

CHROM. 14,222

SYSTEMATIC STUDY OF TERNARY SOLVENT BEHAVIOUR IN REVERSED-PHASE LIQUID CHROMATOGRAPHY*

PETER J. SCHOENMAKERS*, HUGO A. H. BILLIET and LEO DE GALAN

Laboratorium voor Analytische Scheikunde, Technische Hogeschool Delft, Jaffalaan 9, 2628 BX Delft (The Netherlands)

SUMMARY

An extensive experimental survey of the retention behaviour of 32 solutes in the system methanol–tetrahydrofuran–water and 49 solutes in the system methanol–acetonitrile–water is presented. The retention data are fitted to a second order six-parameter equation, describing the capacity factor as a function of mobile phase composition. Iso-elutotropic lines, *i.e.*, lines that connect solvents of equal elutotropic strength, are constructed in the ternary diagrams for the two systems and compared with theoretical lines, predicted from solubility parameter theory. Specific effects are defined as variations in retention for a particular solute, using solvents of equal elutotropic strength. Such effects appear to be larger between different binary mixtures than within the ternary triangle. Ternary solvents thus provide a smooth transition between two limiting binary mixtures.

INTRODUCTION

Phase systems in liquid chromatography can be evaluated using three characteristics:

(i) Retention which is determined by the polarity of the solute, relative to that of the mobile and stationary phases, and by the absolute difference between the polarities of the two phases.

(ii) The latter factor also determines the selectivity of the system, *i.e.*, its general separation power. Therefore, in general, the selectivity of the system cannot be increased without at the same time increasing retention. For example, in reversed-phase liquid chromatography (RPLC), the addition of more water to the mobile phase usually results in an increase of both retention and selectivity¹.

(iii) The specificity of the system, *i.e.*, its increased separation power for certain pairs of solutes, which arises from specific interactions between the solute molecules and those of the chromatographic phases. Unlike retention and selectivity, specificity is hard to predict for LC phase systems.

In RPLC we use a single stationary phase of low polarity for many different

* Part of the Ph.D. Thesis of P.J.S.

samples. By using binary mixtures, the polarity of the mobile phase can be increased continuously until, for a given sample, retention reaches a practical upper limit. This mobile phase will lead to the highest possible selectivity. Different binary mobile phases can be prepared with the same polarity, *e.g.*, a mixture of 60% (v/v) methanol and 40% water has the same polarity as acetonitrile–water (47:53) or tetrahydrofuran (THF)–water (37:63)². Such binary mobile phases of equal polarity can be shown to produce considerable specific effects³. There is, however, a very small number of organic modifiers that can be used in such binary mixtures with water. Many more mobile phases of the same polarity can be used, if we include ternary mixtures. For example, the 60% methanol and the 47% acetonitrile solvents can be mixed in any arbitrary ratio to yield an infinite number of possible ternary mobile phases. Hence, ternary mobile phases greatly increase our flexibility to search for optimum specificity.

In recent years, many practical examples of the advantageous use of ternary mobile phases in RPLC have been published (*e.g.*, refs. 4–8). Also, the combination of water with three organic modifiers has been shown to be of practical use⁸.

The first systematic investigation of ternary mobile phases was performed by Bakalyar *et al.*⁴. They compared seven ternary mixtures containing 50% (v/v) water, 40% methanol and 10% of a second organic modifier. The binary mixture of 50% methanol and 50% water was used as a reference. At first sight the specific effects they reported appear to be striking, but they are obscured by considerable differences in retention between the different mobile phases. Indeed, the specific effects largely vanish when we normalize the retention data in such a way that the same average retention is obtained as for the reference mixture. The remaining differences are much smaller, and give a better insight into the specificity of the different systems. Nevertheless, it is true that even such minor differences can be exploited in practice.

A more recent systematic study of the behaviour of ternary and quaternary mixtures of water, methanol, THF and acetonitrile was reported by Glajch *et al.*⁸. They describe procedures to search for optimal multicomponent mobile phases.

In this paper we report a systematic study of the retention behaviour of two ternary mobile phase systems (methanol–acetonitrile–water and methanol–THF–water). We varied the composition of all constituents from zero to 100%. The data are used to define ternary compositions of equal polarity and to analyse specific separation effects.

THEORETICAL

Retention in RPLC using ternary mobile phases

In previous work we have used the solubility parameter concept to establish the general shape of the relationship between the capacity factor and the binary mobile phase composition⁹. Moreover, this concept yields good estimates of the compositions of different binary solvents that lead to equal retentions². Therefore, we feel encouraged to use it in a similar way for ternary systems.

In LC, the capacity factor can be expressed in terms of activity coefficients¹⁰

$$k_i \cong \frac{\gamma_{i,m}}{\gamma_{i,s}} \cdot \frac{n_s}{n_m} \quad (1)$$

where $\gamma_{i,m}$ and $\gamma_{i,s}$ are the activity coefficients of the solute i in the mobile and stationary phase, respectively, and n_s and n_m are the number of moles of the two phases present in the column. Eqn. 1 is based on the pure liquid solute as the standard state for both phases.

We described elsewhere² how the activity coefficients can be expressed in terms of total solubility parameters. If we neglect entropy effects (*cf.*, ref. 2), we find

$$RT \ln \gamma_{i,f} = v_i (\delta_i - \delta_f)^2 \quad (2)$$

where R is the gas constant ($1.9865 \text{ cal K}^{-1} \text{ mole}^{-1}$), T is the absolute temperature ($^{\circ}\text{K}$), $\gamma_{i,f}$ is the activity coefficient of solute i in phase f , v_i is the molar volume of the solute ($\text{cm}^3 \text{ mole}^{-1}$) and δ is the solubility parameter ($\text{cal}^{1/2} \text{ cm}^{-3/2}$)*. Combination of eqns. 1 and 2 now results in:

$$\ln k_i = \frac{v_i}{RT} \cdot [(\delta_i - \delta_m)^2 - (\delta_i - \delta_s)^2] + \ln \frac{n_s}{n_m} \quad (3)$$

As before⁹, we will assume that the solubility parameter of a mixture can be found from that of its constituents as

$$\delta_{\text{mix}} = \sum_{j=1}^N \varphi_j \delta_j \quad (4)$$

for a mixture of N constituents, each with volume fraction φ_j and solubility parameter δ_j . Since, of course, $\sum_{j=1}^N \varphi_j = 1$, eqn. 4 can be written for a ternary mixture as:

$$\delta_{\text{mix}} = \varphi_1 \delta_1 + \varphi_2 \delta_2 + (1 - \varphi_1 - \varphi_2) \delta_3 \quad (5)$$

From now on we will assign the subscript 1 to methanol and 3 to water. The subscript 2 will then refer to the second organic modifier (acetonitrile or THF).

