2 6 2 2 Constant potential electropolymerisation

The same three electrode electrochemical cell (fig 2 5) was used for the constant potential polymerisations with either a carbon wire or platinum rod counter electrode (CE) The potential across the WE and CE was held at various holding



(a) (b)

Figure 2 3. Schematic diagram of the solid state electrodes, (a) coated wire electrode type, (b) solid contact electrode (A) PVC selective membrane; (B) platinum disc (3mm diamater); (C) teflon electrode body; (D) conducting metal contact, (E) Polypyrrrole (PPy) mediating layer

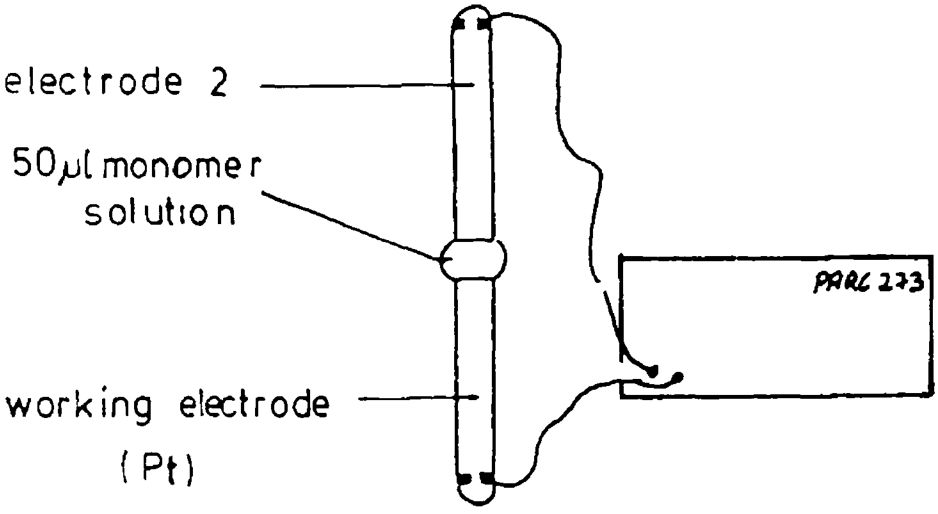


Figure 2 4 Drop polymerisation, the second electrode is a platinum or gold disc electrode of similar diameter to working electrode.

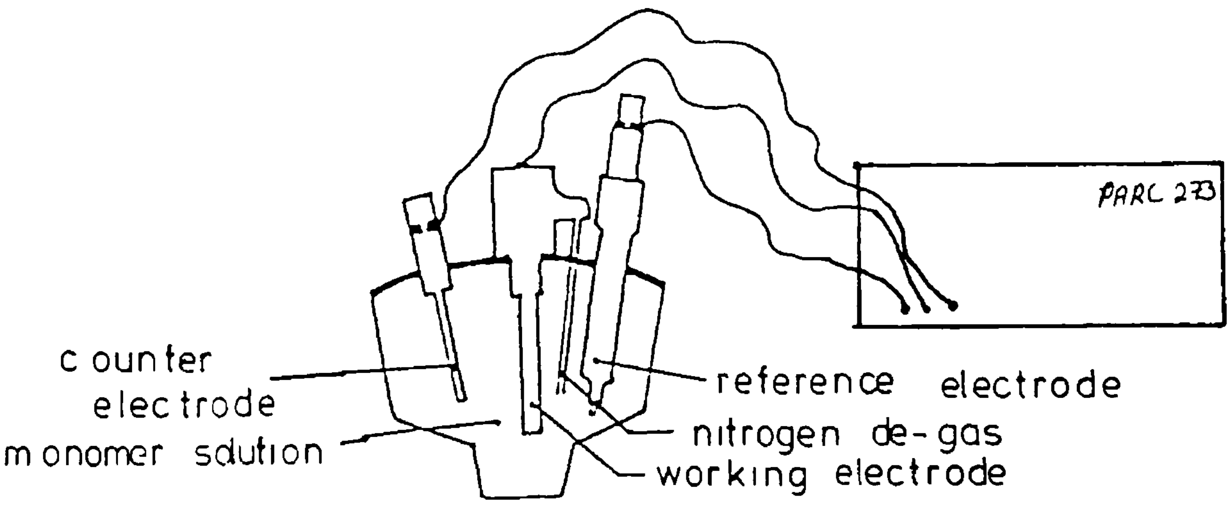


Figure 2 5 One compartment three electrode electrochemical cell

potentials (e g 0 9, 1 0, 1 1 V) for various time periods Oxidation of the monomer thus proceeded and the polymer was laid down on the working platinum electrode

2 6 2 3 Continuous scanning cyclic voltammetry

Again the three electrode electrochemical cell was employed 12-25 ml of the monomer solution was scanned continuously from 0 0 V to 1 0 V at scan rates of 10, 20 and 50 mV/s with scan times of 30, 45 and 60 min The polymer started forming on the first scan and the film thickness increased on each scan Further details of the film properties are described in the results section of chapter 6

2 7 Estimation of selectivity coefficients

The selectivity coefficient (K_{ij}^{pot}) is used to express the degree of preference of an electrode for its primary ion i relative to an interfering ion j K_{ij}^{pot} has already been defined by the Nikolskii equation

$$Ecell = E^o + S \log \left[a_i + \Sigma K_{ij}^{pot} (a_j)^{\frac{zi}{zj}} \right] \qquad (2\ 1)$$

where z_i and z_j are the charges on the ion i and j respectively and E^o is the standard potential of the electrode or a constant Various methods have been outlined for obtaining estimates of K_{ij}^{pot} the most frequently used ones are the separate solution and mixed solution methods which have been outlined in full by Moody and Thomas [6]

2 7 1 Injection of interferents

Preliminary evaluation of electrode selectivity was obtained by injecting known amounts of primary ions and interfering ions into a solution of primary ion of known concentration The difference in potential readings was noted This technique was usually used for investigating the dynamic response of the electrodes or as a rapid, simple estimation of the electrode sensitivity and selectivity before further time consuming methods were attempted

2 7 2 Separate solution method

A calibration curve was obtained for the primary ion (i) over the concentration range, usually 10^{-1} to 10^{-5}M The process was then repeated for the interfering ion (j) and plot similar to fig 2 6 was obtained The selectivity coefficients were then calculated by either of the two methods outlined below

(a) Equal activities
The electrode response (E_I) to a solution containing the primary ion (i) only is given by the Nernst equation

$$E_I = E^o + S \log a_i \qquad (2\ 2)$$

The electrode response to a mixture of cations is given by the Nickolskii equation (2 1 above) If the electrode is placed in a solution containing the interfering cation (j) only, then the potential (E_2) to cation (j) can be obtained from equation 2 1 by letting $a_i = 0$

$$E_2 = E^o + S \log K_{ij}^{pot} a_j \qquad (2\ 3)$$

If the potentials E_1 and E_2 are measured in solutions containing equal primary and interfering ion activities i e $a_i = a_j$ and provided the valency of the charge of the primary and interfering ion are equal i e $z_i = z_j$ then K_{ij}^{pot} can be calculated from the following equation

$$\log K_{ij}^{pot} = \frac{(E_2 - E_1)}{S} \qquad (2\ 4)$$

As the selectivity coefficients are activity dependent, for comparison purposes the chosen activity should always be reported (usually 0 1M or 0 01M)

(b)Equal potentials

Alternatively a method of equal potentials may be used When $E_1 = E_2$ equations (2 2) and (2 3) may be combined to give

$$K_{ij}^{pot} = \frac{a_i}{a_j} \qquad (2\ 5)$$

If the primary and interfering ions have different charges the equation may be modified to

$$a_i = K_{ij}^{pot} (a_j)^{(zi/zj)} \qquad (2\ 6)$$

The activities a_i and a_j can be read from the calibration curve where the potentials E_1 and E_2 are equal (fig 2 6)

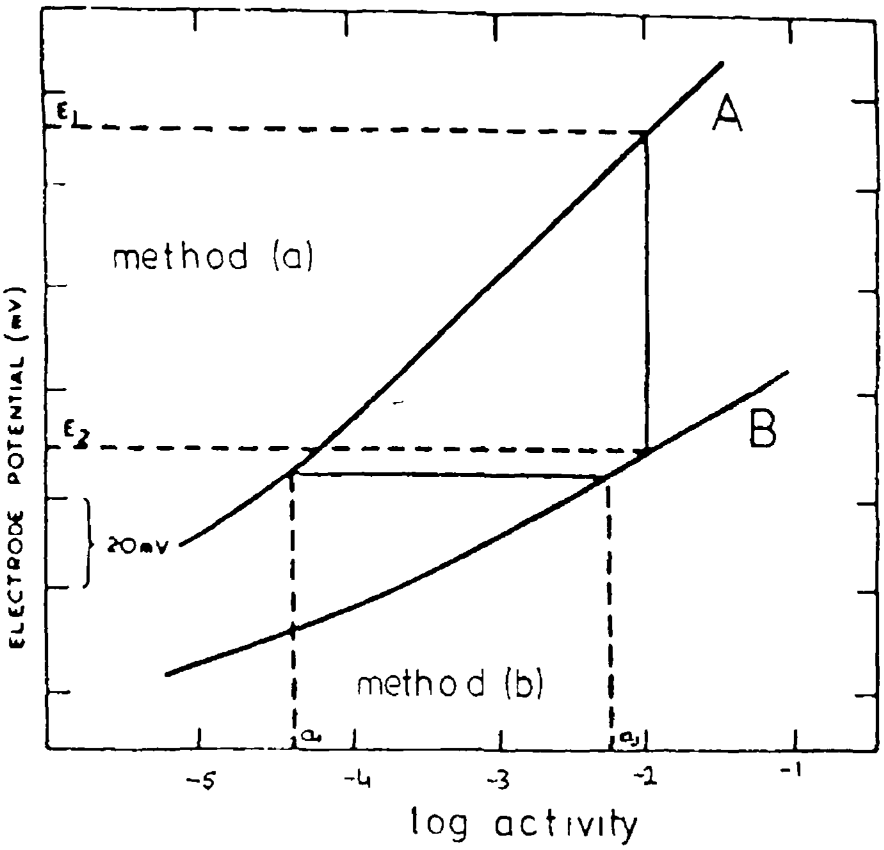


Figure 2 6 Estimation of the selectivity coefficient (K_{ij}^{Pot}) using separate solution method (A) response to primary ion (i) only, (B) response to interfering ion (j) only.

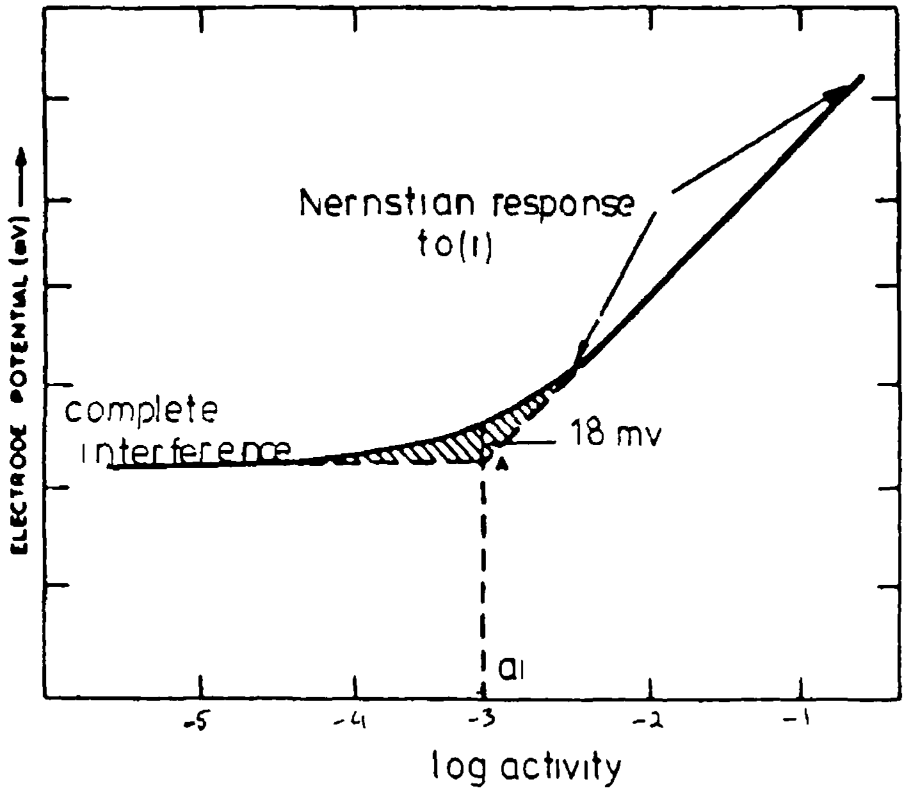


Figure 2 7 Estimation of selectivity coefficient (K_{ij}^{Pot}) using the mixed solution method

2 7 3 Mixed solution method

Here the calibration curve is recorded in (a) the absence and (b) the presence of a fixed level of interfering ion (e g $a_j = 0\ 01M$) throughout the calibration range of the primary ion As the activity of the primary cation falls, the interfering ion j exerts its influence until complete interference sets in along the horizontal plateau and the potential is constant (fig 2 7) The two linear portions are extrapolated to calculate the activity of the primary ion a_i at the intercept and the selectivity coefficient is calculated from equation (2 5) where a_j is the constant background interference activity If drift of the potential is observed in the plateau region when ion (j) provides high interference, then the value of a_i can be taken at the point where the two curves differ by 18 mV In the case where $z_j = 2$ i e divalent ion selectivity a value of 8 9 mV should be used

A second mixed solution method may be employed where the interferent (j) is varied against a constant level of primary ion (i) This method is extensively used in pH studies

The selectivity coefficients obtained by the separate solution method have been critisised since separate solutions of the primary and interfering ions are used The values obtained by the mixed solution methods are more realistic as they follow more closely the conditions that would be present in real sample matrices and are generally recommended [6,7] One of the major drawbacks of selectivity coefficients is that they are not highly reproducible or precise quantities owing to several factors

(a) The selectivity coefficients for any interfering ions is dependent on the ionic strength of the solution and the activity level at which the primary and interfering ions are measured

(b) They depend on whether the values are recorded in mixed solution or separate solutions

(c) The actual method/equations used to obtain the final result may have an effect on the calculated selectivity coefficient value

(d) The membrane composition of the electrode e.g. the amount and type of ionophore, plasticizer and additives which is mainly determined by the membrane manufacturer, will affect the selectivity characteristics of a particular electrode. Therefore it is very important to state exactly the composition of the electrode, the conditions under which the measurements were made and the methods used in the calculations. It is not uncommon to find that the numerical value of the selectivity coefficient for identical electrodes evaluated by different authors show significant discrepancies. This can be seen in the work of Hulanicki and Augustowska [8] who summarised the published data for two ORION ion-selective electrodes from different workers. Differences in selectivity values also occur when different methods are used for the same electrode within the same laboratory[9].

2.7.4 Other methods

Srinivasan and Rechnitz [10] tried to improve the consistancy of selectivity coefficient values by a modified mixed solution method. They claimed that their graphical plots of the manipulated data would increase the confidence in the selectivity values. Gadzekpo and Christian proposed a method which they termed "matched potential" method [11]. The method involves measuring the change in potential upon the addition of the primary ion to a reference solution containing the primary ion. The interfering ion is then added to an identical reference solution until the same change in potential is observed. The change in potential is the same in both cases from a constant initial background. The advantage of the method is that is does not necessitate Nernstian responses to the primary ion by the electrode and it is largely independent of drift. It certainly provides a more direct approach compared to the arithmetically cumbersome mixed solution method of Srinivasan and Rechnitz [10]. More recently Hiiro et al. outlined another method which they termed the "continuous variation" method [12]. The potential of the electrode is measured in a series of mixed solutions in which the logarithmic sum of the concentrations of the primary and interfering ion are kept constant. The method appears to compare well to other mixed solution methods but there is an inherent error in the calculations which presumes that the sum of the logarithm of the activities is constant when in fact it does vary and a mean value must be used instead

Another approach to the determination of more meaningful selectivity coefficient data is the application of sensor arrays and multivariate calibration to determine the slope, standard cell potential and selectivity coefficient data for all the electrodes in the array [13,14] The accuracy of the predicted parameters was tested by using the model to predict the concentrations of the three cations in the mixed calibration solutions and the errors observed were typically no larger than 3%, which is a definite improvement on the accuracy of traditional single electrode methods

2 7 5 Discussion

From a theoretical point of view estimation of the selectivity co-efficients enables the activity of the primary ion to be determined even in the presence of various interfering ions As outlined above the practice and estimation of selectivity coefficients is problematic and a single satisfactory treatment has yet to be widely accepted The separate solution and mixed solution methods in sections 2 7 2 and 2 7 3 are the most commonly quoted methods in the literature They are simple to perform, do not involve complex mathematical formulae, and act as a useful guide-line to the principal interferents to be expected and the approximate activities at which they can be tolerated without major adverse affect on the primary ion response

2 8 Redox responses

The response of any electrochemical reaction which involves a transfer of charge to or from species in solution can be defined as

$$\text{oxidant} + ne^- \rightleftharpoons \text{reductant} \qquad (2\ 6)$$

$$\text{Ecell} = E^{o} + S \log \frac{[\text{oxidant}]}{[\text{reductant}]} \qquad (2\ 7)$$

where Ecell is the measured value of the cell potential, E° is the formal potential for the reaction A plot of potential(Ecell) vs the quantity [oxidant]/[reductant] or the ratio of the concentration of the two species in solution should give a theoretical slope of 59 2mV for a one electron system In order to investigate the ideality of the response at a platinum or polypyrrole/platinum electrode an oxidant/reductant couple was chosen whose standard potential falls within the conducting range of the polymer polypyrrole i e 0 2 V to 1 0 V The redox couple based on the potassium salts of iron ferric/ferro cyanate was found to be suitable

$$\underset{(\text{FeIII})}{\text{Fe(CN)}_6^{3-}} + \bar{e} \rightleftharpoons \underset{(\text{FeII})}{\text{Fe(CN)}_6^{4-}} \qquad E^{o} = 0\ 36\text{V} \qquad (2\ 8)$$

Different ratios of FeIII FeII of 5 1, 2 1, 1 1, 1 2, and 1 5 were prepared and the response of the electrode versus Ag/AgCl was measured in these solutions The slope of the Ecell versus log([FeIII]/Fe[II]) curve was then used to estimate the ideality of the redox response

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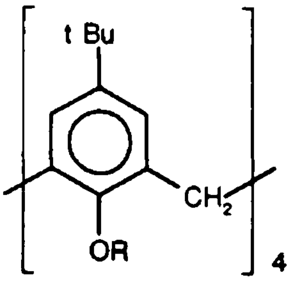
Chapter 3

Sodium PVC membrane electrodes

3 1 Introduction

The best known sodium ISE is the sodium glass electrode, which has been in common use since the early 1960's The principal interferents of sodium glass are hydrogen and silver ions, while potassium ions interfere to a lesser extent Since silver ions are rarely present as sample constituents, problems related to sodium measurement are restricted to pH adjustment in sample solutions The analysis of sodium using PVC electrodes based on neutral carriers is gaining popularity, especially in the area of clinical chemistry, as PVC membranes offer certain advantages over traditional glass electrodes Glass electrodes tend to have a high membrane resistance and are prone to adsorption of organic macromolecules onto the membrane surface and interference from hydrogen ions There are also more engineering difficulties encountered in the design and fabrication of suitable cell assemblies for glass electrodes Apart from the very important clinical analysis of blood electrolytes and urine for sodium there are many other applications where sodium ion-selective electrodes are used in chemical analysis They offer many advantages such as being relatively inexpensive, have fast response times and are unaffected by sample colour, viscosity or presence of suspended solids[1] The amount of sodium in various water sources such as potable water, rivers, estuaries, effluents and boiler feeds may be monitored for reasons of health, safety and efficiency The sodium content of some food stuffs, beverages and agricultural products may also be of interest and can be conveniently measured using ion-selective electrodes[1]

Novel sodium sensors are now described which are based on derivatives of tetrameric *p-t*-butylcalix[4]arenes (fig 3 1) The first group of ligands to be discussed are esters namely the methylester **(Ic)**, ethylester **(Id)** and *n*-butylester **(Ie)** Two of the ligands **(Ic)** and **(Id)** had previously been incorporated into liquid membrane glass pipette electrodes using TCB (trichlorobenzene), toluene and 2-NPOE (2-nitrophenyl octylether) as the liquid matrix[2] Modified versions of these electrodes containing small amounts of ion-exchanger KTpClPB (potassium tetra kis *p*-chlorophenyl borate) worked well as potentiometric ion



R = $CH_2CO_2CH_3$ Ic

R = $CH_2CO_2C_2H_5$ Id

R = $CH_2CO_2(CH_2)_3CH_3$ Ie

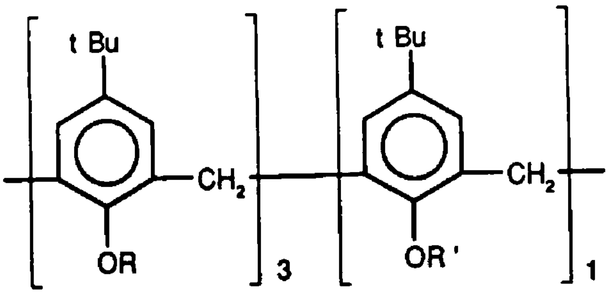
R = CH_2COCH_3 If

R = CH_2COt-Bu Ig

R = CH_2COAdamantyl Ih

R = $CH_2CO_2C_{10}H_{21}$ (4)

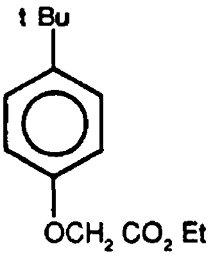
R = CH_2CO_2decylester (5)



R' = CH_2CO_2H R = $CH_2CO_2CH_3$ Ij

R' = CH_2CO_2H R = $CH_2CO_2C_2H_5$ Ik

R' = CH_2CO_2Me R = $CH_2CO_2C_2H_5$ Im



(6)

Figure 3 1 Structure of the compounds discussed.

sensors with high selectivities over the group I and group II cations Subsequently the methylester ligand was shown to work in a PVC membrane electrode[3] The bulkier *n*-decylester derivative of *p*-*t*-butylcalix[4]arene **(4)** has also been used successfully as an ionophore in a PVC membrane electrode[4] A later paper by the same authors described a cyclohexylester derivative **(5)** in a PVC membrane using DOS as a suitable plasticizer and showed it to have excellent selectivity characteristics for the group I and group II metal cations[5] The second group of calix[4]arene derivatives contain ketone functionalities Derivatives containing methylketone **(If)**, *t*-butylketone **(Ig)** and adamantylketone **(Ih)** groups have shown promising results in phase extraction studies (see section 1 15 3 1) In general they showed much broader patterns of ion transport with much higher %extraction for K$^+$, Li$^+$ and Rb$^+$ compared to the ester containing derivatives However the peak ion transport was still for sodium in all cases The third and final group of calix[4]arene derivatives are a relatively new class of ligands where one of the acetate groups of the tetra methyl and tetra ethylesters are hydrolysed to form the monoacid trimethylester **(Ij)** and the monoacid triethylester **(Ik)** respectively

Two different electrode configurations were used to assess the potential use of these new ligands as sensing agents in PVC membrane ISE's during the course of study Accordingly the discussion is divided into two parts, the first deals with those ligands incorporated into mini electrodes and the second part of the discussion deals almost exclusively with a bench type macro configuration The electrochemical half cells in both electrode geometries are identical the only difference between then being that of physical size

3 2 Experimental

The procedure for the preparation of these electrodes is outlined in sections 2 5 1 (mini electrodes) and 2 5 2 (macro electrodes) PVC membrane cocktails were prepared according to the procedure outlined in section 2 4 with typical membrane compositions as in table 3 1 - unless otherwise stated

Injection experiments provide a rough guide to electrode selectivity and may be obtained by injecting known amounts of ions into a sample solution containing the primary ion In addition, extra information is also obtained regarding the response of the electrode to shifts in the measured analyte Unless otherwise stated, 225 μl of 1M NaCl or interfering ion was injected with an autopipette into a rapidly stirred 25 ml aliquot of 10^{-3}M NaCl The change in potential was monitored using a chart recorder The concentration change in the case of a sodium injection involves a step change of approximately one order of magnitude, 10^{-3} to 9 91x10^{-3}M

Unless indicated otherwise the calibration curves in this thesis are plotted as log[concentration] rather than log[activity] Selectivity coefficients were calculated by the separate solution (SS) method in 0 1M solutions of the interfering ions (see section 2 7) The divalent selectivities were confirmed by the mixed solution (MS) method using 10^{-1}M fixed interfering ion concentration

Table 3 1 Membrane compositions of the tetrameric calix[4]arene electrodes

component	weight/mg
ionophore	2 0
ion-exchanger(KTpClPB)	0 5
plasticizer(2-NPOE)	200 0
PVC	100 0

3 3 Ethyl *p*-*t*-butylcalix[4]arene acetate (Id)

3 3 1 General characteristics

A batch of mini electrodes was prepared and the response of the electrodes measured in 10^{-1} to 10^{6}M solutions of pure NaCl The results for 10 electrodes are illustrated in table 3 2 The average slope is 56 5 +/-1 4 mV dec^{1} change in Na^+ over the activity range 10^{-4} to 10^{-1}M, tailing off at lower concentrations to 30 mV dec^{1} The response of electrodes 7, 9 and 10 are shown graphically in fig 3 2 The average estimated limit of detection for sodium is 3 6x10^{-6}M in the absence of interferents The results for the 10 electrodes indicate a Nernstian response extending over the 10^{-1} to 10^{-4}M range, calculated from potentials taken after three minutes immersion in the test solution Measurements of resistance were carried out in 0 1M NaCl unstirred solutions for 4 of the newly constructed electrodes, the electrodes having been stored in 0 1M NaCl previous to measurements The average resistance was found to be 2 32+/-0 35 MΩ This resistance is in accordance with typical values observed for solvent polymer membrane electrodes and is significantly less than the resistance found with glass electrodes[6]

3 3 2 Injection experiments

Injection experiments involving injections of sodium suggest a Nernstian response (fig 3 3) The response was very fast, probably only limited by the stirring rate The response to other alkali and alkaline earth metals was small Although by no means a detailed study, these transients give an indication of the response time of the electrodes The shape of the traces tends to be highly distorted, due to the way the analyte is presented to the surface of the electrodes (fig 3 4) Unfortunately, it is not easy to create reproducible concentration steps at the electrolyte/electrode interface unless conditions are strictly designed for response time experiments, hence the measured data lacks reproducibility However Lindner and Toth[7] have suggested that even with an ideal step change in the sample concentration,

Table 3 2 Response (mV) and slopes (mV dec ^{1}) of 10 electrodes incorporating ethylester ligand **(Id)** in gently stirred solutions at room temperature Slopes over the 10^{1} to 10^{4}M NaCl activity range, ideal slope = 59 62 mV dec ^{1} at 25^{o}C, r = correlation coefficient

Electrode	1	2	3	4	5
[NaCl] /M	Response /mV				
10^{-5}	27 4	35 6	20 0	32 2	108 5
10^{-4}	49 9	36 8	30 3	37 5	85 0
10^{-3}	95 8	91 1	79 4	92 6	136 2
10^{2}	150 3	147 1	136 1	151 7	188 5
10^{-1}	205 6	201 3	192 0	207 6	241 7
Slope mV dec ^{1}	54 0	57 0	56 1	57 3	53 9
r	0 9984	0 9999	0 9991	0 9999	0 9996

Electrode	6	7	8	9	10
[NaCl] /M	Response /mV				
10^{-5}	61 5	55 3	104 5	51 4	42 8
10^{-4}	92 7	98 4	113 5	100 8	91 0
10^{-3}	148 9	154 7	166 4	155 2	144 3
10^{-2}	205 0	211 4	222 5	210 9	204 5
10^{-1}	259 8	266 7	277 0	264 0	254 6
Slope mV dec ^{1}	57 8	58 2	56 7	56 5	57 1
r	0 9999	0 9999	0 9997	0 9999	0 9996

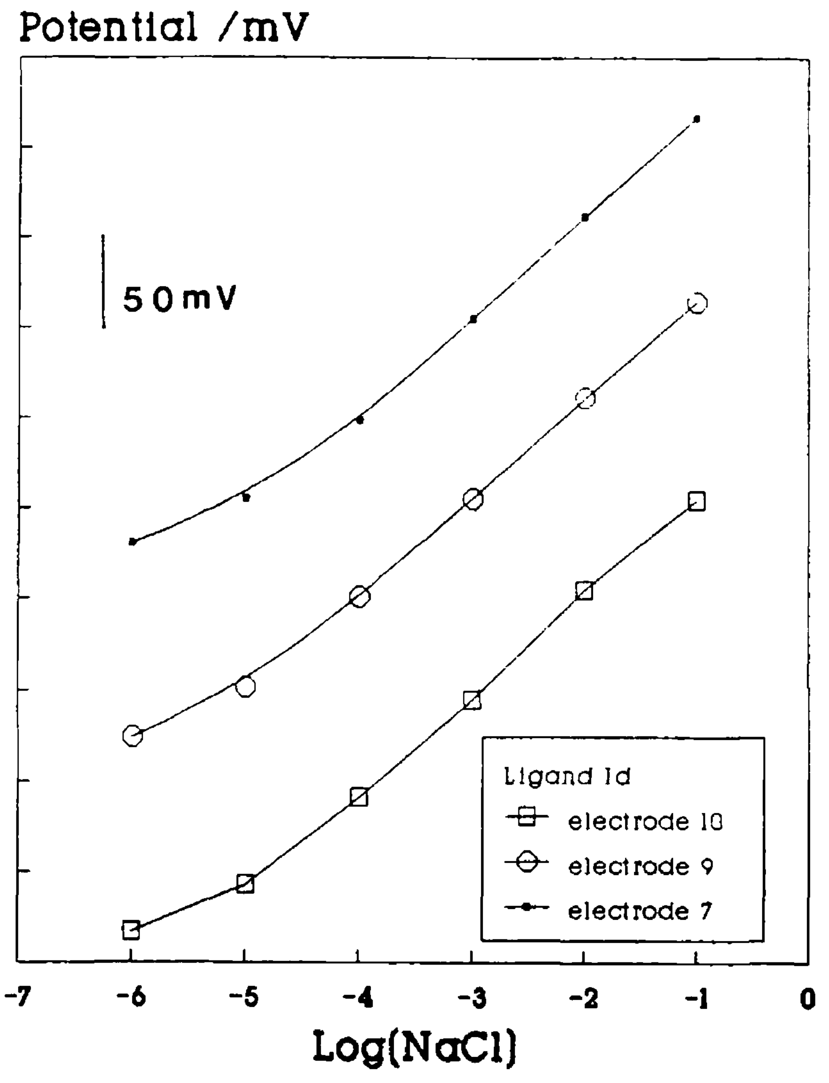


Figure 3 2 Calibration curves for electrodes 7, 9 and 10 incorporating the ligand tetra ethylester *p*-*t*-butyl[4]calixarene (Id) in pure NaCl solutions

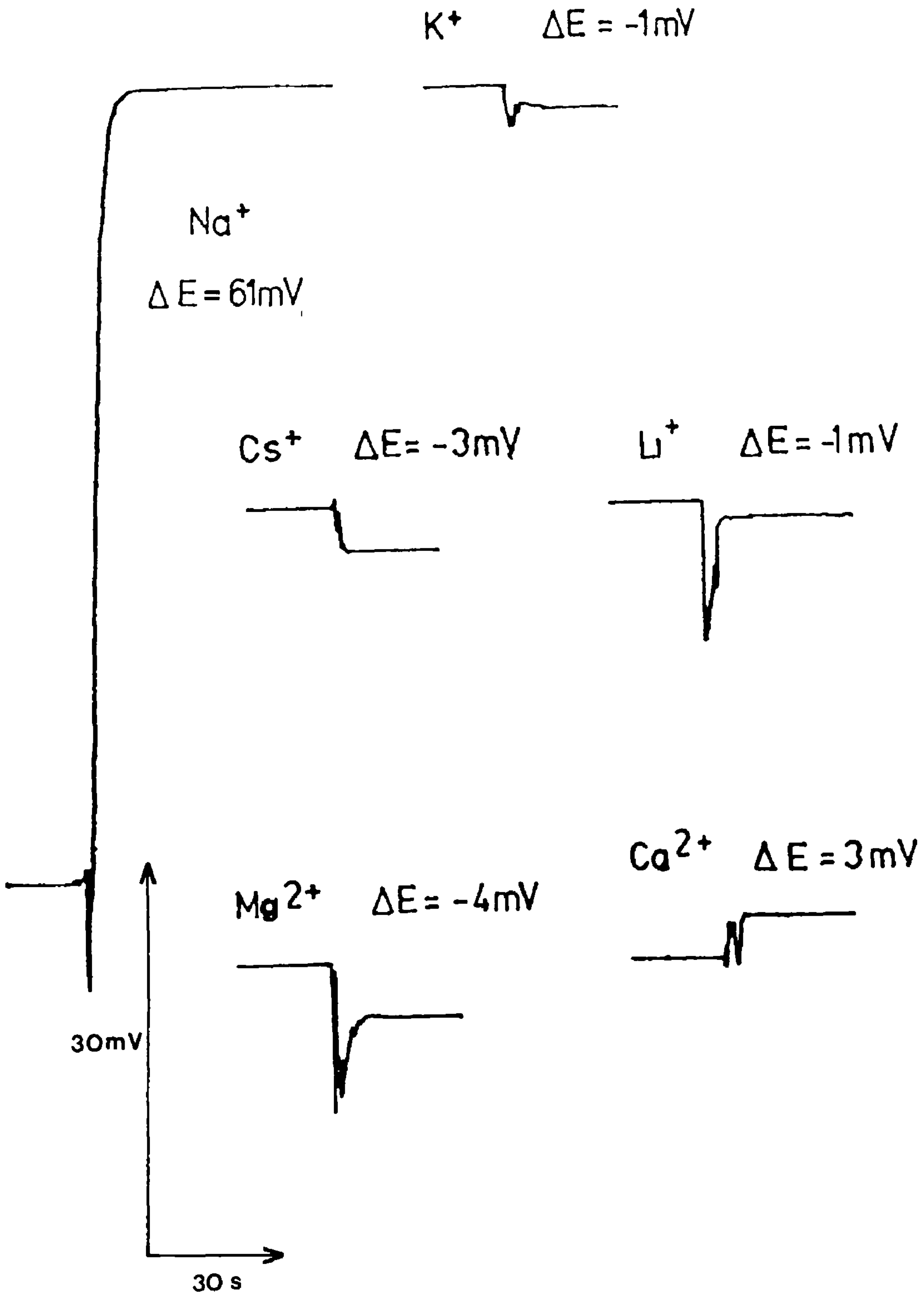


Figure 3.3 Injection experiments. Response (mV) of electrode 7 containing the ethyl ester ligand (Id) to 0.225ml injections of 1M cation solutions into 25ml 10^{-3}M NaCl.

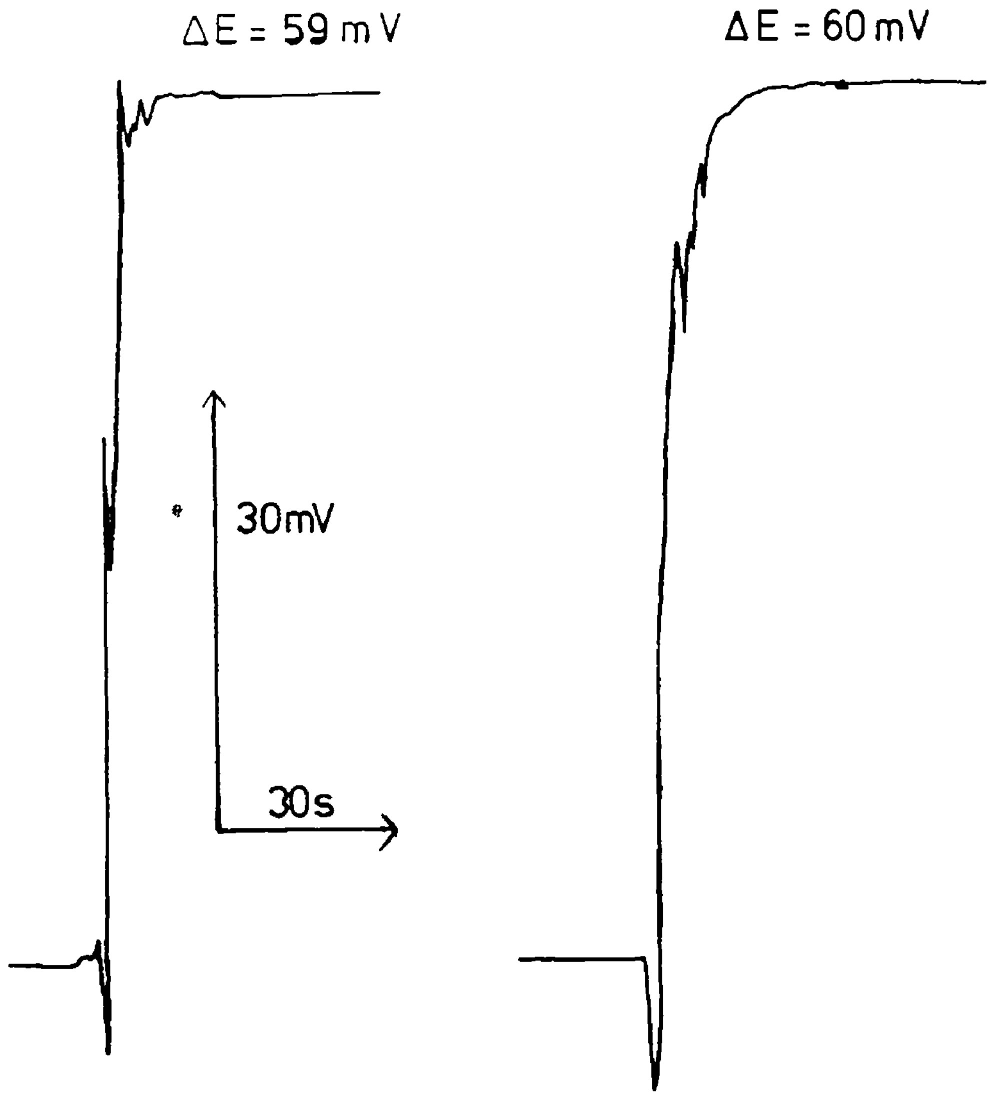


Figure 3 4 Injection experiments. Response (mV) of electrode 7 containing the ethyl ester ligand (Id) to a 10-fold change in NaCl concentration.

where a very fast concentration change is assured at the electrode surface, the electrode may still be in contact with parts of the solution containing different concentrations leading to mixed potentials that may distort the response curve In addition, as mentioned in the theoretical section 1 9, the response time functions are not controlled exclusively by the electrolyte/electrode interface, but by other factors such as technique, concentration change and design and geometry of the cell Several workers have reported specially designed cells to avoid these problems These include a switched wall jet mechanism which allows the flow passing perpendicular to the working electrode to be switched from one activity to another in a time of 7 ms[8] Other workers have concentrated on FIA (flow injection analysis) systems using high flow rates where the solution flow is parallel to the electrode surface The sensitivity of the measurement can in theory be increased by extending the residence time of the sample in the detector cell e g by decreasing the flow rate or by increasing the sample volume[7, p212]

3 3 3 Selectivity coefficients

The average selectivity coefficients for four electrodes based on the ethylester ligand are given in table 3 3 The order of selectivity across the group I alkali metals is

$Na^+ > K^+ > Cs^+ > Li^+$

which is in agreement with the phase transfer data (table 1 2)

$Na^+ > K^+ \approx Cs^+ > Rb^+ > Li^+$

A clear preference for Na^+ ions is apparent with good selectivities against all the other cations tested The selectivity coefficient for potassium ($\log K_{ij}^{pot}$ = -1 9) shows an approximate 100 fold preference by the sensor for Na^+ ions compared to K^+ ions There is some ambiguity in the H^+ response This was attributed to ageing effects of the membrane, with possible leaching of the active components from the membrane It is also thought that hydrolysis of the tetra ester to the monoacid triester may occur (see section 3 13 for a fuller discussion)

Table 3 3 Average selectivity coefficients for electrodes 2,3,9 and 10 incorporating the ethylester ligand (**Id**) Selectivities by the SS method, divalent selectivities confirmed by the MS method, s = standard deviation, n=4

Interfering ion(j)	$\log K_{ij}^{pot}$	(s)
j=Na^+	0 0	
j=Li^+	-2 4	0 01
j=K^+	-1 9	0 2
j=Cs^+	-2 1	0 8
j=H^+	-2 1	0 4
j=NH_4^+	-2 8	0 1
j=Ca^{2+}	-2 4	0 1
j=Mg^{2+}	-2 6	0 4
j=Ba^{2+}	-3 2	0 6

3 3 4 Lifetime

The lifetime of an ion-selective electrode can be an important consideration, the degree of importance depending on the particular application To investigate the useful lifetime, the performance of the electrode was observed over a two month period by measuring the slope of the response function of an electrode in standard 10^{-1} to 10^{-4}M aqueous NaCl solutions The electrode was stored in 10^{-1}M NaCl over the period in question and it would have been used routinely for 5 to 10 hours per week during the period A plot of the electrode slope over the study period is shown in fig 3 5 and indicates a lifetime of up to 2 months before the slope of the tetra ethylester (**Id**) dropped below a value of 50 mV dec^{1}

