

CHROM. 19 153

## CORRELATION BETWEEN REVERSED-PHASE RETENTION AND SOLUTE MOLECULAR SURFACE TYPE AND AREA

### III. THE INFLUENCE OF POLAR AND SOLVENT-INDUCED POLAR GROUPS

H. J. MÖCKEL\*, F. HÖFLER and H. MELZER

Hahn-Meitner-Institut Berlin GmbH, Bereich Strahlenchemie, Glienicker Strasse 100, D-1000 Berlin 39 (F.R.G.)

(First received July 25th, 1986; revised manuscript received September 30th, 1986)

---

#### SUMMARY

The introduction of functional groups into *n*-alkanes causes changes in retention behaviour. As a general rule, in reversed-phase systems an increase in solute polarity lowers retention, due to an increased solute-eluent interaction. The overall retention loss may be caused by (a) direct interaction of the substituent with the eluent ( $-C\equiv N$ ,  $-OH$ ,  $-O-$ ), (b) build-up of polar centres at the  $CH_2-X$  bonds accompanied by solvation of the solute, (c) influence of the substituent on the retention contribution of the alkyl residues. The retention index increment of a methylene group which is 100 in *n*-alkanes is lowered to 86.7 in ethers. The molar free energies of sorption are negative for  $CH_3$ ,  $CH_2$ , Br and chalcogen atoms, positive for  $-OH$ ,  $-CN$ ,  $-O-$  and  $-S-$ . In thioethers and thiols, however, the S atoms themselves seem to be solvophobic, exhibiting negative free energies. In these cases the positive (or zero) values found are due to the strongly positive  $\Delta G$  of solvated polarized bonds. This polarization is about twice as strong in  $CH_2-S$  bonds as in  $CH_2-Se$  or  $CH_2-Te$  bonds.

---

#### INTRODUCTION

Recently<sup>1,2</sup>, we have shown that solute molecular surface area data can be used to calculate accurate retention data in reversed-phase liquid chromatography (RPLC). The total surface area (TSA) is comprised of the respective surface area increments,  $SA_i$ , of the structural units, *i*, of the solute molecule. Since different surface types are not equally effective in producing retention, each area increment  $SA_i$  is multiplied by a quality factor,  $f_i$ . The sum of  $SA_i \cdot f_i$  plus  $\ln \varphi$  then yields  $\ln k'$ , where  $\varphi$  is the phase ratio. So far the retention effects of zero and very low polarity surfaces have been investigated. We now report on more polar solute surface area increments. In some cases the respective structural units are polar *per se*, like OH groups in alcohols or  $-O-$  in ethers. In others, like thioethers, polysulphides and

polyselenides, the structural units  $-S-$ ,  $-S_n-$ ,  $-Se_n-$  are themselves non-polar, but the solute molecules develop some polarity at the  $CH_2-X$  bonds, most probably under the influence of the eluent methanol.

## EXPERIMENTAL

The experimental conditions were as described before<sup>1,2</sup>. However, in one set of experiments, a new octadecylsilica (ODS) column (10 cm  $\times$  8 mm I.D. RadPAK A cartridge) with a new pre-column was used and produced somewhat different retention for *n*-alkanes (see Results).

## RESULTS AND DISCUSSION

The retention times at an eluent flow-rate of 1 ml/min methanol were measured for *n*-alkanes ( $C_5$ – $C_{10}$ ), 1-bromoalkanes ( $C_9$ – $C_{14}$ ), *n*-alcohols ( $C_{12}$ – $C_{16}$ ), *n*-alkane-thiols ( $C_8$ – $C_{16}$ ), nitriles ( $C_9$ – $C_{12}$ ), dialkyl ethers ( $C_6$ – $C_{14}$ ) and dialkyl thioethers ( $C_2$ – $C_{18}$ ). The data were converted into  $\ln k'$  values and then to retention indices,  $I_K$ , using the *n*-alkanes as a reference system. For homologous series,  $\ln k'$  can be expressed as a linear function of the carbon atom number,  $n_C$