Substitution of eqn. 5 into eqn. 3 yields

$$\ln k_i = \frac{v_i}{RT} \cdot \{[\delta_i - \varphi_1 \delta_1 - \varphi_2 \delta_2 - (1 - \varphi_1 - \varphi_2) \delta_3]^2 - (\delta_i - \delta_s)^2\} + \ln \frac{n_s}{n_m}$$

and after rearrangement:

$$\begin{aligned} \ln k_i = \frac{v_i}{RT} \cdot & [\varphi_1^2 (\delta_1 - \delta_3)^2 + \varphi_2^2 (\delta_2 - \delta_3)^2 + \\ & + 2 \varphi_1 (\delta_1 - \delta_3)(\delta_3 - \delta_1) + 2 \varphi_2 (\delta_1 - \delta_3) \times \\ & \times (\delta_3 - \delta_2) + (\delta_3 - \delta_1)^2 - (\delta_s - \delta_1)^2 + \\ & + 2 \varphi_1 \varphi_2 (\delta_3 - \delta_1)(\delta_3 - \delta_2)] + \ln \frac{n_s}{n_m} \end{aligned} \quad (7)$$

* Historically (*cf.*, ref. 10) the solubility parameter is expressed in $\text{cal}^{1/2} \text{ cm}^{-3/2}$. The conversion to S.I. units reads: $1 \text{ cal}^{1/2} \text{ cm}^{-3/2} = 2.05 \text{ MPa}^{1/2}$.

This equation describes the dependence of the capacity factor on the composition of the mobile phase. It is of the form

$$\ln k = A_1 \varphi_1^2 + A_2 \varphi_2^2 + B_1 \varphi_1 + B_2 \varphi_2 + C + D \varphi_1 \varphi_2 \quad (8)$$

with:

$$A_1 = \frac{v_i}{RT} \cdot (\delta_1 - \delta_3)^2 \quad (9)$$

$$A_2 = \frac{v_i}{RT} \cdot (\delta_2 - \delta_3)^2 \quad (10)$$

$$B_1 = \frac{2v_i}{RT} \cdot (\delta_i - \delta_3)(\delta_3 - \delta_1) \quad (11)$$

$$B_2 = \frac{2v_i}{RT} \cdot (\delta_i - \delta_3)(\delta_3 - \delta_2) \quad (12)$$

$$C = \frac{v_i}{RT} \cdot [(\delta_3 - \delta_i)^2 - (\delta_s - \delta_i)^2] + \ln \frac{n_s}{n_m} \quad (13)$$

$$D = \frac{2v_i}{RT} \cdot (\delta_3 - \delta_2)(\delta_3 - \delta_1) = 2\sqrt{A_1 A_2} \quad (14)$$

Eqn. 8 expresses a non-linear dependence of the logarithm of the capacity factor on the two volume fractions of organic modifier. A representative example of its behaviour is shown in Fig. 1. The composition of the ternary mobile phase is represented by the usual equilateral triangle in the horizontal plane at the base. The capacity factor is plotted vertically on a logarithmic scale. The surface described by eqn. 8 is curved, but otherwise quite smooth. Local maxima or minima, discontinuities or asymptotes cannot be observed.

In binary mobile phase systems, the generally non-linear relationship between $\ln k$ and composition can be approximated by a straight line over a limited range of k values ($1 < k < 10$)¹. It should be noted, however, that it does not appear to be feasible to approximate the surface described by eqn. 8 by a plane over a wide range of ternary compositions.

If we consider the values of the solubility parameters of the different mobile phase constituents, some further predictions can be made. The respective δ values are given in Table I. Using these values we expect A_2 to be much larger than A_1 , and, of course, both are positive. Since the solubility parameter of the solute will be of the order of $10 \text{ cal}^{1/2} \text{ cm}^{-3/2}$, B_1 and B_2 are expected to be strongly negative, again with the absolute value of B_2 larger than that of B_1 . The value of D is the geometric mean of that of A_1 and A_2 and is thus expected to be positive. Finally, C is, strictly speaking, equal to $\ln k_w$, the logarithm of the capacity factor of the solute in pure water. The parameters for *o*-cresol in the methanol-THF-water system that were used to construct Fig. 1 follow these guidelines.

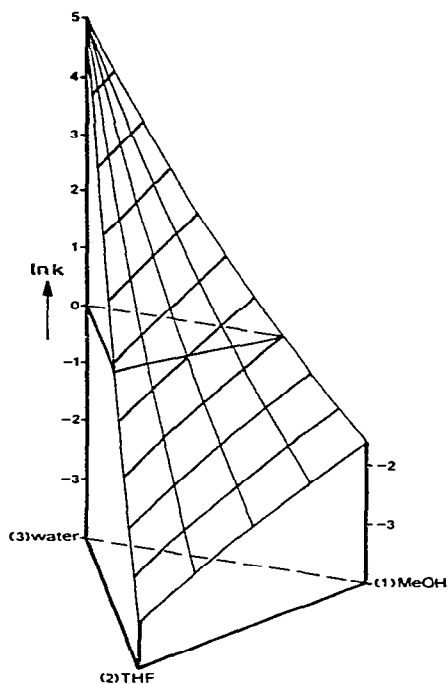


Fig. 1. Dependence of the capacity factor on mobile phase composition, for *o*-cresol in the system methanol (MeOH)-THF-water. The curved surface obeys eqn. 8 with coefficients from Table II.

For each solute the experimental retention data have been fitted to eqn. 8, yielding a set of coefficients (A_1 through D) for a particular solute in each mobile phase system.

We preferred the six-parameter linear equation given by eqn. 8 over a five-parameter non-linear version, in which $D = 2\sqrt{A_1 A_2}$, because it yielded a closer fit in the regression analysis. One reason for this may be found in the factor n_s/n_m . It may be argued that n_s/n_m varies with the composition of the mobile phase. With decreasing water content, n_s probably increases due to solvation (see, *e.g.*, refs. 11 and 12). Even without this effect, n_m is bound to decrease, due to the increase in the molar volume of

TABLE I

SOLUBILITY PARAMETERS FOR THE SOLVENTS USED IN THE PRESENT STUDY

Data taken from ref. 10.

| Mobile phase component | Subscript | Solubility parameter ($\text{cal}^{1/2} \text{cm}^{-3/2}$) |
|------------------------|-----------|---|
| Methanol | 1 | 15.85 |
| Tetrahydrofuran (THF) | 2 | 9.88 |
| Acetonitrile | | 13.14 |
| Water | 3 | 25.52 |

the mobile phase from water ($v = 18 \text{ cm}^3 \text{ mole}^{-1}$) to methanol (40), acetonitrile (52) or THF (81). The latter effect can be mathematically accounted for, by introducing the logarithm of the molar volume of the mobile phase into eqn. 8. In doing so, however, we did not find a significant improvement in the regression analysis. Therefore, we decided to treat (n_s/n_m) as a constant, which means that its variation with mobile phase composition is included in the coefficients A_1 through D in eqn. 8.

Iso-elutotropic diagrams

As stated before, ternary systems in high-performance liquid chromatography (HPLC) offer the possibility to exploit specific effects. For certain solute pairs, the relative retention can be increased considerably, while retention itself remains roughly constant. Theoretically (eqn. 3), different mobile phases will lead to the same retention times if their polarities (solubility parameters) are equal.