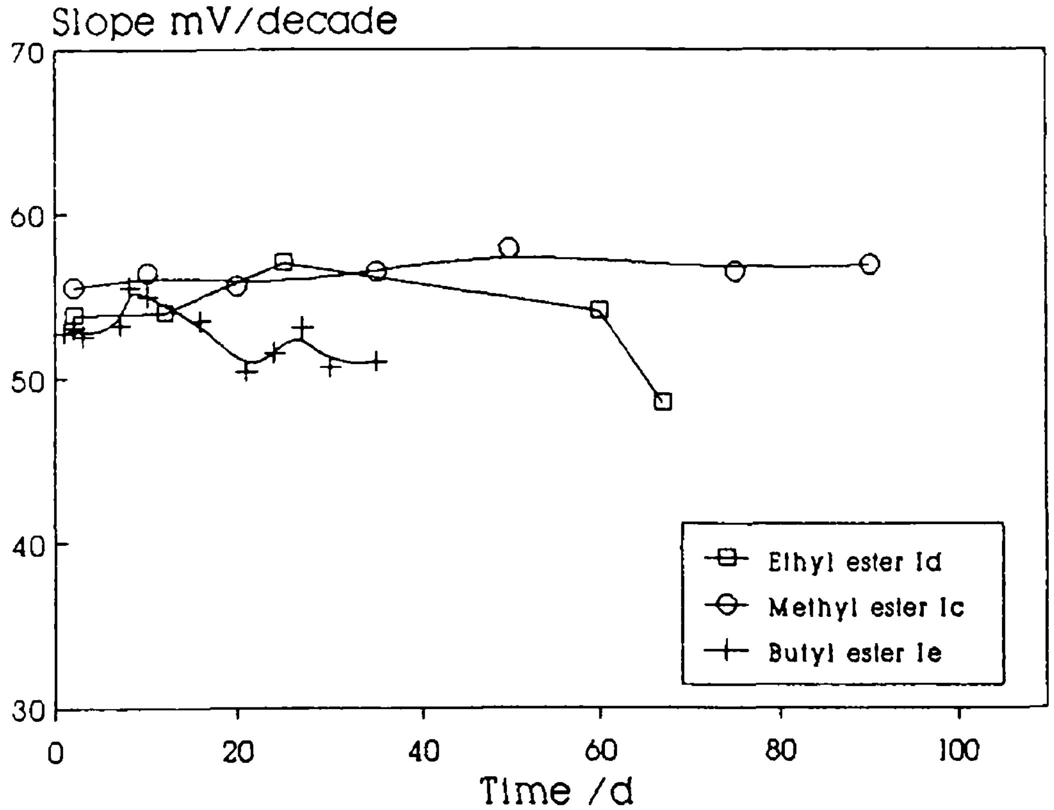


Figure 3 5 Lifetime studies. Slope ($mVdec^{-1}$) vs. time for electrodes containing the ester derivatives. Ligands Ic, Id and Ie as marked. Slopes calculated over the 10^{-1} to 10^{-4}M NaCl activity range

3 3 5 Tetra ethylester (Id) summary

The ionophore **(Id)** has been shown to act successfully as an ion-complexing agent when incorporated into a PVC membrane electrode using 2-NPOE as plasticizer with small controlled amounts of ion-exchanger The electrode has a fast response time and has been shown to maintain its performance for at least two months The electrode showed good selectivity over the group I and group II ions The selectivity was later confirmed by the injection studies

3 4 Methyl *p*-*t*-butylcalix[4]arene acetate (**Ic**)

3 4 1 General characteristics

The potentiometric response for five mini electrodes based on the methylester (**Ic**) over the 10^{-6} to 10^{-1}M NaCl range and the corresponding slopes are presented in table 3 4 The average slope is 58 0 +/-1 1 mV dec ^{1} and the limit of detection for sodium in the absence of interfering ions is 6 8x10^{-6}M

Table 3 4 Response (mV) and slopes (mV dec ^{1}) of 5 electrodes incorporating the methylester ligand (**Ic**) Slopes calculated over the 10^{-1} to 10^{-4}M NaCl activity range, ideal = 59 62 mV dec ^{1}, r = correlation coefficient

Electrode	1	2	3	4	5
[NaCl] /M	Response /mV				
10^{-1}	190 2	190 7	191 6	197 1	195 2
10^{-2}	133 5	134 6	136 3	141 6	140 2
10^{-3}	75 7	76 9	80 3	85 8	85 2
10^{-4}	17 3	22 6	26 4	32 5	30 2
10^{-5}	-22 6	-12 8	-21 7	-14 7	-18 8
10^{-6}	---	---	-32 0	-32 7	-58 8
Slope mV dec ^{1}	59 8	58 3	57 2	57 6	57 0
r	0 9999	0 9997	0 9998	0 9999	0 9999

3 4 2 Selectivity coefficients

From the results presented in table 3 5 it is evident that the electrodes exhibit excellent selectivity against a range of common alkali and alkaline earth metal ions with the order of preference following the sequence

$Na^{+} > Cs^{+} > H^{+} > K^{+} > Li^{+} > NH_4^{+} > Mg^{2+} > Ca^{2+}$

Thus the order of selectivity is similar to that observed in the phase transfer studies of salt picrate extraction (see section 1 15 3 1)

$Na^+ > Cs^+ > K^+ > Rb^+ > Li^+$

and agrees with the values previously reported for the same electrode[3,9]

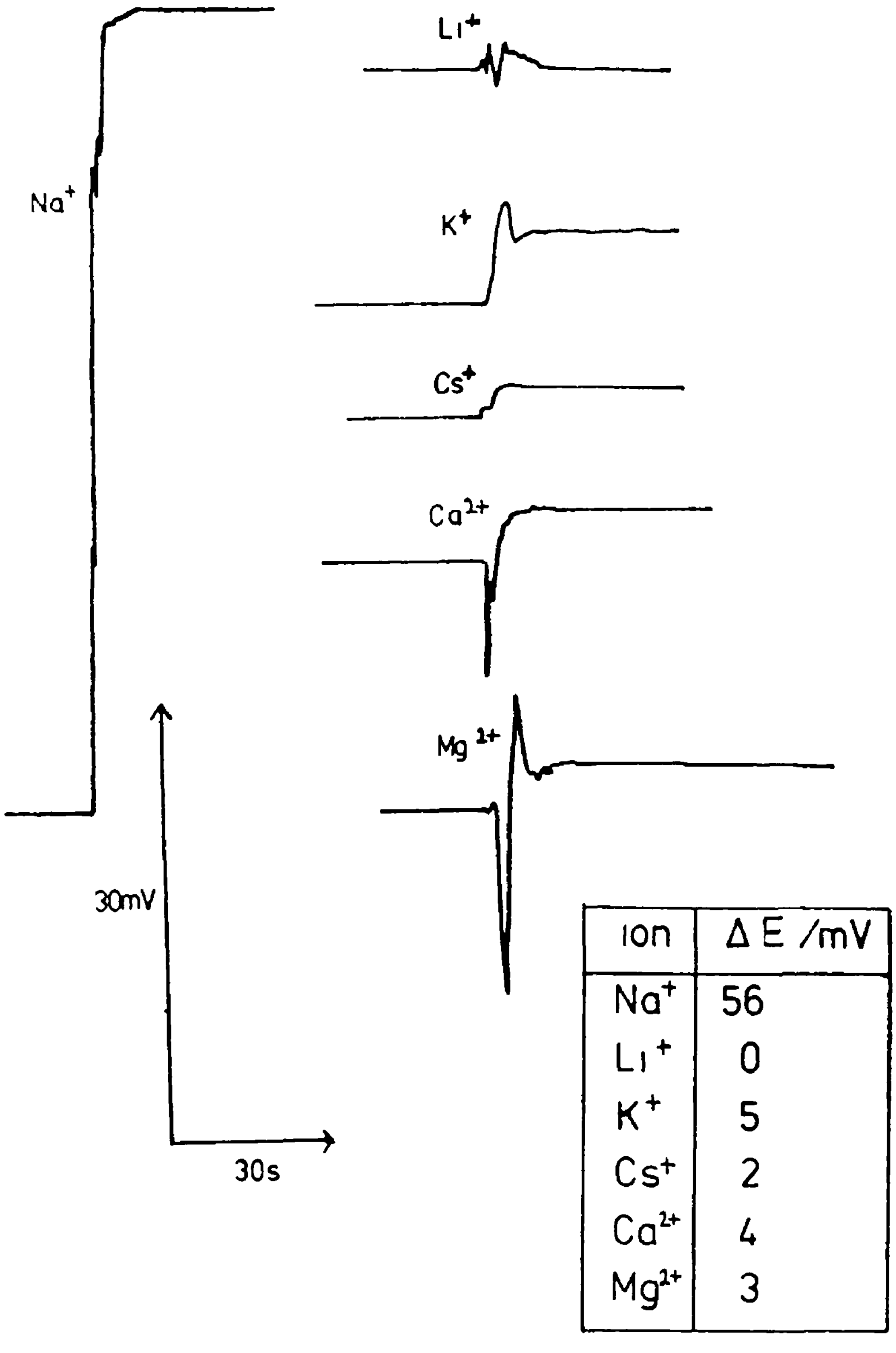
Table 3 5 Selectivity coefficients of PVC mini electrodes based on the methylester ligand (**1c**), standard deviation of $logK_{ij}^{pot}$= 0 04-0 5 units

Selectivities by the SS method, divalent ion selectivities confirmed by the MS method

Average slope/ mV dec ^{1}	58 0 +/- 1 1
Resistance/MΩ	1 03 +/- 0 04
Interfering ion (j)	$logK_{ij}^{pot}$
$j=Na^+$	0 0
$j=K^+$	-2 2
$j=Cs^+$	-1 8
$j=Li^+$	-2 5
$j=H^+$	-1 9
$j=NH_4^+$	-2 7
$j=Ca^{2+}$	-3 7
$j=Mg^{2+}$	-3 1

3 4 3 Injection experiments

Fig 3 6 shows the response of an electrode incorporating the ligand (**1c**) to injections of interfering ions The response to both alkali and alkaline earth metals is small (<5 mV) thus confirming the high selectivity reported in table 3 5 The response to a similar injection of sodium ions (involving a step change of approximately one order of magnitude 10^{-3} to 10^{-2}M) shows a Nernstian response to Na^+ ions (ΔE = 56 mV) The sodium injection also allows one to see graphically the fast dynamic response of the electrode ($t_{90\%}$ < 5 s)



ion	ΔE /mV
Na$^+$	56
Li$^+$	0
K$^+$	5
Cs$^+$	2
Ca^{2+}	4
Mg^{2+}	3

Figure 3 6 Injection experiments. Response (mV) of an electrode containing the methyl ester ligand Ic to 225µl injections of 1M cation solutions into 25 ml 10^{-3}M NaCl.

3 4 4 Lifetime

The performance of an electrode was observed over a three month period by recalibrating the electrode periodically in pure NaCl solutions and measuring the slope of the response function The electrode was regularly utilised during the period and was permanently stored in 10^{-1}M NaCl when not in use The slope versus time plot (fig 3 5) indicates that lifetimes of three months are possible in aqueous solution A more detailed study of the electrode lifetime has been carried out for this ligand and a lifetime of at least one year has been deduced from membrane resistance studies[10]

3 4 5 Tetra methylester ligand (**Ic**) summary

The ionophore has been shown to be an effective ion-complexing agent in PVC membrane electrodes Electrodes with excellent selectivity characteristics have been fabricated using 2-NPOE as plasticizer with small controlled amounts of ion-exchanger They have fast response times and have been shown to maintain their performance characteristics for long periods of time An outstanding property of the electrode is its excellent Na^+ selectivity over H^+ and Li^+ For any application, low interference from H^+ ions is an obvious advantage A high selectivity over Li^+ ions may be desirable in the clinical field where measurement of blood sodium may be carried out against a high background of blood lithium in the case of patients suffering from maniac depression Here the standard treatment is to raise the blood lithium level to between 0 1 to 1 0 mM[11] Electrodes incorporating this ligand have now been applied to measurement of blood sodium in normal serum by dipping methods[12,13] and using a FIA system[14] Results from the indirect potentiometric assessment of large numbers of plasma samples with electrodes incorporating ligand (**Ic**) showed a good correlation with the results from two automated analysers (Technicon SMAC3, Hitachi 704) and with flame photometric data[13] The plasma sodium determination was performed by one of two methods (1) from a calibration curve and (2) the standard addition method The results suggest that the electrode could be used as an alternative to the sodium glass electrode currently used in many hospital analysers The ligand

(Ic) has also been used as a Na^+ selective electrode in a four electrode array comprising of three selective electrodes (Na^+, K^+ and Ca^{2+}) and one sparingly selective electrode. A combination of the data from the four electrodes calibrated in solutions containing mixtures of the three ions, leads to improved accuracy and precision of the measurements in multicomponent analytes such as serum[15].

3.5 Discussion of calix[4]arene ester mini electrodes

It is apparent from the phase transfer data and the potentiometric selectivity data, that the more polar calix[4]arene ester derivatives interact strongly with sodium ions and can be used successfully as sensing agents in ISE's. In general the ligands followed the selectivity patterns from the phase transfer data. A comparison of the selectivity data for the two ISE's is shown in fig. 3.7. There is a great deal of similarity in the selectivity data across the methyl and ethylesters showing that the most important selectivity factor is the preorganisation and the spatial arrangement of the common ester oxygen atoms. The smaller variation arising from the alkyl group attached to the ester has a more subtle affect on the selectivity response. The log selectivity coefficients for the alkali metals lie in the range -1.8 to -2.5 units for the K^+, Li^+ and Cs^+. The selectivity against NH_4^+ is more or less constant across the two derivatives ($\log K_{ij}^{pot} = -2.75$). The selectivity against the hydrogen ion varies from one ligand to another but in general it lies in the range $\log K_{ij}^{pot} = -1.6$ to -1.9 units. The largest variation across the group is found in the selectivity towards the divalent species. The selectivity coefficients increase for both Ca^{2+} and Mg^{2+} on going from the methyl **(Ic)** to the ethylester **(Id)**.

A comparison of the two ester based electrodes with four other available sodium electrodes is shown in fig. 3.7. Three of the electrodes chosen for comparison are neutral carrier based, ETH 157, ETH 227[16] and bis(crown)[17] and the fourth is the sodium glass electrode[18]. The methyl and ethylester calix[4]arene derivatives, although not possessing as good selectivity as the sodium glass electrode with respect to Cs^+, K^+ and NH_4^+, are far more H^+ selective and possess

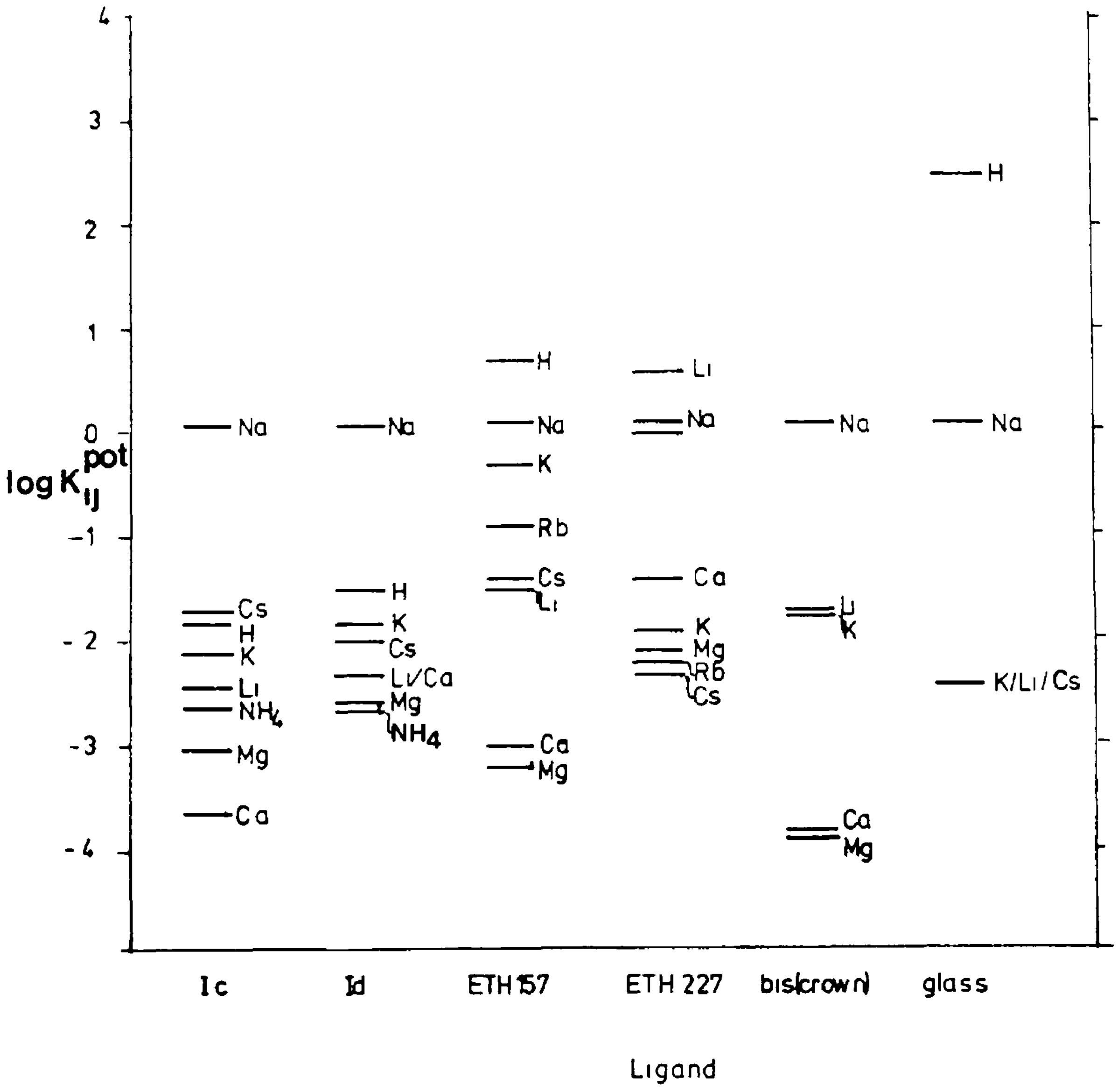


Figure 3 7 Comparison of the selectivity coefficient data for sodium selective electrodes containing the ligand Ic, Id, ETH 227, ETH 157[16], bis(crown)[17] and a glass electrode[18], valency sign omitted for clarity similar Li^+ selectivity The calixarene esters have better selectivity over the group I alkali metals compared to ETH 157 and have more impressive selectivity over H^+ The ligand ETH 227 possesses approximately equal selectivities for K^+, Cs^+ and Mg^{2+} as the ethylester derivative (**Id**) but the Li^+, H^+ and Ca^{2+} selectivity are far better in the case of the ethylester based electrode The 12-crown-4 based electrode shows slightly higher values of selectivity coefficients for Li^+ and K^+ than (**Ic**) and (**Id**), with better selectivity over the divalent ions than the calixarene derivatives[17] Although no value of K^{pot}_{NaH} was quoted for the bis(crown), studies on the response of the electrode across the pH 2-10 range showed little variation in the e m f [17] While the importance of a good selectivity for sodium against potassium and lithium is fundamental in clinical assays, the selectivity against hydrogen is a welcome characteristic in any application, and the calixarenes show an ability to discriminate against H^+ ions far greater than most of the currently available systems As mentioned previously the lithium selectivity can become particularly important while measuring sodium in patients undergoing lithium therapy for maniac depression

Differences in the selectivity is a direct consequence of the spatial arrangement of the polar binding groups in the molecule and so one must relate changes in selectivity to differences in the functional moieties The parent calixarenes are conformationally mobile, that is, one of the aryl groups can rotate around the C-2/C-6 axes in a direction that brings the -OH groups through the center of the macrocyclic ring (see fig 1 12) This is called transformation between conformations If a group larger than a proton is attached to the phenolic oxygen, greater interference in the transformation process occurs This effect is especially pronounced in the smaller calix[4]arene annulus where the ester derivatives become frozen into the so-called cone conformation The x-ray structure of the methyl and ethylesters is shown in fig 3 8 The four ester groups are located on the same side of the molecule which is the preferred conformation for most ester and ketone derivatives [19] The four pendant groups, although mutually syn with respect to the calix, are asymmetrically disposed about the macrocycle In the ethylester (**Id**) two of the aromatic rings are essentially parallel while the other two, on opposite sides of the macrocycle, are almost normal to one another

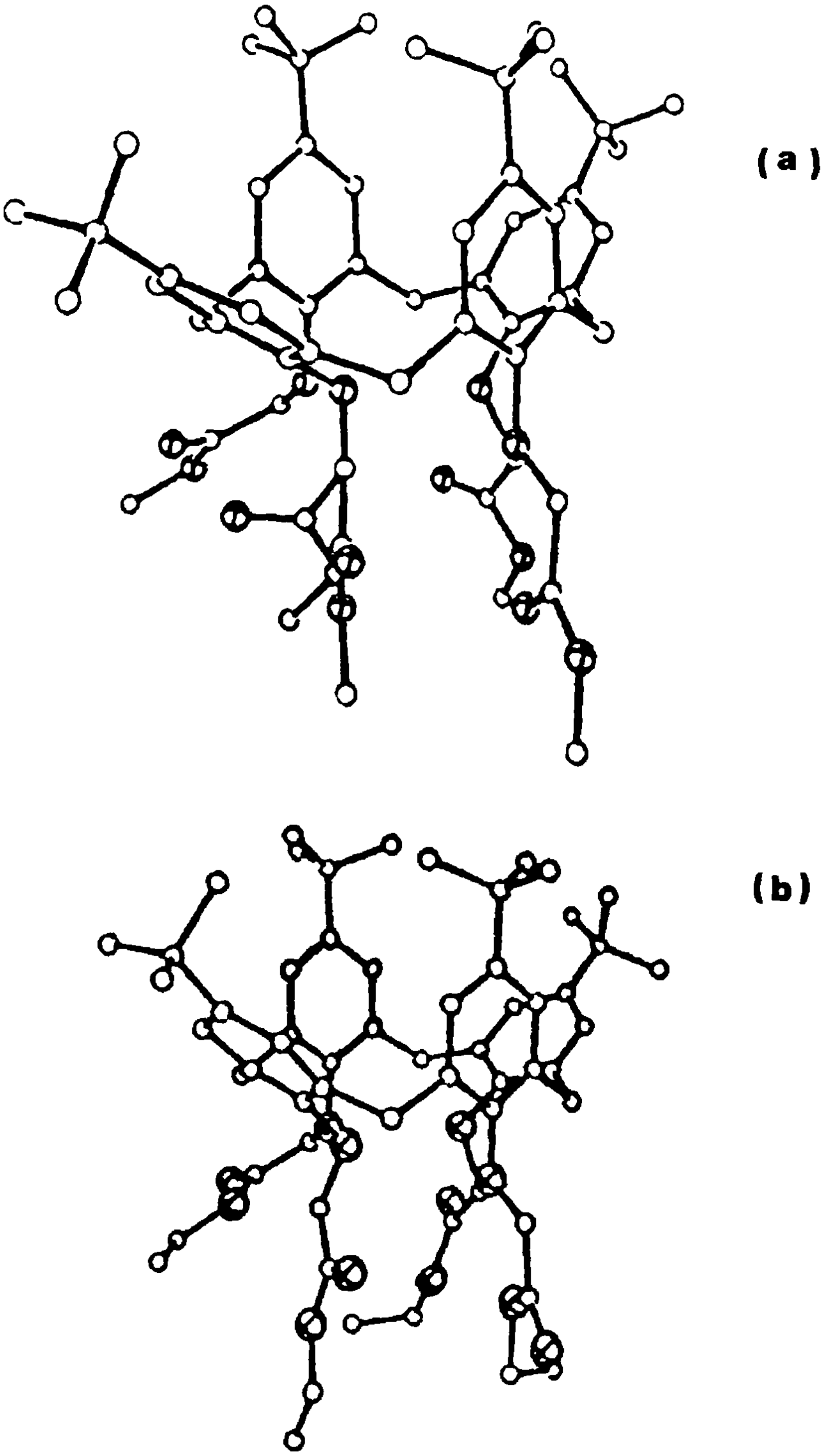


Figure 3 8 Molecular structure of ligands (a) Ic and (b) Id, carbon and oxygen atoms are shown as spheres of arbitrary radius, oxygen atoms are larger circles and are marked with a cross

Much the same type of distorted cone is found for the methylester (**Ic**)[19] The oxygenated pendant groups serve to fix the cone conformation, thus conferring a high degree of primary organisation The four phenolic oxygen atoms and the four ester/ketone carbonyl groups are mutually syn and therefore define a hydrophobic cavity as an extension of the lipophilic calix described by the aromatic nuclei and the four *p-tert*-butyl groups In this arrangement, only a slight rotation of the carbonyl groups towards the inside of the cavity is needed to present a total of eight binding sites towards the guest cation Ungaro et al have prepared the *p-t*-butylcalix[4]arene tetra acetamide[20] and later obtained the x-ray crystal structure of the tetra acetamide potassium complex (fig 3 9) This confirmed the cone conformation of the potassium complex and demonstrated quite elegantly and unequivocally the complete encapsulation of the cation in a polar cavity of eight oxygen atoms[21] Unfortunately, it has been difficult to prepare suitable crystals of the cation complexes of the ester modified calix[4]arenes for x-ray crystallography However all the data point to the formation of a complex in which the cation is centrally located within the hydrophilic cavity defined by the four ester/ketone groups and supported electrostatically by the four phenolic and the four carbonyl oxygen atoms (fig 3 10) This interpretation of complexation by esters and ketones is supported by the x-ray crystal structure of the K^+ complex of the structurally related tetra amide described above, which is conformationally and topologicaly directly related to the ester/ketone series

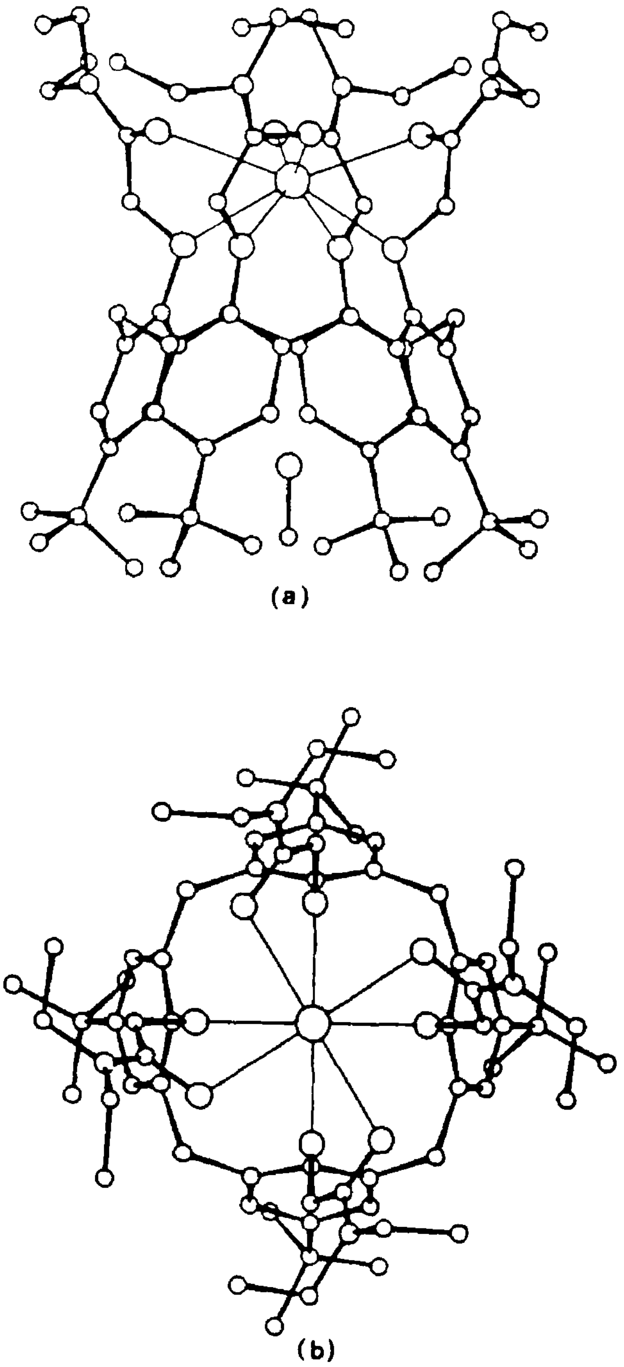


Figure 3 9 Molecular structure of *p*-*t*-butylcalix[4]arene amide 1 1 potassium complex (a) perspective view with one molecule of MeOH occupying the intramolecular apolar cavity (b) view perpendicular to the reference plane[21].

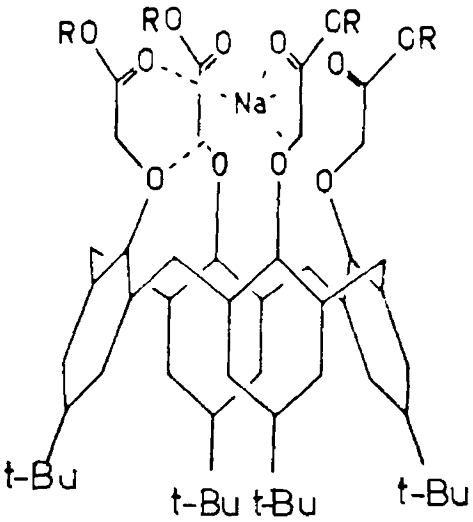


Figure 3 10 Encapsulation of an alkali-metal cation by a tetrameric calixarene ester or ketone

3 6 Tetra methylketone *p-t*-butylcalix[4]arene (If)

3 6 1 General characteristics

The potentiometric response of ligand **(If)** has been investigated in several membrane solvents (plasticizers), 2-NPOE, DOS (dioctyl sebacate), DPP (Dioctyl Phenyl Phosphate) and PP (Phenyl Phthalate) using a 50% mole ratio of ion-exchanger (KTpClPB) to ligand[9] Results are shown in table 3 6 for these electrodes and, for comparison a membrane without the ion-exchanger PP produced membranes with sub-Nernstian responses and was disregarded as a suitable solvent Membranes based on DOS had high resistances at 57 8 MΩ (measured in 0 1M NaCl) approximately 50 times higher than those based on 2-NPOE The electrode based on DPP suffered from reduced linear range so on balance a PVC membrane using 2-NPOE as the solvent with a 50% mole ratio of ion-exchanger to ligand was recommended The present studies adopted the same membrane components with a 50% mole ratio of the ion-exchanger

Table 3 6 Electrode function, resistance, detection limits and drift of mini electrodes incorporating the tetra methylketone ligand (**If**) as ionophore in different membrane solvents[9]

Plasticizer	KTpClPB	Slope	Resistance	LOD	Drift
	%mol	mV dec^{1}	MΩ	M	mV hour^{-1}
2-NPOE	0	57 9	5 3	2 8x10^{6}	+2 1
2-NPOE	50	59 7	1 3	2 3x10^{-6}	+0 1
DOS	50	60 3	57 8	3 1x10^{-6}	+3 0
DPP	50	53 6	3 4	8 7x10^{-4}	+0 4
PP	50	~31	10 3	--	--

A batch of PVC mini electrodes were prepared and the potentiometric response measured in 10^{-6} to 10^{-1}M solutions of pure NaCl Fig 3 11a shows the calibration curves for two of the methylketone electrodes The average slope was 57 5+/-1 3 mV dec^{1} (n=11) for five electrodes with an estimated limit of detection of 5 9x10^{-6}M The values were taken after 3 minutes equilibration and the signal quality was excellent with relatively little noise or drift

3 6 2 Injection experiments

Following the same procedure as outlined previously for the ester ligands injection experiments were conducted The response of the electrode to various interfering ions could then be compared to an identical injection of sodium The transient responses and the overall changes in potential are shown in fig 3 12 for all of the ketone ligands Results for the methylketone (**If**) show a large near Nernstian (ΔE = 55 mV) jump in potential to injections of sodium which is complete within a few seconds The response to the rest of the group I ions is minimal The electrode showed slightly larger responses to the group II alkaline earth metals with an eventual decrease and return to baseline

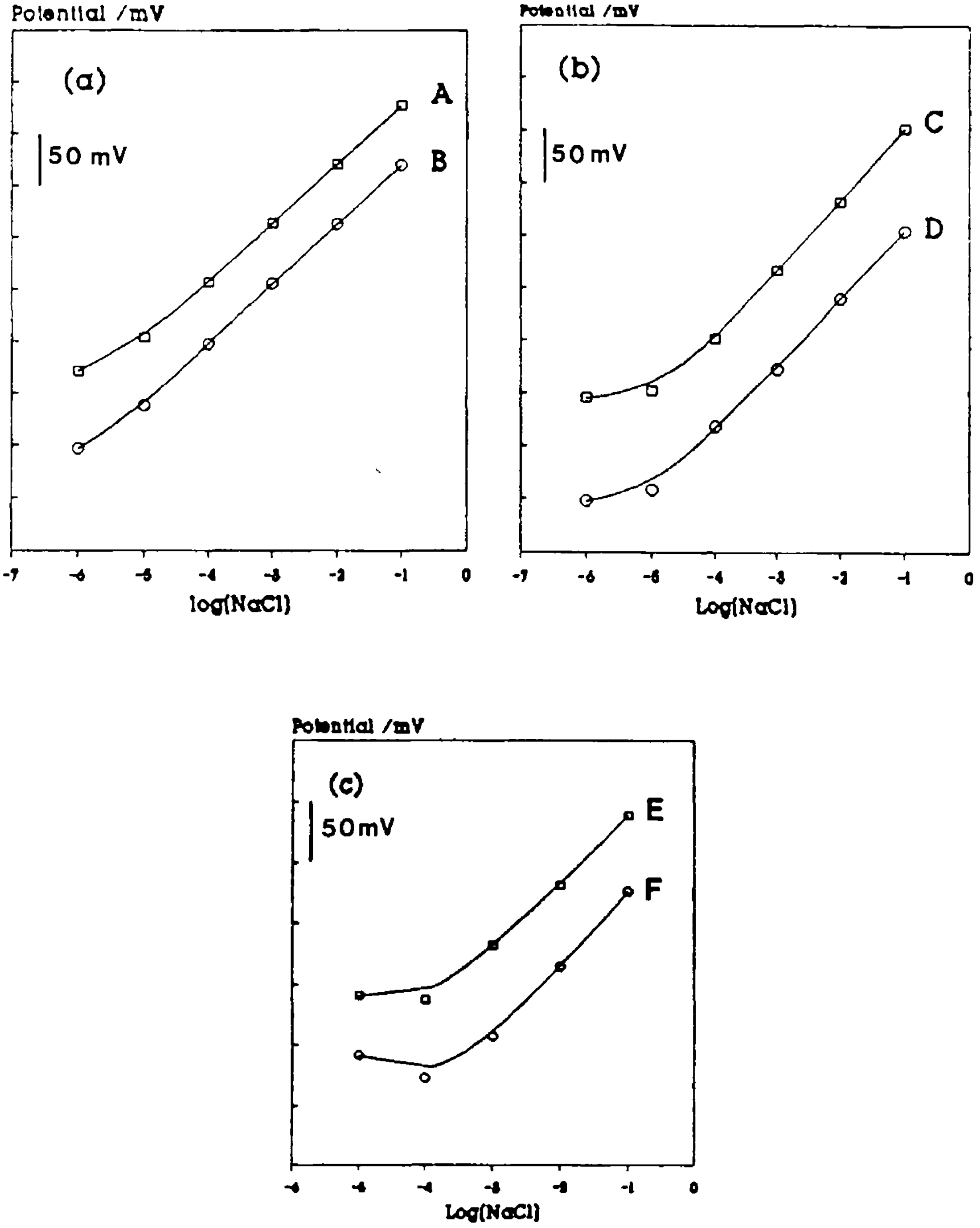


Figure 3 11 Calibration curves and slopes S (mVdec^{-1})of electrodes incorporating the ketone derivatives of *p*-*t*-butylcalix[4]arene (a) methyl ketone If, A S=59 1, B S=59 7, (b) *t*-butyl ketone Ig; C S=59 7, D S=57 6, (c) adamantyl ketone Ih; E S= 62 3, F S= 60 5

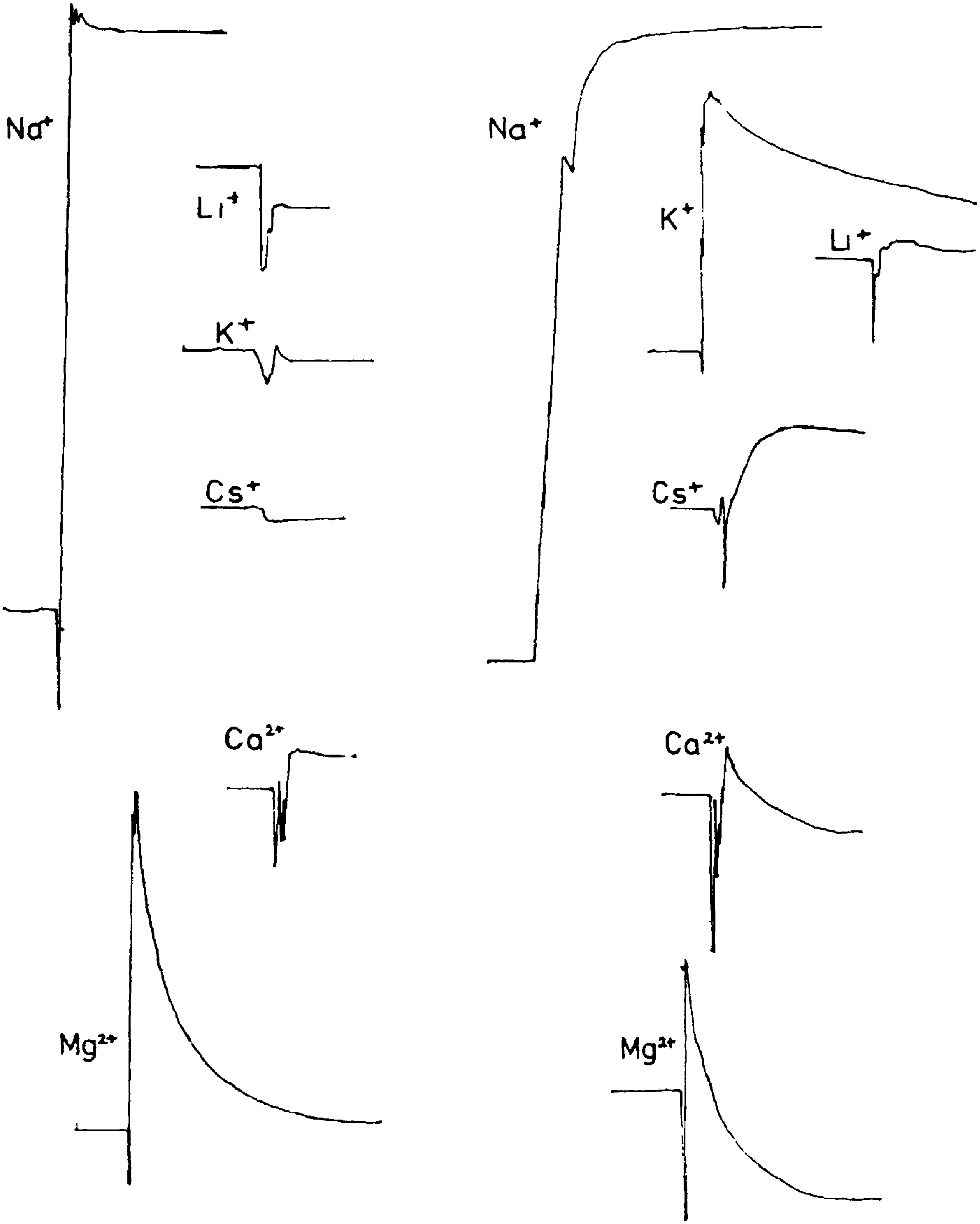
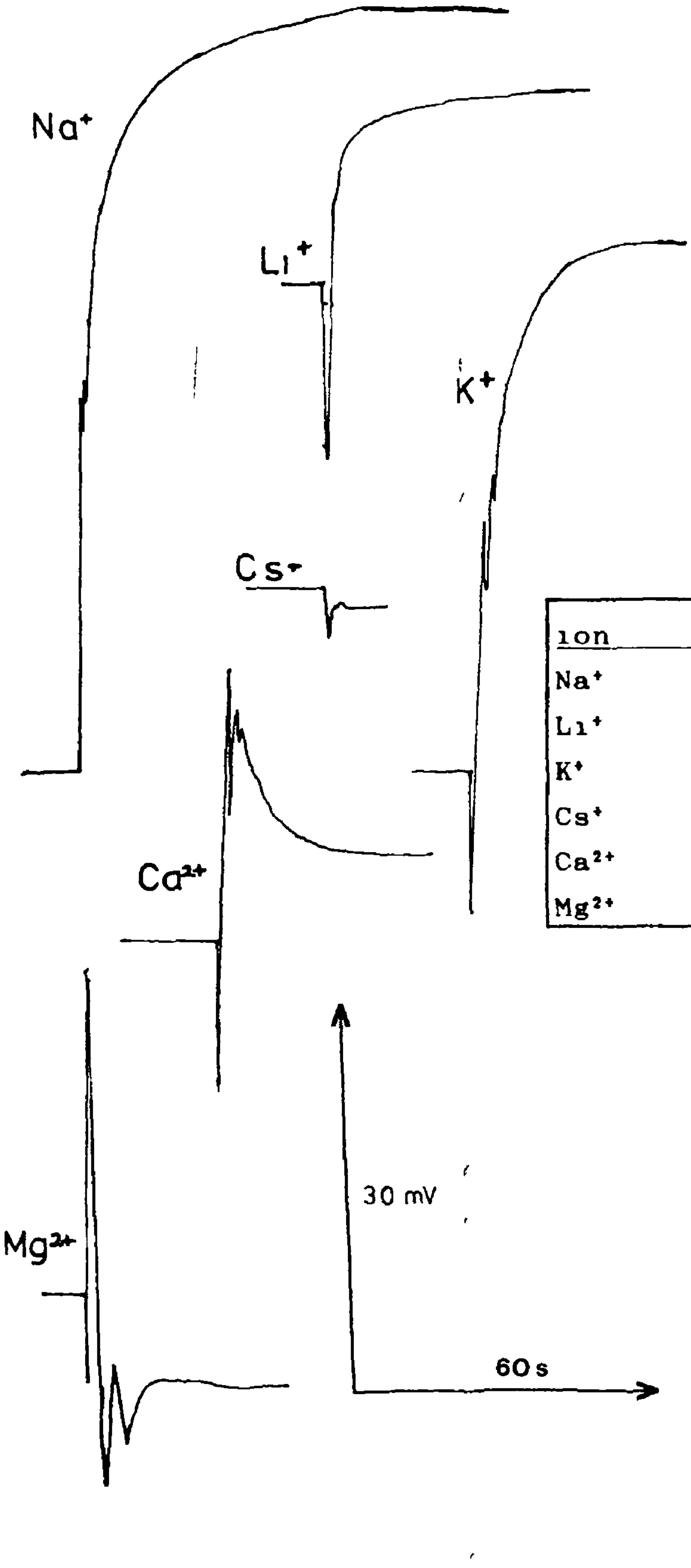


Figure 3 12 Injection experiments Response (mV) of electrodes containing the methyl ketone (If).



ΔE (mV)

ion	(If)	(Ig)	(Ih)
Na^+	55	62	60
Li^+	-4	1	15
K^+	-2	12	43
Cs^+	-1	7	2
Ca^{2+}	3	-4	7
Mg^{2+}	1	-10	-7

3.6.3 Selectivity coefficients

Table 3.7 outlines the average slopes, limits of detection and selectivity coefficients for electrodes based on the three ketone ligands. Excellent selectivities were observed for the methylketone **(If)** against the monovalent and divalent ions and the values of the selectivity coefficients follow closely those reported for the same electrode in a previous study[22]. The order of selectivity was:

$Na^+ > K^+ > Li^+ > Cs^+ \approx H^+$ monovalent ions

$Na^+ > Mg^{2+} > Ca^{2+}$ divalent ions

This agrees broadly with the order of preference in the phase transfer studies (table 1.2). The value of $\log K_{NaLi}^{pot}$ of -2.5 is a little higher than would be expected from the phase transfer studies but it still represents considerable selectivity for Na^+ over Li^+.