$$\ln k' = a + bn_C \quad (1)$$

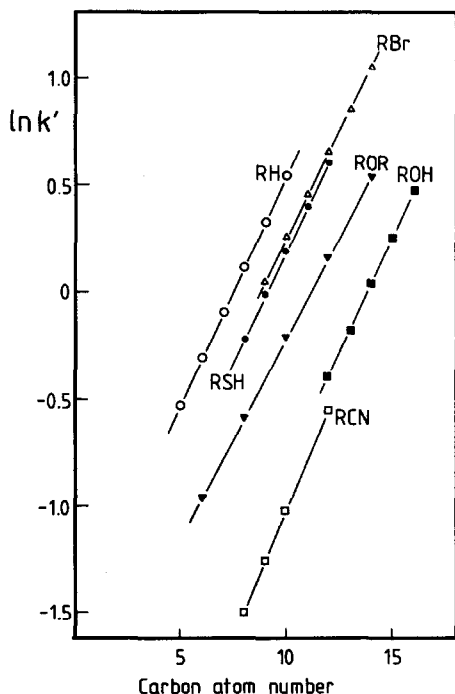


Fig. 1. Dependence of  $\ln k'$  on the carbon atom number,  $n_C$ , for different solute classes. Column: RadPAK A. Eluent: 1 ml/min methanol (same for all figures).

TABLE I

PARAMETERS OF  $\ln k' = a + bn_c$  AND  $I_K = A + Bn_c$  FOR SOME COMPOUND CLASSES IN THE ODS-METHANOL SYSTEM

Solues	<i>a</i>	<i>b</i>	<i>r</i>	<i>A</i>	<i>B</i>	$I_K(11)^*$
RH	-1.3674	0.2000	0.999999	0	100	1100
RBr	-1.5922	0.1949	0.999999	-112.4	97.5	862.6
RSH	-1.6591	0.1968	0.99997	-145.9	98.4	838.1
ROH	-2.6736	0.2026	0.9999	-653.1	101.3	359.9
RCN	-2.6182	0.2025	0.9998	-625.4	101.3	286.3
ROR	-1.8026	0.1734	0.99994	-217.6	86.7	649.4
RSR	-1.5838	0.1817	0.99998	-108.2	90.9	800.8

\*  $I_K$  calculated for solute molecules containing eleven skeletal atoms (other than H).

as shown in Fig. 1. We define  $n_c$  such that only the atoms of the alkyl chain are included, not, for example, the carbon atoms of groups  $-\text{HC}=\text{CH}_2$ ,  $-\text{C}\equiv\text{CH}$ ,  $-\text{C}\equiv\text{N}$  which we regard as substituents. Data pertinent to *n*-alkanes will be denoted by a bar. The retention index of a solute Y is:

$$I_K(Y) = \frac{100}{\bar{b}} [\ln k'(Y) - \bar{a}] \quad (2)$$

Within an homologous series it can be expressed as:

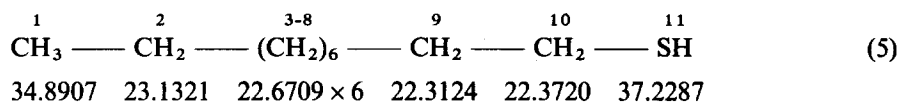
$$I_K = A + Bn_c \quad (3)$$

Table I shows the respective *a*, *b* and *A*, *B* data. It should be noted that the column used for these experiments is somewhat different from the one used for the investigation of polychalcogenides which will be described later. This is most easily seen from the different  $\bar{a}$  and  $\bar{b}$ . From the retention of *p*-polyphenyls,  $\ln \phi$  was found to be  $-1.946^1$ . A physical interpretation of this figure cannot be given.