Let us consider a sample for which a chromatogram has been obtained in a binary mixture of water and methanol, the volume fraction of the latter being φ_M^* . We will refer to this mobile phase as the (binary) reference. Let us assume that the reference chromatogram shows reasonable retention times, but insufficient separation. Eqn. 4 shows that a ternary phase expected to yield roughly the same retention times obeys:

$$\delta^* = \varphi_M^* \delta_1 + (1 - \varphi_M^*) \delta_3 = \varphi_1 \delta_1 + \varphi_2 \delta_2 + (1 - \varphi_1 - \varphi_2) \delta_3 \quad (15)$$

$$\varphi_2 = (\varphi_M^* - \varphi_1) (\delta_1 - \delta_3) / (\delta_2 - \delta_3) \quad (16)$$

Here δ^* is the polarity of the binary reference mixture. As usual, subscript 1 refers to methanol and subscript 3 to water. According to eqn. 16 all ternary mixtures of water, methanol and a second organic modifier that possess a given polarity follow a straight line between two limiting binary compositions. This is illustrated in Fig. 2a. If $\varphi_1 = \varphi_M^*$, φ_2 becomes zero and eqn. 16 defines the reference binary composition of methanol and water. If $\varphi_1 = 0$, a binary mixture of water and the second organic modifier results. The straight line connecting the two binary compositions will be called a (theoretical) iso-elutotropic line. Empirical iso-elutotropic lines can be constructed from experimental data collected for a large number of solutes. The procedure is illustrated in Fig. 2b. Let us consider a ternary mobile phase of composition P (25% methanol, 25% THF, 50% water).

The solute dimethyl phthalate shows a capacity factor of 0.8 in this solvent. The same capacity factor is observed with a binary mixture of 70% methanol and 30% water. Consequently, for dimethyl phthalate the iso-elutotropic line through binary reference composition $\varphi_M^* = 0.7$ passes through P . Other solutes eluted with the ternary composition P not only show different capacity factors, but also yield slightly different binary reference compositions φ_M^* . If, as is the case in practice, the variation in φ_M^* is small, we can take the average reference composition of a large number of solutes and assign this value to the ternary composition P . As shown in Fig. 2b, this average turns out to be 0.63. The same procedure can be applied to other ternary compositions and each of them can be assigned a particular reference value. The data thus obtained are shown in Fig. 2b for a few compositions. Linear interpolation along straight composition lines through the top of the composition triangle then yields the

ternary composition P' , for which $\varphi_M^* = 0.7$. Finally, all the mixtures that yield the same reference value can be connected to form an (empirical) iso-elutropic curve. The example in Fig. 2 shows the difference between the theoretical prediction (eqn. 16) and the empirical curve. Theory predicts a straight line running from $\varphi_M^* = 0.7$ to $\varphi_{\text{THF}} = 0.43$. The empirical curve is slightly concave and intersects the opposite side at $\varphi_{\text{THF}} = 0.44$.

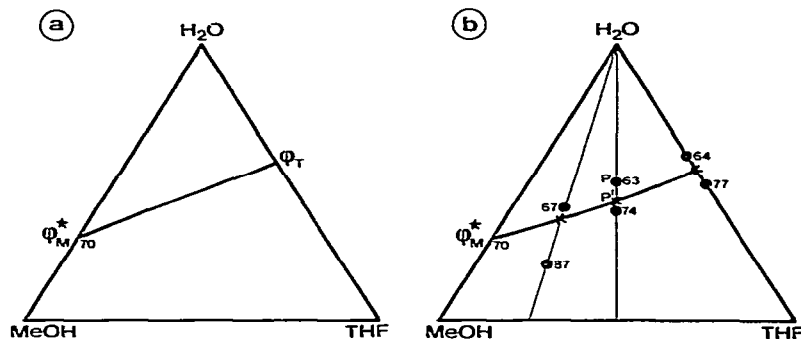


Fig. 2. Illustration of the construction of iso-elutropic lines. a, Theoretical; the straight line from 70% methanol to 43% THF is calculated from eqn. 16. b, Experimental: the numbers at each composition (indicated by a black dot) represent the corresponding reference binary methanol-water composition (in % methanol) averaged over a large number of solutes. The solid, curved line connects interpolated points of equal elutropic strength.

The approach outlined here resembles the one used previously for relating different binary compositions³.

EXPERIMENTAL

The instrumentation used was the same as described before¹, except that a Varian Model 8050 autosampler was used for some of the measurements. Mobile phases were mixed from individually measured volumes of methanol, THF (both from J. T. Baker, Phillipsburg, NJ, U.S.A.), acetonitrile (E. Merck, Darmstadt, G.F.R.) and water (carefully treated as described before¹). Columns (30 cm \times 4.6 mm I.D.) were home-packed with Nucleosil 10-RP18 from Macherey, Nagel & Co. (Düren, G.F.R.).

The flow-rate was set at 1.5 ml min⁻¹ and was measured at regular intervals. All measured retention times were corrected for variations in the flow-rate and for the residence time outside the column.

For these columns at this flow-rate we chose a uniform hold-up time of $t_0 = 125$ sec. Although there are indications that the hold-up volume of an RPLC column varies with mobile phase composition^{12,13}, there seems to be no valid experimental method for its accurate determination. The two methods that give the most realistic results in binary methanol-water systems¹³ cannot be used in the present ternary systems.

The injection of large amounts of inorganic salts leads to solvent demixing. The linearization of a plot of $\ln k$ vs. carbon number for homologous series yields unrealistic results because the Martin rule cannot be applied with mobile phases rich in

acetonitrile or THF¹⁴. The use of ²H₂O (deuterium oxide) as a *t*₀-marker, which has recently been studied extensively¹², also has serious disadvantages.

The exchange of deuterium with hydrogen atoms in water, methanol and even residual silanols might cause a problem¹⁵. Moreover, the necessary assumption that water is not absorbed into the stationary phase clearly does not hold over the whole composition range. Therefore, we decided to use a uniform, realistic *t*₀ value. The consequences of this decision are limited, because the conclusions drawn in this paper apply equally well to gross retention times as to capacity factors.

The present study includes 32 solutes in the system methanol (1)–tetrahydrofuran (2)–water (3) and 49 solutes in the system methanol (1)–acetonitrile (2)–water (3). These two sets of solutes are listed in Tables II and III, respectively. They were used in the highest purity available and diluted in the corresponding mobile phases, if necessary enriched with organic modifier.

The compositions of the two systems that were included in the measurements are indicated in Fig. 3. For each composition solute retention times were measured, up to a maximum value of about 1.5 h (*k* ≈ 40), for practical reasons.

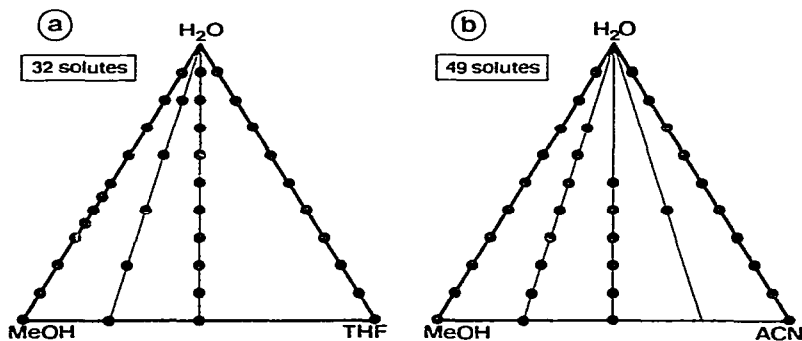


Fig. 3. Overview of the mobile phase compositions used in the present study. ACN = Acetonitrile.

RESULTS AND DISCUSSION

The basic retention data (capacity factors) are given in Appendix I for the methanol–THF–water system and in Appendix II for the methanol–acetonitrile–water system.