Table 3.7 The slopes (mV dec^{-1}) and selectivity characteristics of electrodes based on the ketone derivatives **(If)**, **(Ig)** and **(Ig)**. Selectivities by the SS method, divalent selectivities by the MS method, n=4, standard deviation in parentheses.

Ligand code		**If**	**Ig**	**Ih**
ketone type		methyl	*t*-butyl	adamantyl
Detection limit /10^{-6}M		5.9	15	622
$t_{95\%}$ /s		20	40	60
Average slope /mV dec^{-1}		57.5(1.3)	59.8(1.3)	61.4(2.5)
$\log K_{ij}^{pot}$	$j=Na^+$	0.0	0.0	0.0
	$j=K^+$	-2.3(0.2)	-1.1(0.3)	-0.1(0.1)
	$j=Cs^+$	-2.8(0.4)	-2.3(0.1)	-1.6(0.2)
	$j=Li^+$	-2.5(0.1)	-1.7(0.2)	-0.7(0.1)
	$j=H^+$	-2.8(0.6)	-1.6(0.4)	-1.3(0.3)
	$j=Ca^{2+}$	-2.7(0.4)	-2.8(0.1)	-1.0(0.4)
	$j=Mg^{2+}$	-2.4(0.3)	-2.3(0.1)	-1.9(0.1)

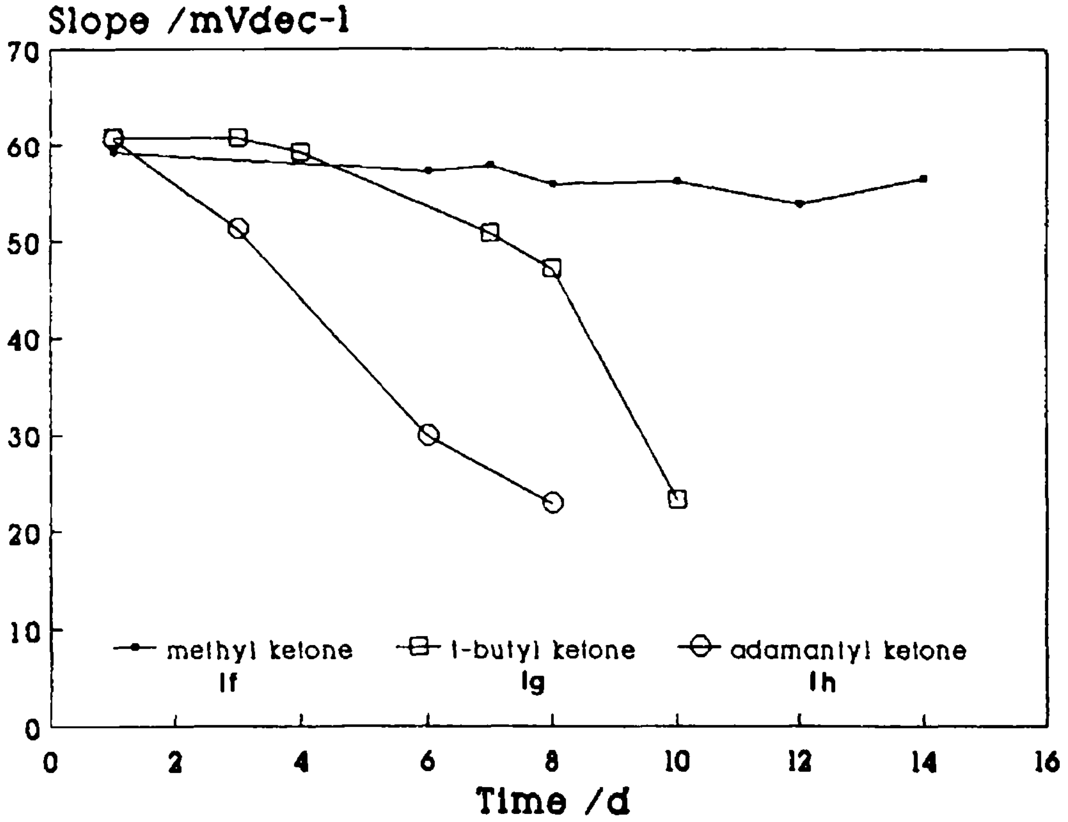


Figure 3 13 Lifetime studies Slope (mVdec^{-1}) vs. time for electrodes containing the ketone derivatives Ligands If, Ig and Ih as marked Slopes calculated over the 10^{-1} to 10^{-4}M NaCl activity range.

3 6 4 Lifetime

The slope of the response function of a tetra methylketone (If) based electrode over the activity range 10^{-1} to 10^{-4}M versus time can be seen in fig 3 13 The electrode showed little variation in performance over a period of two weeks A lifetime of two months has also been observed for the same ligand with two plasticizers (2-NPOE and DOS)[22] This ligand has also been used for the determination of sodium in human plasma samples by discrete dipping methods[22] In a later paper, its use in an FIA system[14] was shown to offer a significant improvement in precision and accuracy over the dipping method described above in reference 21

3 7 *t*-butylketone *p-t*-butylcalix[4]arene (**Ig**) and adamantylketone *p-t*-butylcalix[4]arene (**Ih**)

3 7 1 General characteristics

Much of the work on the ketone derivatives focused on the methylketone (**If**), however two other derivatives *t*-butylketone (**Ig**) and adamantylketone (**Ih**) also showed promising results in phase extraction studies (table 1 2) and were assessed as sensing agents in sodium ISE's

Calibration curves over the 10^{-1} to 10^{-6}M NaCl range are shown in fig 3 11b for the *t*-butylketone ligand and they indicate a Nernstian response to sodium ions The average slope of the linear portion of the curve was 59 8+/-1 3 mV dec ^{1}(n=5) with an estimated limit of detection of 1 5x10^{-4}M The potentiometric response of the adamantylketone (**Ih**) to sodium solutions was linear over the concentration range 10^{-1} to 10^{-3}M but the slope value was higher than expected at 61 4+/-2 4 mV dec ^{1}(n=5) with a limit of detection of 6 2x10^{-4}M These slopes were recorded against a background of diminishing performance characteristics (see lifetime studies) Apart from the severely restricted linear range (see fig 3 11c), electrodes based on the adamantyl ketone displayed more sluggish responses and were more susceptible to noise and drift fluctuations Values were read after 6 minute intervals for the ligand (**Ih**) based electrodes and after 3 minutes for the other two ketone ligands

3 7 2 Injection experiments

Large responses are observed for injections of Na^+ for the *t*-butyl and adamantyl based electrodes (62 mV and 61 mV respectively) (fig 3 12) The *t*-butyl ligand (**Ig**) showed larger responses to K^+ ions and Cs^+ ions compared to the methylketone ligand (**If**) The response to Li^+ was very small and relatively small responses were noted for the divalent ions The adamantylketone based electrode showed the largest responses to the alkali metal cations compared to the other two ketone ligands, K^+ (ΔE = 43 mV) and Li^+ (ΔE = 15 mV) This is also reflected in the high ion transport of these ions in the phase transfer studies (%E values $K^+ = 81\ 3\%$, $Li^+ = 46\ 6\%$)

In addition to a quick estimation of possible selectivity patterns, these results add to the information about the dynamic response of the electrode to shifts in ion activity Comparison of the results following a sodium injection show clearly an increase in response time on going from the methyl to the butyl and to the adamantyl ketone Although all three injections show a large near Nernstian response at long equilibration times the three electrodes take progressively longer to obtain final equilibration approximately $t_{95\%} = 20$ s, 40 s and 60 s respectively

3 7 3 Selectivity coefficients

Table 3 7 outlines some characteristics, slopes and selectivity coefficients of electrodes based on the two ketone ligands **(Ig)** and **(Ih)** The potentiometric selectivity pattern for the *t*-butylketone **(Ig)** is

$Na^+ > K^+ > Li^+ > Cs^+$ monovalent species

$Na^+ > Mg^{2+} > Ca^{2+}$ divalent species

These data agree with the order of preference according to the phase transfer results (table 1 2) A closer examination of the selectivity data for this ligand **(Ig)**, showed that there is a significant difference between selectivity coefficients obtained on day 3 and successive days with the data for fresh electrodes (see table 3 8) There is a much higher selectivity after initial fabrication but this reduces considerably after the first few days of use to steady values

The selectivity data for the adamantylketone **(Ih)** are the least impressive Although some selectivity is observed, again in accordance with the phase transfer patterns, the actual values are very poor In fact the value of $\log K^{pot}_{NaK} = -0\ 1$ suggests that this sensor could function almost equally well as a potassium ion sensor

Table 3.8 Comparison of selectivity co-efficients for ligand (**Ig**) immediately after fabrication and three days later. Selectivities by SS method, divalent ion selectivities by the MS method, standard deviation in parentheses

interfering ion(j)	$\log K^{pot}_{ij}$	
	(day1)	(after 3 days)
Na^+	0.0	0.0
K^+	-1.8 (0.1)	-1.1 (0.3)
Cs^+	-3.3 (0.1)	-2.3 (0.1)
Li^+	-2.6 (0.1)	-1.7 (0.2)
H^+	-3.4 (0.6)	-1.6 (0.4)
Ca^{2+}	-3.1 (0.1)	-2.8 (0.1)
Mg^{2+}	-3.0 (0.2)	-2.3 (0.1)
	n=3	n=4

3.7.4 Lifetime

The slopes of electrodes incorporating methyl ketone (**If**), *t*-butylketone (**Ig**) and adamantylketone (**Ih**) versus time can be seen in fig. 3.13. The *t*-butylketone based electrode maintained its performance for 4-5 days but the slope of the response curve then decreased substantially and reduction of the limit of detection and deterioration of the selectivity characteristics occurred simultaneously. Electrodes based on the adamantylketone showed a severe lack of stability with time. The performance of the electrodes had diminished considerably after a 48 hour period.

3 8 Discussion of the calix[4]arene ketone mini electrodes

The selectivity data for the three ketone derivatives are shown graphically in fig 3 14 and demonstrate clearly a loss in selectivity going across the group from methyl, to *t*-butyl and to adamantyl The methylketone **(If)** derivative produced a very promising sodium ISE with excellent selectivity and stability characteristics In comparison to the ester derivatives, the methylketone showed selectivity characteristics which were in fact slightly superior for the alkali metals than for example the methylester **(Ic)** based electrode The effect of the addition of increasing the bulky nature of the group attached to the ion binding carbonyl oxygen atom is quite drastic, much more obvious than the effect of lengthening the alkyl chain in the ester series The *t*-butyl and adamantylketones become increasingly non-selective in their reponse to the alkali and alkaline earth metals The *t*-butyl ligand based electrode showed an increase in response for the alkali metals K^+, Li^+ and to a lesser extent Cs^+ However, the selectivity over the divalent species is more or less the same compared to the methylketone Electrodes based on the adamantylketone show virtually equal preference for sodium and potassium ions but nonetheless display some ability (albeit severely reduced compared to the *t*-butylketone) to discriminate against the divalent ions and against the larger Cs^+ ion However, the latter ligand also suffers from response time and lifetime problems which would naturally constitute a severe limitation to the usefulness of such an electrode for most applications

It has been shown that the presence of the phenolic oxygen alone is insufficient to extract ions (table 1 2 ligand **(Ia)**) The addition of an ether type oxygen atom in the derivative chain does not enhance the ionophoric activity either (see ligand **(Ib)** table 1 2)[23] Hence it would appear that the presence of the carbonyl oxygen atom is the critical factor which allows the ion binding to occurr i e the structural feature which allows the extraction of sodium ions to become energetically favourable As the three ketones used in the present study possess the necessary carbonyl group for ion binding, the loss in selectivity must be due to some other factor brought on by the increased size of the derivatised group Fig 3 15 shows the x-ray structure of the tetra methylketone[24] This shows that the keto groups, while having a cis conformation with respect to the phenolate oxygen

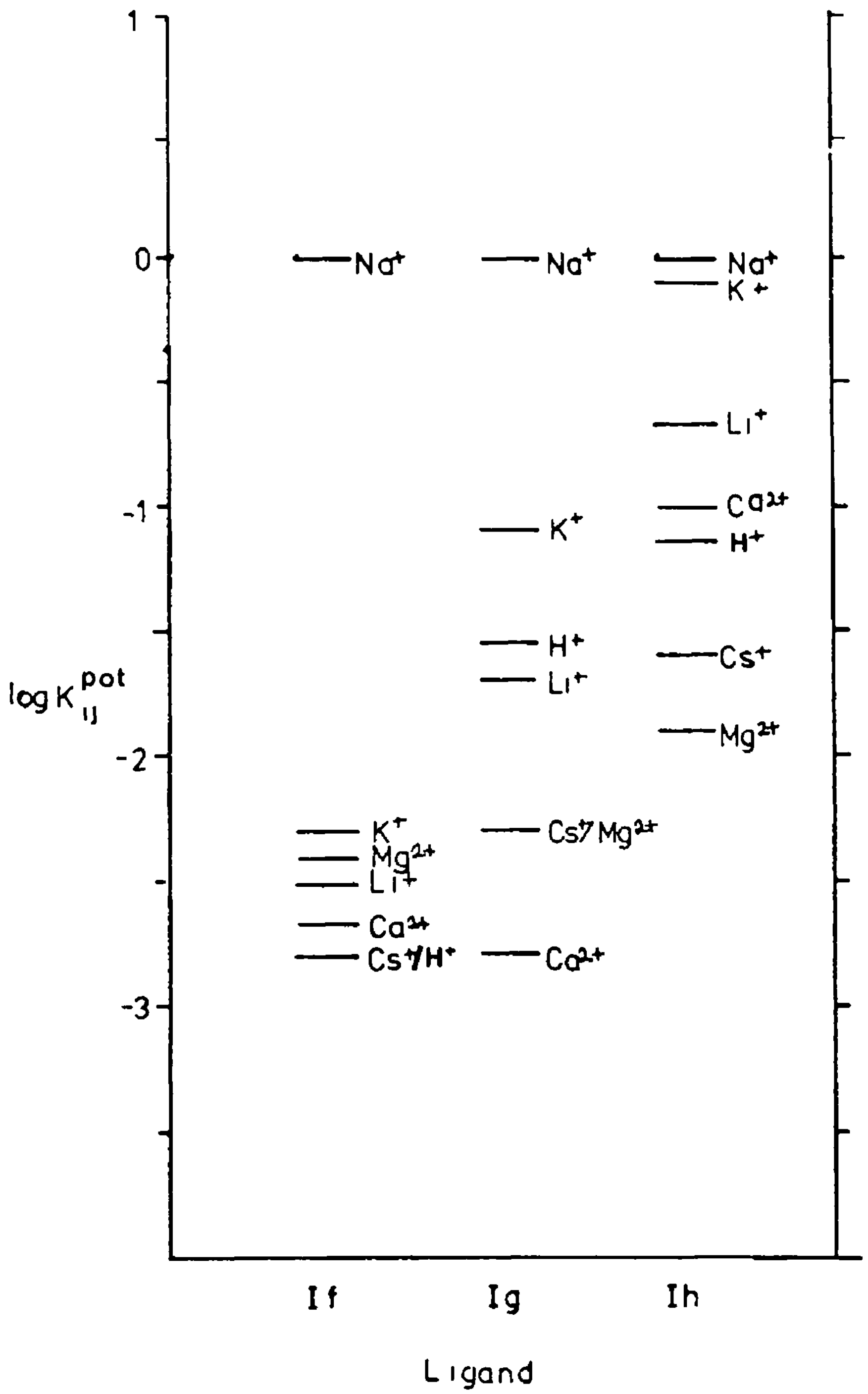


Figure 3 14 Comparison of the selectivity coefficient data for sodium selective electrodes containing the ketone ligands If, Ig and Ih

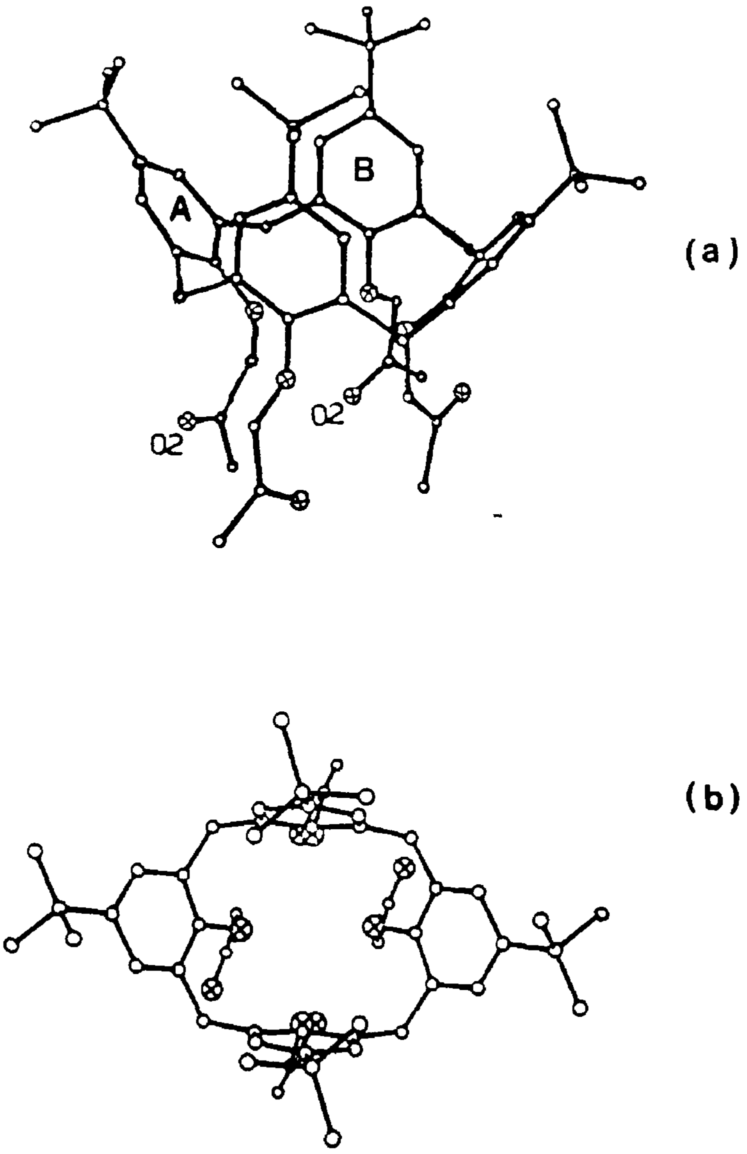


Figure 3 15 Molecular structure of the tetramethyl ketone *p-t*-butylcalix[4]arene If Carbon and oxygen atoms as indicated in figure 3 8 (a) view perpendicular to the reference plane (b) perspective view.

atoms, are quite symmetrically disposed about the cavity, such that the keto O(2A) is directed away from the cavity and the O(2B) points towards it The whole structure is not unlike that of the methylester molecule (**Ic**) which can be seen in fig 3 8 Two of the aromatic rings are approximately parallel while the other two rings on opposite sides of the macro cycle are almost normal to one another The next member of the series, the *t*-butylketone is also known to exist in the characteristic cone conformation The more bulky *t*-butyl groups around the cavity cause a little more hinderance to conformational inversion than with the methylketone derivative The steric bulk of the four adamantyl groups in the highest member of the series (**Ih**) creates an even more rigid cavity with the highest amount of hinderance towards conformational inversion Yet the derivative can still provide the four critical carbonyl oxygen atoms for ion binding We can speculate as to the effects of attaching four such bulky groups to the four carbonyl atoms and the subsequent loss in selective ion-binding

The first possibility is that one of the *t*-butyl or adamantyl groups may actually overhang or fill the cavity to some extent and so block the ion binding process Such steric hinderance would explain the sluggish responses as it is more difficult for the sodium ion to enter the cavity and form a complex, the large bulky adamantyl group providing the largest hinderence and hence having the slowest equilibration time NMR spectra of the *t*-butyl and the adamantylketones reveals that the four derivatised ketone groups attached to the phenolic oxygens by methylene groups are symmetrically arranged (at least on the NMR time scale) around the central cavity[25] Therefore this type of steric hinderance which would lead to a loss of symmetry of the derivatised groups around the cavity does not seem likely

Alternatively, the effect of placing four bulky adamantyl groups in close contact may cause replusion of the groups and an enlargement of the cavity sufficient enough to account the lack of selectivity for the Na^+/K^+ and Li^+ ions The distance between adjacent carbonyl oxygen atoms would be increased and the ion-binding would become increasingly non-selective with both larger cations e g K^+ and smaller ions e g Li^+ entering the cavity The ability of the ligands to accommodate a much wider range of ions may lead to a certain amount of competitive complexation which would slow down the equilibration process and explain the unfavorable kinetics of the dynamic response The increased size of the cavity caused by replusion of the ketone groups would place considerable strain around the cavity In the long term this may lead to decreased stability of the bonds with subsequent cleavage of one or more of the derivatising groups in order to relieve the strain on the cavity If one (or two) of the derivitive groups were completely removed at the phenolic oxygen position the conformational mobility of the molecule would immediately increase resulting in ligands with the partial cone or 1-3 alternate configuration In addition the necessary carbonyl oxygen atoms would no longer be present to facilitate ion binding If cleavage of the adamantyl group occured without the loss of the carbonyl oxygen atom then the symmetry of the molecule would be reduced which would lead to a loss in selective ion-binding Breakdown of the molecule could lead to leaching of the active component out of the membrane and hence explain the severely restricted lifetimes

Unfortunately there is very little information available on the stability constants of the adamantylketone ligand due to limitations in solubility in either H_2O, MeOH or CH_3CN In addition, it has been difficult to grow suitable crystals for x-ray crystal analysis so the structural data available is limited[24] Hence at this stage no proof of either higher structural instability or steric interference is available to explain the loss in ion-binding fully However, it would seem reasonable that the effect of the larger substituent attached to the carbonyl oxygen atom is to create a slightly enlarged cavity which is less selective in its ion-binding and is possibly less stable in the long term

3 9 Macro electrodes

The macro electrodes used in the following part of the discussion are similar in size to the conventional pH electrode The exposed membrane diameter is 7 mm compared to the mini electrodes which have 1 8 mm outer diameter and 1 mm inner diameter Both of the electrodes contain the same electrochemical half cell i e the internal reference electrode is a chloridised silver wire immersed in 0 1 M NaCl and the electroactive membrane is of the same composition in both

3 10 Tetra *n*-butylester *p*-*t*-butylcalix[4]arene (**Ie**)

3 10 1 General characteristics and selectivity

The potentiometric response of a macro electrode based on *n*-butyl ester ligand was tested in 10^{-1} to 10^{-5}M NaCl solutions The electrode showed a Nernstian response to Na^+ ions with an average slope of 54 4 +/- 1 5 mV dec^{1} (n=10) The estimated limit of detection was 7 4x10^{-5}M NaCl which is slightly higher compared to some of the other tetra ester ligands The data for the slopes, limit of detection, membrane resistance (measured in 0 1 M NaCl) and the selectivity coefficients are presented in table 3 9 The data shows a remarkable selectivity against the group I cations with the order of preference

$Na^+ > K^+ > Cs^+ > Li^+ > Rb^+$ group I

$Na^+ > Mg^{2+} > Ca^{2+}$ group II

The available phase extraction data for this ligand in neutral picrate showed a very high %extraction for Na^+ ion (25%) compared K^+ ions (2%) This is confirmed in the potentiometric selectivity coefficient data for potassium ($\log^{pot}_{NaK}$ = -2 2) The selectivity over the other alkali metals Li^+, Cs^+ and Rb^+ are even better There is also appreciable selectivity over the divalent species Ca^{2+} and Mg^{2+} and H^+ ions

Injection experiments (table 3 10) more or less confirm the selectivity data The response to injections involving an approximate 10-fold increase in Na^+ concentration were Nernstian (ΔE= 58-62 mV) and fast ($t_{95\%}$ < 5 s) Much smaller responses were noted to injections of K^+, Li^+, Cs^+ and Rb^+ (0-7 mV) The responses to magnesium and calcium were larger and took considerably longer to

Table 3 9 Selectivity co-efficients of macro electrodes based on the *n*-butyl ester ligand (**Ie**) Selectivities by the SS method (10^{-1} M concentrations) Divalent ion selectivities confirmed by the MS method (10^{-1} M fixed interfering ion), standard deviation in parentheses

Slope /mV dec ^{1}	54 4	(1 5)
Resistance /MΩ	0 32	(0 17)
LOD /M	7 4x10^{-5}	
Interfering ion (j)	$\log K^{pot}_{ij}$	(n=4)
Na^+	0 0	
K^+	-2 2	(0 2)
Li^+	-2 7	(0 5)
Cs^+	-2 4	(0 1)
Rb^+	-3 1	(0 2)
Ca^{2+}	-2 3	(0 2)
Mg^{2+}	-2 2	(0 2)
NH_4^+	-2 8	(0 2)
H^+	-1 7	(0 3)

Table 3 10 Injection experiments Change in potential (mV) of a macro electrode containing the *n*-butyl ester (**Ie**) following 450 µl injections of 10^{-1} M primary and interfering ions into 50 ml of 10^{-3}M NaCl

cation injected	ΔE /mV		
	(i)	(ii)	(iii)
Na^+	58	59	62
K^+	3	1	3
Cs^+	2	2	
Li^+	3	4	
Rb^+	7	6	
Mg^{2+}	20	20	
Ca^{2+}	12	11	

stabilise following the injection ($\Delta E\ Mg^{2+} = 20$ mV and $\Delta E\ Ca^{2+} = 12$ mV).

3.10.2 Lifetime

As regards lifetime, regular re-calibration of the electrode over a one month period in pure NaCl solutions showed no significant decrease in the performance of the electrode. The slope versus time plot for the *n*-butylester can be seen in fig. 3.5. The resistance of the electrode did not increase significantly over the period of use (R = 0.32 +/- 0.17 MΩ).

3.11 Macro electrodes incorporating the methylester (**Ic**), ethylester (**Id**) and the methylketone (**If**) *p*-*t*-butylcalix[4]arene

3.11.1 Introduction

Some of the more successful tetrameric ligands had been used in both conformations (mini electrode and macro electrode) over the period of study according to availability or application. It would seem useful therefore to use the available data to ascertain if any differences in selectivity or performance arose as a result of the different conformations. The *p*-*t*-butyl calix[4]arene ligands incorporated into macro electrodes are the methylester (**Ic**), ethylester (**Id**) and the methylketone (**If**) ligands

3.11.2 General characteristics and selectivity

The potentiometric response of the ligands in bench electrodes over a period of one week was studied to check for variation in the absolute potential. All potential measurements were carried out at 25°C and great care was taken to maintain the reference electrodes in the same condition in order to give reproducible values of E^0 and E_j The potentials were recorded after an equilibration time of 1 minute The electrodes were stored in 0 1 M NaCl in between use The data in table 3 11 show that the macro electrodes had extremely stable values of potential over the week The signal quality was also very stable with very little noise or drift of the potential

Table 3 11 Potential versus SCE measured for methylester (**Ic**), ethylester (**Id**) and methylketone (**If**) ligands over a one week period, equilibration time 1 minute

methylester (**Ic**)

Trial [NaCl] /M	1	2	3	4	5	6	Average
10^{-4}	79 9	80 5	81 6	78 8	76 0	77 3	79 0
10^{-3}	133 9	132 3	134 8	131 3	136 2	132 1	133 4
10^{-2}	188 1	189 0	188 6	187 5	187 8	188 4	188 2
10^{-1}	238 3	239 7	240 0	238 9	238 9	242 5	239 5

ethylester (**Id**)

Trial [NaCl] /M	1	2	3	4	5	Average
10^{-4}	69 8	67 6	67 6	65 3	65 4	67 2
10^{-3}	117 1	116 8	118 2	120 8	115 6	117 7
10^{-2}	174 1	173 9	173 3	176 7	171 8	174 0
10^{-1}	229 9	230 0	229 3	229 9	229 5	229 7

methylketone (**If**)

Trial [NaCl] /M	1	2	3	4	5	Average
10^{-4}	72 7	70 1	69 2	69 8	68 4	70 0
10^{-3}	119 4	120 1	120 9	121 0	120 6	120 4
10^{-2}	174 9	175 0	175 8	175 5	175 8	175 4
10^{-1}	228 9	228 9	230 5	229 8	230 2	229 6

The slopes and selectivity coefficients of these bench size electrodes were calculated as before and are shown in table 3 12 As expected all the three electrodes showed Nernstian responses to sodium ions with excellent selectivity characteristics against the other alkali and alkaline earth cations The electrode response was stable for long periods of time and lifetimes of at least two months were estimated in each case

Table 3 12 Slopes and selectivity coefficients of macro elecrodes based on the methylester (**Ic**), ethylester (**Id**) and methylketone (**If**) ligands Selectivities by the SS method, divalent selectivities confirmed by the MS method NA=not available, standard deviation for the $\log K_{ij}^{pot}$ data is 0 1-0 4 units

ligand		methylester	ethylester	methylketone
code		**Ic**	**Id**	**If**
electrode type		macro	macro	macro
Slope /mV dec ^{1}		55 6	56 4	55 3
	Na^+	0 0	0 0	0 0
	K^+	-2 8	-2 7	-2 8
	Cs^+	NA	-2 5	NA
$\mathrm{Log}K_{ij}^{pot}$	Li^+	-2 6	-2 7	-3 2
	Ca^{2+}	-3 8	-2 3	-3 5
	Mg^{2+}	-4 0	-2 9	-4 1
	H^+	-1 9	-1 3	-2 0
	NH_4^+	-3 4	-3 0	-3 4

3 11 3 Discussion

A comparison of the macro electrode data with that found previously for the mini electrodes is shown in fig 3 16 Surprisingly the macro electrodes had superior selectivities in all cases for the alkali and divalent ions than their mini electrode counterparts, although the order of selectivity remains approximately the same

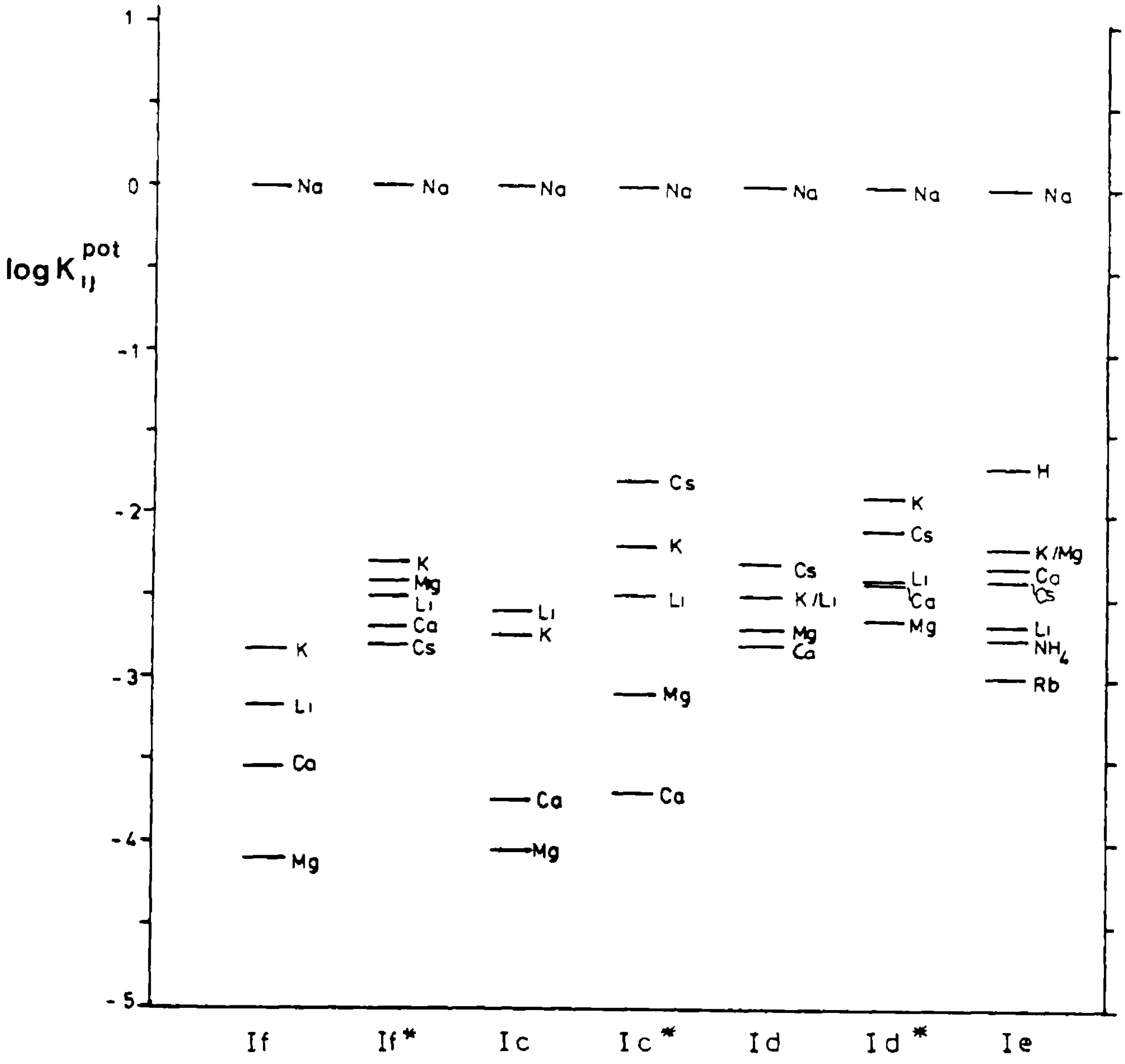


Figure 3.16 Comparison of the selectivity coefficient data for bench electrodes and mini electrodes* containing the p-t-butylcalixarene ligands, methylketone (If), methylester (Ic), ethylester (Id) and *n*-butylester (Ie), valency signs omitted for clarity.

The poorer selectivities of the mini electrodes can be attributed to problems associated with the formation of the PVC membrane and the general non-uniformity of the electrode geometry It is difficult to obtain a uniform coating on the tip without introducing bubbles or aberrations Due to the semi-spherical nature of the tip design the thickness of the PVC membrane will vary over the area of any one tip There is also considerable expertise attached to making membranes of reproducible thickness as the latter is dependent on the consistancy of the PVC cocktail, the number of repeat coatings or the position and environs of the membrane during the drying period The whole assembly is more susceptible to environmental noise from magnetic and electrostatic fields and must be carefully shielded This can lead to reduced limits of detection where the potentiometric signal at low concentrations of analyte cannot be separated from the noise signal Breaks can occur in the internal silver wire of the mini electrodes during injection of the internal electrolyte or through constant usage All of these factors contribute to the decrease in selectivity and general instability of the mini electrode The bench electrodes are simpler to construct, less time consuming, demand less care and attention and it is easier to obtain uniform PVC membranes by virtue of the casting method used for preparation They also have more stable noise free responses and the membranes may have longer lifetimes as a result of increased mechanical stability They are very suited to research or teaching purposes However, the mini electrodes have one important advantage over the macro electrodes in that they require much lower quantities of ligand (essential where expensive ionophores such as valinomycin are being utilised) and they can also be adapted for use in catheters for in-vivo use

3 12 Response range and limit of detection (LOD)

3 12 1 Introduction

The response range of a potentiometric electrode may be defined as the range of concentration for which the E_{cell} versus log a curve is linear Hence the lower limit of the response range is where the curve begins to depart from linearity and beyond which the curve reaches a steady value of E_{cell}, where the electrode fails to register any further changes in the analyte activity The definition of the limit of detection is more problematic IUPAC has defined the limit of detection as the concentration at the point of intersection of the extrapolated segments of the curves[26] Earlier, IUPAC[27] used the concentration of the determmand ion at which E_{cell} deviates by $18/z_i$ mV (z_i is the valency of the primary ion i) from the extrapolation of the linear portion of the graph for the definition of limit of detection These definitions rely to a large extent on the visual judgement of the two segments of the curve A less subjective definition was applied to ion-selective electrodes by Midgley[28] This statistical definition recognised that the problem is to discriminate, within a given degree of confidence, between a sample containing some minimum level of sample and one containing none Statistical methods like this give a better description of the electrode performance and allow comparison with other methods of analysis For the purposes of this research the method used for the determination of the LOD was the more recent of the IUPAC recommendations based on the concentration at the point of intersection of the two linear segments of the graph

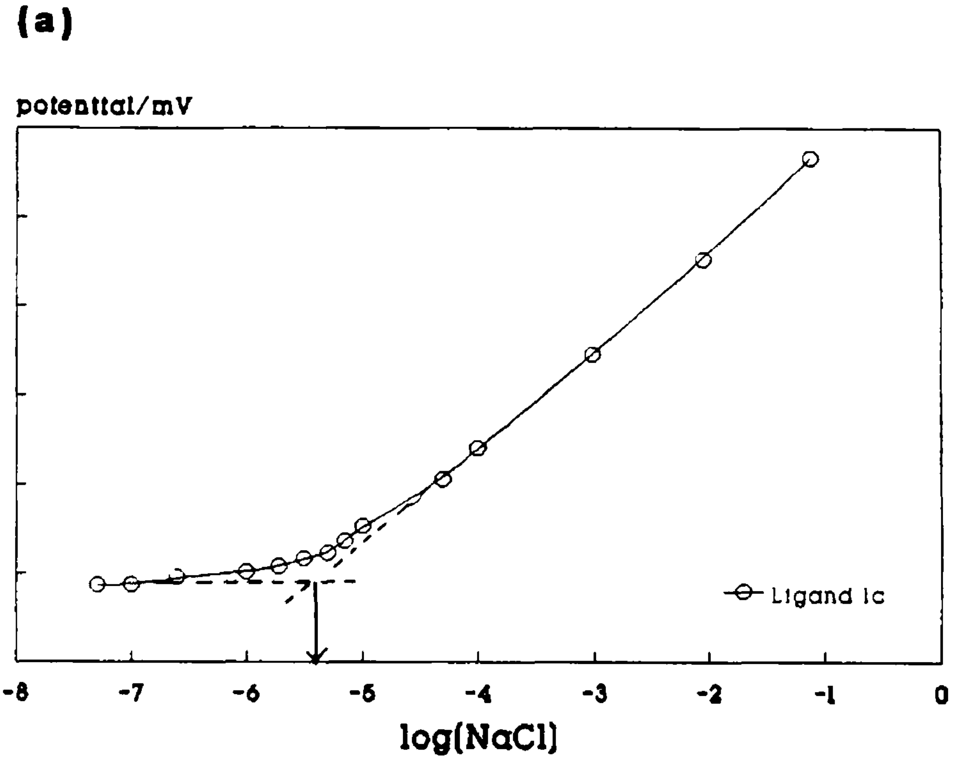
3 12 2 Limit of detection

A more thorough investigation of the LOD was undertaken for macro electrodes incorporating two ligands the methylester (**Ic**) and the methylketone (**If**) In order to ensure the accuracy of the calibration solutions, containers of high grade ultra pure water were obtained from a local power station This "polished" water has ionic levels around 10^{-10}M All pipettes and flasks used for the standards were acid washed and rinsed several times with the ultra pure water before use All potential measurements were carried out at 25°C Potential readings versus SCE were taken for approximately one week and the results for the two ligands are outlined in table 3 13 and fig 17a and b The final value of the limit of detection and the slopes over the linear range (10^{-1} to 10^{-4}M) for the two electrodes are shown in table 1 14 No significant deviation was observed from the estimated limits of detection obtained previously using the milliQ water at the laboratory and the result obtained under these more stringent conditions

Table 3 13 Limit of detection studies Potential (mV) of electrodes containing the methylester (**Ic**) and methylketone (**If**) ligands in solutions of pure NaCl Potential measurements taken over a one week period

Methylester (**Ic**)	Potential /mV					
Trial log [a_{Na}]	1	2	3	4	5	Average
-7 3	-7 1	-6 6	-6 0	-5 5	-7 2	-6 5
-7 000	-8 0	-7 2	-7 2	-6 8	-5 1	-6 9
-6 601	-3 2	-2 9	-4 3	-0 5	-0 7	-2 3
-6 001	-1 5	2 4	-2 5	2 0	4 2	0 9
-5 722	4 1	3 3	1 3	4 1	6 2	3 8
-5 509	7 6	7 1	6 4	9 6	8 4	7 8
-5 302	9 8	12 5	10 6	13 0	10 3	11 2
-5 156	16 5	17 3	18 1	18 4	18 1	17 7
-5 002	25 2	28 6	26 2	25 3	26 0	26 3
-4 304	51 5	51 6	54 2	50 7	53 2	52 2
-4 005	70 5	69 7	70 3	71 0	70 1	70 3
-3 015	123 1	121 9	122 4	122 2	122 3	122 4
-2 045	177 2	175 5	175 1	176 3	176 2	176 0
1 112	233 5	232 2	233 8	233 4	233 5	233 3

Methylketone (**If**)	Potential /mV					
Trial log [a_{Na}]	1	2	3	4	5	Average
-7 000	7 9	10 0	9 2	8 5	10 8	9 3
-6 301	11 4	12 7	10 9	11 3	11 7	11 6
-6 000	14 5	14 5	13 8	13 8	13 4	14 0
-5 509	24 6	18 4	22 5	21 9	23 5	22 2
-5 302	24 8	19 9	24 4	23 8	24 6	23 3
-5 156	28 9	23 7	28 2	28 6	29 0	27 7
-5 005	32 1	27 2	31 5	32 7	32 9	31 3
-4 303	54 4	52 0	53 6	52 1	53 7	53 1
-4 005	71 2	72 0	70 7	71 5	70 8	71 2
-3 015	122 6	121 9	122 9	122 6	122 5	122 5
-2 045	177 2	176 1	176 9	177 5	177 9	177 1
-1 112	233 2	232 5	233 8	233 5	233 7	233 3



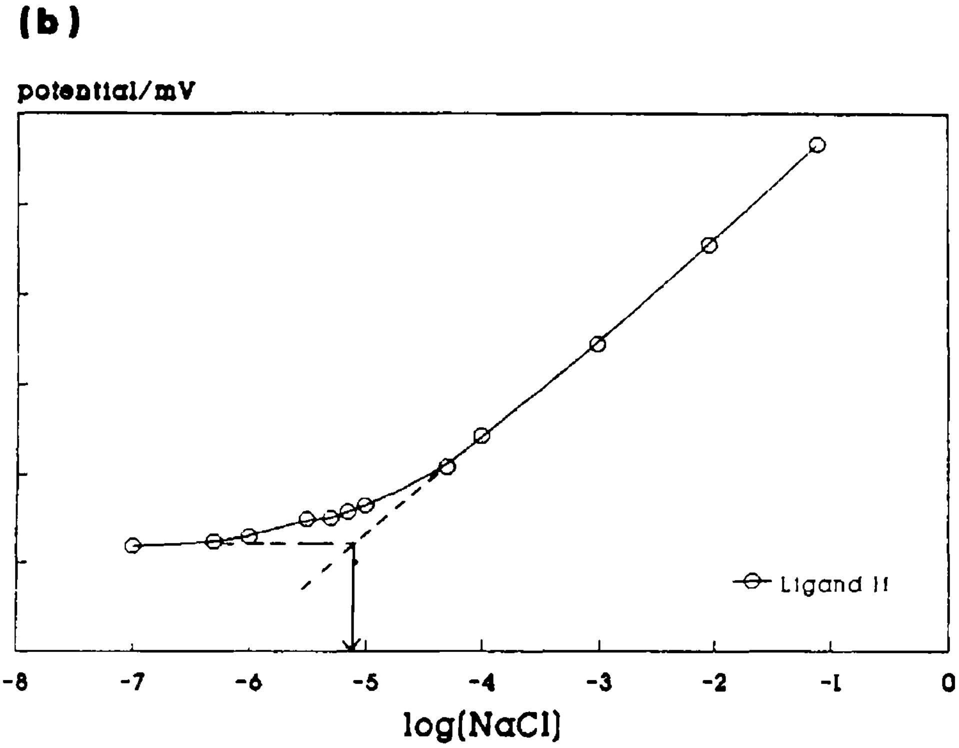


Figure 3 17 Limit of detection (LOD) Calibration curves showing the LOD for (a) methyl ester Ic (b) methyl ketone If.