The correlation between  $\ln k'$ , solute surface area and type of terminally substituted solutes R-X is

$$\ln k' = \text{DA}_{\text{CH}_3} \cdot f_{\text{CH}_3} - \text{DA}_{\text{CH}_2} \cdot f_{\text{CH}_2} + \text{RA} \cdot f_{\text{CH}_2} + \text{DA}_X \cdot f_X + \ln \phi + n_c \cdot \text{DA}_{\text{CH}_2} \cdot f_{\text{CH}_2} \quad (4)$$

where RA is the residual area,  $\text{DA}_i$  is the surface area increment of a structural unit *i* and  $f_i$  is the respective factor for the conversion into  $\ln k'$  increments. Decanethiol may serve as an example:



The surface area contributions of groups 3-8 are identical. Due to different degrees of overlap, the contributions of groups 2, 9 and 10 are slightly different. The sum of the differences is lumped together in RA.

TABLE II

SURFACE AREA INCREMENTS ( $\text{\AA}^2$ ) OF STRUCTURAL UNITS FOR SOME SOLUTE CLASSES $DA_{\text{CH}_3} = 34.8907$ ;  $DA_{\text{CH}_2} = 22.6709 \text{ \AA}^2$  in each case. Data are valid only for  $n_{\text{skeletal}} > 5$ .

Solutes	RA	X	$DA_X$
RH	0.9226	—	—
RBr	-0.4939	-Br	38.6328
RSH	-0.1962	-SH	37.2287
ROH	2.0664	-OH	21.5921
RCN	0.5723	-CN	41.8647
ROR	2.1363	-O-	9.7051
RSR	-0.3009	-S-	25.0574

From a comparison of eqns. 1 and 4 it is seen that:

$$a = DA_{\text{CH}_3} \cdot f_{\text{CH}_3} - DA_{\text{CH}_2} \cdot f_{\text{CH}_2} + RA \cdot f_{\text{CH}_2} + DA_X \cdot f_X + \ln \varphi \quad (6)$$

$$b = DA_{\text{CH}_2} \cdot f_{\text{CH}_2} \quad (7)$$

In Table II the surface area increments are listed. From  $DA_{\text{CH}_2}$  and the  $b$  data from Table I, the quality factors,  $f_{\text{CH}_2}$ , for methylene groups are calculated (Table III). It is seen that  $\text{CH}_2$  groups in different compound classes slightly different  $\ln k'$  contributions. We have attributed this effect to both electron shifts within the solute and changes in cavity structure<sup>1</sup>. Using  $f_{\text{CH}_2}$  and  $\ln \varphi$  we can calculate  $f_{\text{CH}_3}$  for  $n$ -alkanes and find  $f_{\text{CH}_3} = 0.01396$ . The methyl quality factors for the other solutes were calculated according to

$$f_{\text{CH}_3} = \frac{\bar{f}_{\text{CH}_3}}{\bar{f}_{\text{CH}_2}} \cdot f_{\text{CH}_2} \quad (8)$$

and are included in Table III. Finally, eqn. 6 is solved for the quality factor,  $f_X$ , of the functional group X. The  $f_X$  values are also listed in Table III.

If the respective  $f_i$  is multiplied by  $RT = 2477.7 \text{ J/mol}$ , we get  $\delta G_i$  which is the chromatographic free energy of sorption at 298 K produced by 1 mol of  $6.022 \cdot 10^{23} \text{ \AA}^2$  of surface area of type  $i$ . Multiplication of  $\delta G_i$  with the respective surface area

TABLE III

QUALITY FACTORS,  $f_i$ , FOR STRUCTURAL UNITS IN SEVERAL SOLUTE CLASSES

Solutes	$f_{\text{CH}_3}$	$f_{\text{CH}_2}$	$f_X$
RH	0.01396	0.00882	—
RBr	0.01361	0.00860	0.0018
RSH	0.01374	0.00868	0.00007
ROH	0.01415	0.00894	-0.04804
RCN	0.01414	0.00893	-0.0231
ROR	0.01211	0.00765	-0.03823
RSR	0.01268	0.00801	-0.00626