For all solutes the experimental retention data were fitted to eqn. 8. The resulting coefficients for each solute are given in Table II for the methanol (1)–THF (2)–water (3) system and in Table III for the system methanol (1)–acetonitrile (2)–water (3). The total number of datapoints, *N*, for each solute is also listed in the tables. The coefficients follow reasonably well the general behaviour discussed in Theoretical. The values of *A*₁ and *A*₂ are usually positive and the values of *A*₂ are much larger than those of *A*₁. However, some *A*₁ values are negative. As expected, all *B* values are strongly negative, with the absolute value of *B*₂ being larger than that of *B*₁. *C* is, of course, positive, but the two *C* values for a solute that appears in both tables are not exactly the same. The values of *D* are usually positive, but larger than the geometric mean of *A*₁ and *A*₂. Considering the approximate character of eqns. 9–14 after omitting entropy and phase ratio terms, these results are not discouraging.

The last column in Tables II and III shows the average error between the model (eqn. 8) and the experimental data points. Note that the absolute deviations in $\ln k$ are approximately the same as the relative deviations in k . The average deviation for all data points is 13% for the THF-containing system and 12% for the system with acetonitrile.

Closer examination of the data reveals that moderate capacity factors ($k < 10$) are described consistently better (deviations less than 10%) than large capacity factors ($k > 10$). This is due to the fact that a fixed C term was adopted. In reality, different ternary systems (compare Tables II and III) and different binary systems^{1,9} yield different values of C for the same solute.

As a result, the average deviation between the model (eqn. 8) and the larger values observed in water-rich solvents is 20% for the THF system and 18% for the

TABLE II

RETENTION BEHAVIOUR OF 32 SOLUTES IN THE SYSTEM METHANOL-THF-WATER

Coefficients according to eqn. 8. N = Number of data points included in the regression analysis; a.d. = average deviation between the experimental value for $\ln k$ and the calculated value from eqn. 8, for all data points.

| No. | Solute | A_1 | A_2 | B_1 | B_2 | C | D | N | a.d. |
|-----|-----------------------------|-------|-------|-------|--------|------|-------|-----|------|
| 1 | Acetophenone | 0.25 | 4.66 | -5.54 | -11.27 | 3.89 | 3.90 | 35 | 0.16 |
| 2 | Anethole | -2.44 | 3.51 | -4.51 | -12.68 | 6.47 | -0.05 | 22 | 0.09 |
| 3 | Aniline | 0.09 | 1.10 | -4.91 | -6.54 | 2.90 | 2.20 | 31 | 0.18 |
| 4 | Anisole | 0.44 | 4.94 | -7.02 | -12.88 | 5.51 | 4.79 | 30 | 0.12 |
| 5 | Anthracene | -2.53 | 4.17 | -4.72 | -14.34 | 7.38 | 0.06 | 18 | 0.07 |
| 6 | Benzaldehyde | 0.10 | 2.92 | -4.97 | -9.12 | 3.39 | 2.42 | 35 | 0.12 |
| 7 | Benzene | -0.51 | 2.08 | -5.17 | -9.15 | 4.70 | 1.20 | 30 | 0.07 |
| 8 | Benzonitrile | 1.08 | 3.39 | -6.69 | -10.35 | 4.00 | 4.00 | 36 | 0.12 |
| 9 | Benzophenone | 0.37 | 6.21 | -8.28 | -16.07 | 6.91 | 5.19 | 27 | 0.15 |
| 10 | Benzyl alcohol | 0.71 | 4.40 | -5.37 | -10.43 | 2.96 | 4.69 | 36 | 0.16 |
| 11 | Biphenyl | -2.60 | 4.08 | -4.99 | -13.92 | 7.15 | 0.28 | 22 | 0.09 |
| 12 | Chlorobenzene | 0.28 | 5.21 | -7.82 | -14.25 | 6.70 | 4.99 | 27 | 0.08 |
| 13 | <i>o</i> -Cresol | 1.68 | 2.94 | -8.27 | -11.13 | 4.97 | 5.22 | 32 | 0.10 |
| 14 | Diethyl phthalate | 0.05 | 6.11 | -7.37 | -15.08 | 5.84 | 4.90 | 30 | 0.17 |
| 15 | N,N-Dimethylaniline | 2.30 | 8.13 | -9.90 | -16.59 | 7.04 | 10.73 | 25 | 0.23 |
| 16 | 2,4-Dimethylphenol | 1.89 | 4.52 | -9.40 | -13.82 | 6.13 | 6.67 | 30 | 0.07 |
| 17 | Dimethyl phthalate | 0.75 | 5.93 | -6.75 | -13.31 | 4.27 | 5.23 | 34 | 0.18 |
| 18 | <i>m</i> -Dinitrobenzene | 0.06 | -0.79 | -5.92 | -6.98 | 4.26 | -0.05 | 31 | 0.11 |
| 19 | Diphenyl ether | -2.16 | 4.05 | -5.68 | -14.00 | 7.20 | 0.86 | 22 | 0.08 |
| 20 | Ethylbenzene | -1.70 | 3.30 | -5.33 | -11.99 | 6.42 | 0.78 | 23 | 0.06 |
| 21 | N-Methylaniline | 0.92 | 5.01 | -7.52 | -12.04 | 5.19 | 6.69 | 26 | 0.21 |
| 22 | Naphthalene | -3.28 | 6.23 | -4.10 | -15.64 | 7.10 | -0.21 | 22 | 0.27 |
| 23 | <i>p</i> -Nitroacetophenone | 1.17 | 2.17 | -7.09 | -9.91 | 4.41 | 3.57 | 33 | 0.07 |
| 24 | <i>o</i> -Nitroaniline | 2.21 | 3.00 | -8.56 | -10.99 | 4.70 | 6.45 | 32 | 0.11 |
| 25 | Nitrobenzene | 1.03 | 3.22 | -7.23 | -10.92 | 4.86 | 4.14 | 32 | 0.05 |
| 26 | <i>m</i> -Nitrophenol | 1.04 | 1.16 | -7.47 | -9.35 | 4.54 | 3.21 | 32 | 0.19 |
| 27 | Phenol | 1.48 | 0.99 | -6.79 | -7.85 | 3.47 | 2.86 | 36 | 0.09 |
| 28 | 1-Phenylethanol | 0.19 | 4.25 | -5.51 | -10.78 | 3.65 | 3.65 | 35 | 0.11 |
| 29 | 2-Phenylethanol | 0.25 | 5.27 | -5.63 | -12.03 | 3.69 | 4.55 | 35 | 0.11 |
| 30 | 3-Phenylpropanol | 1.59 | 7.52 | -8.33 | -15.91 | 5.33 | 8.58 | 33 | 0.16 |
| 31 | Quinoline | 0.74 | 9.47 | -6.15 | -15.56 | 4.60 | 8.25 | 26 | 0.26 |
| 32 | Toluene | -0.18 | 4.16 | -6.80 | -12.58 | 6.23 | 3.25 | 26 | 0.07 |

acetonitrile system. Somewhat surprisingly, such large deviations are not observed for very small capacity factors ($k < 1$). Measurement errors and the assumption of a uniform hold-up time, which would predominantly affect the smallest capacity factors, appear to be of little significance.

Iso-elutotropic lines

Following the procedure outlined in Theoretical, iso-elutotropic lines of constant solvent strength have been constructed for both ternary systems. Theoretically predicted and empirical lines are presented in Figs. 4 and 5. A good agreement is observed, except for the very strong solvents, which are of limited practical value. This suggests that eqn. 16 offers a good first order approximation of iso-elutotropic lines in other ternary systems.