Table 3 14 Limit of detection (LOD) and slopes (S) for macro electrode incorporating the ligands **(Ic)** and **(If)**

Ionophore	LOD /M	S /mV dec^{1}
tetramethylester **(Ic)**	4 1x10^{-6}	56 3
tetramethylketone **(If)**	7 9x10^{-6}	55 5

3 13 Monoacid trimethylester *p-t*-butylcalix[4]arene acetate **(Ij)** and monoacid triethylester *p-t*-butylcalix[4]arene acetate **(Ik)**

3 13 1 Introduction

The discovery by Bohmer et al [29] that the tetraethylester **(Id)** can undergo hydrolysis by trifluoroacetic acid (TFA) with the loss of one and only one ester group has opened up the possibility of synthesising new calixarene derivatives with mixed ligating functions During the course of their experiments, they found that the tetraethylester ligand in chloroform underwent a surprisingly rapid reaction at room temperature which was complete after 1 hour The reaction changes could be followed by NMR spectroscopy In order to establish the nature of the reaction several factors were investigated No measureable hydrolysis occurred with the simple ethylester, ethyl *p-t*-butyl phenoxyacetate **(6)** If a solution of **(Id)** was saturated with sodium thiocyanate prior to treatment with TFA no hydrolysis occurred either They proposed that the hydrolysis was initiated by reversible hydronium ion complexation **(Id)** forms a kinetically stable complex with sodium ion in $CDCl_3$ and when the cavity is occupied with a Na^+ ion, no hydronium ion can enter the cavity and initiate the reaction Hence there is no hydrolysis following presaturation with sodium thiocyanate The reaction is shown schematically below where LCOOR represents the tetra ester ligand and LCOOH its monoacid analog

$$\mathrm{LCOOR} + \mathrm{H_2O} \overset{\mathrm{TFA(H^+)}}{\rightleftharpoons} \mathrm{LCOOH} + \mathrm{ROH} \qquad (3\ 1)$$

$$\mathrm{LCOOH} \rightleftharpoons \mathrm{H^+} + \mathrm{LCOO^-} \qquad (3\ 2)$$

$$\mathrm{Ka} = \frac{[\mathrm{H^+}][\mathrm{LCOO^-}]}{[\mathrm{LCOOH}]} \qquad \mathrm{pKa} = 10\ 25 \qquad (3\ 3)$$

The parent ethylester calixarene **(Id)** adopts a very rigid cone conformation with the four polar ester groups mutually syn with respect to the macro cycle CPK models indicate that conformational inversion of the monoacid is very unlikely as the system in the cavity is still too crowded by the remaining three ester groups for inversion to take place[25] It is a surprise therefore that phase transfer studies of the monoacid triethylester reveal very low %extraction (<6%) for all the alkali metals (table 3 15) Furthermore, replacement of the -COOH group by a -COOMe group to give the monomethylester triethylester **(Im)** results in the restoration of the ion binding power with the same trends of alkali extraction as the ester ligands

The cone conformation of the monoacid is still rigid and it seems unlikely that the collapse of the three ethyl groups into the cavity can occur and be responsible for the loss in complexation (see fig 3 18) The absence of one ethyl group would make the cavity less symmetrical and there is also the possibility that the carboxylic acid could participate in hydrogen bonding across the cavity A combination of these factors may be responsible for the reduction in ion uptake Further experiments show that similar hydrolysis to the monoacid trimethylester **(Ij)** occurred when the tetramethylester **(Ic)** was similarly treated with TFA Samples of both monoacids were incorporated into PVC membranes to elucidate further their ion binding ability Results are presented below for mini electrodes based on the monoacid triethylester **(Ik)** and macro electrodes based on the monoacid trimethylester **(Ij)**

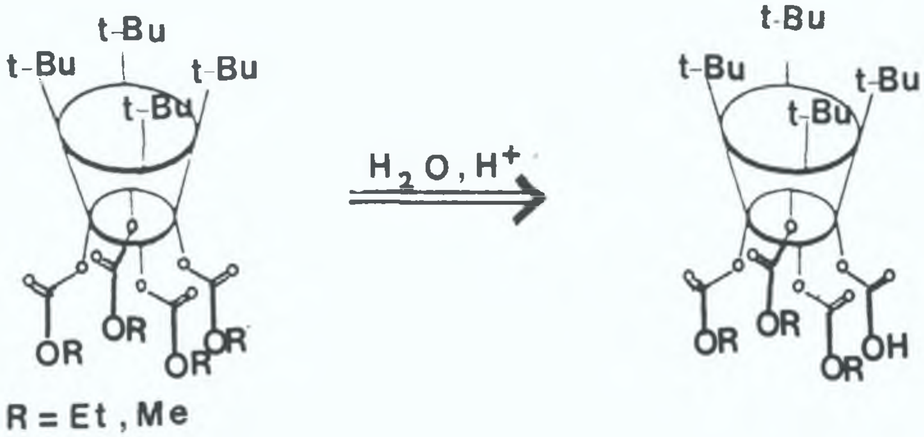


Figure 3.18 The hydrolysis of tetraester *p*-*t*-butylcalix[4]arene to the monoacid triester *p*-*t*-butylcalix[4]arene.

Table 3.15 % extraction of alkali metal picrate into CH_2Cl_2 at 20°C [23]. Method as in table 1.2.

	%E				
	Li^+	Na^+	K^+	Rb^+	Cs^+
(Ik)	1.2	5.6	3.9	1.1	3.7
(Im)	10.5	87.9	31.4	21.8	32.0

3.13.2 General characteristics and selectivity

A batch of 10 mini electrodes containing the ligand monoacid triethylester **(Ik)** were prepared and their response in NaCl measured. All of the electrodes showed slopes in the activity range 10^{-1} to 10^{-4}M NaCl in excess of 50 mV dec^{1} The best five of these electrodes were selected for further use and the results of these electrodes are illustrated in table 3 16 The average resistance of two of the electrodes having been stored in 0 1 M NaCl previous to measurements was 2 33+/-0 25 MΩ Two macro electrodes containing the ligand monoacid trimethylester were prepared and the responses tested in pure NaCl solutions The results presented for triplicate measurements versus SCE obtained over three days for the two electrodes are included in table 3 16

Table 3 16 Response (mV) and slopes (mV dec^{1}) over the activity range 10^{-1} to 10^{-4}M NaCl of electrodes based on ligands (**Ik**) and (**Ij**) in gently stirred solutions at room temperature, equilibration time 3 min, r = correlation coefficient

Monoacid triethylester (Ik)			Response /mV		
Electrode	1	2	3	4	5
[NaCl] /M					
10^{-4}	72 9	75 0	58 2	41 9	56 5
10^{3}	129 3	129 2	112 1	98 3	111 0
10^{2}	184 2	184 1	167 6	152 4	165 3
10^{-1}	240 0	240 2	221 6	207 5	220 7
Slope /mV dec^{1}	57 6	57 1	56 6	57 0	56 7
r	0 9999	0 9998	0 9999	0 9999	0 9998

Monoacid trimethylester (Ij)			Response /mV			
Electrode	1(i)	1(ii)	1(iii)	2(i)	2(ii)	2(iii)
[NaCl] /M						
10^{-4}	67 5	67 5	69 2	71 2	72 0	70 7
10^{-3}	122 4	121 3	122 2	122 6	121 9	122 9
10^{-2}	176 9	117 4	176 4	177 2	176 1	176 9
10^{-1}	229 5	230 4	228 9	233 2	232 5	233 8
Slope /mV dec^{1}	55 9	55 8	55 3	56 0	55 5	53 3
r	0 9999	0 9991	0 9999	0 9995	0 9993	0 9995

Both types of electrode responded rapidly to changes in ion activity ($t_{95\%} < 10$ s). Some characteristics, slopes and selectivity data for the two monoacid ligands are presented in table 3.17. Included for comparison are the data obtained with the parent ester compounds for the same electrode configurations.

Table 3.17 Some characteristics, slopes and selectivity coefficients of mini and macro elecrodes incorporating the monoacid triester groups. Selectivities by the SS method (10^{-1}M), divalent selectivities by the MS method (10^{-1}M interfering ion), standard deviation for $\log K_{ij}^{pot}$ = 0.01 to 0.8 units.

Ligand		**Id**	**Ik**	**Ic**	**Ij**
electrode type		mini	mini	macro	macro
Slope/ mV dec^{-1}		56.5(1.4)	57.0(0.25)	55.6(0.9)	55.3(1.0)
LOD/ M		3.6x10^{-6}	3.2x10^{-5}	4.1x10^{-6}	8.8x10^{-6}
$\log K_{ij}^{pot}$	Na^+	0.0	0.0	0.0	0.0
	K^+	-1.9	-2.2	-2.8	-2.4
	Cs^+	-2.1	-2.0	--	--
	Li^+	-2.4	-2.4	-2.6	-3.1
	Ca^{2+}	-2.4	-2.4	-3.8	-3.5
	Mg^{2+}	-2.7	-2.5	-4.0	-3.3
	NH_4^+	-2.8	--	-3.4	-3.3
	H^+	-2.1	-1.3	-1.9	-1.7

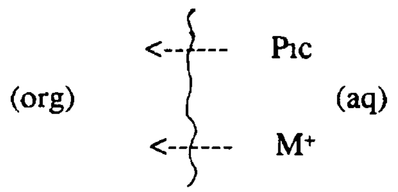
3.12.3 Discussion

The first point to note is that both the monoacid derivatives exhibited a Nernstian response to sodium ions and good linearity with limits of detection comparable to their parent compounds. This confirms the retention of the rigid cone structure in both the ligands following hydrolysis. Inversion of one of the ligating groups would lead to a more open structure and loss in selectivity of the ion binding. The response is very stable for both ligands, with no decrease in performance over a period of two weeks (monoacid trimethylester (**Ij**)) or one month (monoacid triethylester (**Ik**)) The selectivity data indicates that the selectivity in each case roughly follows the same trends as the parent compound

The success of the two systems raises several questions Firstly, why did the monoacid triethylester ligand give low rates of ion transport when it is without doubt capable of complexing cations? The answer to this may not be in the fundamental properties of the ligand itself but in the nature of the actual picrate extraction experiment Under a normal experiment with a neutral ligand (L) the metal ion is complexed and transferred from the aqueous (aq) to the organic (org) phase The picrate anion (Pic) also transfers into the organic layer to preserve electroneutrality with equal moles of metal cation and picrate ion being transfered, scheme 1 In the case of the monoacid (LH) a competing process may occur where the transfer of metal cations into the organic phase is accompanied by a flux of H^+ ions in the opposite direction to maintain electroneutrality, scheme 2 Hence the metal ion would be extracted into the organic phase without the accompanying picrate ion and as it is the absorbance of the picrate ion which is measured the transport of M^+ would not be detected The pKa of the monacid ethylester (**Ik**) is 10 25 (see equation 3 3) which would mean that dissocation of the acid with the loss of a proton would be favoured by alkaline conditions in the aqueous phase

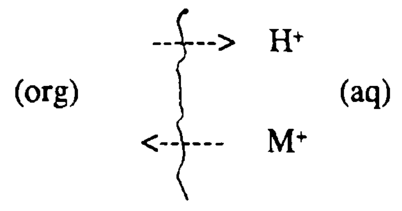
<u>Scheme 1</u>

$$L_{(org)} + M^+_{(aq)} + Pic_{(aq)} \rightleftharpoons LM^+_{(org)} + Pic^-_{(m)}$$



<u>Scheme 2</u>

$$LH_{(org)} + M^+_{(aq)} + OH_{(aq)} \rightleftharpoons LM_{(org)} + H_2O_{(aq)}$$



The second question that arises is the possible effect of the pH of the analyte solution on the ligand ion complexing ability The selectivity data for the monoacid trimethylester and its parent compound for hydrogen are similar The selectivity coefficient of the monoacid triethylester for hydrogen ions is higher than that of its parent compound indicating some increase in the response to H$^+$ ions Some variation in the speed of the response to hydrogen ions is observed with time - older membranes having a high transient response to hydrogen ions which stabilises to a lower reading with time However the effect is not reproducible and further studies need to be undertaken to clarify the situation It might be useful to look at the response of the electrodes over the concentration range in different pH buffers In strongly alkaline media dissociation of the acid group will occur leaving the ligand with a negative charge

A third question which arises and perhaps the most interesting aspect arising out of the practicaly equal performance of the two esters and their acid analogues is to establish the active form of the ligand in the tetraester membrane If hydrolysis of the tetraester occurs in the membrane i e the monoacid might be formed even if one incorporates the tetraester initially into the membrane, it would be useful to determine to what extent and how readily the reaction might occur This could be investigated by means of some HPLC studies on the new and old PVC membranes

3 14 Conclusion

Calixarenes are a relatively new class of ion complexing molecules which are recieving increasing interest both from a synthesis stand point and in view of the potential applications stemming from their receptor activity The tetrameric calixarenes discussed here have all exhibited a peak ion complexing ability for sodium This preference for sodium ions is predetermined to a large extent by the cavity size of the macrocyclic ring formed by the four aromatic ring units and the small diameter of the sodium ion The various derivatives studied contain carbonyl and ester oxygen groups and the incorporation of these ligands into potentiometric sensing devices has led to the development of a host of ionophoric molecules with varying degrees of selectivity and stability A comparison of the various potentiometric selectivity trends allows us to speculate as to the exact nature of the ion binding and to identify the functionalities most likely to enhance selectivity

Three ketone derivatives have now been examined and the work has shown that the carbonyl atom attached to the phenolic oxygen atom by a methylene group is the critical factor facilitating the ion extraction process The interaction of the metal ion with the polar cavity defined by these eight oxygen atoms, combined with the tetrameric cavity size induces considerable sodium selectivity within the system e g the response to sodium is at least 600 times larger than for any likely interferent (see macro electrode based on **(If)** fig 3 16) When the ordered arrangement of the polar binding atoms is disrupted by the addition of large bulky groups e g *t*-butyl or adamantyl then the highly selective binding for sodium is diminished considerably A recent paper reported the use of this *t*-butylketone and a further phenylketone derivative as the active sensing agents in a CHEMFET and good selectivites were obtained[30]

Tetrameric derivatives containing ester groups have also provided excellent binding sites for the selective complexation of sodium ions Three derivatives containing methyl, ethyl and *n*-butyl groups performed well as ionophores in PVC membrane sensors with excellent selectivity and stability characteristics A comparison of the three ester derivatives (fig 3 16) illustrates that the selectivity towards the K$^+$, Li$^+$ and Cs$^+$ alkali ions remains approximately the same for the three esters This confirms that the crucial ion-binding factor is the carbonyl oxygen atoms and the phenolic oxygen atoms common to each ligand The influence of increasing the length of the alkyl chain is more subtle It would appear that there is some slight increase in the divalent selectivity on going from the methyl to the ethyl and to the *n*-butyl group The main dipole interactions involved in stabilising the cation in the cavity are imparted by the phenolic and carbonyl oxygen atoms (fig 3 10), with the oxygen atom in the ester group having a smaller contribution to the overall stabilisation of the cation Other workers have confirmed the ion complexing ability of ester groups Kimura et al developed potentiometric sensors with a decylester *p-t*-butylcalix[4]arene and a cyclohexylester *p-t*-butylcalix[4]arene and reported appreciable selectivites for the sensors[5] Other work has shown that the addition of a further oxygen atom in the derivitising chain i e a -$CH_2CH_2OCH_3$ moiety attached to the ester also produces a sodium sensor with comparable or even slightly improved selectivities[31}

The work conducted on the monoacid trimethylester (**Ij**) and the monoacid triethylester (**Ik**) derivatives affirms that loss in ion binding does not ensue if one of the ester methyl or ethyl groups is replaced by a hydrogen atom Indeed sensors containing the ligands (**Ij**) and (**Ik**) produced stable working electrodes with selectivities equivalent to their parent counterparts As the hydrolysis does not involve a change in the presence of the critical carbonyl and phenolic oxygen atoms the overall ion-complexing ability of the ligands is retained Any small variation in selectivity can be attributed to some decrease in overall symmetry of the ligating atoms

One of the great advantages of calixarenes over similar sodium or potassium selective neutral carrier compounds is their relative ease of synthesis which would allow them to be produced in large quantities more economically They are also more lipophilic than for example crown compounds and this may increase their effective lifetimes as sensors due to reduced leaching of the active components from the membrane Initial toxicity studies on modified calixarenes reveals favorable results The LD_{50} of ethylester ligand (**Id**) in rats is > 5000 mg/Kg which may have obvious environmental and safety advantages[32]

3 15 Future trends

The development of sodium and potasium ion-selective electrodes has challenged the previously popular flame emission spectroscopic methods of analysis In the modern clinical laboratory potentiometric analysis of electrolytes such as Na^+, K^+, Ca^{2+} and H^+ has become the method of choice for their determination in biological fluids such as whole blood , plasma, serum, and urine Currently sodium in body fluids is determined mainly using glass membrane electrodes The problems associated with sodium glass membranes are well documented with regard to their high membrane resistance[6], poor hydrogen selectivity and tendancy to absorb biological molecules (e g proteins) on the glass surface[33] Technically glass electrodes are more difficult to design and fashion, especially into miniaturised flow cells, and they require the expertise of highly skilled glass blowers All of these engineering complications add to the manufacturing costs and are eventually borne by the customer i e the hospital The problem is compounded by the fact the PVC ion-selective electrodes are already used for the determination of potassium and calcium and these essentially different membrane geometries must be configured into the one sensing array The use of a sodium selective PVC membrane would enable a single coherent ISE block to be manufactured In short, adoption of PVC membranes for sodium analysis would significantly reduce costs and simplify detector design and fabrication Two of the tetrameric calixarenes, the methyl ketone (**If**) and the methyl ester (**Ic**) have been applied to sodium analysis of human plasma[12-14] These electrodes exhibit selectivity over K^+, Li^+ , Cs^+ and Ca^{2+} equivalent to, and H^+ selectivity far greater than the sodium glass electrode Dipping and FIA methods have been employed for the analysis with the latter providing the best precision and accuracy The better stability, more precise sampling and more reliable calibration afforded by the highly controlled FIA system increases the accuracy of this method At its present stage, the ligands have shown great potential as suitable replacements for the glass electrodes under the experimental laboratory conditions The next step would be to subject the membrane to the huge volume of samples and stringent controls that can only be provided by the big giants of the clinical analyser industry for complete validation

New industrial applications for these calixarenes are continually emerging[34] The monoacid ligands can be exploited as a route to synthesising compounds with mixed ligating functions i e ligands containing both amide and ester moities with retention of their sodium complexing ability[35] The monacids may also be used to covalently attach calixarene molecules to a polymer backbone via the carboxcylic acid moiety again without loss of the ion complexing ability[36]

Tetrameric structures modified with amide groups have been shown to exhibit substantial complexation of the alkaline earth metals[37] Other electroanalytical applications of the calixarenes include their use in carbon paste electrodes in cyclic voltammetry for the preconcentration of metals such as lead(II), copper (II) and mercury(II) with potential applications in analytical environmental chemistry[38] Calixarenes are also starting to find use in the fast developing area of Langmuir Blogett monolayers Langmuir films of ion-complexing calixarenes may be used to form thin films bearing uniformly orientated adjustable micropores[39] The possible applications for such films may lie in their unique permeation characteristics which enable them to be used for membrane filtration and separation

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Chapter 4

Caesium Selective PVC Membrane Electrodes

4 1 Introduction

Caesium is widely distributed in the earths crust at low concentrations (1 ppm) Its source in nature is the rare mineral pollucite[1] The main commercial applications of caesium are in the manufacture of vacuum tubes, photoelectric cells and infra-red detectors There has been increasing interest in analytical methods for determining the alkali metal ions, due in part to the importance of Na^+, K^+ and Li^+ in biological processes, the production of radioactive caesium-137 during nuclear fission of uranium, and the possible use of Li^+ as a fusion fuel The measurement of radioactive caesium due to the effects of fallout from nuclear accidents and nuclear weapons testing has become important in the light of recent events e g the Chernobyl disaster of 1986 Traditionally, caesium and the other alkali metals have been determined by gravimetric methods and instrumental techniques such as flame photometry, atomic absorption spectroscopy (AAS) or atomic emission spectroscopy (AES)[2,3] Direct spectroscopic methods of caesium analysis are complicated by ionisation and chemical interferences from the other alkali ions, and the analysis demands time-consuming modified methods[3] Ion chromatography can now be used for the routine separation of all the alkali metals[4] More recently, the technique of inductively coupled plasma mass spectrometry (ICP-MS) has been applied to the analysis of caesium in serum[5] and has been suggested as a powerful alternative for the determination of trace elements in serum The technique compares very favourably to Cs^+ analysis by neutron activation analysis (NAA), the major trace analysis technique for Cs^+ available to date

Compared to the advances made in potentiometric analysis of sodium and potassium, relatively little attention has been directed towards the development of similar caesium electrodes The crypta hemispherand-3 of Cram and Ho[6] is capable of selective ion binding in the order $Cs^+ > Rb^+ \approx NH_4^+ > K^+ > Na^+ > Li^+$ They used the ratio of the association constants of the complexes with the alkali metal ion to estimate ion selectivity and found a ratio of 0 09 i e a selective binding factor of 11 for the crypta hemispherand for caesium over rubidium Despite the indications of possible use of these crypta hemispherands as suitable ion complexing agents no further potentiometric applications have been reported

Membranes based on valinomycin have been used in Rb^+ and Cs^+ electrodes, provided the K^+ activity is relatively low[7,8]. Frensdorff investigated the relationship between ring size and cation size for the crown compounds and he showed that compounds with an 18-21 polyether ring (e.g. 21-crown-7, dibenzo-24-crown-8) possess the optimum cavity size for Cs^+ ions[9]. The potassium selective crown ether, dibenzo-18-crown-6, was suggested to bind caesium in a 2:1 ratio of the crown ether:ion[10] however the use of these crown ethers as ionophores in caesium selective ISE's has not been explored. Kimura et al. developed some crown ether based caesium selective electrodes using a range of bis(benzo-18-crown-6) ligands[8]. They reported selectivity coefficients for three bis(benzo-18-crown-6) derivatives for Cs^+ in the range 10^{-3} (Na^+), 10^{-1} (K^+), 10^{-1}(Rb^+) and 10^{-2} (NH_4^+). Attiyat et al.[11] developed an ISE system based on TMC-crown formazone, a di-benzo-14-membered ring cyclic compound, with two nitrogen atoms and two oxygen atoms in the ring skeleton. Good selectivities over Rb^+ and K^+ (approximately 10^{-1}) were reported with better selectivities over the smaller Li^+ and Na^+ ions and the divalent ions. A liquid ion-exchange membrane containing the caesium tetraphenylborate salt with nitro benzene as the solvent[12] exhibited a caesium selective response in the order $Cs^+ > Rb^+ > K^+ > NH_4^+ > Na^+$ but suffered from slow response times especially at low caesium concentrations. Another ion-exchange liquid membrane based on the caesium tetrachlorophenylborate salt in 2-NPOE had some selectivity over Li^+, Na^+ and NH_4^+ but K^+ was found to constitute a large interference[13]

4.2 Calix[6]arenes and calix[8]arenes

Hexameric and octomeric *p-tert*-calixarenes have shown an ability to complex the larger alkali metals. One of the oldest patents concerning calixarenes is for the recovery of caesium[14]. Izatt et al. used the alkali cation binding ability of *p-tert*-butyl-calix[8]arene to recover caesium from an aqueous solution of a mixture of ions found in solutions of waste materials. The stirred organic membrane phase containing 10^{-3} mol/l of calixarene in dichloromethane/carbon tetrachloride is brought into contact with the aqueous source phase. The caesium ions are transferred, albeit slowly, from the source phase to a pure water phase also in contact with the organic layer see fig 4 1[15] Other experiments involving ion transport with calixarenes included the use of a carboxylate *p*-sulphate-calix[6]arene as an uranophile[16] In this case it was predicated that the calix[6]arene was an ideal molecule for the uptake of UO_2^{2+} due to the nearly coplanar arrangement of the six carboxylate ligand groups Nomura et al [17] synthesised a calix[6]arene compound with an azo dye attached and demonstrated a high ion transport with neutral picrates for Ag^+, Hg^+ and Hg^{2+}

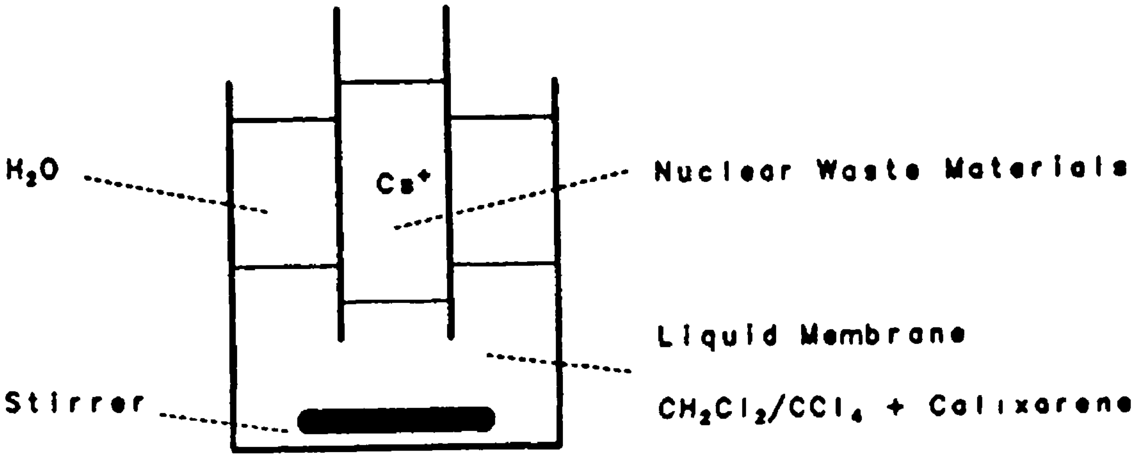

Figure 4 1 Recovery of caesium, schematic representation of the experimental set-up [15]

Phase transfer studies of alkali metal picrates have shown that the modified calix[6]arene derivatives have an ability to extract the larger alkali metal ions such as Cs^+ and Rb^+ (table 1 2) Both the hexameric esters **(IIb)** and **(IIa)** (fig 4 2) exhibited good ion transport ability with efficiency decreasing in the order $Cs^+ > Rb^+ > K^+ > Na^+ > Li^+$[18] Diamond[19] prepared liquid membrane glass pipette electrodes with these two ligands using TCB (trichlorobenzene) as the solvent Sub-Nernstian responses were observed when the two ligands were dissolved in TCB on their own, but a substantial improvement in slope and selectivity characteristics was observed when small amounts of an ion-exchanger (KTpClPB) was added

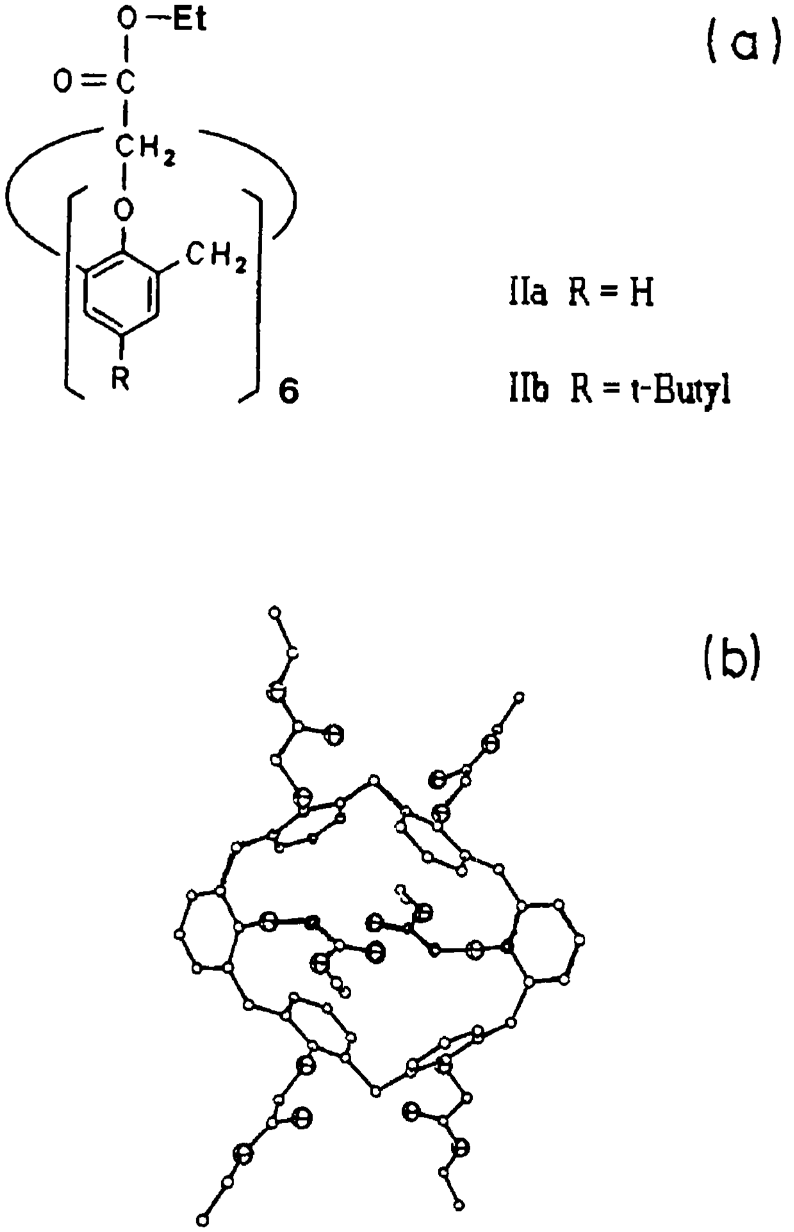

Figure 4 2 (a)The calix[6]arene esters IIa and IIb (b) A view of the molecule IIa almost normal to the plane of the six marcocyclic CH_2 carbon atoms The molecule has a 0 404 and 0 47 nm separation between adjacent phenolic oxygen atoms Carbon and oxygen atoms are shown as spheres of arbitary radius, the oxygen atoms are larger marked with a cross[18]

4 3 Experimental

Solvent polymeric membranes incorporating the two ionophores **(IIb)** and **(IIa)** were prepared using the bench size configurations outlined previously (see section 2 5 2) Preliminary studies of electrodes using a membrane composition of 1 mg ligand, 0 25 mg ion-exchanger (KTpClPB), 100 mg plasticizer (2-NPOE) and 50mg PVC dissolved in THF produced electrodes with slopes of about 45-50 mV dec^{1} in CsCl solutions but the response was unstable Upon examination, it became apparent that small crystals of ionophore were forming in the PVC membrane so a higher proportion of plasticizer was used to completely dissolve the ionophore Five different membrane compositions containing the ionophore **(IIa)** and **(IIb)** and one containing ion-exchanger only are shown table 4 1 In order to produce sufficient quantity to cast the membrane, three times the amounts shown in table 4 1 were mixed and dissolved with 5-7 ml tetrahydrofuran (THF)

Table 4 1 Composition of the electrodes in mg Ligands as in fig 4 2 2-nitrophenyloctylether (2-NPOE), potassium tetrakis(*p*-chlorophenyl) borate (KTpClPB), poly(vinyl)chloride (PVC)

electrode number	1	2	3	4	5	6
ligand **(IIb)** /mg	1	1	0	0	0	0
(IIa) /mg	0	0	1	1	1	0
KTpClPB /mg	0	0 25	0	0 25	0 1	0 25
2-NPOE /mg	180	180	180	180	180	180
PVC /mg	90	90	90	90	90	90

The membranes were then cast, fabricated and conditioned as described in section 2 5 2 The selectivity coefficients were determined by the separate solution (SS) method using 10^{-1}M chloride salts of the cations involved The group II cation and hydrogen ion selectivities were confirmed by the mixed solution (MS) fixed interference method using 10^{-1} and 10^{-2}M solutions of the interfering ions respectively

4 4 Response and selectivity

Typical calibration graphs for electrodes 1-4 containing the hexameric ligands are shown in fig 4 3 All four electrodes produced slopes in excess of 52 mV dec^{1} change in caesium concentration over the approximate range $1x10^{-4 5}$ to $1x10^{-1}$ in pure CsCl solutions The response of the electrodes to pure chloride solutions of the group I metal cations was tested over the 10^{-6} to 10^{-1} M range and the results for ligand **(IIb)**(electrode 2) are shown in fig 4 4 The largest response was to Cs^+ ions with a lower response to rubidium and potassium and some measure of selectivity over sodium and lithium The selectivity coefficients for a range of cationic species are summarised in table 4 2 Fig 4 5 shows the calibration curves for the estimation of the calcium and magnesium selectivities by the mixed solution method using 10^{-1}M fixed interfering ion concentration

Electrodes 1 and 3 demonstrate the ability of the ligands to act as neutral carriers independent of the presence of other membrane additives Electrode 1, containing the ligand **(IIb)** only, displayed a near Nernstian response to Cs^+ ions in CsCl solutions over the range 10^{-4} to 10^{-1}M The potentiometric selectivity pattern against the group I ions broadly followed the phase transfer trends, $Cs^+ > Rb^+ = K^+ > Na^+ > Li^+$ with reversal of the K^+/Rb^+ values and good preference for Cs^+ over the group II ions The $\log K_{ij}^{pot}$ values for H^+ and NH_4^+ ions were reasonable ($\log K_{ij}^{pot}$ = -1 95 and -1 87 respectively) but were further improved by the addition of KTpClPB in a 1 4 mass ratio which is equivalent to a 1 4 1 ligand exchanger mole ratio (see electrode 2 table 4 2) The addition of the ion exchanger produced some stabilisation of the signal at low concentrations ($<10^{-4}$M) and the selectivities against the group I and group II ions remained approximately the same

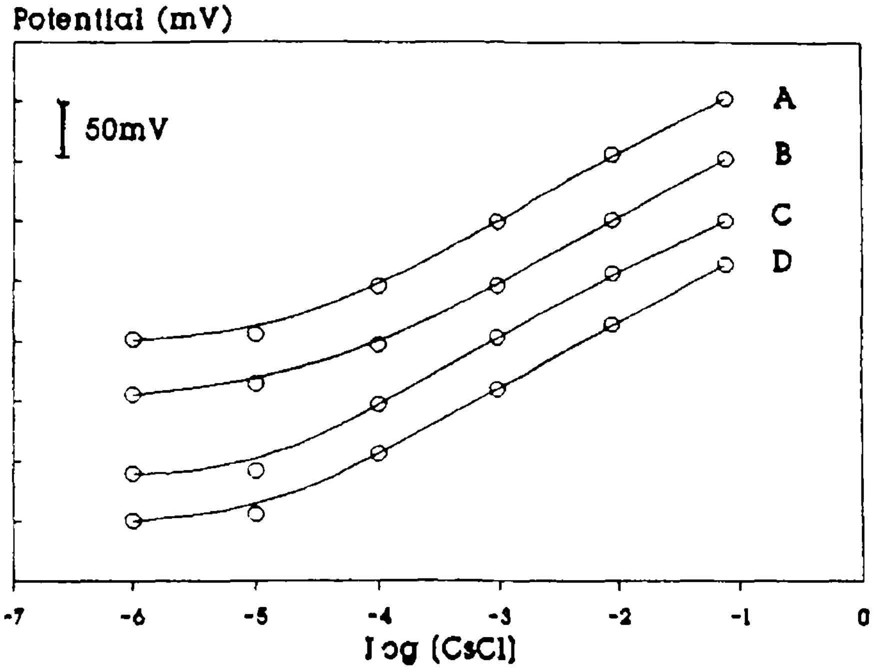

Figure 4 3 Typical calibration curves of electrodes incorporating the calix[6]arene esters IIa and IIb Ligands as in fig 4 2, electrodes as in table 4 1, S=slope (mVdec^{-1}) over the activity range 10^{-1}-10^{-4}M (A)=IIa(electrode 4), S= 54 6 (B)=IIa(electrode 3), S=53 1, (C)=IIb(electrode 2), S=54 0 and (D)=IIb(electrode 1), S=55 1

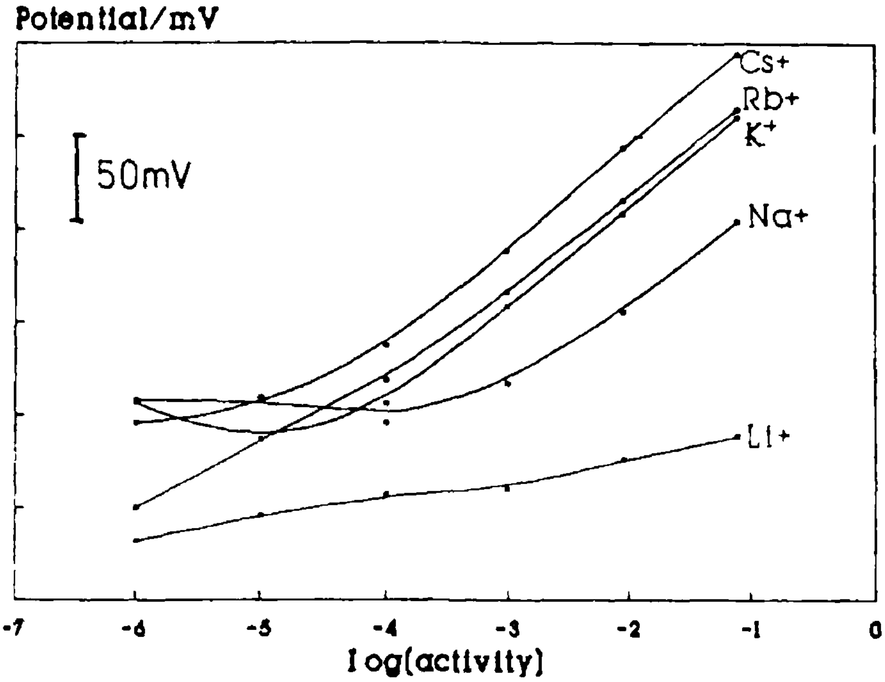

Figure 4 4 Response curves of electrode 2 incorporating the ligand IIb to pure chloride solutions of the alkali metal cations (as marked) Electrodes as in table 4 1, S=slope (mVdec^{-1}) over the activity range 10^{-1}-10^{-4} M Cs$^+$, S=54 6, Rb$^+$, S=50 2, K$^+$, S=53 1

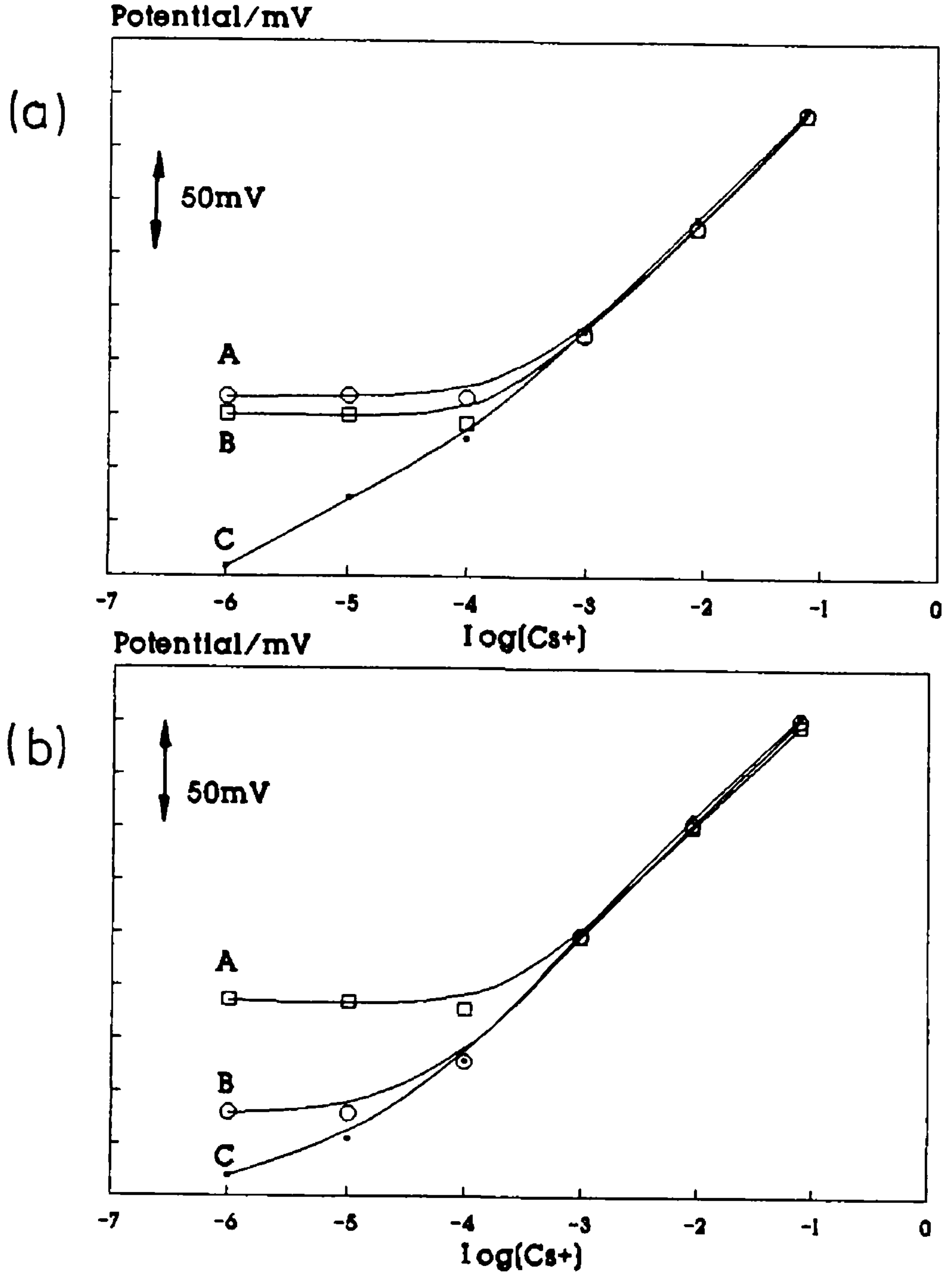

Figure 4.5. Selectivity studies using the mixed solution method for (a) ligand IIb(electrode 2) and (b) ligand IIa(electrode 4). (A) CsCl + 10^{-1}M Mg^{2+}; (B) CsCl + 10^{-1}M Ca^{2+} and (C) pure CsCl. Electrodes as in table 4.1