TABLE IV

MOLAR FREE ENERGIES (J/mol) OF SORPTION OF SOME STRUCTURAL UNITS AT 298 K

Solutes	$\Delta G(\text{CH}_2)$	$\Delta G(\text{CH}_3)$	X	$\Delta G(X)$
RH	-495	-1207	-	-
RBr	-483	-1177	-Br	-173
RSH	-488	-1188	-SH	-6
ROH	-502	-1223	-OH	+2570
RCN	-502	-1222	-CN	+2398
ROR	-430	-1047	-O-	+919
RSR	-450	-1096	-S-	+389

$\text{DA}_i$  yields the molar sorption free energy contribution of the structural unit under consideration. These  $\Delta G_i$  data are given in Table IV.

The bromine atom produces some retention but only 14% of the retention of the  $\text{CH}_3$  group which has been replaced. This effect alone would cause a drop in  $\ln k'$  from 0.8326 for *n*-undecane to 0.4090 for *n*-decyl bromide. Since the introduction of bromine has lowered the *a* and *b* terms in Table I, the actual  $\ln k'$  is 0.3568. The experimental value is 0.3572.

The highly polar alcohols, ethers and nitriles have strongly positive  $\Delta G$  values. As seen from  $f_x$  in Table III, the OH group is most effective on a per area basis, followed by the ether. Since the eluent-accessible surface area of oxygen in ethers is small (Table II),  $\Delta G(-\text{O}-)$  is markedly less positive than  $\Delta G(-\text{OH})$ .

The  $\Delta G$  value of a SH group is practically zero. Hence the loss of a  $\text{CH}_3$  group and the substitution influence on  $\Delta G(\text{CH}_3)$  and  $\Delta G(\text{CH}_2)$  determines the retention. In the (isomeric) thioether,  $\Delta G(\text{S})$  is positive, this substitution of one  $\text{CH}_2$  group lowering  $\ln k'$ .

A better understanding of these observations can be reached from the retention of dialkyl polychalcogenides, in particular of polysulphides. It has been shown that the  $\ln k'$  or  $I_K$  increments of alkyl chains and sulphur chains in polysulphides are not constant but rather depend on each others length<sup>2-4</sup>. In terms of  $\ln k'$ , the  $n_c$  and  $n_s$  dependence can be expressed separately:

$$\ln k' = a_c + b_c n_c \quad (9)$$

$$\ln k' = a_s + b_s n_s \quad (10)$$

These equations can be combined to yield  $\ln k'$  as a function of the sulphur and carbon surface areas accessible to the eluent

$$\ln k' = \text{SA}(\text{alkyl}) \cdot f(\text{alkyl}) + \text{SA}(\text{sulphur}) \cdot f(\text{sulphur}) + \ln \phi \quad (11)$$

where  $\text{SA}(\text{alkyl})$  is the total hydrocarbonaceous area,  $\Sigma \text{DA}_{\text{CH}} + \text{RA}_{\text{CH}}$ , and  $\text{SA}(\text{sulphur})$  is the total sulphur area,  $n_s \cdot \text{DA}_s + \text{RA}_s$ . This equation, however, does not reproduce the experimental results.

Since  $f(\text{sulphur}) > f(\text{alkyl})^2$ , a conversion of, for example, undecane into 6-thiaundecane (dipentyl sulphide), is expected to be accompanied by a retention increase. The experiment shows a marked retention loss of  $\Delta \ln k' = -0.5898$  in the system in use which is characterized by  $\bar{a} = -1.4488$  and  $\bar{b} = 0.1981$  (*n*-alkane