As expected from Fig. 1, the iso-elutotropic lines show a very regular behaviour. Significant maxima or minima are absent, not only for the averaged curves in Figs. 4 and 5, but also for iso-elutotropic lines referring to individual solutes. This indicates that ternary mixtures provide a smooth transition from one binary solvent to another.

Specific effects

Each iso-elutotropic line in Figs. 4 and 5 offers a guideline to the elution of a given sample with different mobile phases, but with roughly constant retention. Since, however, the iso-elutotropic line represents the average over a large number of solutes, minor variations in retention should be expected for individual solutes. We will refer to these variations as specific effects.

When we gradually replace the methanol in a binary methanol-water mixture by THF (*i.e.*, move to the right along one of the iso-elutotropic lines in Fig. 4), some solutes will move forward in the chromatogram and will be eluted more quickly than with the binary reference mixture. Obviously, such solutes show a specific preference to THF over methanol. On the other hand, other solutes interact more favourably with methanol, and hence are comparatively retarded when methanol is replaced by THF.

Fig. 6 illustrates the specific effects that can occur in ternary systems. It shows a series of chromatograms taken along the curve for $\phi_M^* = 0.5$ in the methanol-THF-water system. The upper chromatogram shows that in methanol-water (50:50) the sample is eluted in 20 min, but that the first two solutes coincide. When we elute the sample with the corresponding binary mixture of THF-water (32:68), the total analysis time indeed remains approximately the same, but the separation is again incomplete. However, the solute pair that coincides in methanol-water (benzyl alcohol and phenol) is different from the unresolved couple in THF-water (phenol and 3-phenylpropanol). Moreover, the sequence of the last bands eluted has reversed in going from methanol-water to THF-water. This reversal originates from the specific acceleration of 2,4-dimethylphenol and the specific retardation of diethyl phthalate. The third solute, benzene, is hardly affected by the changing composition.

Such changes as observed between the top and bottom chromatograms of Fig. 6 form a strong argument in favour of ternary mobile phase systems.

The second chromatogram from the top in Fig. 6 shows the elution with a ternary mixture, in which only a small amount of THF (10%) is present. Not un-

TABLE III

RETENTION BEHAVIOUR OF 49 SOLUTES IN THE SYSTEM METHANOL-ACETONITRILE-WATER

Details as in Table II.

| No. | Solute | A_1 | A_2 | B_1 | B_2 | C | D | N | <i>a.d.</i> |
|-----|--|-------|-------|--------|--------|------|-------|-----|-------------|
| 1 | Acetophenone | 1.07 | 5.37 | - 7.80 | -11.45 | 4.83 | 7.77 | 33 | 0.11 |
| 2 | Anisole | 2.13 | 5.10 | - 9.06 | -11.97 | 5.82 | 6.79 | 30 | 0.12 |
| 3 | Benzaldehyde | -0.18 | 3.64 | - 6.08 | - 9.55 | 4.38 | 6.62 | 34 | 0.18 |
| 4 | Benzene | 2.31 | 4.19 | - 8.66 | -10.82 | 5.56 | 5.42 | 29 | 0.14 |
| 5 | Benzonitrile | 2.67 | 4.43 | - 9.24 | -10.81 | 4.90 | 7.87 | 32 | 0.08 |
| 6 | Benzophenone | 1.68 | 5.59 | -10.15 | -13.85 | 7.39 | 6.81 | 26 | 0.12 |
| 7 | Benzyl alcohol | 0.47 | 5.43 | - 6.09 | -10.38 | 3.32 | 8.09 | 34 | 0.09 |
| 8 | Biphenyl | 0.00 | 4.15 | - 8.60 | -12.78 | 7.97 | 3.02 | 24 | 0.13 |
| 9 | <i>n</i> -Butylbenzene | -1.43 | 3.78 | - 7.46 | -12.46 | 8.39 | 1.10 | 23 | 0.12 |
| 10 | <i>p</i> -Chlorobenzaldehyde | 0.59 | -0.16 | - 5.52 | - 5.09 | 3.78 | 3.37 | 26 | 0.33 |
| 11 | Chlorobenzene | 1.73 | 5.78 | - 9.75 | -13.56 | 7.05 | 6.96 | 27 | 0.13 |
| 12 | <i>p</i> -Chlorophenol | 1.88 | 6.71 | - 9.26 | -13.75 | 5.60 | 9.58 | 32 | 0.10 |
| 13 | <i>p</i> -Chlorotoluene | 0.08 | 4.12 | - 7.96 | -11.80 | 7.08 | 3.28 | 25 | 0.10 |
| 14 | <i>o</i> -Cresol | 2.04 | 5.47 | - 8.56 | -11.79 | 4.80 | 8.35 | 33 | 0.09 |
| 15 | <i>o</i> -Dichlorobenzene | -0.31 | 3.09 | - 6.85 | -10.13 | 6.43 | 1.94 | 25 | 0.12 |
| 16 | Diethyl phthalate | 2.85 | 7.21 | -11.87 | -15.79 | 7.47 | 10.10 | 29 | 0.14 |
| 17 | Dimethyl phthalate | 2.58 | 5.94 | -10.06 | -13.07 | 5.59 | 9.72 | 31 | 0.14 |
| 18 | <i>m</i> -Dinitrobenzene | 1.71 | 3.25 | - 8.44 | -10.14 | 5.12 | 5.52 | 31 | 0.10 |
| 19 | <i>o</i> -Dinitrobenzene | 2.50 | 3.93 | - 9.96 | -11.41 | 5.57 | 7.41 | 31 | 0.10 |
| 20 | <i>p</i> -Dinitrobenzene | 1.71 | 2.57 | - 8.48 | - 9.36 | 4.92 | 5.35 | 32 | 0.09 |
| 21 | 2,4-Dinitrotoluene | 1.77 | 3.90 | - 9.41 | -11.77 | 6.18 | 5.84 | 29 | 0.11 |
| 22 | 2,6-Dinitrotoluene | 2.33 | 4.70 | -10.30 | -12.72 | 6.40 | 7.23 | 28 | 0.11 |
| 23 | 3,4-Dinitrotoluene | 3.07 | 5.32 | -11.59 | -13.65 | 6.75 | 9.07 | 30 | 0.11 |
| 24 | Diphenyl ether | 0.25 | 4.58 | - 9.22 | -13.48 | 8.16 | 3.84 | 24 | 0.12 |
| 25 | Ethylbenzene | -0.76 | 2.69 | - 6.18 | - 9.35 | 6.15 | 0.65 | 22 | 0.12 |
| 26 | <i>m</i> -Fluoronitrobenzene | 1.41 | 3.94 | - 8.27 | -10.83 | 5.50 | 5.44 | 30 | 0.09 |
| 27 | <i>o</i> -Fluoronitrobenzene | 1.77 | 4.21 | - 8.67 | -11.04 | 5.31 | 6.45 | 31 | 0.11 |
| 28 | <i>p</i> -Fluoronitrobenzene | 2.10 | 3.88 | - 9.06 | -10.81 | 5.42 | 6.51 | 30 | 0.11 |
| 29 | <i>p</i> -Fluorophenol | 0.70 | 4.61 | - 7.04 | -10.51 | 3.95 | 7.90 | 35 | 0.11 |
| 30 | <i>p</i> -Hydroxybenzaldehyde | 1.55 | 7.07 | - 7.54 | -12.32 | 3.47 | 11.59 | 36 | 0.12 |
| 31 | <i>p</i> -Methoxybenzaldehyde | 0.49 | 4.23 | - 6.74 | -10.29 | 4.57 | 6.82 | 28 | 0.08 |
| 32 | <i>p</i> -Methylbenzaldehyde | 0.08 | 4.20 | - 7.05 | -10.66 | 5.18 | 7.39 | 29 | 0.14 |
| 33 | Methyl benzoate | 2.87 | 6.62 | -10.27 | -13.84 | 6.26 | 9.16 | 29 | 0.15 |
| 34 | Naphthalene | 0.36 | 3.91 | - 8.01 | -11.53 | 6.91 | 3.39 | 25 | 0.11 |
| 35 | <i>p</i> -Nitroacetophenone | 2.18 | 4.39 | - 8.97 | -11.11 | 5.13 | 7.27 | 32 | 0.12 |
| 36 | <i>p</i> -Nitrobenzaldehyde | -0.18 | 2.06 | - 6.48 | - 8.42 | 4.38 | 6.64 | 32 | 0.20 |
| 37 | <i>p</i> -Nitrobenzaldehyde | -0.63 | 2.77 | - 6.14 | - 8.78 | 3.97 | 7.69 | 34 | 0.23 |
| 38 | Nitrobenzene | 2.18 | 4.17 | - 8.88 | -10.90 | 5.34 | 6.59 | 31 | 0.09 |
| 39 | <i>m</i> -Nitrophenol | 1.57 | 5.69 | - 8.16 | -11.96 | 4.62 | 8.56 | 35 | 0.11 |
| 40 | <i>o</i> -Nitrophenol | 1.44 | 4.46 | - 7.46 | -10.25 | 4.64 | 5.47 | 33 | 0.13 |
| 41 | <i>p</i> -Nitrophenol | 1.98 | 5.17 | - 8.43 | -11.64 | 4.50 | 8.65 | 35 | 0.12 |
| 42 | Phenol | 0.92 | 3.82 | - 6.38 | - 9.02 | 3.30 | 6.80 | 36 | 0.09 |
| 43 | 2-Phenylethanol | 0.61 | 6.69 | - 6.68 | -12.02 | 4.09 | 8.39 | 35 | 0.10 |
| 44 | <i>p</i> -Phenylphenol | 2.83 | 8.63 | -12.21 | -17.68 | 7.91 | 11.56 | 28 | 0.12 |
| 45 | 3-Phenylpropanol | 1.53 | 8.26 | - 8.82 | -14.72 | 5.49 | 10.16 | 37 | 0.09 |
| 46 | <i>n</i> -Propylbenzene | -1.04 | 2.37 | - 6.61 | - 9.97 | 7.02 | 0.29 | 25 | 0.13 |
| 47 | Toluene | -0.91 | 3.40 | - 8.12 | -10.83 | 6.30 | 3.97 | 28 | 0.14 |
| 48 | α,α,α -Trichlorotoluene | 0.09 | 5.46 | - 9.72 | -14.77 | 8.80 | 5.20 | 18 | 0.09 |
| 49 | 2,4-Dimethylphenol | 1.95 | 6.75 | - 9.46 | -13.89 | 5.93 | 9.17 | 31 | 0.11 |