Table 4 2 Response slopes (mV dec ^{1}) and selectivity coefficients of electrodes containing caesium selective ligands **(IIa)** and **(IIb)**, electrodes as in table 4 1 Selectivities by the SS method(10^{-1}M), divalent ion selectivity by MS (10^{-1}M fixed interfering ion)

electrode number		1	2	3	4	5	6
ligand		**IIb**	**IIb**	**IIa**	**IIa**	**IIa**	--
Average Slope (mV dec ^{1})		54 3	56 5	52 7	55 4	55 4	57 0
	$j=Cs^+$	0 0	0 0	0 0	0 0	0 0	0 0
	$j=Rb^+$	-1 24	-0 99	-1 85	-1 52	-1 83	-0 52
	$j=K^+$	-0 66	-0 79	-2 68	-2 53	-2 59	-1 21
	$j=Na^+$	-2 13	-2 05	-3 87	-3 73	-3 67	-2 67
$\log K_{ij}^{pot}$	$j=Li^+$	-3 29	-3 25	-4 20	-4 45	-4 01	-3 36
	$j=Ca^{2+}$	-3 56	-3 12	-3 39	-3 96	-3 53	-3 33
	$j=Mg^{2+}$	-2 80	-3 39	-4 04	-3 92	-3 94	-3 02
	$j=H^+$	-1 95	-3 02	-3 71	-4 26	-3 02	-1 85
	$j=NH_4^+$	-1 87	-2 06	-2 83	-2 75	-2 39	-1 50

Electrodes based on ligand **(IIa)**, with no membrane additives also displayed a near-Nernstian response to CsCl solutions over the range 10^{-1} to 10^{-5}M The potentiometric selectivity pattern (electrode 3 table 4 2) followed the group I phase transfer trends, $Cs^+ = Rb^+ > K^+ > Na^+ > Li^+$, and excellent selectivity coefficient values were obtained for the group II, H^+ and NH_4^+ ions The selectivity over rubidium was much higher than expected from the phase transfer results in alkali metal picrate as the latter showed approximately equal transfer of Cs^+ and Rb^+ (%E = 95% and 94% respectively) The phase transfer experiments represent a simple cation transfer system from an aqueous to an organic phase at high pH and provide a rapid method of evaluating the selectivity behaviour of a new ligand However, bearing in mind that the electrode membrane is a more complex ion-exchange system and that the conditions under which the selectivity of an ISE is examined are very different, the phase transfer results should be regarded only as a rough guide to electrode selectivity The addition of KTpClPB in the ligand **(IIa)** preparation (electrode 4) in a mass ratio of 4 1 (equivalent to a mole ratio of 1 7 1 of ligand exchanger) helped to increase the selectivity against the hydrogen ion, the other selectivity coefficients were largely unaffected In order to clarify the role of the ion-exchanger in the response, electrodes containing no ligand (electrode 6) and an electrode containing a greater ligand ion-exchanger ratio of 10 1 m/m or 4 1 mole ratio using ligand **(IIa)** (electrode 5) were investigated As expected from previously reported work[20] a selectivity pattern of Cs$^+$ > Rb$^+$ > K$^+$ > Na$^+$ > Li$^+$ was obtained for electrode 6 containing KTpClPB only The ion-exchanger KTpClPB used in these experiments is known to exhibit some caesium sensor activity in PVC membrane systems due to an ion-exchange mechanism between the positive Cs$^+$ ions and the large bulky negative anions In the absence of a "best-fit" cavity mechanism, cations are drawn into the membrane in reverse order of their hydration enthalpies With the alkali metals, this means that the preferred cation is that with the largest diameter, and hence the lowest hydration enthalpy The selectivity sequence obtained for electrode 6 containing KTpClPB only follows this predicted sequence[20] and the values are close to those obtained by other workers[21] Electrode 5 with the 4 1 mole ratio of **(IIa)** exchanger showed good potentiometric selectivity, however the addition of the exchanger in this ratio did not improve the characteristics of the electrode significantly compared to electrode 3 containing **(IIa)** on its own

The dc resistance of the membranes in 10^{-1}M CsCl solutions was measured with a Fluke 8060A digital multimeter Resistance measurements were made on different days over the period of use and the values lay in the range 0 1 to1 5 MΩ for electrodes 1 to 6 No differences were observed between those electrodes with or without ion-exchanger However a general improvement in the response time and stability of the response (less drift) was observed for those electrodes including the higher ion-exchanger concentration i e electrodes 2 and 4

4 5 Injection experiments

Injection experiments involved the addition of 0 180ml of 10^{-1}M solutions of various cations into 20 ml of 10^{4}M CsCl using a moderately fast stirring speed This is equivalent to an approximate 10-fold change in concentration, i e 10^{-4} to 9 91x10^{4}M, for a caesium injection In some cases a further aliquot of 0 180 ml 1M cation was injected into the sample bringing about a further increase in the concentration The changes in potential were followed on a chart recorder set at 60 mm/min chart speed Table 4 3 shows the change in potential following the concentration changes for electrodes 2 and 4 In all cases the response to Cs^+ was very fast ($t_{90\%}$ <10 s) Electrode 2 containing the ligand **(IIb)** had fast ($t_{90\%}$ <20 s) responses to Li^+, Rb^+, NH_4^+, Ca^{2+} and Mg^{2+} with slightly longer times for full equilibration of the K^+ and H^+ injections The magnitude of the potential changes are a good reflection of the selectivity coefficients The largest responses were exhibited for Rb^+ and K^+ injections and approximately the same magnitude (ΔE = 25-30 mV) The responses for the other ions were smaller as expected from the lower selectivity coefficient values Electrode 4 containing the ligand **(IIa)** had even smaller responses to injections of interfering ions The largest response was approximately 10 mV for a Rb^+ injection Again these results confirm the selectivity coefficients given in table 4 2 The dynamic response to injections of Cs^+, Na^+, K^+, Rb^+ and NH_4^+ were fast (<20 s) with slower equilibrations following injections of Li^+, Ca^{2+}, Mg^{2+} and H^+ (up to 60 s)

A second set of injection studies were carried out to determine the dynamic response of the electrodes to changes in caesium concentration (fig 4 6) 0 225 ml of 1M CsCl solution was injected into 25 ml 10^{-3}M CsCl on a fast chart speed (60 mm/min) thus producing a 10^{-3} to 9 91x10^{-3}M change in CsCl concentration In all cases the change in potential was near Nernstian (56-61 mV) and all electrodes responded rapidly to changes in Cs^+ concentration with time constants of the order of a few seconds The rate of response was only limited by the speed of stirring and injection technique

Table 4.3 Injection experiments Change in potential ΔE (mV) to injections of 0.180 ml of 10^{-1}M or 1M solutions of various cations into 20ml 10^{-4}M or 10^{-3}M CsCl, NA not available

Electrode (ligand)		2 (**IIb**)	4 (**IIa**)	4 (**IIa**)
Approx conc change		10^{-4}->10^{-3}M	10^{-4}->10^{-3}M	10^{-3}->10^{-2}M
Cation injected				
	Cs^+	49.1	55.0	55.3
		50.6	55.5	56.3
	Na^+	3.4	0.1	-0.6
		4.0	0.0	-0.9
	K^+	28.6	0.0	-0.4
		26.6	0.1	-0.8
	Rb^+	26.2	10.2	7.8
		29.4	10.0	8.6
ΔE /mV	Li^+	0.2	-0.2	-0.4
		1.4	-0.7	-0.5
	H^+	2.3	1.4	0.0
		6.2	1.8	-0.1
	NH_4^+	9.0	NA	0.2
		8.4	NA	-0.2
	Ca^{2+}	0.6	0.1	-0.5
		0.9	0.6	-1.2
	Mg^{2+}	2.2	0.1	-0.4
		0.7	1.1	-0.7

4.6 Lifetime studies

The lifetime of the electrodes was studied via a periodic recalibration routine using standard solutions and calculating the response slope over the range 10^{-1} to 10^{-4}M CsCl During the observation period (4-6 weeks) the electrodes were used for an average of 10 hours per week and stored in 10^{-1} M CsCl solution between use

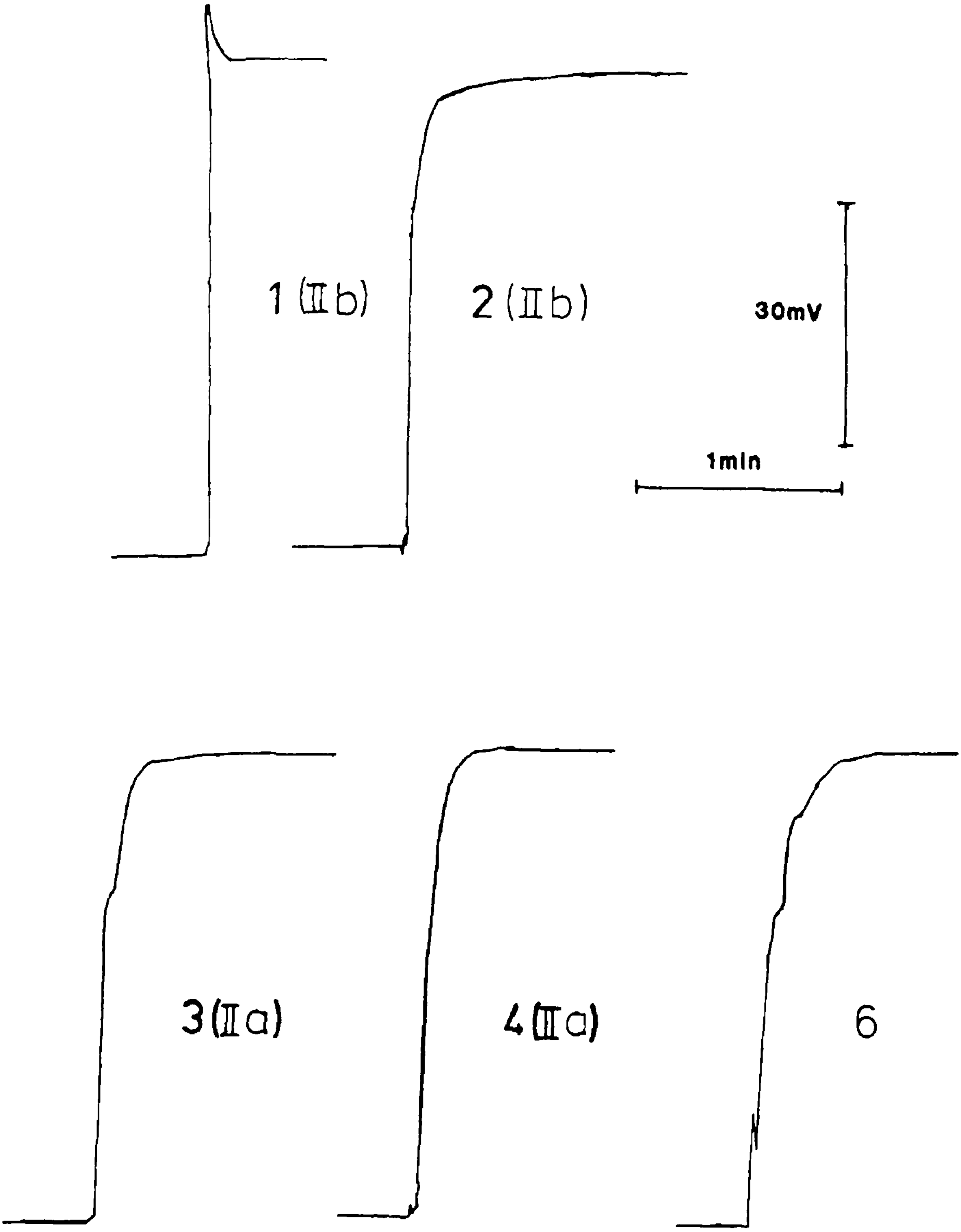

Figure 4 6 Injection experiments. Response (mV) of electrodes 1-4 and 6 to≈10-fold increase in CsCl concentration 0 225 ml of 1M CsCl solution was injected into 25 ml 10^{-3}M CsCl Electrodes as in table 4.1.

The slopes versus time are plotted for electrodes 1-4 and 6 (fig 4 7) The results point to a stability of at least one month for both ligands Although simplistic in the approach, these experiments suggest that the electrodes have useful lifetimes of at least several weeks with occasional use

4 7 Discussion

In general, ion-exchangers such as KTpClPB are incorporated into PVC membrane systems in small amounts to reduce anion interference, lower the membrane resistance, improve electrical properties, and enhance the selectivity characteristics by increasing the cation extraction efficiency[21,22] The selectivity may be adversely affected by the addition of too much exchanger, as the overall selectivity pattern of the membrane depends on subtle interactions between the aquo-cations and the membrane solvent (mediator), the exchanger anions and the carrier molecules In this instance, the situation is further complicated by the caesium sensor abilities of the KTpClPB, leading to the question of which, (the exchanger or the ligand) is dominating the overall performance of membranes incorporating both substances

Examination of the selectivity data for the electrodes indicates that the dominant factor is the presence or absence of the calixarene ligand **(IIa)** or **(IIb)** Both calixarene ligand based systems have much lower selectivity coefficients for Cs^+ over Rb^+ and H^+ compared to the ion-exchange system in electrode 6 The addition of the exchanger to membranes containing excess ligand suppressed the selectivity against Rb^+ slightly and improved the H^+ ion selectivity, but otherwise had no beneficial effect on the selectivity coefficients Overall, the ligand **(IIa)** had superior performance and selectivity characteristics as an ionophore for caesium compared to the *p-t*-butyl substituted derivative **(IIb)** Recent work in our laboratory has shown that the unsubstituted methylester calix[6]arene derivative can also be used as a caesium ionophore in a PVC membrane electrode using 2-NPOE as the solvent mediator[23]

It has already been established that the primary factor in determining the selectivity of the response in calixarenes towards the alkali metal cations is the

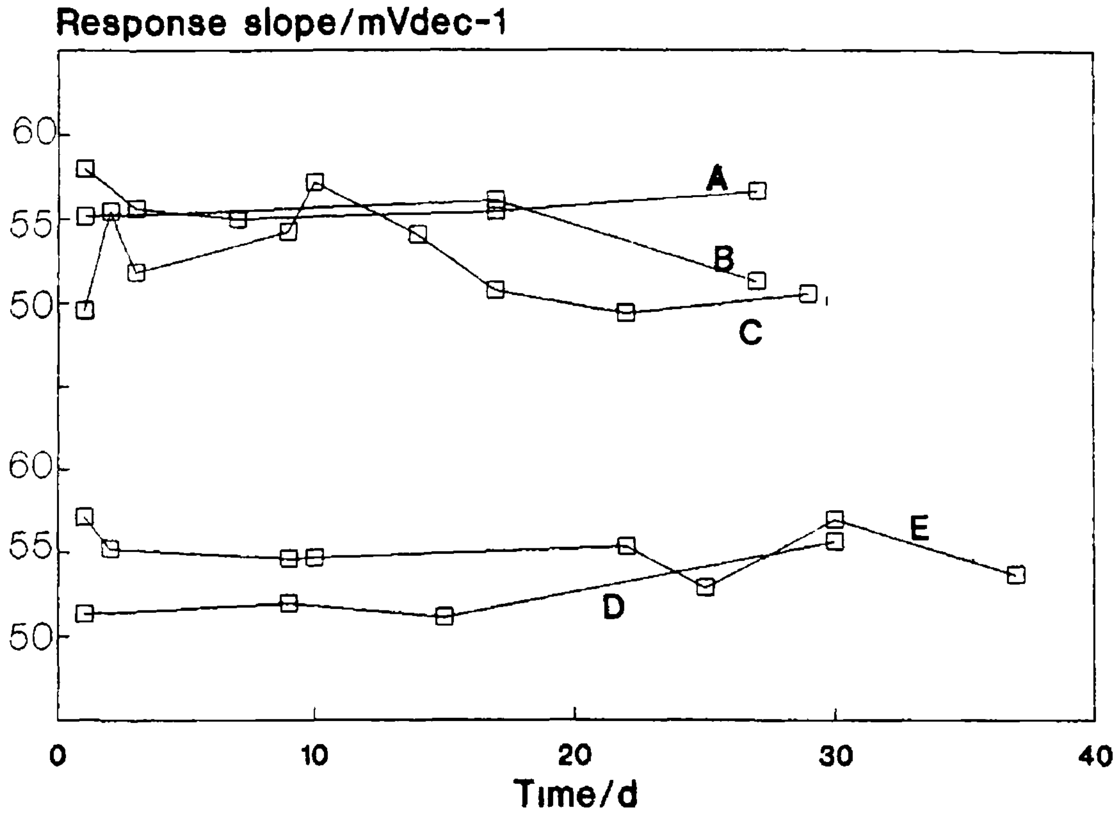

Figure 4 7 Lifetime studies Average slopes (mVdec^{-1}) vs time for PVC membrane electrodes incorporating calix[6]arene IIa and *IIb* (A) electrode 6, no ligand, (B) electrode 1(IIb), (C) electrode 4(IIb), (D) electrode 3(IIa), E electrode 4(IIa)

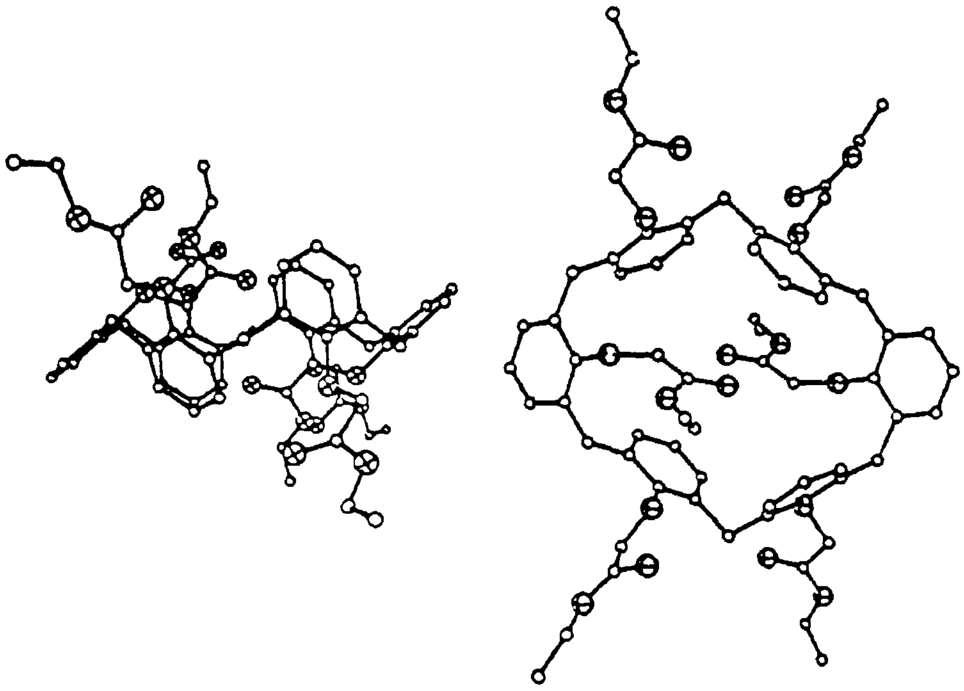

Figure 4 8 X-ray crystal structure of the hexaester IIa; two views of the molecule showing the disposition of the ester groups with respect to the central cavity.

size of the macro ring, hence the calix[4]arenes are sodium selective and the calix[n]arenes where n = 6,8 show a preference for the larger cationic species such as caesium and rubidium ions These larger macrocycles are expected to be more flexible and presumably less preorganised for complexation than the rigid tetramers[18] The effects of the side groups are more complex, though smaller than those of the main ring size In calix[6]arenes the increased size of the macro ring leads to an enhancement of the conformational mobility, as the six aromatic rings have more freedom to rotate about their C-2/C-6 axis Two views of the crystal structure of the unsubstituted ethylester hexamer **(IIa)** are shown in fig 4 8[24] The ester groups are no longer mutually syn with respect to the calix as they are in the calix[4]arenes Three adjacent ester groups are cis but the conformation transformation places the other cis ester groups in the anti position on the opposite side of the macro ring A pair of symmetry related ester groups overhang the cavity

From observations of the tetramers it appears that the phenolic and carbonyl oxygen atoms are primarily responsible for the ion binding with perhaps some extra stabilisation provided by the second oxygen of the ester group It would seem likely that these oxygen atoms are also responsible for the ion binding in the hexameric calixarenes, although the exact contribution of each of the three oxygen atoms remains unclear at this stage With regard to ligand **(IIa)**, it is conceivable that on complexation the ion binding oxygen atoms of the phenolic and ester groups are flexible enough to orientate themselves so as to maximise the ion dipole interactions between the cation and the ligand Some reorganisation of the ion binding atoms would seem necessary as the uncomplexed form of the ligand does not have its binding sites convergently arranged for complexation

Although the peak ion transport is still for caesium ion for electrodes based in the hexamer **(IIb)**, there is a loss in selectivity Substitution of the H by a *t*-butyl group may lead to steric effects which reduce the mobility of the molecule freezing it into a conformation which limits the mobility of the ligating ester oxygens and prevents stabilisation of the incoming cation The bulky *t*-butyl groups may have the effect of increasing the cavity size slightly, leaving it more open and allowing other larger ions to enter and leave the cavity Unfortunately there is only limited information available on the stability constants for the ethylester hexamer derivatives owing to solubility problems and it has not been possible to obtain the x-ray crystal data of the free or cation complexes or the hexamers, except for the ligand **(IIa)** as shown Hence the preceding discussion must be by its nature speculative It does seem likely though that steric interference in ligand **(IIb)** may prevent the cation from getting into close proximity to the oxygen atoms where the negative charge density is highest and/or enlargement of the ring reduces the strength of the ion dipole interactions because the cation cannot be simultaneously close to all the negatively polarised oxygen atoms

Finally, a comparison between the calixarene based electrodes, Cs^+ selective (18-crown-6) systems of Kimura et al [8] and valinomycin based caesium electrodes is shown in fig 4 9 The results indicate that both the crown and the calixarene systems are far superior to the valinomycin based system With regard to the crown compounds, the bis(benzo-18-crown-6) electrode performs markedly better than its monocyclic analog Comparison of the bis(crown) to the calix[6]arene derivatives shows that calixarene **(IIb)** has approximately equal selectivity against Rb^+ and NH_4^+ species with lower selectivity against the Na^+ and K^+ species Of the five electrodes the ethylester calix[6]arene **(IIa)** has the best selectivity characteristics overall with excellent selectivity against the alkali metals and against hydrogen and ammonium ions The electrode also has the advantage of being robust, simple to prepare, having a fast response time and lifetime of at least one month

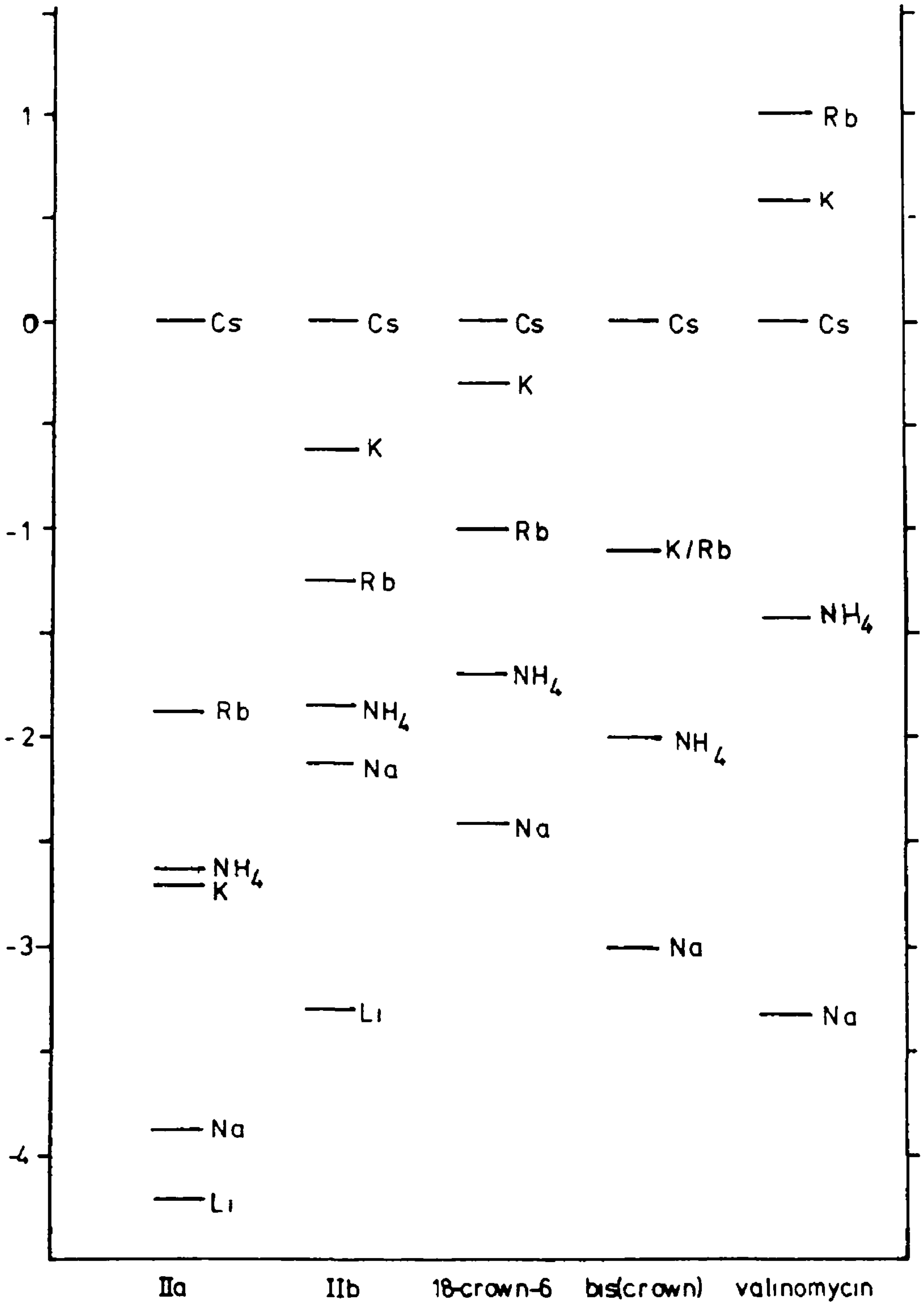

Figure 4 9 A comparison of the selectivity coefficients for caesium selective PVC membrane electrodes incorporating the calix[6]arenes IIa and IIb, bis(benzo18-crown-6), its monocyclic analogue and valinomycin[8] Valency charges ommitted for clarity.

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Chapter 5

Potassium Selective PVC Membrane Electrodes

5 1 Introduction

The field of neutral carrier electrodes for potassium determination has been almost completely dominated by the success of the naturally occurring antibiotic valinomycin Numerous studies have been performed with valinomycin as the active agent in the selective transport of cations across membranes The ionophoric capability of valinomycin has led to its incorporation into organic matrices to give ion-selective membranes with electrochemical sensor applications It has been successfully used in all types of electrode conformations, conventional bench electrodes[1], micro electrodes[2], flow systems[3], ISFETs[4,5] and even optical devices[6] with the number of papers published running into thousands Extensive lists of various membrane compositions, their corresponding selectivity coefficients, the possible applications for the devices and details of commercial clinical analysers which use valinomycin can be found in various reviews[2,7-9]

Clinical measurements in a variety of body matrices (urine, saliva, whole blood, blood serum and plasma) are by far the most important analytical application for valinomycin based potassium sensors It has been estimated that more than 30 manufacturers all around the world produce at least one clinical analyser which utilise neutral carrier based ion-selective electrodes to assay alkali and/or alkaline earth metal cations [9] All the potassium ISE's in these analysers rely on valinomycin as the electroactive agent The extraordinary success of the valinomycin system stems from the high selectivity over sodium and lithium which is vital for the clinical determination of serum potassium The clinically relevant reference range for potassium in blood is 3 5 to 5 0 mmol l^{1}[10] Valinomycin based membranes are often used as the reference neutral carrier system for comparison to newly synthesised ion-complexing ligands Other areas where potassium assays are important are in geology and analysis of urine, sea-water, sewage, grass and vegetables [11]

Valinomycin is a macrocyclic antibiotic cyclodepsipeptide obtained from the culture Streptomyces fulvissimus In its natural environment it controls the transport of potassium across mitochondrial membranes by virtue of its solubility in an organic lipid phase The antibiotic can diffuse together with the potassium ion through a lipid barrier that would normally be impermeable to the ion itself The whole molecule forms a donut shape with a polar cavity to accommodate the potassium ion after it has been stripped of its hydration shell X-ray analysis of the potassium complex reveals that the potassium is co-ordinated to the six inward pointing carbonyl atoms of the ester groups (fig 5 1)[12] The dehydration of the potassium ion and subsequent stabilisation of the complex formed with the ionophore, as well as the tight geometric fit of the ion in the rather rigid valinomycin cavity, all play a role in generating the high selectivity of this ionophore for K$^+$

In recent years there has been an impressive effort directed into designing new synthetic neutral carrier ionophores, some of which have potassium ion-binding ability Certain representatives of the class of crown ethers show sufficient selectivity for K$^+$ over Na$^+$ and have been used as ionophores[13] Kimura and co-workers[14] developed a range of potassium selective bis(crown)ethers, the most successful of which, bis(benzo-15-crown-5) was applied to the determination of serum potassium and showed some promising results as a sensor for clinical analysis [15] Naphtho crown ethers have also been shown to have selectivity coefficients for Na$^+$ of 10^{-2} to 10^{-3} in potassium selective ISE's[16] Somewhat less successful were the systems based on crown ethers with acidic side arms[17], an acyclic dibenzyl ethylene glycol molecule[18] and a macrocyclic pyridine polyether compound[19] All these systems seek to provide more economic alternatives to the highly expensive valinomycin compound and some of them come close to matching the K$^+$/Na$^+$ selectivity of valinomycin based sensors However, as yet, a synthetic neutral carrier has not been found which surpasses the performance of the natural valinomycin compound and which can be synthesised in large amounts more economically

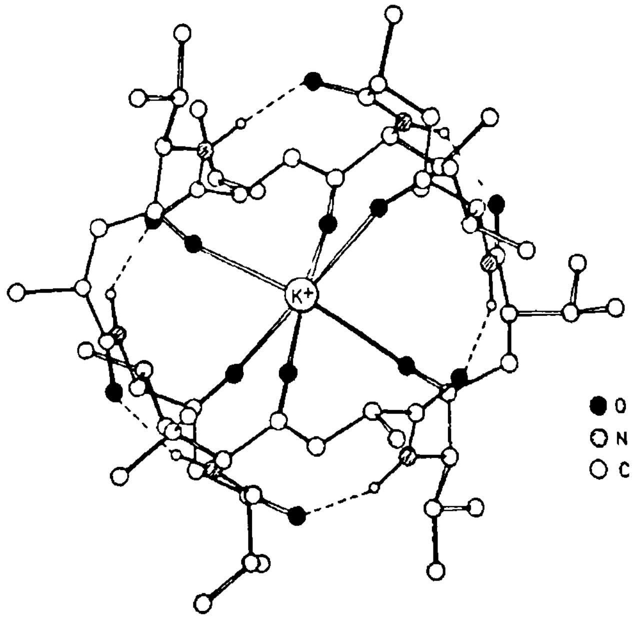


Figure 5 1 The structure of the potasium complex of valinomycin Dotted line represents intra-ligand hydrogen bonds Hydrogens attached to carbon have been omitted[12]

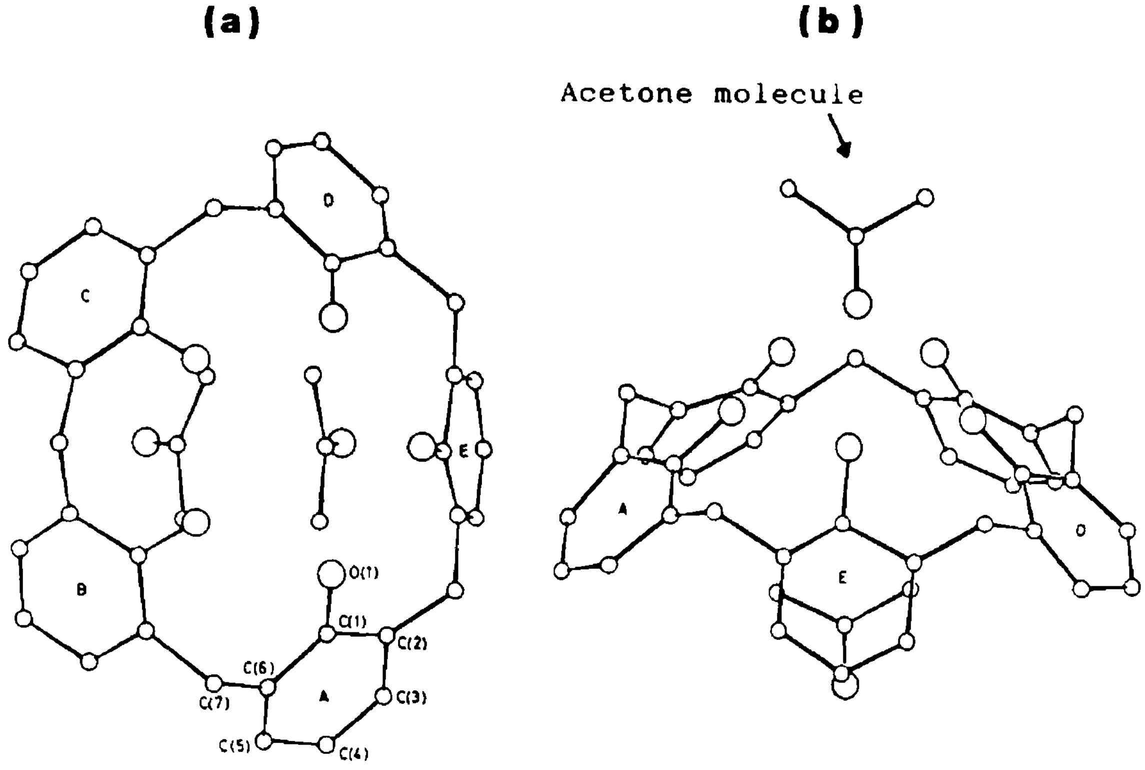


Figure 5 2 Crystal structure of 2 1 clathrate of base calix[5]arene and acetone, view (a) of the cavity (b) perpendicular to the cavity[20].

5 2 Calix[5]arenes and Oxa calixarenes

The previous two chapters have outlined the performance of calix[4]arenes and calix[6]arenes as ion-complexing agents Both the phase transport studies and the ionophoric performance of various tetrameric and hexameric derivatives have confirmed that the host-guest interaction which occurs between alkali metal cations and the modified calixarenes is determined by the macrocyclic structure (notably cavity size) and the nature of the functional groups which act as binding sites within the supra molecule Hence the tetrameric calixarenes offer a cone formation of optimum size for Na^+ ions, while in contrast the hexameric calixarenes offer a less well defined, more flexible cavity of suitable size for Cs^+ ions, supporting a direct correlation between the cavity size and the ionic radius of the primary ion As the ionic radius of the potassium ion (1 33 Å) is intermediate between that of sodium (0 98 Å) and caesium (1 65 Å) and it would appear that calixarenes of intermediate size could produce ion-complexing compounds of suitable cavity size to complex ions of intermediate radius such as K^+ or Rb^+ Although the synthesis of the corresponding pentameric calix[5]arene is difficult, it is not impossible Coruzzi et al studied the crystal structure of a 2 1 clathrate between acetone and the base calix[5]arene with five phenolic units (fig 5 2) [20] One of the acetone molecules is located within the calix and another external to it The calix[5]arene still adopts a cone conformation which places the -OH groups in a circular array in the same plane The distance between the adjacent O O contacts is longer than that observed for the tetramers, giving a sort of flattened cone appearance Unfortunately there are no x-ray structural data available on the funtionalised pentamers

Oxa calixarenes, in which additional methoxy groups have been incorporated into the macro cycle have now become available[21] Compounds containing both monooxa units, where one $-CH_2-$ bridge has been replaced by a $-CH_2OCH_2-$ group, and dioxa units, where two $-CH_2OCH_2-$ groups have been introduced into the macrocycle, have been synthesised This again provides a range of structures with cavity sizes intermediate between that of the tetramers and hexamers The potentiometric properties of PVC membranes based on the penta ethylester *p-t-*

butyl calix[5]arene **(IIIa)** and monooxa and dioxa calix[4]arenes with ethylester, *t*-butylester and methoxyester groups (fig 5 3) will be the focus of this chapter

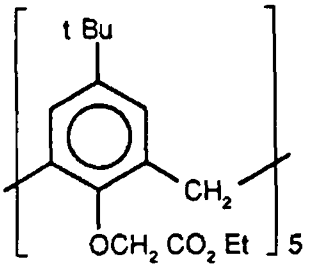
The x-ray crystal structure of the dioxa ethylester *p*-*t*-butyl calix[4]arene **Va** is shown in fig 5 4[22] In general, no phase transfer experiments had been carried out with these derivatives with the exception of some neutral picrate extraction for the dioxa ethylester *p*-*t*-butyl calix[4]arene **(Va)** which are shown in table 5 1[23] Included for comparison are the neutral picrate results for the corresponding ethylester *p*-*t*-butyl calix[4]arene **(Id)** Based on the size related host-guest interaction of the tetrameric and hexameric derivatives, these compounds, of intermediate cavity size, were incorporated into PVC membranes with a view to obtaining a potassium selective response

Table 5 1 Phase transfer in neutral picrate solutions of the dioxa ethylester *p*-*t*-butyl calix[4]arene **(Va)** and the structurally related ethylester *p*-*t*-butyl calix[4]arene **(Id)** [23]

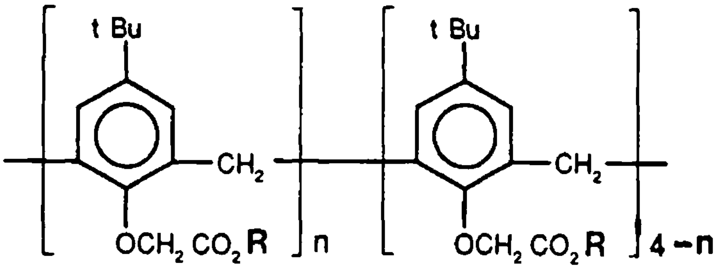
Metal ion	Li^+	Na^+	K^+	Rb^+	Cs^+	Ca^{2+}	Mg^{2+}	Ag^+
ligand				% Extraction				
Va	2 5	2 0	15 9	15 2	13 7	2 0	1 6	5 2
Id	7 2	29 0	4 7	3 6	5 6	4 3	---	16 2

5 3 Experimental

The membrane composition of the various ligands was as outlined in table 5 2 The membrane components were mixed to a total weight of approximately 300 mg and 5 ml THF added The cocktail was stirred for at least 2 hours to ensure complete mixing, cast and bench electrodes assembled as outlined in section 2 5 2 The internal reference electrolyte was 10^{-1}M KCl All electrodes were conditioned before use in 10^{-1}M KCl and stored between use in the same solution



IIIa



n	R	Code	Name
1	Et	IVa	**monooxa ethylester**
1	t-Bu	IVb	**monooxa t-butylester**
1	$CH_2CH_2OCH_3$	IVc	**monooxa methoxyester**
2	Et	Va	**dioxa ethylester**
2	t-Bu	Vb	**dioxa t-butylester**
2	$CH_2CH_2OCH_3$	Vc	**dioxa methoxyester**

Figure 5 3 Structure of the calix[5]arene, monoxa and dioxa derivatives

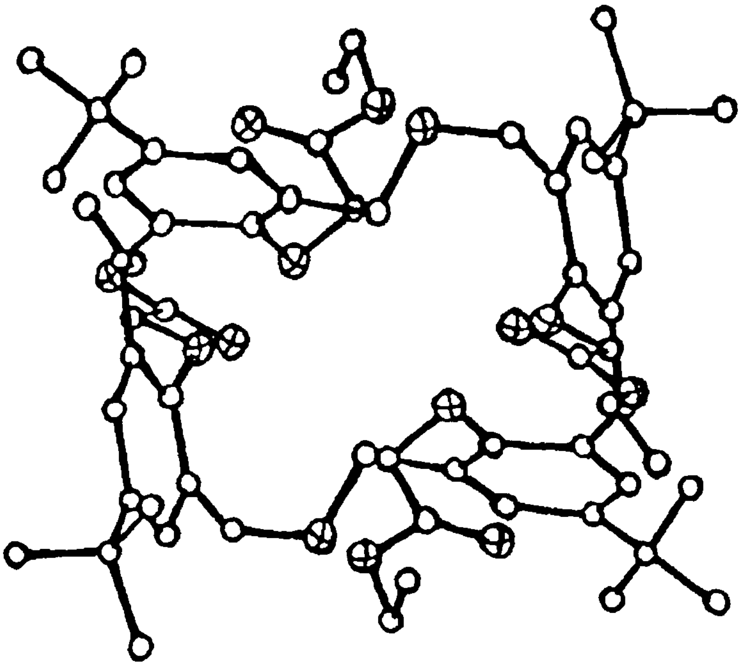


Figure 5 4 Crystal structure of dioxa ethylester *p-t*-butyl calix[4]arene (Va).