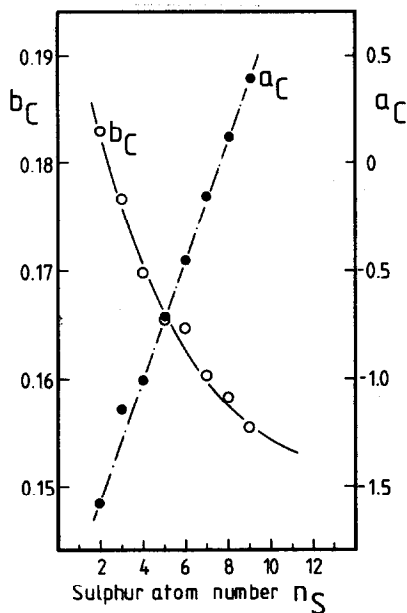


Fig. 2. Parameters of  $\ln k' = a_c + b_c n_c$  as a function of the sulphur chain length,  $n_s$ , in dialkyl polysulphides.

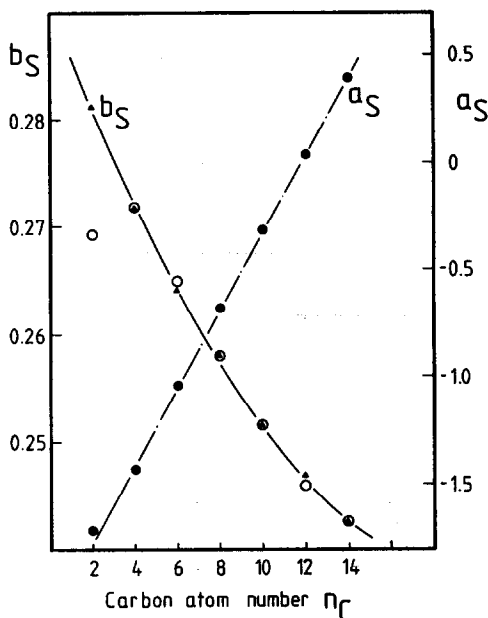


Fig. 3. Parameters of  $\ln k' = a_s + b_s n_s$  as a function of the alkyl chain length in dialkyl polysulphides;  $n_c$  denotes the sum of carbon atoms (6 for dipropyl).

data). Sulphur atoms in S chains as well as  $\text{CH}_2$  and  $\text{CH}_3$  groups in alkyl chains produce a positive  $\Delta \ln k'$ . We have attributed the retention loss observed with the first thia substitution in an alkane molecule to the build-up of local polar centres at the  $\text{CH}_2\text{-S}$  bonds. These can be effectively solvated by the eluent methanol<sup>3</sup>. Correspondingly, a (negative) term  $2 \lambda_{\text{CH-S}}$  has to be included in eqn. 11. Then the general expression for  $\ln k'$  of diethylpolysulphides is:

$$\ln k' = 2 \cdot \text{DA}_{\text{CH}_3} \cdot f_{\text{CH}_3} + (n_c - 2) \cdot \text{DA}_{\text{CH}_2} \cdot f_{\text{CH}_2} + \text{RA}_{\text{CH}_2} \cdot f_{\text{CH}_2} + n_s \cdot \text{DA}_S \cdot f_S + \text{RA}_S \cdot f_S + 2 \lambda_{\text{CH-S}} + \ln \varphi \quad (12)$$

The quality factors of the recurring units  $\text{DA}_{\text{CH}_2}$  and  $\text{DA}_S$  are calculated from the slopes in eqns. 9 and 10:

$$b_c = \text{DA}_{\text{CH}_2} \cdot f_{\text{CH}_2} \quad \text{and} \quad b_s = \text{DA}_S \cdot f_S \quad (13)$$

All coefficients of eqns. 8 and 10 are shown in Figs. 2 and 3.  $a_c$  and  $b_c$  depend on  $n_s$ ,  $a_s$  and  $b_s$  depend on  $n_c$ . The dependence of the "a" terms is linear, that of the "b" terms is not. For the "b" term we found a perfect fit with:

$$b_c = 0.1981 + 0.00064 \cdot n_s - 0.02177 \cdot \ln n_s \quad (14)$$

$$b_s = 0.2910 + 0.00183 \cdot n_c - 0.00892 \cdot \ln n_c \quad (15)$$

For the column used in these experiments,  $\bar{f}_{\text{CH}_3}/\bar{f}_{\text{CH}_2} = 1.214$  and  $\ln \varphi = -1.821$  were found<sup>1</sup>. Using these data and combining eqns. 9-15, we calculated  $(\ln k' - 2\lambda_{\text{CH-S}})$  for  $\text{Bu}_2\text{S}_n$  and  $\text{R}_2\text{S}_5$  as test groups. The results are shown in Fig. 4 and compared to the experimental data. It is found that the retention loss due to a solvated local polar centre ("solvation patch") is not really constant for a series but becomes less negative with increasing length of the alkyl chains or the sulphur chains.

Consequently, the retention increase of polysulphides with increasing  $n_s$  is due not only to the linearly increasing surface area  $\text{SA}_s$ , but also to the change in  $\lambda_{\text{CH-S}}$ . In Fig. 5 the retention index of di- $n$ -heptyl polysulphides is compared to that of sulphur rings  $\text{S}_n$ . The  $I_K$  increase per S atom is somewhat greater in  $\text{C}_7\text{S}_n\text{C}_7$ , although the surface area increase is the same for both  $\text{S}_n$  chains and  $\text{S}_n$  rings when  $n > 9$ . If the  $\Delta I_K$  corresponding to change in  $\lambda_{\text{CH-S}}$  is taken into account, the two lines are parallel.

The  $\Delta G(-\text{SH})$  and  $\Delta G(-\text{S}-)$  values given in Table IV comprise both the "real" free sorption energy contribution from the respective structural unit and a contribution from  $\lambda_{\text{CH-S}}$ . From the arguments given above, we think that both the groups  $-\text{SH}$  and  $-\text{S}-$  have a negative free energy contribution which is overcompensated by the influence of the solvation patches. The more positive  $\Delta G(-\text{S}-)$  compared to  $\Delta G(-\text{SH})$  is thought to be caused by an expansion of the solvation patch in two directions. Comparable observations can be made for organic selenium and tellurium compounds, the main differences being the less negative solvation contributions of

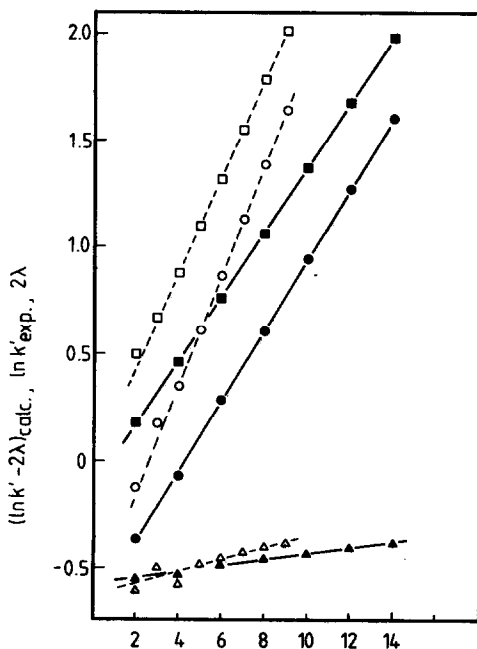


Fig. 4. Comparison of  $(\ln k' - 2\lambda_{\text{CH-S}})$  with experimental data for di- $n$ -butyl polysulphides ( $\square$ ,  $\circ$ ,  $\triangle$ ) and for dialkyl pentasulphides ( $\blacksquare$ ,  $\bullet$ ,  $\blacktriangle$ ). Squares:  $(\ln k' - 2\lambda)$  calculated from eqn. 12; circles, experimental  $\ln k'$ ; triangles,  $2\lambda$  calculated from the difference.