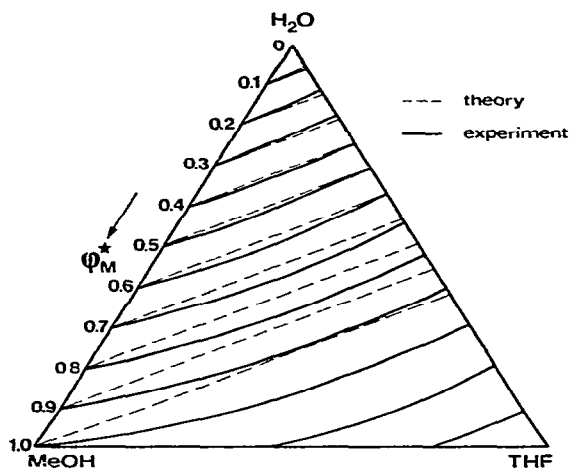


Fig. 4. Iso-elutotropic diagram for the system methanol-THF-water. Theoretical and experimental curves are constructed as shown in Fig. 2, for reference methanol-water compositions at 10% intervals.

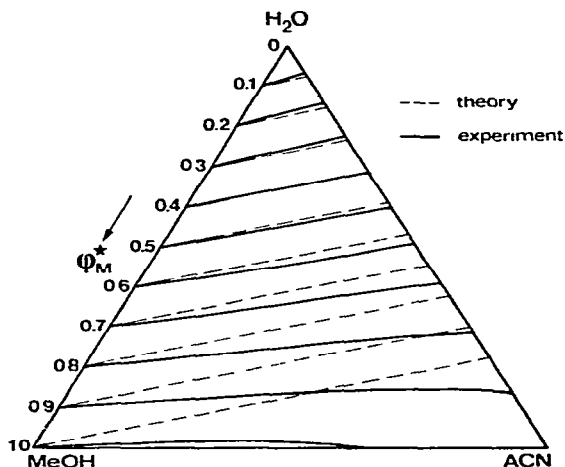


Fig. 5. Iso-elutotropic diagram as in Fig. 4 for the system methanol-acetonitrile-water.

expectedly, the three early peaks are now well separated. However, the three later bands merge into a single peak. This is not surprising, considering the top and bottom chromatograms. The third chromatogram from the top shows the excellent separation that can be obtained by applying the appropriate ternary composition to this particular sample.

We can define the specificity of a mobile phase with respect to a binary mixture of methanol and water for a solute i as:

$$S_i = \ln k_{i,M}^*/k_i \quad (17)$$

Here k_i is the capacity factor of i in the mobile phase, while $k_{i,M}^*$ is the capacity factor in the binary reference solvent. Defined in this way, zero specificity ($S_i = 0$) results if

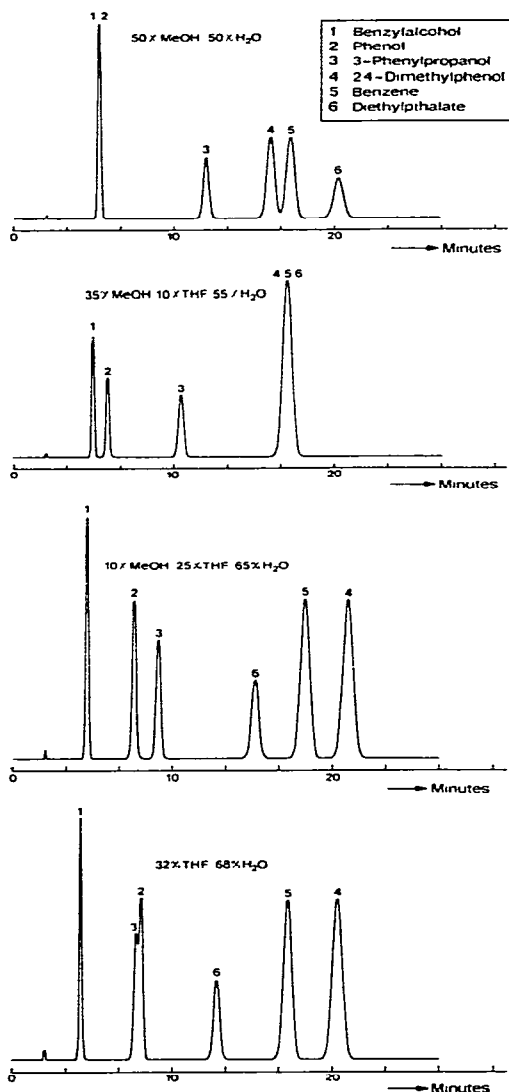


Fig. 6. Chromatograms illustrating the specific effects occurring in some iso-elutropic mixtures of methanol, THF and water. Retention data taken from Table II. Mobile phase compositions follow the experimental iso-elutropic curve for $\varphi_M^* = 0.5$ in Fig. 4.

the capacity factor remains unaltered when a binary methanol–water mixture is replaced by another solvent of equal elutropic strength. Positive S values indicate a specific acceleration of the solute i . A very high S value is found when the solute is essentially non-retained in the eluent chosen. Negative S values signify a specific retardation of the solute relative to its behaviour in methanol–water.