The potentiometric responses of the electrodes were tested in 10^{-5} to 10^{-1}M KCl and the slopes (mV dec ^{1}) calculated over the 10^{-1} to 10^{-3} or 10^{-1} to 10^{-4}M activity range Selectivities were calculated by the separate solution method using 10^{-1}M solutions of the interfering ions (section 2 7) Injection experiments involved the injection of 0 360 ml of 10^{-1}M KCl or interfering ion solution into a rapidly stirred aliquot of 40 ml 10^{-4}M KCl, equivalent to a 10^{-4} to 9 91x10^{-4} increase in concentration for a potassium injection The results were monitored on a chart recorder Estimation of the useful lifetime of an electrode was carried out by periodic recalibration in 10^{-4} to 10^{1} M pure aqueous KCl solutions and calculating the slope of the linear portion of the curve

Table 5 2 Membrane composition of the potassium ligands Solvent = 2-NPOE except * solvent = DOS (dioctyl sebacate), $ ref [24]

Ligand	electrode	%m/m			
		Ligand	KTpClPB	solvent	PVC
Calix[5]arene					
ethylester (**IIIa**)		1 1	0 1	66 6	33 3
Oxa calix[4]arene					
ethylester monooxa (**IVa**)	1	1 6	0 2	65 7	32 2
	2	2 2	---	65 1	32 7
ethylester dioxa (**Va**)	1	0 7	0 2	66 2	32 9
	2	0 7	---	66 3	33 0
	3*	0 5	0 1	66 0	33 4
t-butylester monooxa (**IVb**)	1	1 0	0 2	66 1	32 7
	2	1 1	---	65 9	33 0
t-butylester dioxa (**Vb**)	1	0 7	0 2	66 0	33 0
	2	0 7	---	66 3	63 0
methoxyester monooxa (**IVc**)		1 9	0 2	65 2	32 7
methoxyester dioxa (**Vc**)$		0 4	0 1	66 3	33 2

5.4 Penta ethylester *p-t*-butylcalix[5]arene **(IIIa)**

5.4.1 General characteristics and selectivity

The electrode response was tested in aqueous chloride solutions of K^+, Na^+ and Cs^+ over the concentration range 10^{-1} to 10^{-5}M (table 5.3), and showed a near Nernstian response to the three cations with slopes in the range 49-53 mV dec^{-1}. The dynamic response was very fast and the signal quality was extremely clear and steady, especially for the measurements in KCl. This latter stability is presumably due to the soaking and storage of the electrode in 10^{-1}M KCl over the period of use. The average response of the electrode to a range of 0.1M monovalent and divalent cation chloride solutions is shown in fig. 5.5. The data show a very high response to Na^+, K^+, Cs^+ and H^+ ions with slightly lower responses to Rb^+, NH_4^+ and the group II ions. The only appreciable selectivity shown by the electrode is over the smaller Li^+ ion. The electrode maintained its performance for 4-5 days after which the slope of the response function fell below 45 mV dec^{-1}.

Table 5.3. Response (mV) and slopes (mV dec^{-1}) of an electrode incorporating the ligand **(IIIa)** in standard aqueous chloride solutions of potassium, sodium and caesium. Values taken after 3 minutes equilibration, slope measured over the 10^{-1} to 10^{-3}M range. * Unconditioned membrane.

Conc. M	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	Slope mV dec^{-1}
K^{+*}	40.4	62.6	109.6	159.3	207.9	51.7
K^+	36.4	62.1	107.1	158.0	208.4	53.3
K^+	45.6	67.2	106.4	156.7	207.5	53.2
K^+	76.9	90.9	114.0	160.5	208.1	49.5
K^+	55.1	73.8	110.3	162.3	208.9	51.9
Na^+	52.6	68.1	101.3	148.5	198.1	50.9
Na^+	54.5	67.5	100.0	116.0	195.9	49.5
Cs^+	--	76.3	112.8	161.7	211.5	52.9
Cs^+	--	81.7	119.3	163.2	213.2	49.3

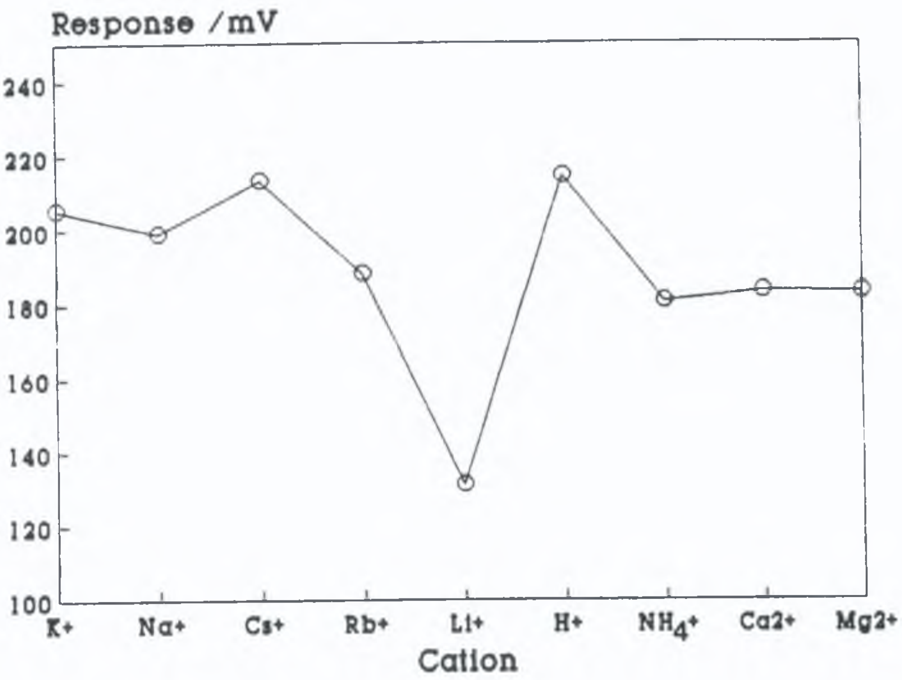


Figure 5.5 Average potential (mV) of a PVC membrane electrode incorporating the ligand IIIa to 10^{-1} M chloride solutions of some monovalent and divalent ions.

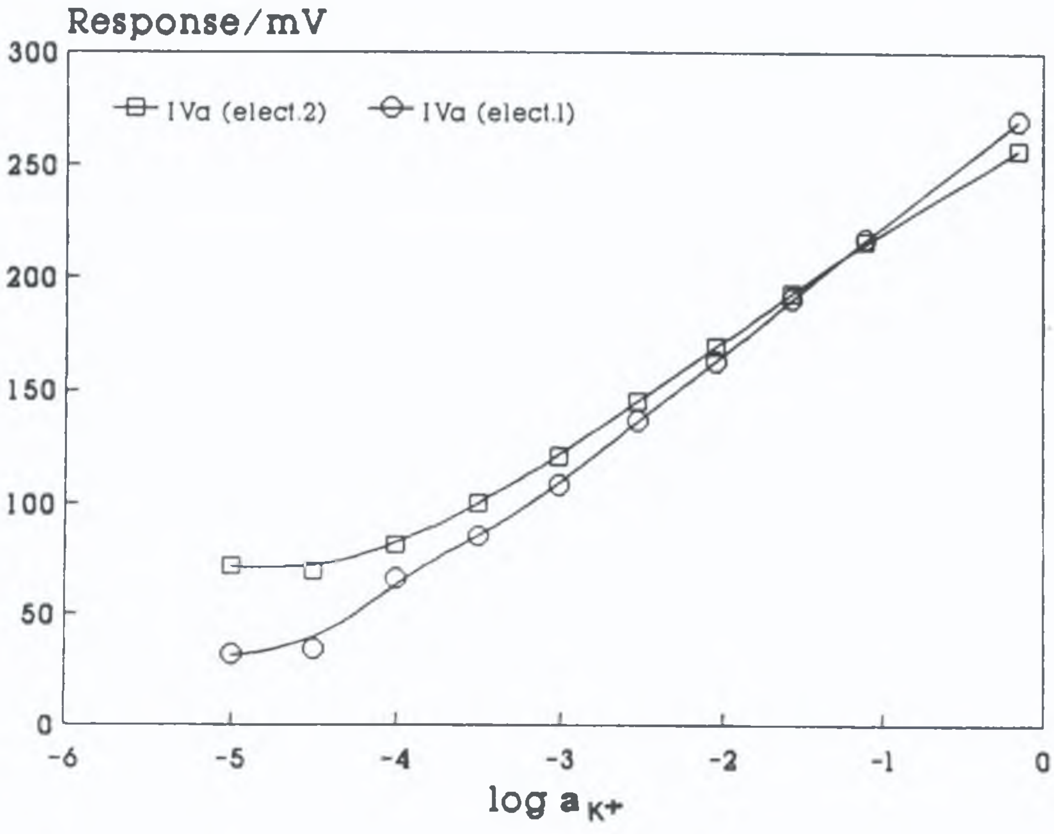


Figure 5.6. Calibration curves for electrode 1 and 2 incorporating the ligand monoxa ethylester *p-t*-butylcalix[4]arene (IVa) in pure aqueous KCl solutions.

5 5 Monooxa ethylester *p-t*-butyl calix[4]arene **(IVa)**

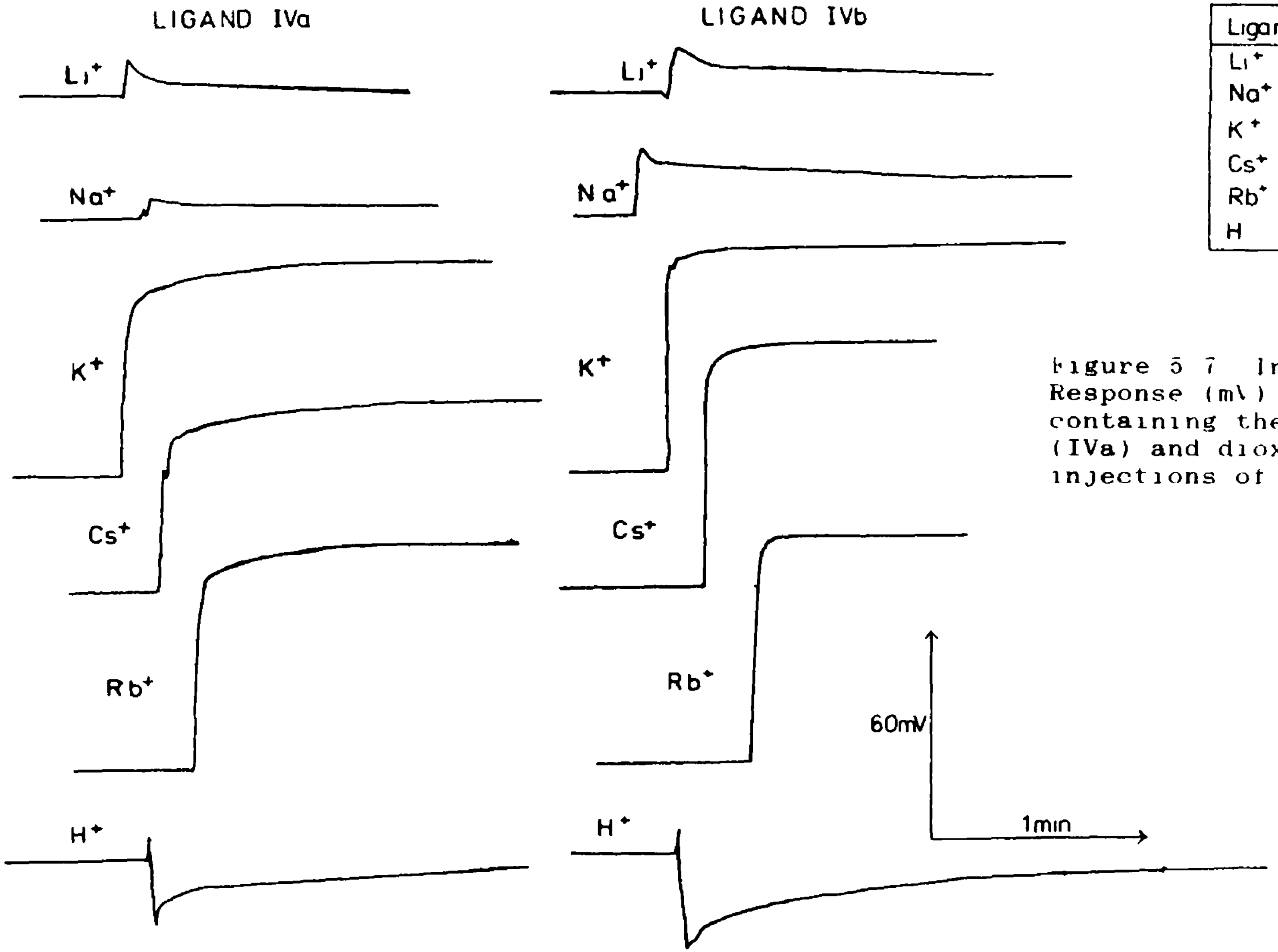
5 5 1 General characteristics

Two different membrane compositions were investigated (table 5 2) Electrode 1 contains ligand **(IVb)** and a 4 1 mole ratio of the ion-exchanger and electrode 2 contains the ligand **(IVb)** only The average slope calculated over the activity range 10^{-1} to 10^{-4}M in pure KCl solutions for electrode 1 was 56 8+/-1 16 mV dec^{1} (n=12) and for electrode 2 was 54 2+/-1 8 mV dec^{1} (n=10) Two calibration curves are shown in fig 5 6 for electrodes 1 and 2 The estimated limit of detection was 2×10^{-5}M in KCl for electrode 1 and slightly higher for electrode 2 The dc resistance of the membranes measured in 0 1M KCl solution for electrodes containing no ion-exchanger was 1 05+/-0 15 MΩ (n=5) and for electrodes containing the exchanger was 0 16+/-0 02 MΩ (n=5) The responses were generally slower for membranes containing the ligand only and so potentials were taken at 3 minute and 5 minute periods respectively In general the electrode response was stable although the addition of the ion-exchanger enhanced the signal quality and extended the linear dynamic range slightly (fig 5 5)

5 5 2 Selectivity coefficients

The selectivity coefficients for some monovalent and divalent ions are shown in table 5 4 Electrode 2, with no ion-exchanger showed some selectivity over the group I cations with good selectivities over hydrogen and ammonium ions and the divalent species The addition of the ion-exchanger (electrode 1) improved the Na^+, Li^+, H^+ and the divalent selectivity and showed a tendency to depress the selectivity over Cs^+ and Rb^+

The responses of electrodes to injections of various cations can be seen in fig 5 7 for the monooxa ethylester ligand **(IVa)** (electrode 1) and the dioxa ethylester ligand **(Va)** (electrode 1) The change in potential to injections of K^+, Cs^+ and



	ΔE (mV)	
Ligand	IVa	Va
Li+	2	3
Na+	2	8
K+	50	52
Cs+	44	56
Rb+	55	55
H	-3	-2

Figure 5.7 Injection experiments Response (mV) of electrodes containing the monooxa ethylester (IVa) and dioxa ethylester (Va) to injections of various cations

Rb^+ ions is quite high as expected from the selectivity data for ligand **(IVa)**, withsmaller responses to Li^+, Na^+ and H^+ The electrodes had a fast response to changes in the analyte ion With regard to lifetime, periodic recalibration of electrodes 1 and 2 showed no decrease in the value of the slope function over a period of two weeks

Table 5 4 Selectivity coefficients of electrodes incorporating ligand **(IVa)** Electrodes as in table 5 2 Selectivities by the SS method (10^{-1} M) n=4

Electrode	$\log K_{ij}^{pot}$								
j=	K^+	Na^+	Cs^+	Rb^+	Li^+	H^+	NH_4^+	Ca^{2+}	Mg^{2+}
1	0 0	-1 49	-0 91	-0 52	-2 93	-3 26	-1 62	-3 39	-2 64
2	0 0	-0 37	-1 18	-0 87	-2 56	-2 94	-1 75	-2 52	-2 35

5 6 Dioxa ethylester *p*-*t*-butylcalix[4]arene (Va)

5 6 1 General characteristics

Electrode 3 (table 5 2) using DOS (dioctyl sebacate) as the plasticizer displayed a much reduced slope of 20-22mV dec^{1} and was not considered for further use The results for membranes using 2-NPOE were much better and are shown in table 5 5 for electrode 1 (with incorporated ion-exchanger) and electrode 2 in aqueous 10^{-1} to 10^{-5} M KCl solutions The average slope for electrode 1 with incorporated ion-exchanger was 52 4 +/- 2 4 mV dec^{1} and for electrode 2 containing the ligand only was 53 1 +/- 0 86 mV dec^{1} The dc resistance of the membranes for electrodes containing exchanger was 0 08+/-0 01 MΩ (n=5)

Table 5.5. Response(mV) and slopes S (mV dec^{-1}) of electrodes incorporating the ligand dioxaethylester **(Va)** in standard aqueous solutions of KCl.

[KCl] /M	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	Slope
electrode 1	---	-97.4	-88.2	-33.5	21.0	56.1
"	-95.2	-92.3	-76.3	-32.7	21.0	51.1
"	-116.2	-109.8	-80.1	-30.0	21.0	50.6
"	-152.4	-132.7	-93.2	-37.0	18.7	52.9
"	-122.7	-104.7	-74.5	-31.2	19.8	49.5
"	-142.8	-87.5	-85.7	-34.5	17.2	54.1
electrode 2	-83.4	-95.8	-66.1	-10.3	35.8	53.6
"	-127.3	-74.1	-31.8	-4.6	34.1	53.6
"	-149.3	-116.4	-68.2	-16.6	34.0	52.1

5.6.2 Selectivity coefficients

The selectivity coefficients for electrode 1 are shown in table 5.6. Reasonable selectivity for Na^+, Li^+ and the divalent ions was observed but the selectivity coefficients for Cs^+ and Rb^+ indicate a very high response to these larger ions. A large variation in the H^+ ion selectivity was observed with values of $\log K_{ij}^{pot}$ ranging from +0.4 to -3.3. The dynamic response of the electrodes was fast, of the order of a few seconds and the signal quality was good. The traces for the injection experiments can be seen in fig. 5.7 and they show large responses to K^+, Cs^+ and Rb^+ as expected from the selectivity data. With regard to lifetime the electrode maintained its performance for a few days but the response decayed severely after that.

Table 5.6 Selectivity coefficients of electrodes incorporating ligand **(Va)**. Electrodes as in table 5.2. Selectivities by the SS method (10^{-1} M) n=2, * see text.

$\log K_{ij}^{pot}$

j=	K^+	Na^+	Cs^+	Rb^+	Li^+	H^+	NH_4^+	Ca^{2+}	Mg^{2+}
Electrode 1	0.0	-1.56	-0.15	-0.03	-1.92	*	-0.50	-1.80	-1.44

5 7 *t*-butylester *p*-*t*-butyl monooxa calix[4]arene (**IVb**) and *t*-butylester *p*-*t*-butyl dioxa calix[4]arene (**Vb**)

5 7 1 Response, selectivity and general characteristics

Electrodes based on ligand (**IVb**) and ligand (**Vb**) displayed near Nernstian responses to potassium ions with detection limits in the range 1×10^{-3} to 3×10^{-5} M The slopes and selectivity data for both electrodes is shown in table 5 7 Some selectivity by the sensor for potassium over sodium is evident but the larger Cs^+ and Rb^+ ions constitute severe interferences particularly in the case of the larger dioxa ligand Both ligands show reasonable selectivity over Li^+ and the divalent ions The response of electrodes containing (**Vb**) were very sluggish with a lot of random drift in the signal (5 mV hour^{-1}) in the signal As regards lifetime, the electrode performance of electrode with (**IVb**) was retained for about one week but the performance of electrodes with (**Vb**) decreased significantly within 24 hours

Table 5 7 Slopes (S) (mV dec ^{1}) and selectivity coefficients for electrodes incorporating the monooxa and dioxa *t*-butylester derivatives (**IVb**) and (**Vb**) respectively Electrodes as in table 5 2 Selectivities by the SS method(10^{-1} M), * data from ref 24

Code	electrode	S			$\log K_{ij}^{pot}$				
j=			K^+	Na^+	Cs^+	Rb^+	Li^+	Ca^{2+}	Mg^{2+}
IVb*	1	56 3	0 0	-1 8	-0 6	-0 3	-2 7	-2 8	-2 0
IVb	2	57 9	0 0	-0 3	-1 1	-0 9	-2 5	-2 3	-1 7
Vb	1	58 5	0 0	-1 6	-0 01	-0 03	-2 4	-2 1	-0 5
Vb	2	53 7	0 0	-1 4	-0 1	-0 6	-2 4	-2 0	-2 1

5.8 Monooxa methoxyester *p*-*t*-butylcalix[4]arene (**IVc**)

5.8.1 Response, selectivity and general characteristics

The electrode response was tested in aqueous chloride solutions of K^+, Na^+ and Cs^+ over the concentration range 10^{-1} to 10^{-5} M (table 5.8), and showed a near Nernstian response to the three cations with slopes in excess of 50 mV dec^{-1}. Good stability of the signal was evident, with a fast response to changes in analyte ion ($t_{90\%}$ < 30 s). The estimated linear range for the electrodes was 1×10^{-1} to 5×10^{-4} M. The average response of the electrode to a range of 0.1 M monovalent and divalent cation chloride solutions is shown in fig. 5.8. The data show a very high response to Cs^+, Rb^+ and K^+ ions with slightly lower responses to Na^+, NH_4^+ and some selectivity over the group II ions. The best selectivity shown by the electrode is over the smaller Li^+ and H^+ ions. With respect to lifetime, the electrode maintained its usefulness for at least 7 days.

Table 5.8. Potentiometric response (mV) and slopes (mV dec^{-1}) over the activity range 10^{-1} to 10^{-3}M for electrodes incorporating the ligand methoxyester monooxa calixarene (**IVc**) in standard aqueous chloride solutions of potassium, sodium and caesium. Values taken after 3 minutes equilibration.

[cation] /M	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	Slope mV dec^{-1}
K^+	38.9	69.9	107.5	162.8	218.1	58.1
"	65.3	65.0	108.0	162.7	219.6	58.7
"	76.5	73.2	118.9	168.5	223.0	54.7
"	39.5	75.9	110.4	166.9	222.3	58.8
"	72.4	85.7	116.4	170.3	225.4	57.3
"	63.4	73.0	113.6	169.4	233.8	57.6
Na^+	5.2	34.4	81.0	126.1	180.4	52.1
"	64.4	26.5	70.4	125.7	182.4	58.9
Cs^+	113.5	83.6	142.7	199.7	253.9	58.4
"	64.5	94.6	147.7	203.6	256.8	57.4

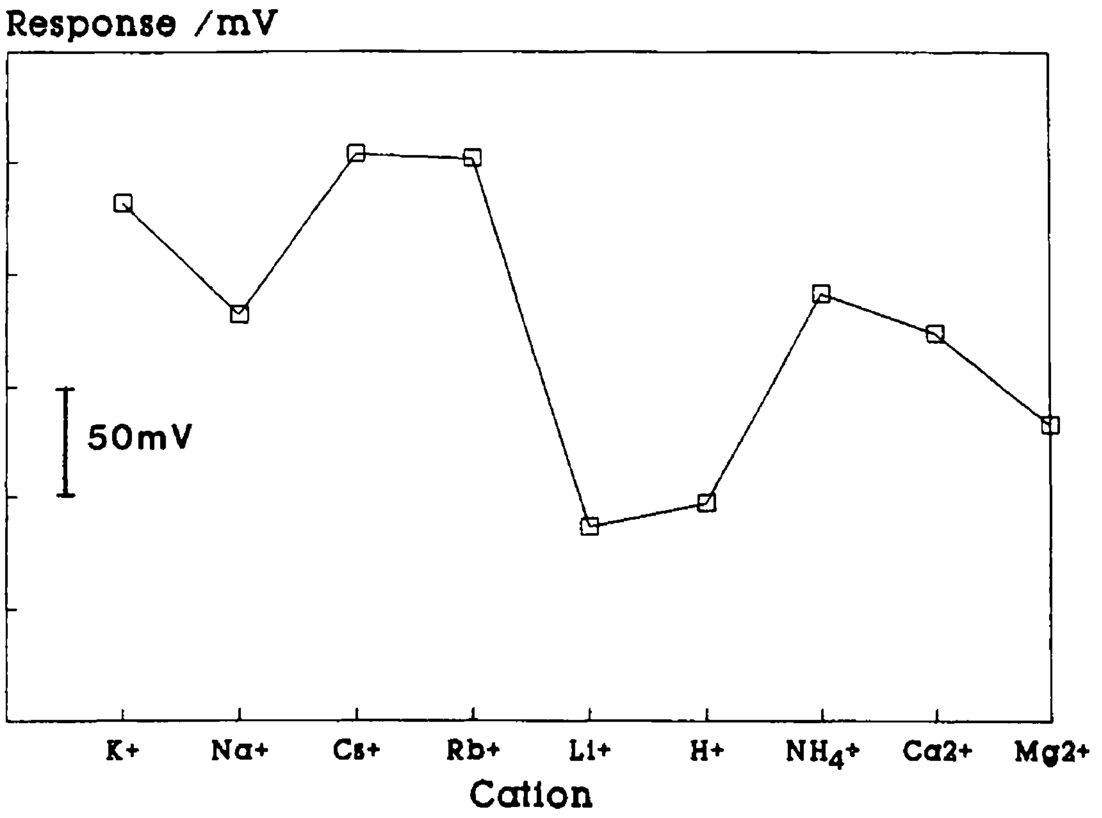


Figure 5 8 Average potential (mV) of a PVC membrane electrode incorporating the ligand monoxa methoxyester (IVc) to 0 1M chloride solutions of some monovalent and divalent cations

5 9 Discussion

5 9 1 Penta ethylester calix[5]arene

The pentamer displayed almost equal responses to potassium, sodium and caesium with slopes in the range 49-54 mV dec^{1} In addition there was also quite a high response to Rb$^+$ and H$^+$ ions The responses in each case were extremely stable Compared to the selectivity of the corresponding tetramer (**Id**) (table 3 2) for Na$^+$ and the hexamer (**IIb**) (table 4 2) for Cs$^+$, the calix[5]arene ligand did not display the selectivity of response towards K$^+$ as hoped The lack of the stability of the odd numbered calix[n]arenes may be due to a decrease in intramolecular hydrogen bonding [25] The selectivity of the tetramers to Na$^+$ is attributed to the size and rigidity of the cavity which places the oxygen atoms in an ideal preorganised array for complexation In the hexamers the combination of the larger cavity size and the greater flexibility of the ligating groups allows the oxygen atoms to orientate themselves in a suitable position for stabilisation of the Cs^+ ion. NMR studies of the ethyl ester calix[5]arene have indicated that the molecule exists in the cone conformation with the five ligating ester groups mutually syn with respect to the macrocycle[27]. In this case the whole molecule would have quite a high degree of rigidity. It would be reasonable to speculate from the selectivity data that the pentamer does not possess either an apropriate preformed rigid array of oxygen atoms suited to selective complexation, as a result its increased cavity size, or sufficient conformational mobility to orientate its ligating groups into a conformation suited to complexation of a particular cation. As a result the ligand had some degree of complexation to all the larger group I cations and very broad selectivity patterns were obtained. Lack of selectivity does not automatically mean that the ligand has no usefulness as a sensor material. In fact the signal from such sparingly selective electrodes is used for cross-talk between the highly selective electrodes and can thus improve the accuracy and precision of data from the array[26].

5.9.2 Monooxa and dioxa calix[4]arenes

From the analysis of the data available in the preceding sections the monooxa ligands **(IVa)**, **(IVb)** and **(IVc)** and dioxa ligands **(Va)** and **(Vb)** have shown varying ionophoric abilities. A comparison of the $\log K_{ij}^{pot}$ data is shown in fig. 5.9. Included for comparison are the data for the dioxa methylester **(Vc)** [24], valinomycin in DOS[7] and bis(benzo-15-crown-5) using NPOE as the plasticizer with a 50% mole ratio of KTpClPB[18]. In general the ligands displayed a Nernstian response to potassium and in some cases a Nernstian response to Rb^+, Cs^+ and Na^+ as well. The selectivity coefficient for sodium was lowest for the monooxa *t*-butylester **(IVb)** with approximately equal selectivities for sodium for the dioxa *t*-butylester **(Vb)** and the monooxa and dioxa ethylester ligands **(IVa)** and **(Va)**. The worst sodium selectivity was displayed for the monooxa and dioxa methoxyethylester derivatives **(IVc)** and **(Vc)**. All the ligands display a high response to rubidium and caesium with selectivity coefficients ranging from positive values for ligand monooxa methoxyester **(IVc)** to the lowest values for the monooxa ethylester ligand **(IVa)**. There are no clear systematic differences in the selectivity patterns on going from monooxa to dioxa. In the case of the ethylester and *t*-butylester derivatives the addition of the extra bridging oxygen seems to increase the ion-binding ability of the ligands for the alkali metal ions (Na^+, Cs^+, Rb^+ and Li^+) and the divalent species, hence a general increase in the log K_{ij}^{pot} values is observed for these ions The opposite is the case for the derivatives with the methoxyethylester in the modified chain (**IVc**) and (**Vc**) Here the addition of the second oxa $-OCH_2-$ in the macrocyclic ring leads to a slight improvement in the selectivity for Cs^+, Rb^+, Li^+, NH_4^+ and the divalent species This may be due to the extra ether oxygen of the methoxyethylester group in the modified chain which contributes some extra stability to the cationic complex

The tetrameric calixarenes are characterised by an extremely rigid 3-D structure which confers a high degree of selectivity for sodium The incorporation of an oxa spacer units within the cavity increases the cavity size and thus favours complexation with larger ions such as potassium and rubidium As further oxa spacer units are introduced the annulus diameter increases and complexation with larger ions is enhanced further This increase in cavity size and/or flexibility of the calixarene arising from the incorporation of these spacer units eventually leads to derivatives which are largely incapable of discriminating between potassium, rubidium and caesium

As well as the selectivity being dependent on the cavity size the conformation of the molecule, the nature of these functional groups which provide the binding sites also influences the selectivity of the response In the tetrameric calixarenes, the high selectivity for Na^+ is assured by the rigid placement of the four phenolic oxygen atoms and the four carbonyl oxygen atoms of the derivative chain, thus assuring a symmetrical stabilisation of the Na^+ ion on complexation Further enhancement of the response can be obtained by fine tuning the groups in the derivative chain In the case of the monooxa and dioxa ligands not only is the cavity size increased by the addition of the spacer units but the symmetrical arrangement of the phenolic and carbonyl oxygens of the derivatising chain is forced slightly askew and a rigid symmetrical arrangement of the polar binding sites is no longer available for the incoming cations, hence the loss in selectivity

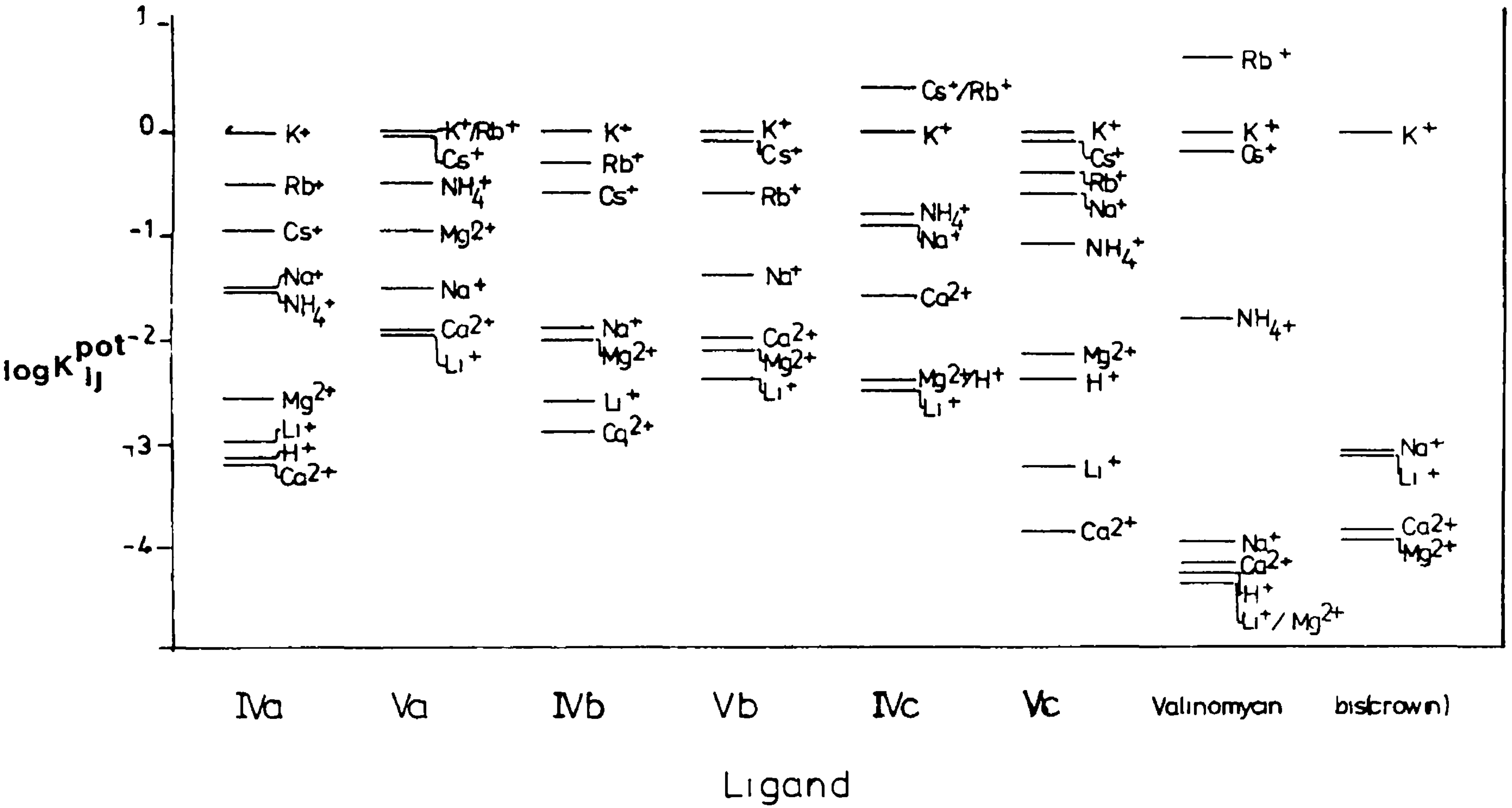


Figure 5 9 Selectivity coefficients for the monoxa and dioxa derivatives Included for comparison are data for dioxa methoxyester [24], valinomycin [7] and bis(benzo-15-crown-5)[15]

The X-ray crystal structure of the dioxa ethylester calix[4]arene (**Va**) is shown in fig 5 4 and it clearly illustrates that the inclusion of the two ether bridges between opposing aromatic rings creates a larger rectangular cavity compared to that of the tetraester (fig 3 8(b)) In fact the dioxa ethylester is conformationally more similar to the hexamer (**IIb**), although the cavity dimensions of the latter are much larger

5 10 Conclusions

None of the ligands displayed potassium selectivity comparable to similar PVC electrodes incorporating the crown compound or the natural antibiotic valinomycin However these results do demonstrate that the monooxa and dioxa derivatives of the calix[4]arenes are potassium selective and can be used to produce functioning potassium electrodes The phase transfer studies using neutral metal picrates for the dioxa ethylester (**Va**) revealed some interesting complexation to the actinide uranium and silver ions which may lead to other applications [20] Although U^{4+} is a smaller cation than K^{+} or Ba^{2+}, it is the concentration of charge, that is, the presence of 4 positive charges on U^{4+} that allows stronger co-ordination to the electron rich ligand Given the numerous options for structural modification of both calixarenes and oxa calixarenes and the attendant variability of selectivity there is a clear possibility of producing a wide range of new and more efficient ionophores for various applications not just ISE's targeted at various cations

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Chapter 6

Solid State Devices

6 1 Introduction

Many of the recent developments in sensor technology have been in the development of new and improved solid state sensors The major advantages of solid state sensors stem from their simplicity of function, small size and projected low cost fabrication Substitution of the liquid internal contact with a solid contact means the devices can have a reduced number of phases which allows them to be mass produced using planar fabrication technologies already established by the microchip industry They can be used in any space position, inverted, horizontal or vertical and their small size, usually centimetres to micrometers, makes them more adaptable to a wider range of applications The major disadvantages of solid state chemical sensors are lack of stability, lack of reproducibility, lack of selectivity or insufficient sensitivity for some purposes In many cases the true form of the electrochemical equilibrium in the system is poorly defined Clearly there must be some mechanism present to maintain the transition from chemical (usually ionic) to electronic conductivity but its exact nature is not always fully understood

The term "solid state" is used in the literature to describe a broad range of sensor conformations[1] It includes silicon based sensors such as ISFET's (ion-selective field effect transistors) and CHEMFET's (chemically sensitive field effect transistors), semiconducting metal oxide sensors for gases, coated wire electrodes (see section 1 14) and solid contact electrodes which utilize various types of crystal, solid electrolytes or redox materials as the contacting layer between the conducting metal and the electroactive material

6 2 Conducting polymers

Conducting polymers such as polypyrrole (PPy) have recently been recognised as a class of membrane material having some novel electrochemical analytical applications[2] Ikariyama and Heineman reported the use of PPy as a detector of anions in a flowing stream[3] The electrode potential was held at 0 9 V and the anodic current recorded as the electrode was doped by anions (carbonate phosphate and acetate) flowing through the cell The doping current of the conducting polymer was found to depend on anion concentration in the flowing stream The electrode was undoped by applying a negative bias to the PPy after each analytical signal A second paper outlined the determination of chloride, bromide and iodide[4] Other authors have reported similar work based on a polyaniline membrane sensitive to the doping effect of nitrate, chloride, sulphate and oxalate in a flowing stream[5] Dong et al showed that PPy could be used as an anion sensitive potentiometric membrane material[6] and constructed a chloride selective electrode on glassy carbon[7] They reported selectivity for chloride over the larger sulphate and acetate anions with less selectivity over the other halides, iodate and perchlorate ions They constructed a micro sensor using PPy coated carbon fibres and reported its use for the determination of serum chloride[8] The same authors constructed a perchlorate selective electrode based on $LiClO_4$ doped PPy[9] They showed that the potentiometric response was only present when the polymer was in the doped state and the response potential was bound up in the doped ClO_4 concentration in the PPy film

$$\underset{\text{undoped state}}{PPy^{o} + ClO_4\ (\text{solution})} \rightleftharpoons \underset{\text{doped state}}{PPy^{+} + ClO_4\ (\text{film}) + \bar{e}} \qquad (6\ 1)$$

The doping process of conducting polymers is also known to be accompanied by a large increase in electronic conductivity, hence the polymers posses some mixed ionic/electronic conduction and could act as a novel membrane material for potentiometric sensors They also offer advantages such as external control of the conductivity/redox state and they have low resistance, which is important for many types of sensors

In this chapter a new type of solid contact electrode is described where a layer of polypyrrole (PPy) is used as the mediating layer between a metal substrate and a sodium selective PVC membrane containing the tetrameric ethylester *p-t*-butyl calix[4]arene ligand (**Id**) described in chapter 3 Although results are shown mainly for platinum (Pt) substrate, essentially the same results are obtained for glassy carbon (GC) In order to determine the mechanism of charge transport involved in the use of conducting polymers as a solid contact three different systems were proposed as the focus of our study (see fig 6 1 for a schematic diagram) The first is PPy directly coated on the substrate (Pt/PPy/Na$^+$ or GC/PPy/Na$^+$) The second system is a coating of sodium selective PVC directly on platinum (Pt/PVC/Na$^+$) The final system is the solid contact electrode where a layer of PPy is used as the mediating layer between the substrate and PVC (Pt/PPy/PVC/Na$^+$) Four compositions of PVC membranes all containing the ionophore (**Id**) with and without different ion-exchanger compositions were examined for their performance as sodium ion-selective membranes (see table 6 1) These contained

1) Ionophore and KTpClPB (potassium tetra-*kis*-*p*-chlorophenyl borate) only (PVC1)
2) Ionophore, KTpClPB and $NaBF_4$ (sodium tetrafluoroborate) (PVC2)
3) Ionophore and $NaBF_4$ only (PVC3)
4) Ionophore only

The electrodes were fabricated as outlined in section 2 6

Table 6 1 General composition of the PVC cocktail solutions The following components were mixed 1ml THF / 100mg plasticizer

	%w/w			
	PVC1	PVC2	PVC3	PVC4
ionophore	0 7	0 7	0 8	0 9
Ion-exchanger KTpClPB	0 2	0 1	--	--
$NaBF_4$	--	0 1	0 1	--
Plasticizer 2-NPOE	66 1	66 1	66 1	66 1
PVC	33 0	33 0	33 0	33 0

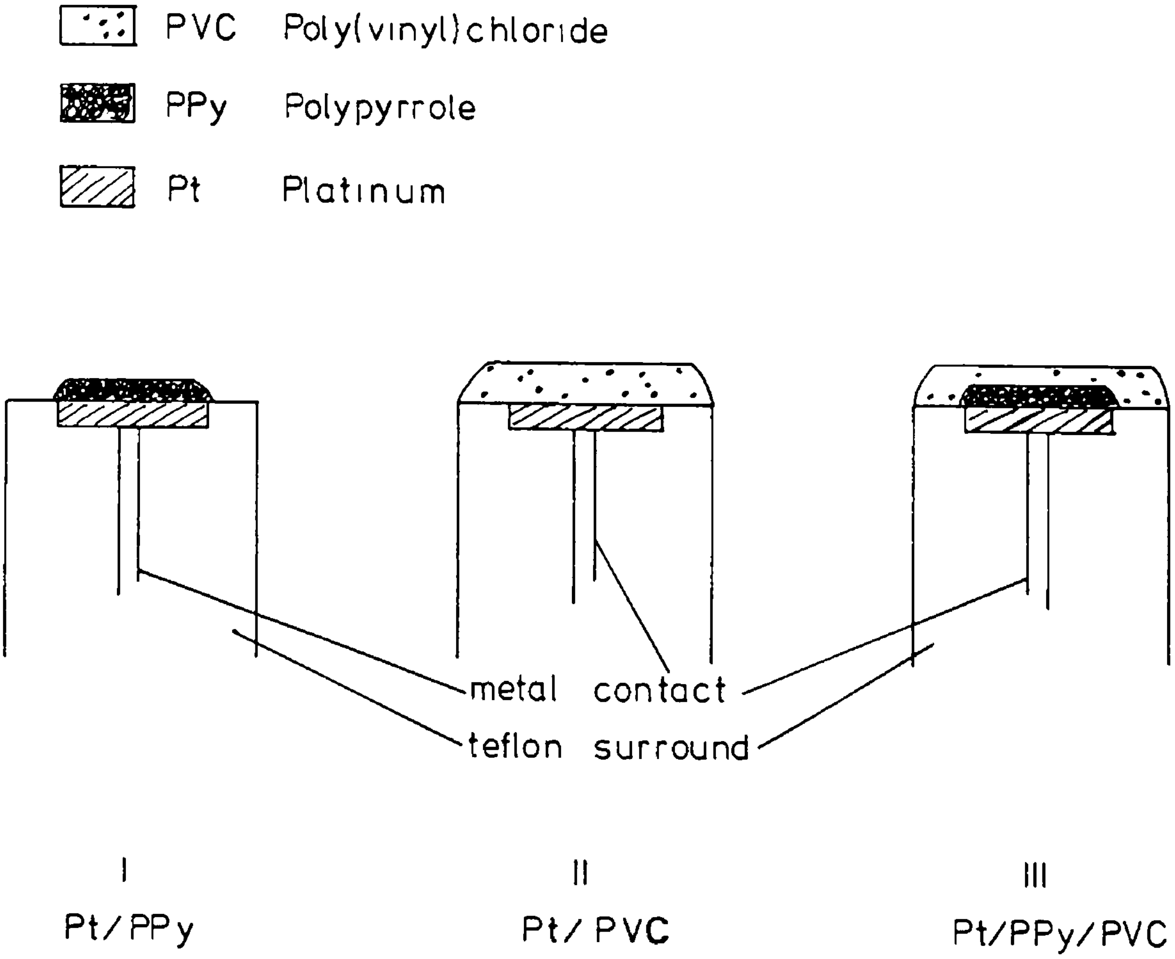

Figure 6 1 Schematic diagram of the three systems studied

6 3 Electropolymerisation and potentiometric responses of polypyrrole (System I Pt/PPy/Na^+)