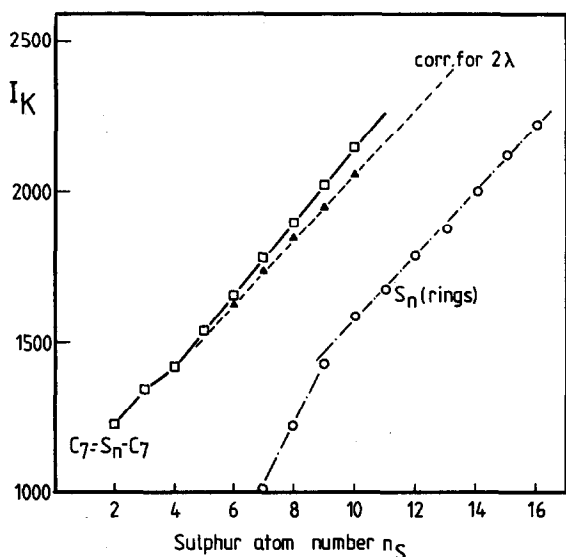


Fig. 5. Retention indices,  $I_K$ , of di-*n*-heptyl polysulphides (squares) and sulphur rings (circles). Triangles show  $I_K$  of  $C_7S_nC_7$  after correction for  $2\lambda$ .

$\lambda_{CH-Se}$  and  $\lambda_{CH-Te}$ , respectively, and a practically linear dependence of  $b_C$  on  $n_{Se}$  and of  $b_{Se}$  on  $n_C$ .

The retention of dialkyl polychalcogenides  $R_2X_n$  can be equally well expressed in terms of retention index increments,  $\delta I(X)$ ,  $\delta I(CH_2)$  and  $\delta I(CH_2-X)^4$ . Then  $\delta I(X)$  depends on  $n_C$ ,  $\delta I(CH_2)$  on  $n_S$  and  $\delta I(CH_2-X)$  on both  $n_C$  and  $n_S$ . On extrapolation to the respective  $n = 0$ , we get the  $\delta I^0$  values listed in Table V. It is seen that the solvation effect around  $-CH_2X-$  destroys as much retention as 1.7  $CH_2$  groups can produce when  $X = S$ . For  $X = Se$  or  $Te$  the effect is only half as strong, which indicates that the bonds to methylene are less polarized and less solvated.

TABLE V

RETENTION INCREMENTS OF DIALKYL POLYCHALCOGENIDES EXTRAPOLATED FOR ZERO EXTERNAL INFLUENCE

Solutes	$\delta I^0(CH_2)$	$\delta I^0(CH_2-X)$	$\delta I^0(X)$
$R_2S_n$	91.0	-167.1	142.2
$R_2Se_n$	89.1	-86.5	172.4
$R_2Te_n$	87	-82.7	239.0

## CONCLUSIONS

Retention expressed as  $\ln k'$  can easily be calculated from solute molecular surface areas once the  $\ln k'$  contributions per unit area (quality factors,  $f_i$ ) of the respective surface types have been determined. The calculation of  $f_{CH_2}$  is straightforward.



ward and very precise. The other factors, however, are influenced by errors in the determination of the *n*-alkane  $\ln k'$ , intercept  $\bar{a}$  and the phase ratio,  $\varphi$ . Since these data may vary from column to column, the whole procedure is sufficiently accurate only when applied to retention on one particular column.

We have found that retention indices,  $I_K$ , show only very small changes in systems with zero or low eluent water contents, even when column packings like RadPaK A, Nucleosil C<sub>18</sub> or Spherisorb are compared. Therefore, we are now converting the existing data into index increment data  $\delta I_I$ , which apparently are invariant towards ODS column changes. These data will be presented elsewhere.

#### REFERENCES

- 1 H. J. Möckel, G. Welter and H. Melzer, *J. Chromatogr.*, 388 (1987) 255.
- 2 H. J. Möckel, F. Höfler and H. Melzer, *J. Chromatogr.*, 388 (1987) 267.
- 3 H. J. Möckel, *J. Chromatogr.*, 317 (1984) 589.
- 4 H. J. Möckel, H. Melzer, F. Höfler and A. T. Fojtik, *5th Annual American-East European Symposium on Chromatography, Budapest, 1985*.