As an example, Fig. 7 shows the specificities of the mobile phases used in the chromatograms of Fig. 6 towards each of the six solutes, as a function of the decreasing methanol content of the solvent. Two additional horizontal axes have been drawn

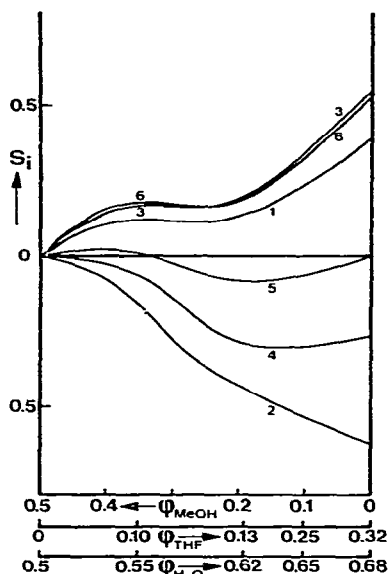


Fig. 7. Specificity according to eqn. 17 in ternary mobile phases containing methanol, THF and water, for the six solutes shown in Fig. 6. The mobile phase composition follows the experimental iso-elutropic line for $\varphi_M^* = 0.5$ in Fig. 4.

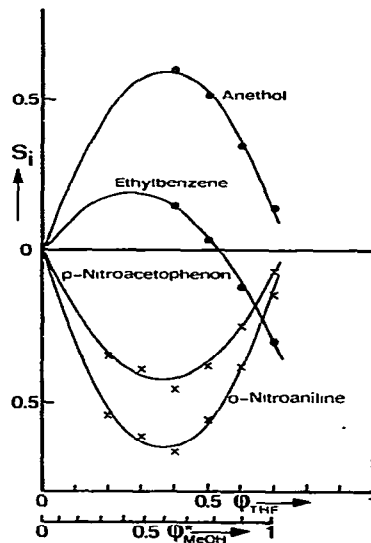


Fig. 8. Specificity for four solutes as a function of THF content in binary mixtures with water. The (non-linear) scale at the bottom indicates the composition of the corresponding reference methanol-water mixture.

to indicate the volume fractions of THF and water, respectively. Note that both of these axes are slightly non-linear.

Obviously, all curves in Fig. 7 start at $S = 0$ for the binary reference composition of methanol-water (50:50). With decreasing amount of methanol and increasing amount of THF the positive specific effects for benzyl alcohol, 3-phenylpropanol and diethyl phthalate become clear, whereas phenol and 2,4-dimethylphenol show negative specificity. Benzene shows approximately zero specificity along this particular iso-elutropic line. Fig. 7 suggests that the specificity changes quite regularly when methanol is gradually replaced by another organic modifier. This appears to be a general rule for all solutes. A binary solvent almost always shows a more pronounced specific effect relative to methanol-water than the intermediate ternary solvents of the same elutropic strength. Indeed, in Fig. 6, phenol is separated from its neighbours because the specific effect of a ternary mixture of methanol, THF and water is smaller than that of a binary mixture containing only THF and water.

It should be noted that the specificity curves in Fig. 7 correspond to one particular iso-elutropic line, the one for $\varphi_M^* = 0.5$ in Fig. 4. Hence, a large number of specificity curves can be constructed for each solute. However, we can simplify the discussion, if it is realized that the specificity of ternary mixtures is intermediate between those of the limiting binary mixtures. Therefore, a classification of the specific effects in binary mixtures is indicative of the behaviour of ternary systems. We can now construct specificity curves that cover the entire binary composition range, and hence a wide range of retention times. Some examples are shown in Fig. 8, where

the specificity of THF–water mixtures towards four solutes is presented. Each point represents the specificity of a particular mixture of THF and water, relative to the corresponding binary methanol–water reference mixture. For example, the points at $\varphi_{\text{THF}} = 0.4$ indicate the specificity relative to a binary mixture of 65% methanol and 35% water ($\varphi_{\text{M}}^* = 0.65$). Note that binary mixtures containing more than 70% THF have a solvent strength larger than that of 100% methanol. For the solutes included in the present study, such very strong solvents are of little interest. When such solvents are required for very hydrophobic solutes, binary mixtures of water and THF can be taken as a reference instead of methanol–water mixtures.

Naturally, all curves start at $S = 0$ for $\varphi_2 = 0$, which point refers to pure water. Two typical shapes can be observed, one with a minimum and one with a maximum. Only occasionally (*e.g.*, benzene in THF–water) the S vs. φ curve shows no extrema. An equation for the specificity as a function of binary mobile phase composition can be derived from eqns. 8 and 16. If we substitute the appropriate compositions in eqn. 8, *i.e.*, $\varphi_1 = 0$ to find $k_{i,2}$ and $\varphi_1 = \varphi_{\text{M}}^*$, $\varphi_2 = 0$ to find $k_{i,\text{M}}^*$, we obtain:

$$\begin{aligned} S_i &= \ln k_{i,\text{M}}^* - \ln k_{i,2} \\ &= A_1 (\varphi_{\text{M}}^*)^2 - A_2 \varphi_2^2 + B_1 \varphi_{\text{M}}^* - B_2 \varphi_2 \end{aligned} \quad (18)$$

Moreover, for the binary mixture of the second modifier and water, we can substitute $\varphi_1 = 0$ in eqn. 16 and hence

$$\varphi_2 = \varphi_{\text{M}}^* \left(\frac{\delta_1 - \delta_3}{\delta_2 - \delta_3} \right) = \frac{\varphi_{\text{M}}^*}{\lambda} \quad (19)$$

where λ is the constant ratio of solubility parameter differences. Combination of eqns. 18 and 19 now yields:

$$\begin{aligned} S &= \varphi_2^2 (A_1 \lambda^2 - A_2) + \varphi_2 (B_1 \lambda - B_2) \\ &= P \varphi_2^2 + Q \varphi_2 \end{aligned} \quad (20)$$

The solid lines drawn in Fig. 8 represent the quadratic curves according to eqn. 20. The P and Q values for the individual solutes are found from regression analysis on the experimental data for S and are represented in Fig. 9 for the THF–water system and in Fig. 10 for the acetonitrile–water system. The numbers in these two figures refer to the solutes as they occur in Tables II and III. Solute that experience positive specificities can be found in the upper left corner, while the retarded solutes are situated at the bottom right.