Even though the practical process of electrochemical polymerisation is straightforward and simple, the chemical processes leading to film formation are complicated The physico-chemical properties of the resulting film are ultimately affected by many factors, such as solvent, impurities, and the type and concentration of doping salt, current/voltage conditions, duration of polymerisation and concentration of monomer We investigated the potentiometric behaviour of thin and thick polypyrrole layers on platinum and glassy carbon with four commonly used doping salts Three different methods of polymerisation were investigated, constant current, constant potential and continuous scanning (section 1 16 3) The experimental procedures for electropolymerisation are outlined in sections 2 6 2 1 - 2 6 2 3

6 3 1 PPy films formed by constant current oxidation

The monomer solution was 0 1 M - 0 5 M pyrrole with 0 1 M LiCl, $LiBF_4$ or $LiClO_4$ in tetrahydrofuran (THF) Currents of 100-600 μA, with a polymerisation time of 1-4 minutes were used and smooth shiny films with varying colours from gold through to black were obtained The potentiometric response of a thin dark gold/brown film deposited on the working electrode with a current of -300 μA for 100 s using 0 5 M pyrrole and 0 1 M $LiBF_4$ was measured in 10^{-1} to 10^{-4} M aqueous solutions of the sodium salts of various anions The results are shown in fig 6 2 for the potential response versus Ag/AgCl for Cl, ClO_4 and SCN over short periods of time (up to 8 minutes) The films were soaked in 10^{-2} M solution of each new ion for 20 minutes prior to measuring The potential response over long periods (up to 45 minutes) in SO_4^{2}, NO_3 and CH_3COO^- solutions (fig 6 3) showed drift of the potential at all concentration levels towards the same rest potential (+/- 20 mV) The use of higher currents in constant current polymerisation led to over-oxidation of the polymer and with longer polymerisation times the film grew to a limiting thickness, beyond which the passage of additional current had little effect on film thickness Some of the

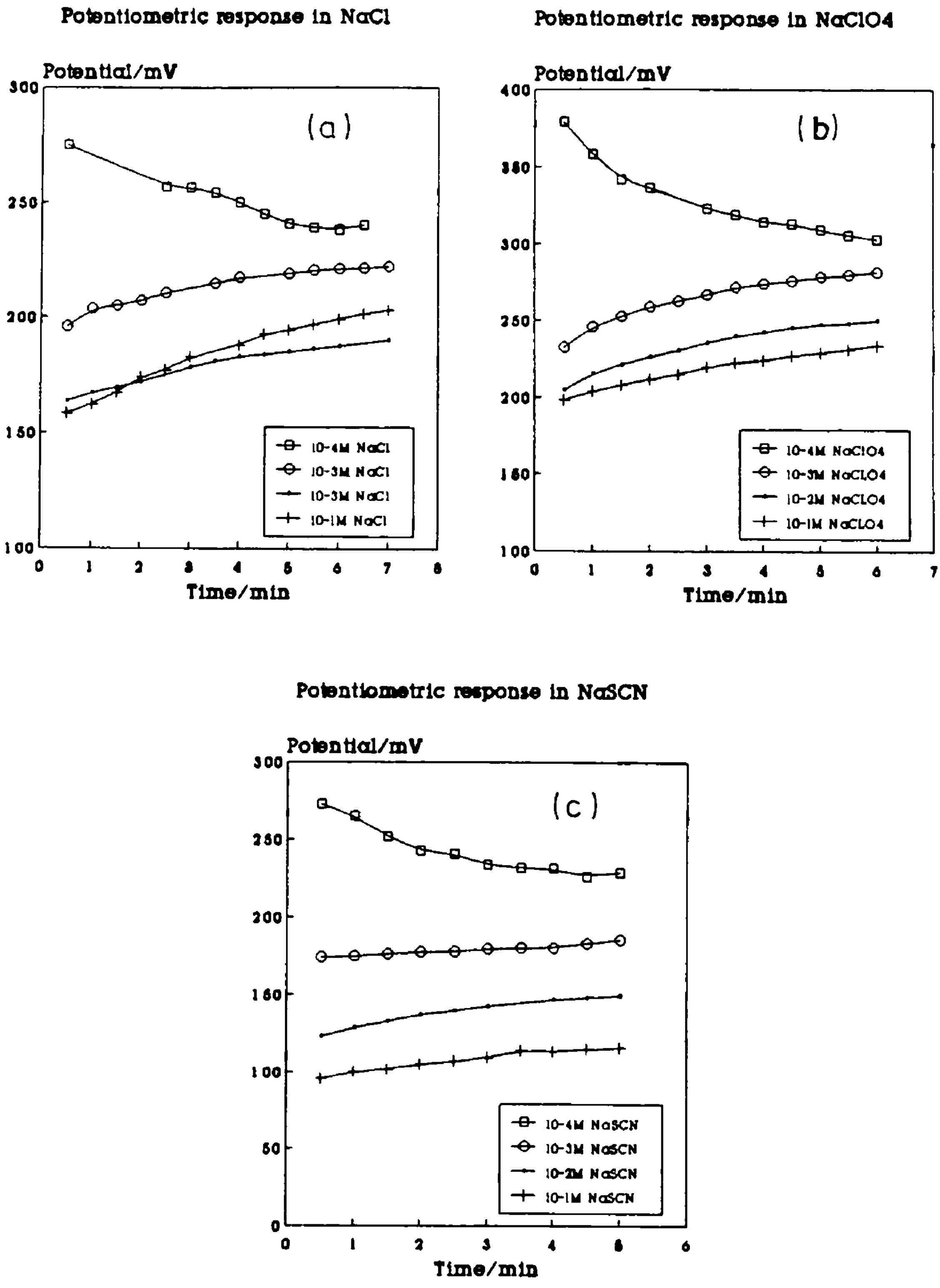

Figure 6 2 Potentiometric response (mV) of a thin PPy film made by constant current oxidation with 0 5 M pyrrole and 0 1 M $LiBF_4$ for 100s at -300µA to 10^{-4} to 10^{-1}M solutions of (a) NaCl; (b) $NaClO_4$ and (c) NaSCN

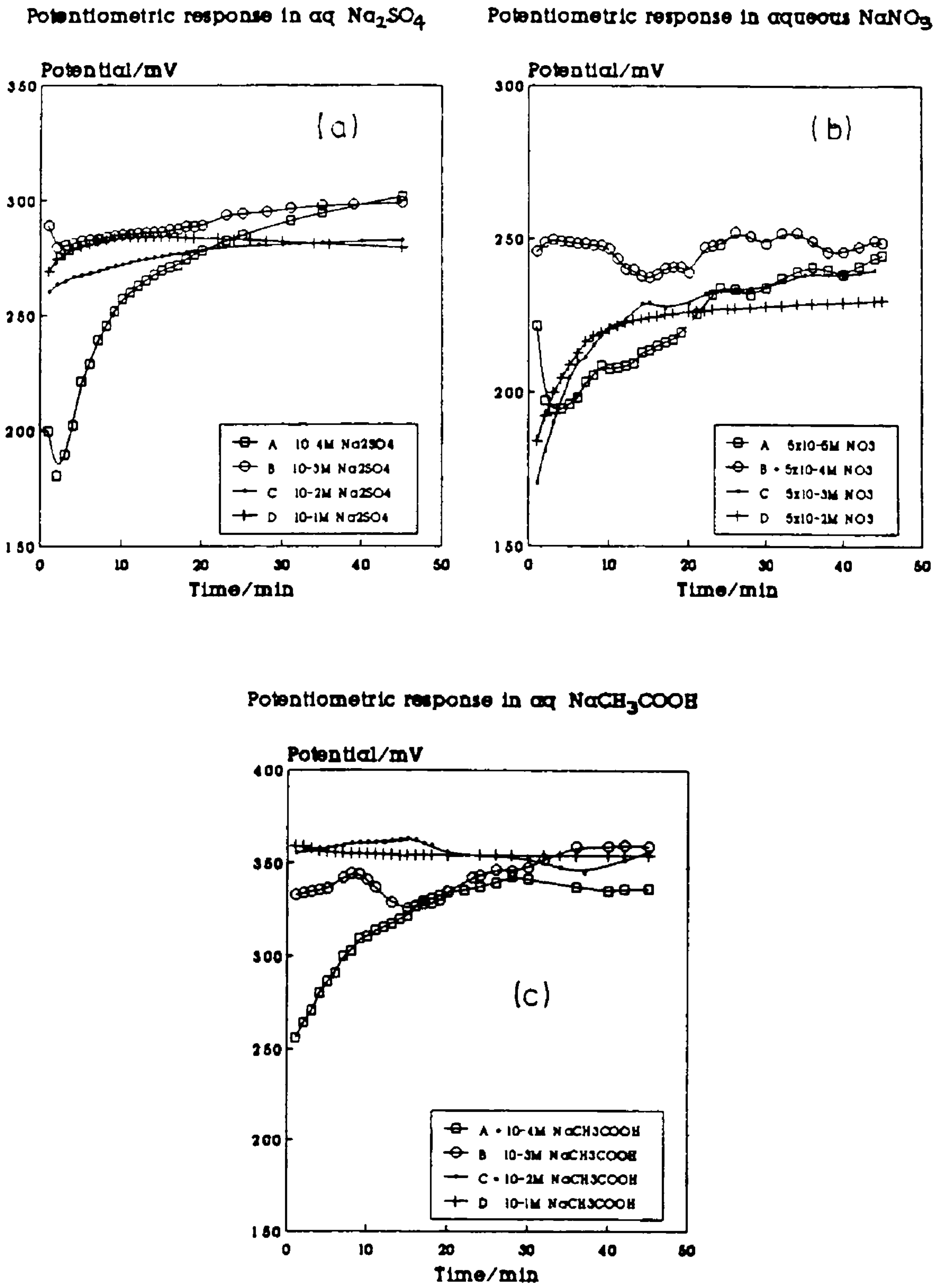

Figure 6 3 Potentiometric response (mV) of thin PPy films made by constant current oxidation with 0 5 M pyrrole and 0 1 M $LiBF_4$ for 100s at -300μA to 10^{-4} to 10^{-1}M solutions of (a) Na_2SO_4; (b) $NaNO_3$ and (c)CH_3COONa over extended time periods constant current oxidations were performed in a droplet which leads to depletion of the monomer solution at long polymerisation times

6 3 2 PPy films formed by constant potential oxidation

The polymerisation conditions and characteristics of PPy films formed by constant potential oxidation are shown in table 6 2 At higher holding potentials (>0 9 V) breakdown of water occurs Films PPy(BF_4)3 and PPy(Cl)5 were soaked for a minimum of 6 hours in 0 1 M lithium salts of fluoroborate and chloride respectively and the potentiometric responses were tested in 10^{-1} to 10^{-3} M lithium salts of the dopant ions The results in fig 6 4 show again a drift of the potential at all concentration levels stabilising at the rest potential of the films in the aqueous electrolyte

Table 6 2 Polymerisation conditions of PPy films prepared by constant potential oxidation in 0 1 M aqueous pyrrole

Film #	Potential (V)	time (s)	Doping salt (0 1M)	Film appearance
PPy(BF_4)1	0 8	20	$LiBF_4$	gold/green
PPy(BF_4)2	0 8	30	$LiBF_4$	dark gold
PPy(BF_4)3	0 9	15	$LiBF_4$	dark brown
PPy(BF_4)4	0 9	60	$LiBF_4$	black
PPy(Cl)5	0 9	15	LiCl	dark brown

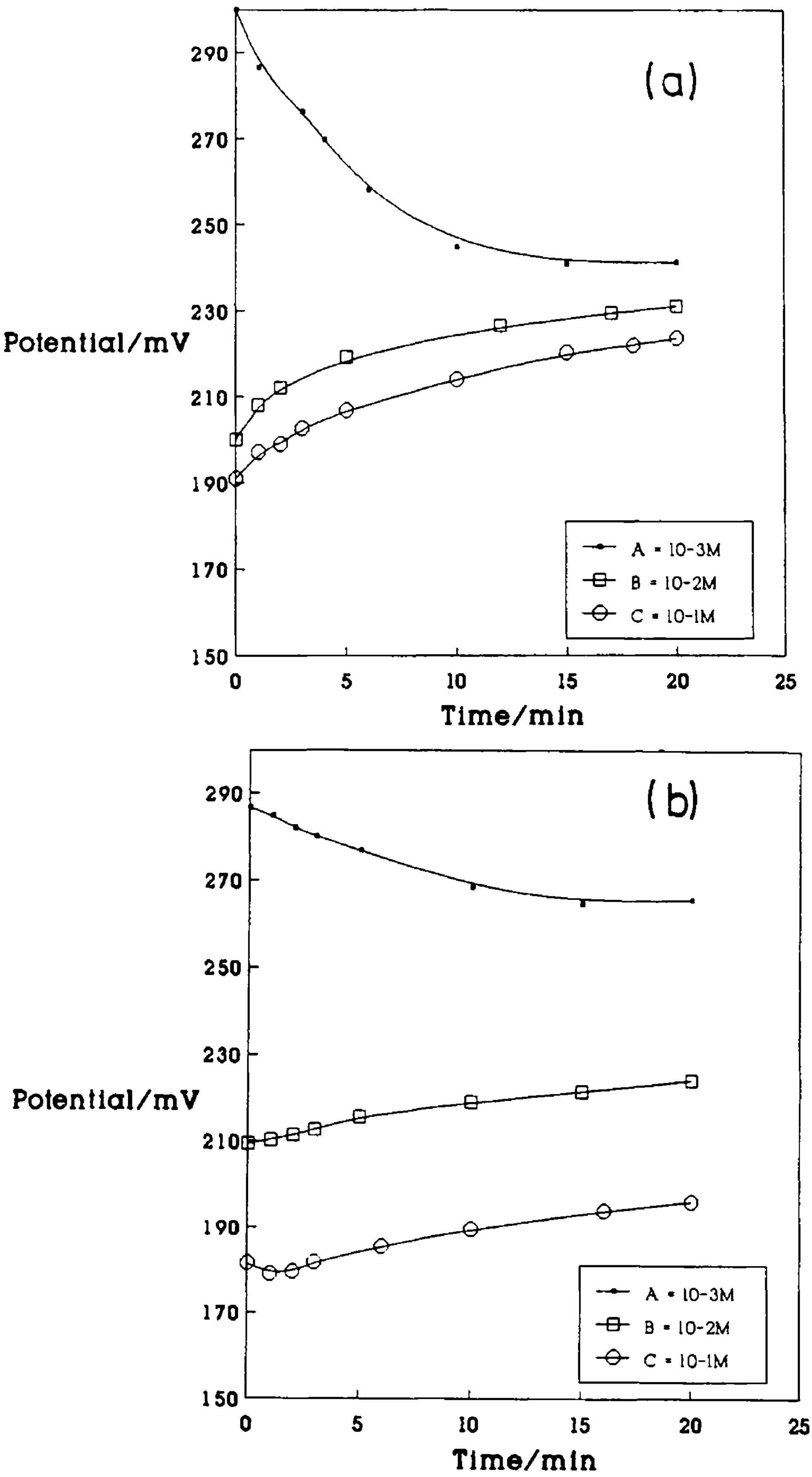

Figure 6 4 Potentiometric response (mV) of thin films made by constant potential oxidation 0 9 V for 15 s to (a) 10^{-3} to 10^{-1} M aqueous LiBF4 solutions using electrode PPy(BF4)3 (table 6 2) and (b) 10^{-3} to 10^{-1} M aqueous LiCl solutions using electrode PPy(Cl)5 (table 6 2)

6 3 3 PPy films formed by continuous scanning methods

Polypyrrole films were prepared by continuous scanning from 0 0 V to 1 0 V in 0 1 M pyrrole and 0 1 M aqueous electrolyte solutions for various time periods Three doping electrolytes were used LiCl, $LiBF_4$ and $NaBF_4$ PPy films were synthesised with scan rates of 10, 20 and 50 mV/s with scan times of 30, 45 and 60 minutes Those films prepared by continuous scanning were much thicker than by other methods Scanning Electron Micrograph (SEM) measurements of films formed at 20 mV/s for 45 minutes with 0 1 M $NaBF_4$ as the doping salt showed an average film thickness of 7-8 μm with a slight thickening of the film at the outer edges 10-11 μm The photograph of the cross section (fig 6 5) also shows quite clearly one smooth side (in contact with the platinum surface) and the solution side which has a more non-uniform textured appearance due to the complex polymerisation processes occurring during the build-up of the polymer

The films started to appear on the first scan and gradually thickened on further scanning Fig 6 6 shows a typical cyclic voltammogram (CV) of the first, fourth and last scan (#27) for a polypyrrole film made using a scan rate of 20 mV/s in 0 1 M pyrrole and 0 1 M $NaBF_4$ (total polymerisation time 45 minutes) The voltammograms show a constant build up of the polymer on the electrode Fig 6 7a shows the CV of the same film in a 0 1 M aqueous solution of $NaBF_4$ scanned from -2 0 to 0 8 V The CV shows a large capacitative current due to the large surface area of the film The peak current is of the order of mA, which confirms the greater thickness of the film If the potential sweep is continued beyond +1 0 V the film appears to be irreversibly oxidised (fig 6 7b) On the first cycle there is a current peak of approximately 1 mA at a potential of 0 7 V where the polypyrrole is oxidised, followed by a larger current peak at >1 0 V There is no reduction peak on the reverse scan On the second cycle the oxidation peak is sharply reduced and again there is no reduction peak Over-oxidation of PPy films above 1 0 V is a well established phenomena[10,11] due to a deeper oxidation of the polymer leading to the breakdown of the aromatic system

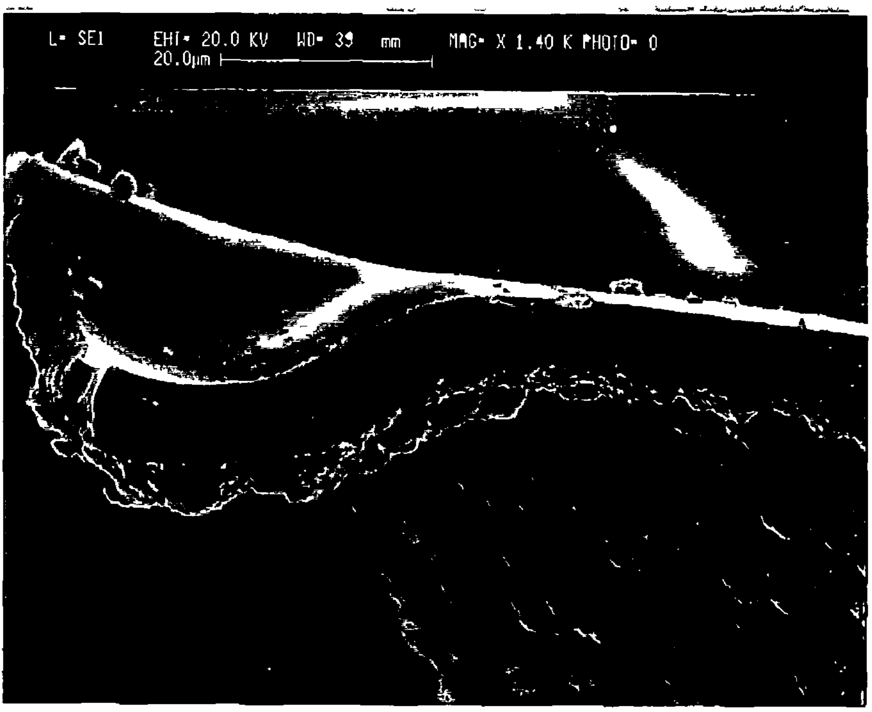

Figure 6.5 SEM photograph of a polypyrrole film. See text for details

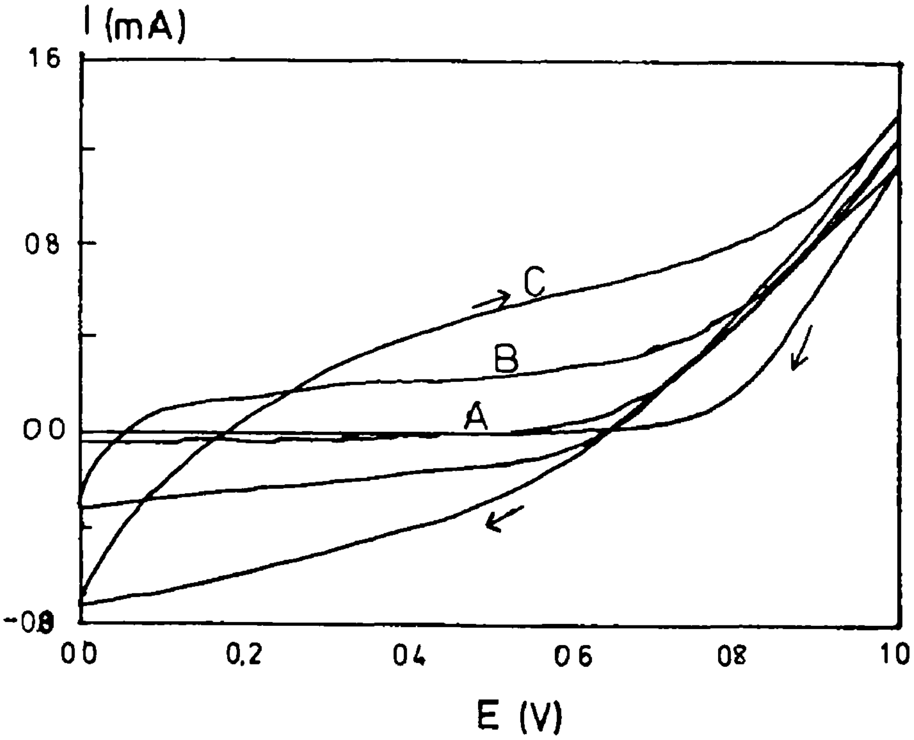

Figure 6 6 Electropolymerisation by continuous scanning in 0 1 M pyrrole and 0 1 M $NaBF_4$, scan rate 20 mV/s, scan time 45 minutes, A = cycle 1, B = cycle 4 and C = cycle 27

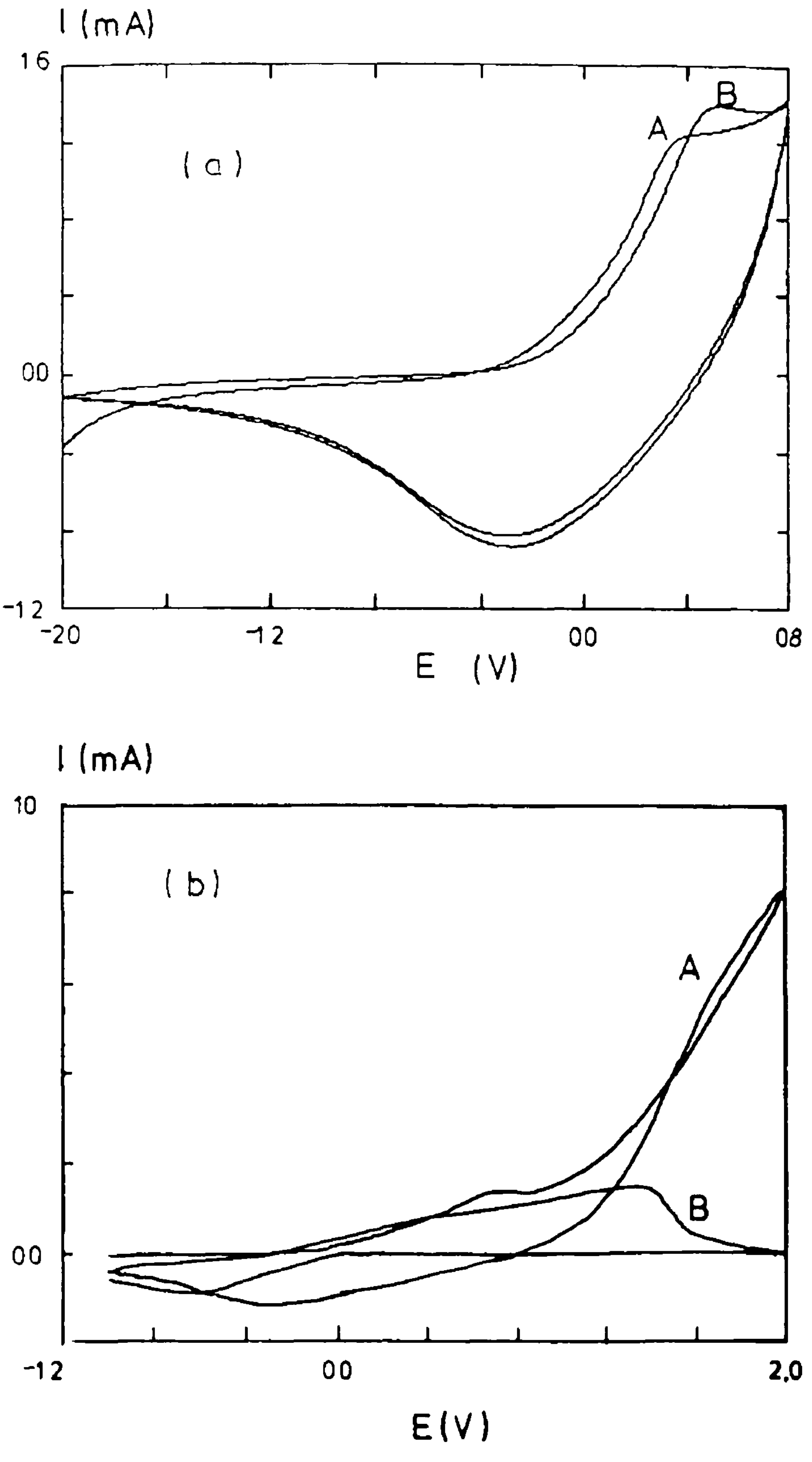

Figure 6 7 Cyclic voltammograms of PPy film formed in figure 6 6 in 0 1M aqueous $NaBF_4$, 20mV/s scan rate, (a) A = cycle 1 and B = cycle 4, (b) A = cycle 1 and B = cycle 2

6 3 3 1 Potentiometric responses

The PPy films were activated by soaking in 0 1 M solutions of the doping salt for at least 3 hours after preparation and the potentiometric response of each electrode was recorded after 6 minutes In some cases the potential of electrodes formed under a particular set of conditions continued to drift beyond that 6 minutes and when there was no indication of stabilisation, a reading of "npr"- no stable potentiometric response - was recorded Table 6 3 shows the slopes of the potentiometric responses of the PPy film electrodes to the small Cl anion and the larger BF_4 anion recorded in the activity range 10^{-1} to 10^{3} M Negative slopes were recorded in each case, indicating an anionic potentiometric response In each case the potential was measured in solutions containing the same cation as that used in the electropolymerisation The values in table 6 3 are the average of 2-3 measurements The standard deviation in the slopes varies in the range +/-0 1 to 4 0 units This error is quite high and is a direct reflection of the difficulty in making reproducible films It is well recognised that each process of polymerisation will give rise to a slightly different material due to the complex actions occurring during film formation[12] Due to the high errors involved it is more appropriate to follow the general trends shown by the films rather than the absolute values of the slopes The linear range for electrodes incorporating the BF_4 doping anion was 10^{-1} to 10^{-3} M and somewhat better for electrodes containing Cl as the anion, typically 10^{-1} to 10^{-4} M Irrespective of the anion used for doping, higher slopes were observed in chloride solutions than in fluoroborate solutions This is especially pronounced in the cases where Cl was used as the doping anion in preparing the film as well as in the bathing solutions It is obviously easier for the smaller Cl anion to be intercalated in the polymer film and show an anionic potentiometric response when the film is in contact with the electrolyte solution PPy($NaBF_4$) electrodes tended to lose their potentiometric properties after 24 to 48 hours of continuous contact with the aqueous electrolyte but PPy($LiBF_4$) and PPy(LiCl) films showed better stability with time

Table 6 3 Response slopes (mV dec ^{1}) of thick polypyrrole film electrodes made by continuous scanning in solutions of chloride and tetrafluoroborate (10 ^{3} to 10^{-1}M), in each case the potentials were recorded with the same cation as used in the synthesis Equilibration time 6 minutes

Electrode no	scan rate mV/s	scan time min	slope mV/decade Cl	slope mV/decade BF_4
LiCl as doping salt**				
PPy(LiCl)1	20	30	-49	*npr
PPy(LiCl)2		45	-53	-20
PPy(LiCl)3		60	-52	-36
PPy(LiCl)4	50	30	-46	-28
PPy(LiCl)5		45	-51	-38
PPy(LiCl)6		60	-54	-39
$LiBF_4$ as doping salt**				
PPy($LiBF_4$)7	10	30	-39	*npr
PPy($LiBF_4$)8		45	-50	-33
PPy($LiBF_4$)9		60	-47	-45
PPy($LiBF_4$)10	20	30	-42	*npr
PPy($LiBF_4$)11		45	-47	-37
PPy($LiBF_4$)12		60	-50	-43
PPy($LiBF_4$)13	50	30	-33	-32
PPy($LiBF_4$)14		45	-50	-35
PPy($LiBF_4$)15		60	-53	-47
$NaBF_4$ as doping salt**				
PPy($NaBF_4$)16	10	30	-50	*npr
PPy($NaBF_4$)17		45	-47	-28
PPy($NaBF_4$)18		60	-46	-45
PPy($NaBF_4$)19	20	30	-48	-42
PPy($NaBF_4$)20		45	-49	-42
PPy($NaBF_4$)21		60	-51	-46
PPy($NaBF_4$)22	50	30	-39	*npr
PPy($NaBF_4$)23		45	-53	-42
PPy($NaBF_4$)24		60	-53	-44

*npr = no stable potentiometric response

** the doping salt used in the electrochemical polymerisation

6 3 3 2 Effect of scanning time/film thickness

The thicker films, formed at 45 and 60 minutes, showed stable responses to both chloride and tetraflouroborate anions With thin films, (<30 minutes scanning time) a stable anionic response was observed for a few minutes but this was followed by drift of the potential at all concentration levels to a rest potential (+/- 20mV) of the PPy film in the supporting electrolyte used If during polymerisation scanning periods longer than 60 minutes were used the polymer growth went beyond the platinum over the teflon surround and the film became very brittle and difficult to remove intact from the platinum If membranes were made too thick, they tended to lift off the platinum surface following long periods of soaking in aqueous solutions This behaviour arises from over oxidation of the polymer material, which is an unavoidable consequence of long polymerisation times

6 3 3 3 Anion and cation selectivity

Figure 6 8 shows the absolute potentials of the response of electrode PPy($NaBF_4$)21 (table 6 3) to other electrolyte solutions over the concentration range 10^{-1} to 10^{-4} M The electrode was soaked in a 10^{-2} M solution of each interfering ion for 20 minutes before measuring the response There is relatively little selectivity toward the various anions as the electrode responded well to Cl , ClO_4 , NO_3 and slightly less well to BF_4 with some selectivity over SCN Similar responses to anions were obtained for electrodes based on PPy(LiCl)3 and PPy($LiBF_4$)11 as can be seen in fig 6 9 and fig 6 10 respectively

Table 6 4 shows a comparison of the responses in terms of slope for three electrodes PPy(LiCl)3, PPy($LiBF_4$)11 and PPy($NaBF_4$)21 to various solutions of sodium and lithium salts The values reported in table 6 4 are the average of at least two measurements +/- 0 01 to 3 0 In general the PPy films responded better in the electrolyte containing the same cation as that used for the electrochemical synthesis This effect is clearest in the case of the PPy($LiBF_4$)11 response to $NaBF_4$ and $LiBF_4$ and the response of the PPy($NaBF_4$)21 electrode to $NaBF_4$ and $LiBF_4$ The major influence of the anion occurs during the synthesis of the

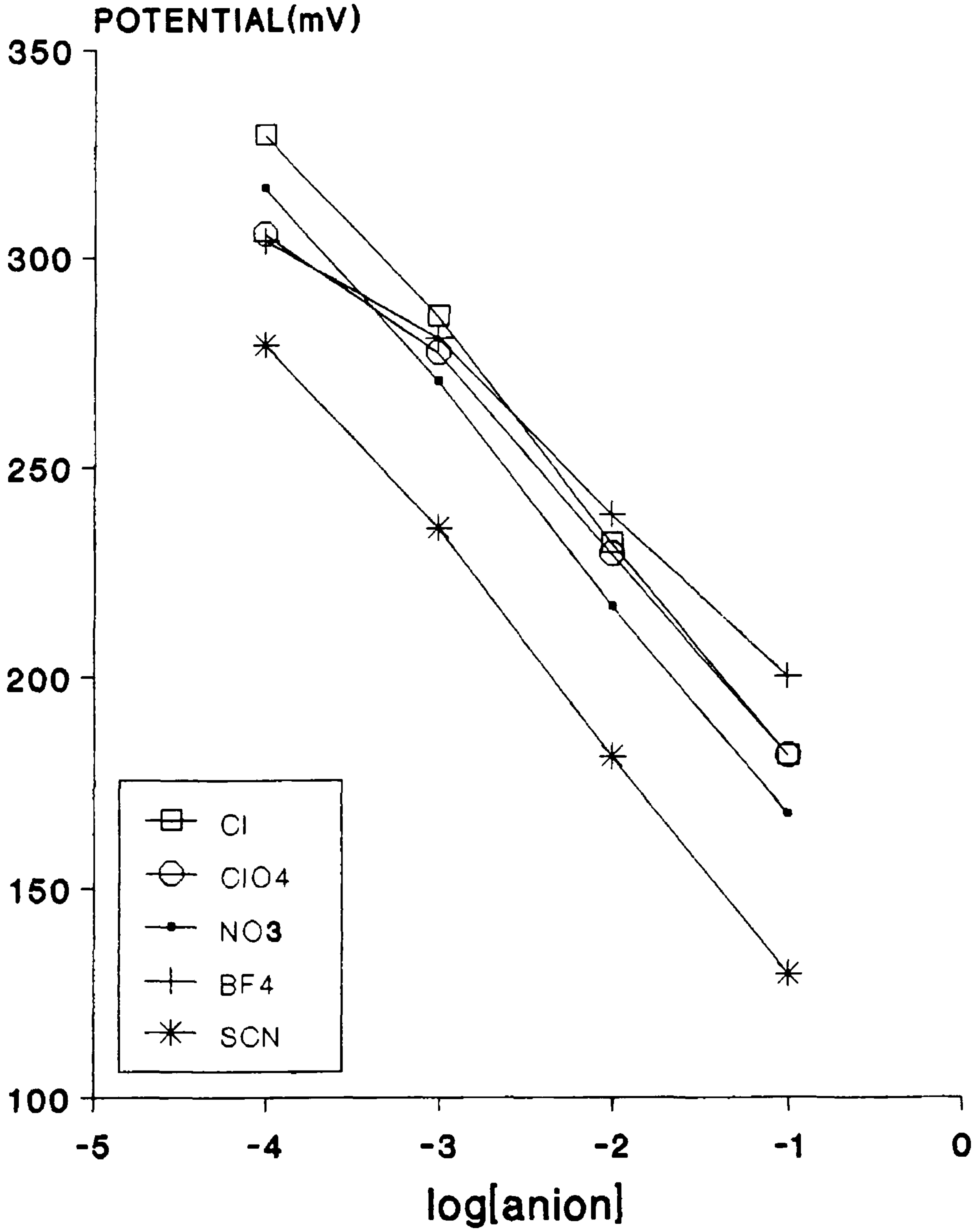

Figure 6 8 Potentiometric response (mV) of a thick PPy film formed by continuous scanning to aqueous sodium solutions of various cations Electrode PPy(NaBF$_4$)21 (table 6.3). Equilibration time 6 minutes Film prepared in 0 1 M pyrrole and 0 1 M NaBF$_4$, 20mV/s scan rate, 60 minutes scan time and potential range 0 0 to 1 0 V

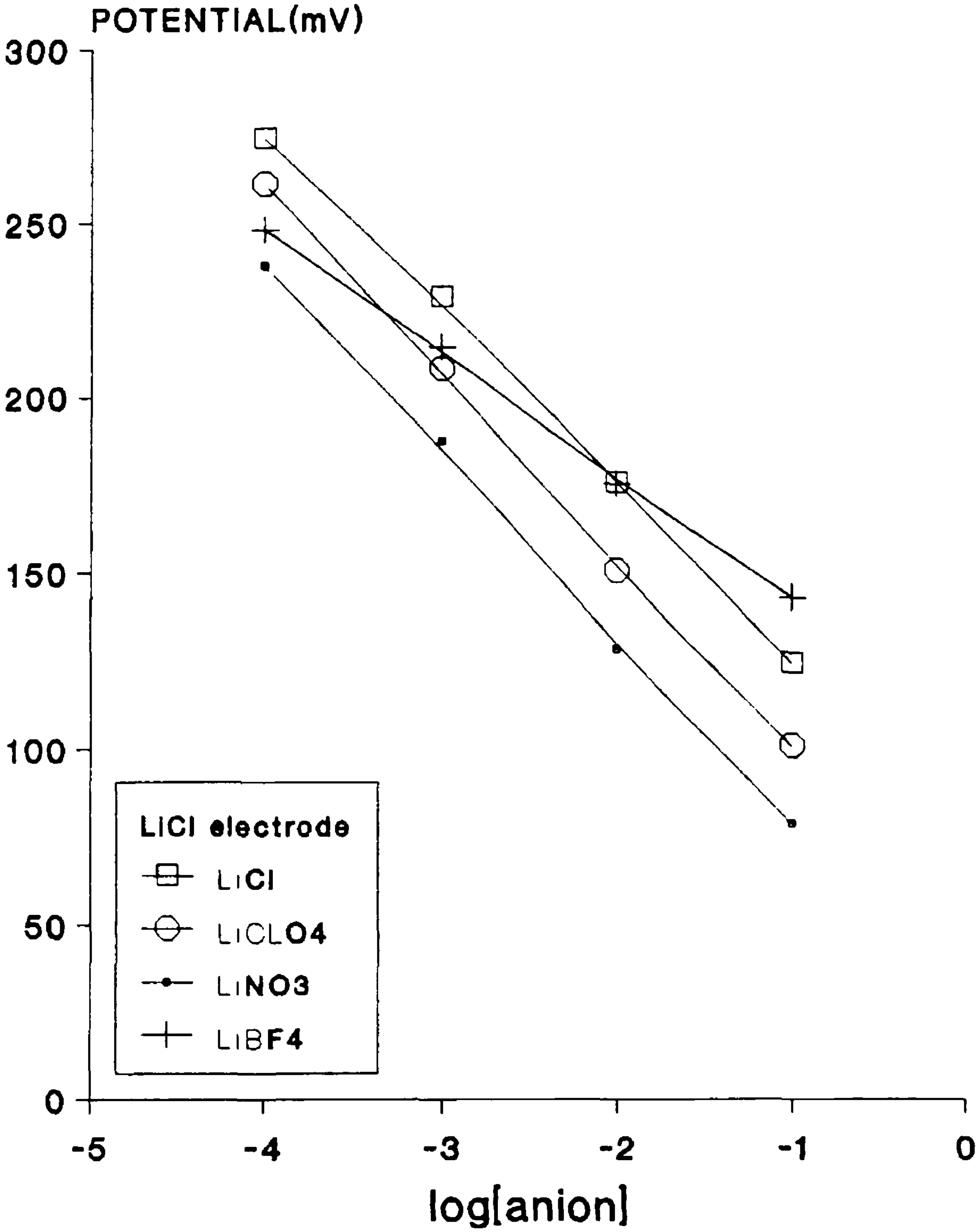

Figure 6 9 Potentiometric reponse (mV) of a thick flim, electrode PPy(LiCl)3 (table 6 3) to aqueous solutions of salts shown Equilibration time 6 min. Film prepared in 0 1 M pyrrole and 0 1 M LiCl using 20 mV/s scan rate, 60 minutes scan time over the potential range 0 0 to 1 0 V

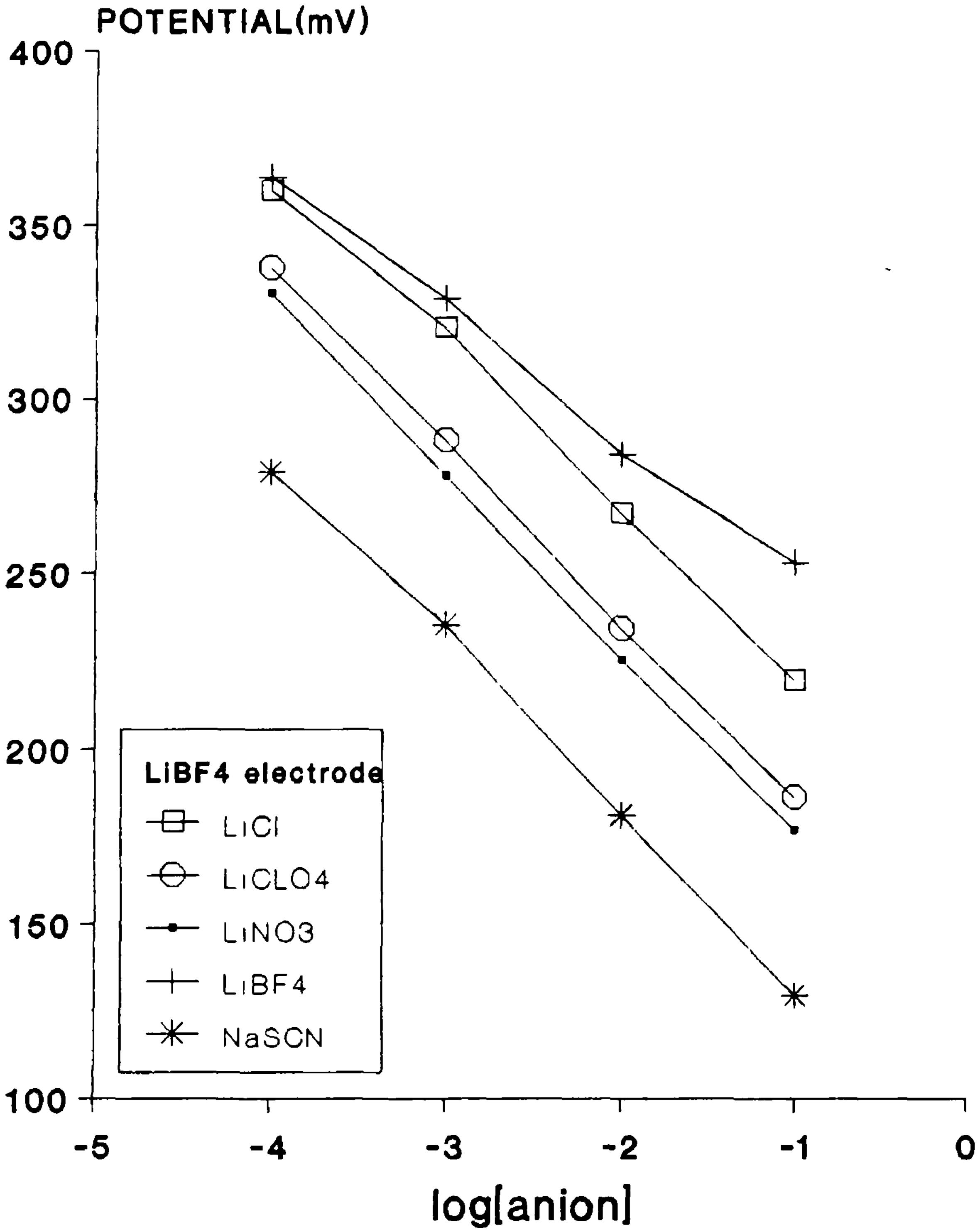

Figure 6 10 Potentiometric reponse (mV) of a thick film, electrode PPy($LiBF_4$)11 (table 6 3) to aqueous solutions of salts shown Equilibration time 6 min. Film prepared in 0 1 M pyrrole and 0.1 M $LiBF_4$ using 20 mV/s scan rate, 45 minutes scan time over the potential range 0 0 to 1 0 V polymer The size and type of counter cation used in the polymerisation seems to affect the electrochemical properties rather than the structure This suggests that some sort of memory effect exists which assists the response in the electrolyte solution containing the same cation This type of memory effect was also noted by Marque et al [13] in their studies on the electrolyte effects of poly(3-methylthiophene) films

Table 6 4 Slopes (mV dec ^{1}) of polypyrrole electrodes formed by constant scanning in 0 1 M pyrrole and 0 1 M aqueous electrolyte solutions Electrodes as in table 6 3, average of two measurements +/-0 01 to 3 0

Doping salt		LiCL	$LiBF_4$	$NaBF_4$
Electrode		PPy(LiCl)3	PPy($LiBF_4$)11	PPy($NaBF_4$)21
			Slope mV/decade	
anion	cation			
Cl	Li^+	-52	-47	-49
	Na^+	-49	-41	-51
NO_3	Li^+	-54	-53	-49
	Na^+	-50	-49	-51
ClO_4	Li^+	-54	-54	-50
	Na^+	-50	-49	-48
BF_4	Li^+	-36	-37	-34
	Na^+	-40	-29	-42
SCN	Na^+	-53	-57	-53

6 3 4 PPy films incorporating larger doping anions

As the primary aim of the project was to construct solid state electrodes using a PVC membrane incorporating a ligand and the ion-exchanger KTpClPB an attempt was made to synthesise PPy films incorporating the tetraphenyl borate or tetrachlorophenyl borate anions as the dopant The two salts chosen were the potassium salt of tetrachlorophenyl borate (KTpClPB) and the sodium salt of tetraphenyl borate ($NaBP_4$) This would reduce the array of anionic and cationic species present throughout the layers and so lead to simplification of the mechanistic explanations Monomer solutions containing 0 1 M pyrrole and 0 1 M KTpClPB or 0 1 M $NaBP_4$ in THF were prepared and electropolymerisations attempted by all three methods of polymerisation The results (table 6 5) indicate that the attempts at polymerisation were largely unsuccessful and no working films were produced Due to the lower aqueous solubility of the phenylborate salts aqueous electropolymerisations were ineffective by either of the three methods One final attempt was made to incorporate the bulky tetraphenyl borate anion into a PPy film by forming the film in 0 1 M pyrrole and 0 1 M $NaBF_4$ (electrode PPy($NaBF_4$)21 table 6 3) and then scanning in an aqueous solution of 0 05M $NaBP_4$ to try to see if the phenyl borate anion could be taken up into the film on the oxidation scan The first scan gave a peak current of 0 6 mA on the forward scan but no reduction peak on the backward scan (fig 6 11) The peak current decreased significantly on the second and subsequent scans until no oxidation or reduction peaks were observed Some small amount of anion may have been incorporated into the polymer film on the first forward scan but this somehow blocked or poisoned the electrode for any further reversible anion movement in or out of the polymer When the film was removed, rinsed and placed in 0 05 M aqueous $NaBF_4$ the film activity was not completely regained showing some irreversible blockage of the polymer by the BP_4 anions Clearly the large BP_4 or *p*ClP_4B anions are not suitable dopants for electrochemical polymerisation of polypyrrole

Table 6 5 Electropolymerisation of polypyrrole using NaBF$_4$ and KTpClPB as doping salts in THF CC = constant current method, CP = constant potential method and CV = continuous scanning method ** some black specks, incomplete surface coverage

NaBF$_4$

method	pyrrole (M)	dopant (M)	current (µA)		time (min)	film appearance
CC	0 5	0 1	50		2-5	no film
			100		2-5	no film
			100		10-20	**
			500		4-10	no film
			500		>10-15	**
CP			potential (V)		time (min)	
	0 5	0 1	0 95		0-30	no film
			1 0		0-30	no film
			1 1		0-30	no film
CS	pyrrole (M)	dopant (M)	range (V)	rate (mV/s)	time (min)	
	0 5	0 1	-0 1-1 2	50	25-30	no film

KTpClPB

Method	pyrrole (M)	dopant (M)	current (µA)		time (min)	film appearance
CC	0 5	0 1	-100		2-5	thin green film
			200		2-5	no film
	0 5	0 01	100-500		2-10	no film
CS	pyrrole (M)	dopant (M)	range (V)	rate (mV/s)	time (min)	
	0 5	0 1	-0 1+1 2	50	25-30	no film

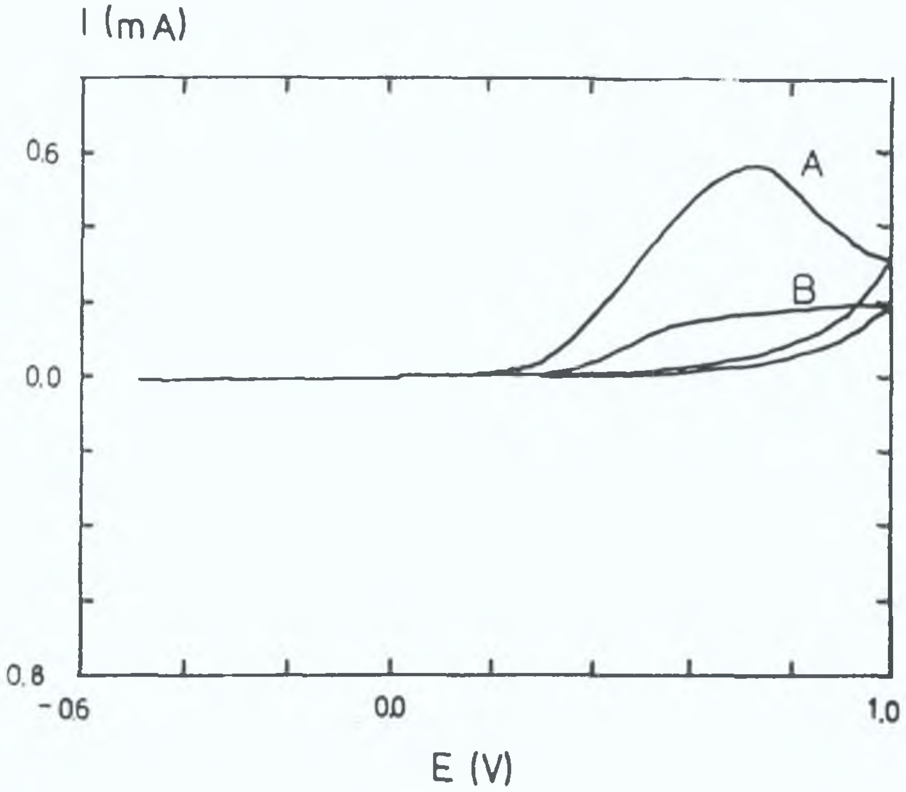

Figure 6.11 Cyclic voltammogram of film formed by same method as in fig 6.6 scanned in 0.05 M aqueous $NaBP_4$; A = cycle 1, B = cycle 2.

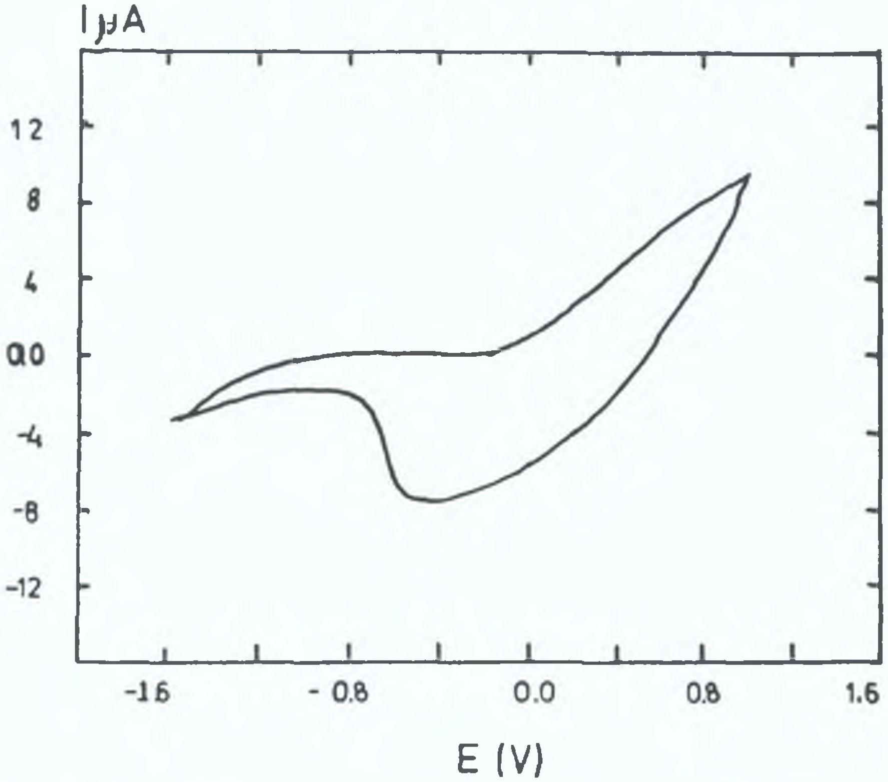

Figure 6.12 Typical CV of PPy film in 0.1 M $LiBF_4$ in THF 50mV/s scan rate. Constant current electropolymerisation in 0.5 M pyrrole and 0.1 M $LiBF_4$, current = 100 µA for 3 min.

6 3 5 Redox responses

The redox sensitivity of the different electrode assemblies was checked by measuring the potential in various ratios of the redox couple Fe(II)/Fe(III) with a constant ionic background of 10^{-1} M NaCl and then plotting the potential versus log([ox]/[red]) The concentration ratio changed from 5/1 to 1/5 The results are given in table 6 6 An instantaneous Nernstian response was obtained at the Pt and GC electrodes and also at the PPy coated Pt and GC electrodes The reading for the Pt and Pt/PPy coated electrodes showed the same absolute potential values to within 1 mV, with the calibration curve lying in the 100 to 250 mV range

Table 6 6 Redox responses of the electrodes Slopes (mV dec ^{1}) of the potential versus log([FeIII)]/[Fe(II)]) curves The concentration ratio was changed from 5/1 to 1/5 Theoretical response is 59 2 at 25°C PVC compositions from table 6 4, PPy layer in each case is PPy(NaBF$_4$)20 from table 6 3

electrode #	substrate and coating	slope mV dec ^{1}
1	Pt	58 2
2	GC	57 6
3	Pt/PPy	55 6
4	GC/PPy	56 9
CWE1	Pt/PVC1	0 8
CWE2	GC/PVC1	0 7
SC1	Pt/PPy/PVC1	0 7
SC2	Pt/PPy/PVC2	4 4
SC3	Pt/PPy/PVC3	1 3
SC4	GC/PPy/PVC1	1 6

6 3 6 Summary of potentiometric response of polypyrrole

Both the constant current and constant potential methods described so far produced thin shiny films which displayed unstable time dependent potentiometric responses in aqueous solutions The initial response does appear to be anionic from the direction of the initial potential changes (see fig 6 2 and 6 4) but the potentials are unstable A typical CV of a film formed by constant current oxidation is shown in fig 6 12 and it shows a peak oxidation current of approximately 10 µA It is well documented that thin PPy films tend to be porous in nature and that the underlying substrate can still undergo reaction (at a reduced rate) although covered by the film[14] This effect is even more pronounced in films formed from aqueous solution compared to those formed from non-aqueous (e g acetonitrile), where the later tends to be smoother and have better adhesion to the substrate surface It would seem probable that the potentiometric responses observed have contributing factors from both the PPy layer and the underlying platinum due to incomplete surface coverage

The PPy films electropolymerised by continuous scanning methods in LiCl, $LiBF_4$ and $NaBF_4$ display stable potentiometric responses to anions The increase in thickness is immediately obvious upon examination of the films They can be removed intact from the substrate surface Confirmation of the film thickness was provided by the SEM analysis (fig 6 5) and the larger currents in the CV (fig 6 7a) Some of the PPy(LiCl), PPy($LiBF_4$) and PPy($NaBF_4$) films displayed stable near Nernstian responses to anions These PPy films display a sensitivity to anions, but from the selectivity data it can be seen that there is not much discrimination between the anions

6 3 7 Explanation of the potentiometric response

When PPy is oxidised it changes to PPy^+ and anions are doped into the film in order to balance the charges (6 2) When the polymer is reduced PPy^+ changes into PPy^o the polymer becomes electroneutral and anions are released into solution (6 3)

Cl (solution) + PPy^o —> PPy^+Cl (film) + é oxidation (6 2)

PPy^+Cl (film) + é(Pt) —> PPy^o + Cl (solution) reduction (6 3)

The positively charged PPy moieties form a highly conjugated series of linked cations which are very hydrophobic When the PPy layer is brought in contact with the aqueous solution an equilibrium distribution of chloride ions is formed which yields a film potential which will be related to the amount of Cl ions in solution i e

$$\text{Cl film} \rightleftharpoons \text{Cl solution} \qquad (6\,4)$$

The degree of association of the anion with the large PPy^{+} cation will determine the response to that ion Smaller anions such as Cl and ClO_4 will probably be able to enter and leave the polymer more easily and so higher responses are observed to these ions Miller et al [15] studied the incorporation of electrolyte cations into polypyrrole and showed a certain amount of cation incorporation into polypyrrole occurred upon reduction of the polymer The effect was greatest with a film doped with *p*-toluenesulphonate(OTs) which took up Na^{+}, Cs^{+} and Li^{+} on reduction PPy^{+}/Cl polymers took up less Na^{+}, Cs^{+} and Li^{+} but PPy^{+}/ClO_4 only took up Li^{+} ions on reduction They concluded that the extent to which anions leave or cations are taken in during reduction depends on the identity of the anion and the solvent used They also noticed that the salt leaches out of the film as time passes (on standing in aqueous solution)

$$\mathrm{PP^{+}OTs} + \acute{e} \xrightarrow[\text{reduction}]{\text{aq NaCl}} \mathrm{PP^{O}Na^{+}OTs} \xrightarrow[\text{open circuit}]{\text{30 min soak}} \mathrm{PP^{O}} \qquad (6\,5)$$

Cation insertion has also been observed by other workers[16,17] and it is highly dependent on the nature of the doping salt and the polymerisation conditions From our studies no clear and definite explanation of the potentiometric behaviour of the PPy film can be given at this stage In order to obtain a clearer picture of the nature of the potentiometric response of these films, more studies involving a wider range of anions as the doping salts with various counter cations would need to be carried out However, we have observed a stable response to anions in thick PPy films

6 4 Coated wire electrode system II (Pt/PVC/Na$^+$)

The second system studied was based on the application of a PVC membrane directly onto the surface of a Pt or GC disc This system will be referred to as the "coated wire electrode" (CWE) type due to the similarity of the contact with conventional coated wire electrodes

The slopes of the redox response for CWE electrodes with Pt and GC substrates are shown in table 6 6 Both of the electrodes showed no redox sensitivity as would be expected from a PVC coating

The response (versus Ag/AgCl) of a Pt/PVC1 electrode to 10^{-4} to 1 M NaCl solutions over a two week trial period are shown in table 6 7 The average slopes over the 10^{-1} to 10^{-4} M activity range, estimated limit of detection and the selectivity coefficients for the same electrode are shown in table 6 8 Included for comparison is the data for the conventional bench electrode based on the same ligand The response of the electrode to changes in the NaCl concentration were very fast, <20s for complete equilibration after a 10-fold increase in concentration The electrode displayed good Nernstian responses to sodium with selectivity in the order Na$^+$ > K$^+$ > Cs$^+$ > Li$^+$ A GC/PVC1 electrode also exhibited a Nernstian responses to sodium ions with an average slope = 57 5 mV dec^{-1}

6 5 Solid contact electrode system III (Pt/PPy/PVC/Na$^+$)

In this system a layer of conducting PPy was used as the contact between the substrate and the PVC BF$_4$ was chosen as the doping anion because members of the class of borates have previously been used as ion-exchangers in PVC membrane systems The sodium salt was chosen due to the Na$^+$ selectivity of the calixarene ligand The polymerisation conditions chosen were the same as those for electrode PPy(NaBF$_4$)20 in table 6 3 and the composition of the solid contact electrodes (SC) are outlined in table 6 6

Table 6 7 Response (mV) of CWE1 electrode (Pt/PVC1 table 6 6) and slopes (mV dec ^{1}) over the activity range 10^{1} to 10^{-4} M NaCl over a two week period

[NaCl]/M	10^{4}	10^{-3}	10^{2}	10^{-1}	1	Slope mV dec ^{1}
trial 1	370 1	428 0	482 5	535 7	593 6	58 1
trial 2	429 9	486 1	540 4	597 9	656 9	59 2
trial 3	432 7	486 8	542 7	599 5	--	57 7
trial 4	416 9	478 3	533 1	588 3	646 3	59 5
trial 5	434 9	487 4	544 9	600 3	658 2	58 6
trial 6	446 7	500 0	555 0	606 9	664 4	56 8
trial 7	430 5	480 5	531 9	585 8	643 3	55 6
trial 8	382 0	432 7	490 7	545 5	603 3	58 1
trial 9	391 1	449 2	503 9	559 6	617 9	59 0
trial 10	410 6	463 7	521 6	578 0	636 1	58 0

Table 6 8 Response characteristics and slopes of PVC based solid state electrodes Selectivities by the SS method (10^{-1} M), standard deviation in parentheses

Electrode	LOD (10^{-5}M)	Slope(n=10) mV dec ^{1}	Log K_{ij}^{pot}(n=4)		
			j= K^+	j=Cs^+	j=Li^+
CWE1	1	58 1(1 1)	-2 7(0 01)	-3 3(0 04)	-3 5(0 06)
SC1	1	58 7(1 0)	-2 7(0 01)	-3 4(0 1)	-3 4(0 04)
SC2	3	58 1(0 8)	-2 1(0 01)	-3 3(0 04)	-3 5(0 14)
SC3	3	56 7(1 0)	-2 7(0 06)	-3 0(0 06)	-3 2(0 13)
Conventional*	0 3	56 4	-2 7	-2 5	-2 7

* Data taken from table 3 12

The slope of the redox response for the electrodes with Pt/PPy/PVC or GC/PPy/PVC can be seen in table 6 6 and as expected no redox sensitivity is observed

The response (versus Ag/AgCl) of SC1 electrode containing the normal PVC membrane to 10^{-4} to 1 M NaCl solutions over a one week trial period is shown in table 6 9 The average slopes, selectivity coefficients and estimated limits of detection for the solid contact electrodes containing the three different types of PVC membrane are shown in table 6 8 All the electrodes showed good Nernstian responses to sodium ions with selectivity in the order $Na^+ > K^+ > Cs^+ > Li^+$ The three PVC compositions all performed well showing that the membrane can also function adequately in the absence of the KTpClPB ion-exchanger Differences in the properties of the two membranes with different ion-exchangers (SC1 and SC3) may only become apparent following studies on the long term stability of the slope

Table 6 9 Response (mV) of SC1 electrode (Pt/PPy/PVC1 table 6 6) and slopes (mV dec-1) in pure NaCl solutions over a one week trial period

[NaCl]/M	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	Slope mV dec^{1}
trial 1	392 9	441 6	497 1	550 1	606 1	55 99
trial 2	385 1	441 4	497 2	551 6	607 2	58 04
trial 3	399 2	446 2	501 2	555 8	611 3	55 86
trial 4	397 0	446 7	502 6	558 1	613 7	56 39
trial 5	396 5	443 6	498 5	555 5	610 8	55 10
trial 6	400 2	447 0	499 2	556 1	612 9	56 25

As can be seen in table 6 8 both the CWE based system (Pt/PVC1) and the solid contact electrode system (electrodes SC1, SC2 and SC3) showed basically the same performance characteristics in terms of selectivity and behaviour The selectivity coefficients at the coated wire and the solid contact electrodes were comparable with the best selectivity coefficients calculated for the same ligand in the bench electrode configuration In fact the selectivity coefficients appear to be marginally higher for the former two systems Higher selectivity coefficients have been claimed for coated wire electrodes compared to their conventional counterparts but bearing in mind the variation and inconsistency attached to measurements of selectivity coefficients the differences seen here can not be regarded as a significant improvement over the conventional system The response of all the electrodes to changes in activity was very fast, of the order of a few seconds (see fig 6 13)

Typically the performance of many CWE's is characterised by irreproducible potentials, noise and overshoots of potential These problems are usually more evident in the first few days of use From table 6 7 and 6 9 it is apparent that the Pt/PVC or coated wire electrode has a much greater day to day variation in the absolute electrode potentials than the PPy solid contact system This is more closely examined in fig 6 14 which shows a comparison of the potential of electrodes CWE1 and SC1 in 0 1 M NaCl over the first 10 days of use The CWE1 system, Pt/PVC1, exhibits large jumps in potential both in the positive and negative direction (+/-50 mV) The SC1 system, Pt/PPy/PVC1, showed more stable potential readings (+/-8mV) over the period studied The potential of CWE's is also known to be dependent on the partial pressure of oxygen[18,19] Fig 6 15 shows the effect of N_2 on the potential of bare Pt and Pt/PPy The electrodes were kept in open stirred solutions of aqueous 0 1 M $NaBF_4$ for several days and then purged with nitrogen The bare platinum showed a large dependence on the oxygen content of the solution, the potential decreased rapidly as the cell was switched to nitrogen This type of behaviour is not unexpected for a bare platinum surface The Pt/PPy was more stable to oxygen effects with no obvious increase or decrease in the potential following the switch to nitrogen Similar experiments with a Pt/PVC2 electrode showed a change in potential of approximately -30mV thus indicating the ability of the oxygen to penetrate through the PVC layer to the Pt/PVC2 interface

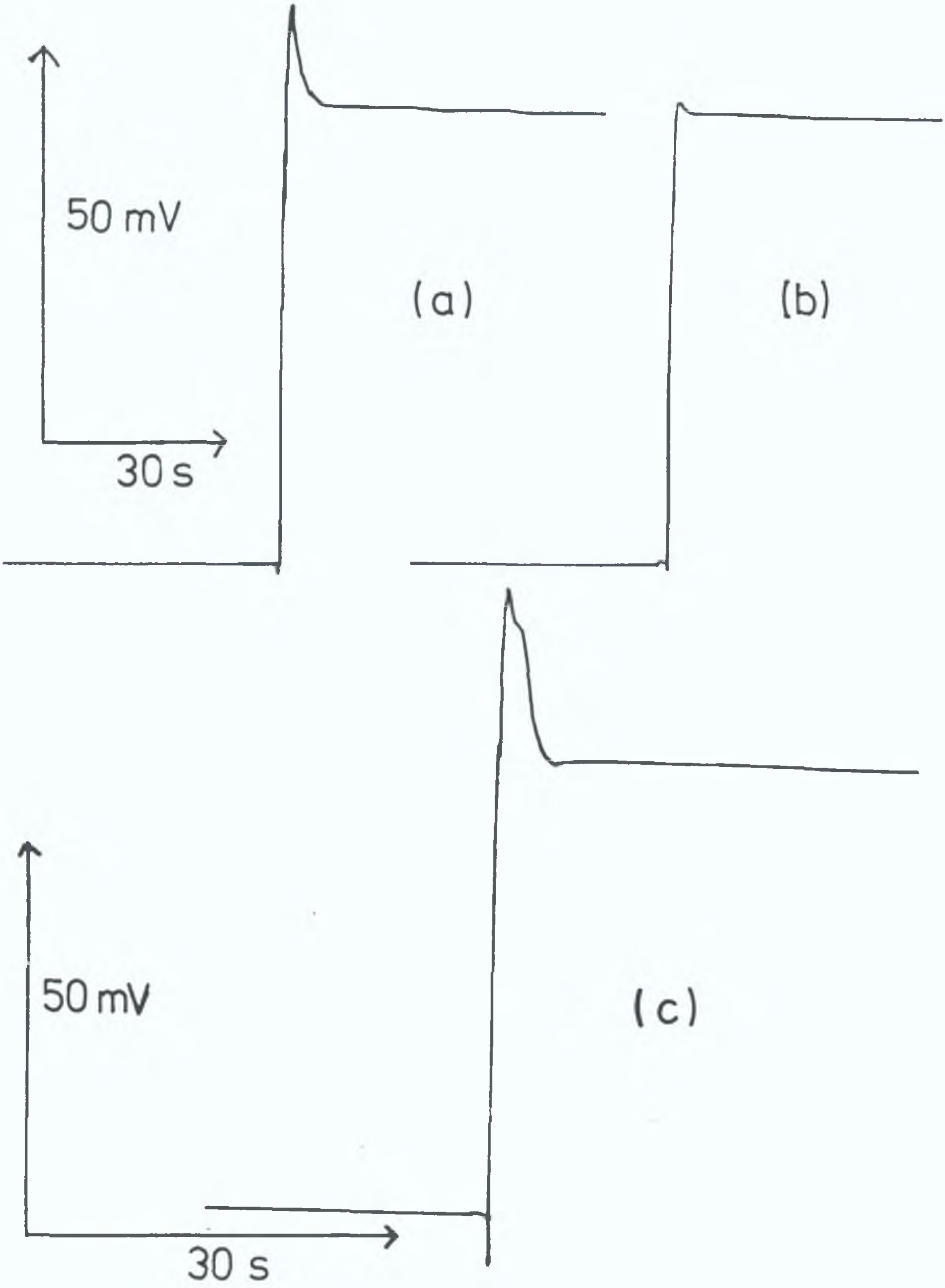

Figure 6.13 Response of the solid contact SC1, SC2 and SC3 (table 6.6) to injections of 0.450 ml 10^{-1} M NaCl into 50 ml 10^{-4} M NaCl which is equivalent to a tenfold increase in Na^+ concentration. (A) SC1; (B) SC2; (C) SC3.

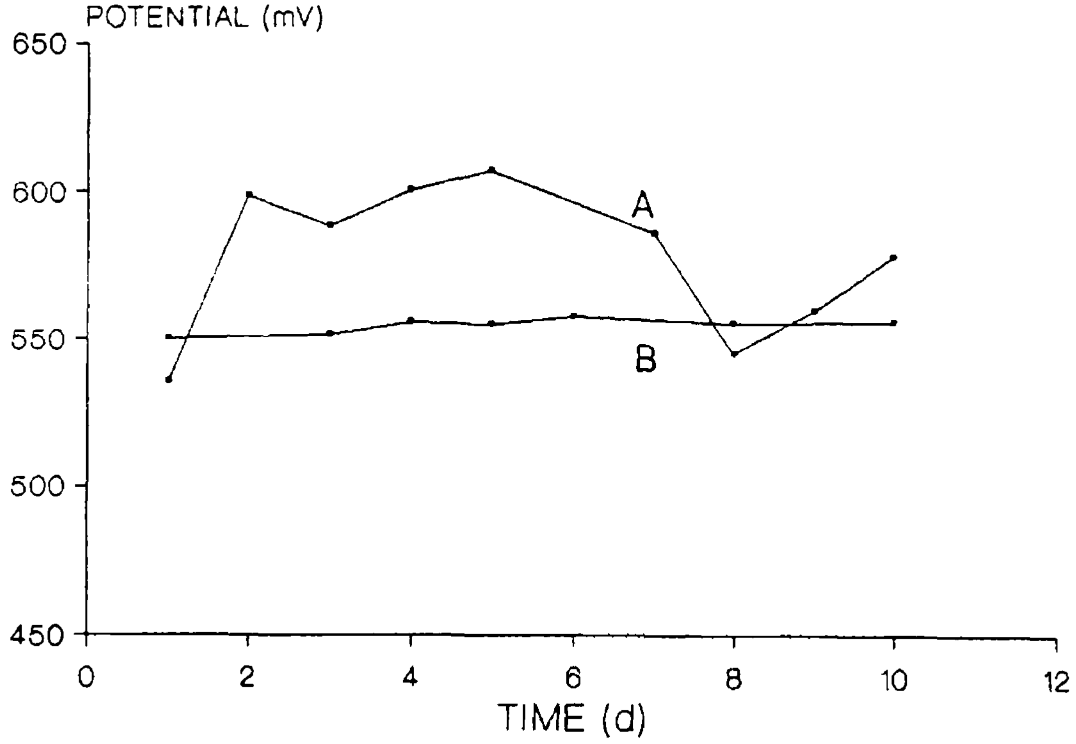

Figure 6 14 Stability study. Response of (A) CWE1 (B) SC1 electrodes (table 6 6) to 10^{-1} M NaCl solution over 10 days

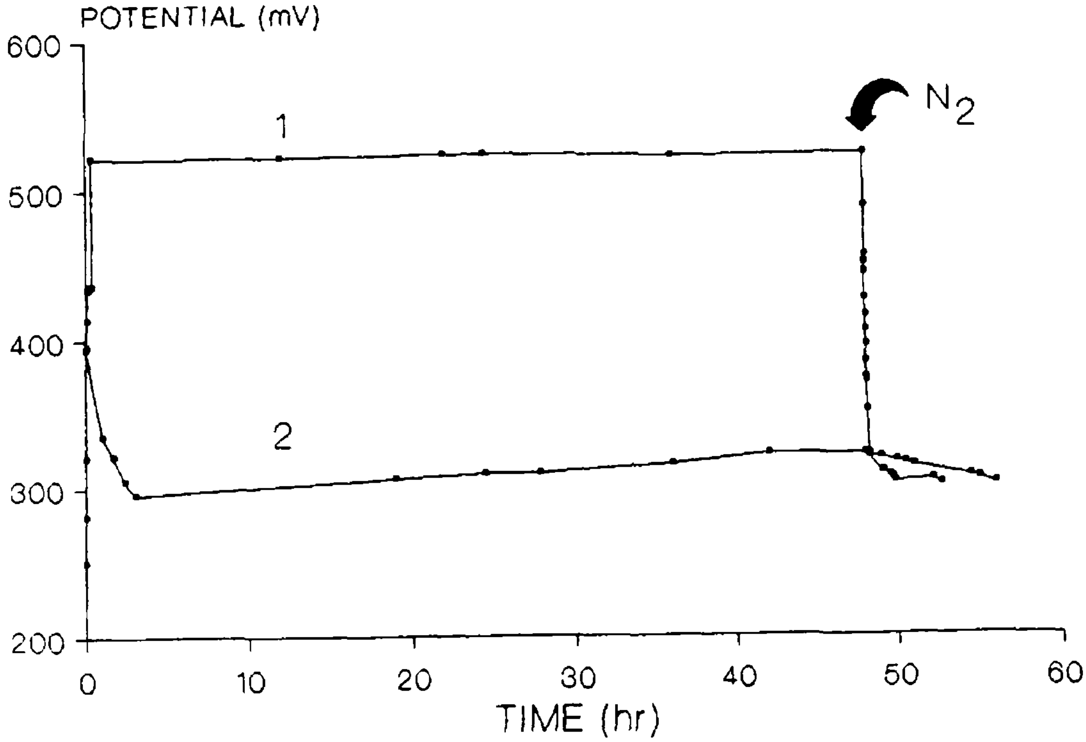

Figure 6 15 Effect of nitrogen on the rest potential of (1) Pt and (2) Pt/PPy($NaBF_4$)21 in 0 1M aq $NaBF_4$ Electrodes were held in an open stirred solution for 48 hours, then purged with nitrogen as marked

6 6 Discussion

Analytically, the electrode incorporating polypyrrole as a solid contact between platinum and an ion-selective PVC membrane showed improved performance over an electrode without the polypyrrole layer In order to understand the basis of these improved performance characteristics it is necessary to investigate fully the charge transfer processes and equilibrium processes occurring at each interface in the system

The redox studies have shown that both PPy and Pt are capable of similar electronic conductivity In this way the thick polypyrrole coating serves as an extension of the electronically conducting metal surface However the polypyrrole layer also has an ability to respond to changes in the concentration of ions in solution The ability of thick PPy layers doped with chloride or fluorborate ions to give a stable response to anions in solution is most likely due to its acting as classical ion-exchanger membrane with fixed cationic sites, the latter is provided by the positively charged polypyrrole units in the doped polymer A change in the concentration of ions in solutions will not change the redox state or the electronic conductivity of the PPy Electrodes coated with PVC membranes show no electronic conductivity from the redox studies, as would be expected, there is no system present in the hydrophobic PVC layer for electronic charge conduction The potentiometric response of the PVC films confirms that the charge transport mechanism in the PVC is ionic due to the movement of cations into the membrane from solution and the translocation of sodium complexes across the membrane

The instability of so called "blocked interfaces" is commonly attributed to the instability of the rest potential of the underlying contact However, as fig 6 15 shows, the formation of the PPy layer on the Pt helps to stabilise the rest potential to the presence of oxygen As oxygen controls the rest potential at the Pt electrode the thick covering of Polypyrrole on the Pt shields the Pt from the effects of ambient pO_2 fluctuations This added stability of the PPy film is the key to the improved performance of the solid contact electrode

The equilibrium processes present throughout the PPy contact system are shown in fig 6 16 The equilibrium at the PPy/Pt interface has to be due to the exchange of electrons from the metal to the conducting polymer layer The equilibrium at the PVC/solution interface must be due to the exchange of Na^+ ions across the interface following the complexation of cations by the ionophoric ligand Throughout the PVC layer the charge transfer is facilitated by the movement of ionic complexes in the membrane The charge transfer across the PVC/PPy interface is less well defined but clearly there must be some mechanism present to mediate the charge transfer The movement of sodium complexes across the PVC membrane may lead to Na^+ ions being released at the inner PVC interface It is doubtful that such positively charged cations could migrate across and enter into the PPy polymer as such phenomena of cation insertion into PPy have only been observed when the polymer is electrochemically reduced to the neutral state by external control of the oxidation state and not under open circuit conditions As most of the potential generated by the indicating electrode occurs at the solution/PVC boundary any potential drop near the PPy film would be insufficient to drive the oxidation or reduction of the polymer In any case the insertion of cations into the polymer in still a matter of discussion In the oxidised state PPy contains a high concentration of dopant anion in this case BF_4 It may be possible that such anions can transfer across the the PPy/PVC interface into the hydrophobic PVC (tetrafluorborate anions are soluble in PVC) Alternatively Na^+ cations released at the inner PVC boundary may form some type of ion pair with the doping anions of the PPy which would remain at the interface or perhaps even enter the PVC membrane

Further studies on the charge transfer mechanism have been carried out using ac impedance techniques to measure the charge transfer resistance, Rct, of these coated wire and solid contact electrode systems[20] As expected analysis of the impedance spectra from PVC membranes with exogenous charge carriers i e $NaBF_4$ and/or KTpClPB led to a significant decrease in the membrane resistance i e the resistance of a membrane containing Pt/PVC2 was 200kΩ compared to a membrane containing the ionophore only, Pt/PVC4, where the resistane was 900kΩ The introduction of the electronically and ionically conducting PPy layer between Pt and PVC membranes containing the ionophore and controlled amounts

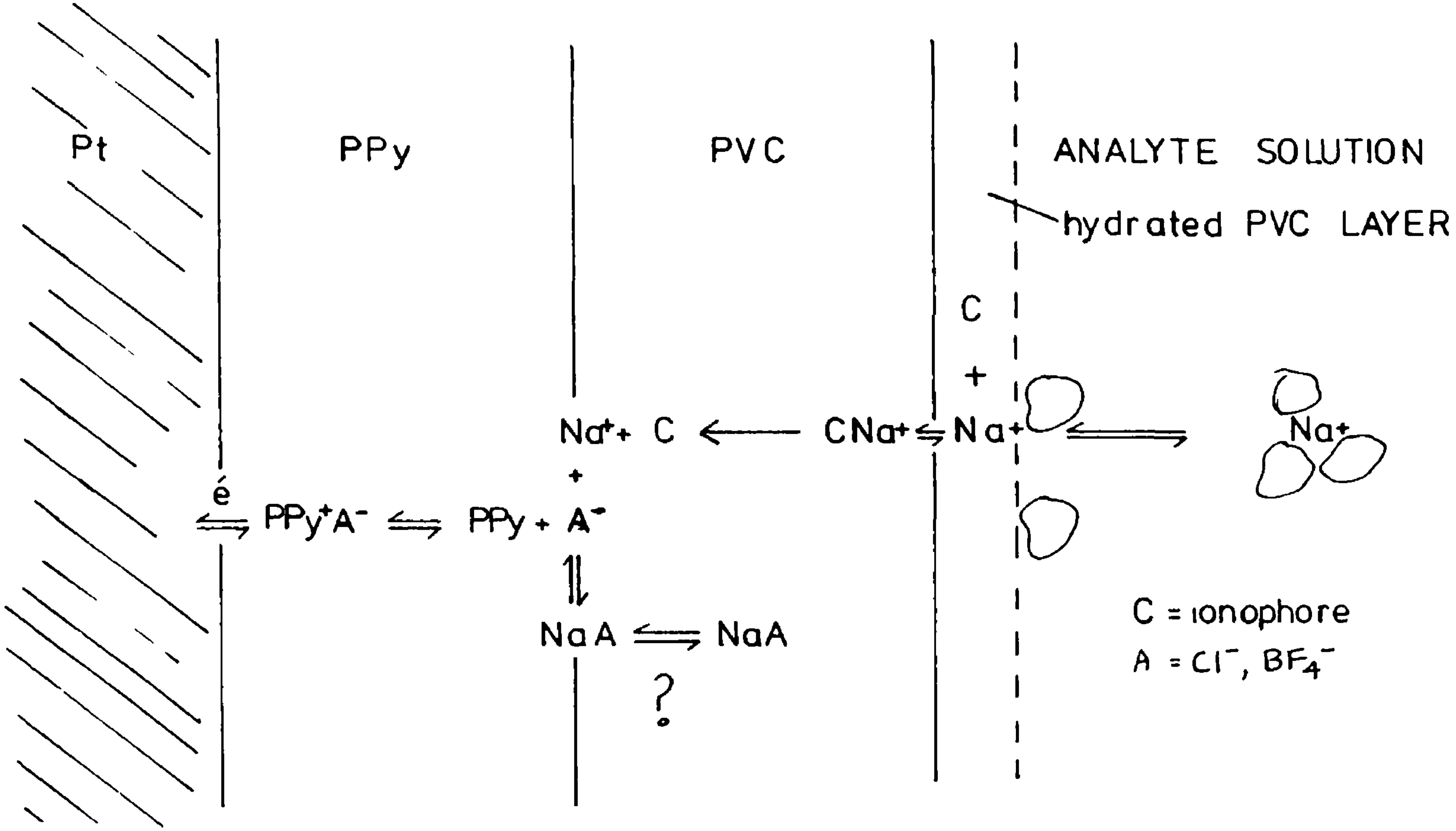

Figure 6 16 Schematic drawing of the equilibrium processes in the solid state contact electrode of ion-exchangers Pt/PPy/PVC1 and Pt/PPy/PVC2 led to a decrease in resistance from 200kΩ to approximately 70 kΩ This can be regarded as a significant decrease in charge transfer resistance far greater than changes in resistance that would be associated with variations in film thickness These results indicate that the ionic and electronic conductivity of the mediating PPy layer may be used to bridge a material with a purely electronic nature, Pt, and a material with a purely ionic conductance, ion-selective PVC In this way both interfaces become unblocked to some extent and the PPy/PVC interface acts as a pseudo reference electrode assuming that the PPy is in the oxidised state and contains a high concentration of doping anions and that the PVC membrane contains a constant concentration of exogenous charge carrier ions

6 7 Conclusion

From the studies of the redox and potentiometric responses of the polypyrrole and PVC membranes we conclude that the polypyrrole could provide a mediating layer for blocked electrodes such as coated wire electrodes in order to improve the stability characteristics of such electrodes This kind of electrode construction lends itself well to the possibility of miniaturisation by the use of thin platinum wire instead of the disc and also to the substitution of cheaper metal contacts such as copper and silver

6 8 Future work

Further work is necessary on the configuration of the PPy/PVC layers In its present configuration, seepage of the solution electrolyte may occur under the PVC layer with time following mechanical abrasion of the electrode A better seal might be accomplished by the use of a platinum wire as the working electrode which is coated electrochemically with conducting polymer, dip coated with PVC and then sealed with parafilm tape using a procedure similar to that described for the classical coated wire electrode[21] The electrical properties of conducting heterocyclic polymers such as polypyrrole are remarkable stable in ambient conditions, however they lack the mechanical properties of non-conductive polymers such as PVC and PVA (poly(vinyl alcohol)) which may limit the extent of their applications[22] In recent years there has been an effort towards producing composite films with high electrical conductivities and good mechanical properties The preparation of polypyrrole within a PVC membrane, previously deposited on a clean Pt electrode surface by dip coating was reported by [23-25] The method was improved by polymerising pyrrole in PVC blended with an electrolyte, to produce a conductive network more uniformly distributed in the PVC film[26] The use of such composites was suggested by Mizutani et al to be suitable for the immobilisation of particles or molecules such as catalysts in the conducting polymer phase by first immobilising the catalyst in PVC [27] This work has been extended to the formation of a conductive PPy/PVA composite films in aqueous solution on a precoated PVA anode[28] Ojio and Miyata have reported the chemical polymerisation of pyrrole in the gas state on an insulating polymer containing ferric chloride[29] A direct one step preparation of homogeneous PMeT (polymethylthiophene) PVC films with improved electrochemical stability has also been reported[30] This prevents de-lamination of the layers The use of such composites in a solid state sensor or the layering of conductive polymer/composite/PVC layers may help to improve the adhesion of the contact and lead to improved mechanical stability of the whole sensor

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