The correlation between the P and Q values is remarkable. In fact, almost all solutes fall close to the line $P = -Q$ included in Figs. 9 and 10. If we now substitute $P = -Q$ into eqn. 20, we find that the specificity S is zero for $\varphi_2 = 1$. This leads to the conclusion that solvents rich in either acetonitrile or THF show very little specific effect in comparison to methanol–water mixtures. If specific effects occur they are most pronounced in mixtures containing moderate amounts of water (40–70%).

From Figs. 9 and 10 it appears that the specific effects in THF–water mixtures are larger than those in acetonitrile–water mixtures. Note that Figs. 9 and 10 differ in scale by a factor of 2. Several groups of solutes can be identified. In the THF–water system, large hydrophobic solutes appear to be specifically accelerated, *e.g.*, naphthalene (22), biphenyl (11), anthracene (5), diphenyl ether (19) and ethylbenzene (20). Note that quinoline (31) behaves similarly to naphthalene, despite the introduction of a heterogeneous nitrogen atom. Phenolic compounds, such as phenol (27), *o*-cresol (13) and 2,4-dimethylphenol (16), and nitro compounds, such as *m*-nitrophenol (26), *m*-dinitrobenzene (18), *o*-nitroaniline (24), *p*-nitroacetophenone (23) and nitrobenzene (25), are specifically retarded. The specificities for aliphatic alcohols [benzyl alcohol (10), 1-phenylethanol (28), 3-phenylpropanol (30) and 2-phenylethanol (29)] are slightly positive, in sharp contrast to the large negative effects observed with phenolic hydroxy groups. Esters (14, 17), ketones (1, 9), ethers (4) and aldehydes (6) show small specific effects. In acetonitrile–water mixtures, a large positive specificity is observed for aliphatic alcohols (solutes 45, 43 and 7). Again, phenolic solutes (14, 42 and 49) behave differently, with only slight positive effects. Substituted phenols (40, 41, 39, 29, 12, 44) all behave similarly. Nitro compounds all show negative specificities. The specific effects seems to be larger for dinitro compounds (20, 19, 23, 18, 22, 21) than for molecules containing only one nitro group (28, 38, 27, 26). The specific effects are small for non-polar compounds, esters, ethers and ketones. The behaviour of the various *para*-substituted benzaldehydes is somewhat puzzling. The specific effects are small for most of these compounds (3, 32, 31, 37, 36). However, *p*-hydroxybenzaldehyde (30) shows a large acceleration, while *p*-chlorobenzaldehyde (10) is greatly retarded.

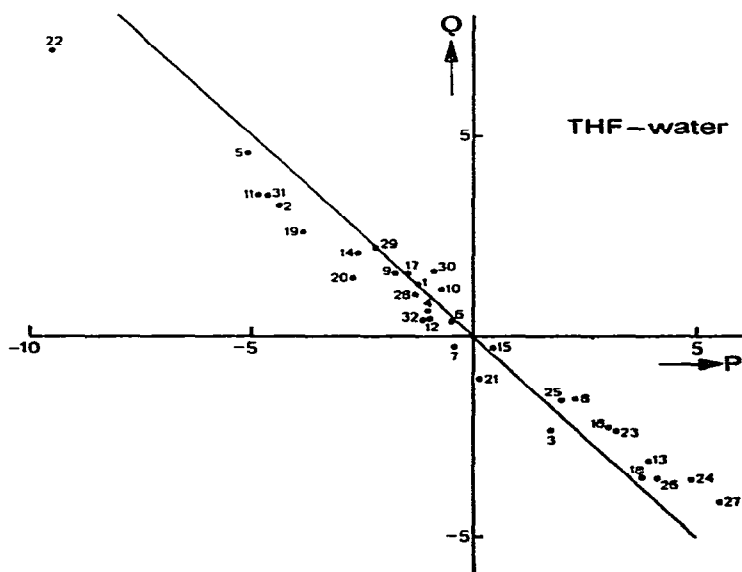


Fig. 9. Coefficients describing the specificity in the system THF–water (eqn. 20). Numbers refer to solutes listed in Table II. A positive Q value indicates specific acceleration in THF–water in comparison to methanol–water. A negative Q value indicates specific retardation of a solute. The straight line represent $Q = -P$.

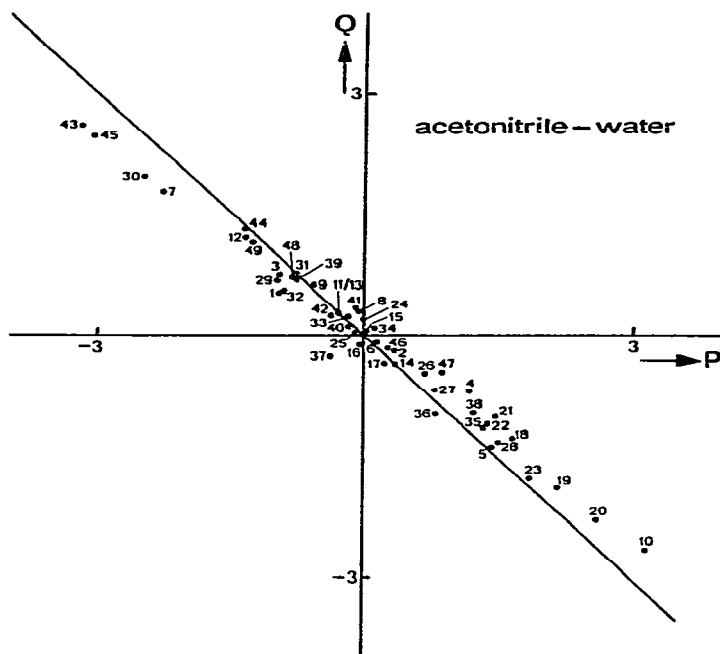


Fig. 10. As Fig. 9, but for the system acetonitrile-water. Solute identification numbers refer to Table III.

Table IV gives a summary of the specific effects encountered in the two binary systems classified according to functional groups. Slight effects are indicated by square brackets.

TABLE IV

SUMMARY OF SPECIFIC EFFECTS IN BINARY MIXTURES OF THF-WATER AND ACETONITRILE-WATER FOR VARIOUS SUBSTITUENTS

| <i>Specific effect</i> | <i>THF</i> | <i>Acetonitrile</i> |
|------------------------|--|---|
| Retardation | Phenolic OH NO ₂ NH ₂ CN | NO ₂ CN |
| Acceleration | CH ₃ CH ₂ Phenyl | Aliphatic OH [Phenolic OH] [CH ₃ ; CH ₂] [Phenyl] [Cl] |
| Negligible | Ketones Esters Aliphatic OH Ethers Secondary and ternary amines | Ketones Esters Ethers |

CONCLUSIONS

The retention of a wide variety of solutes in the ternary systems methanol-THF-water and methanol-acetonitrile-water can be described by a regular but non-linear three-dimensional surface. A quadratic equation relates the logarithm of the capacity factor to the volume fractions of the two organic modifiers.

Retention data on a large number of solutes can be used to construct iso-elutotropic lines, that connect mixtures of equal solvent strength within the ternary triangle. All the mixtures on such a line will yield roughly the same retention times for

APPENDIX I

EXPERIMENTAL CAPACITY FACTORS IN THE SYSTEM METHANOL-THF-WATER

| No. | Solute | ϕ_{MeOH} | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.55 | 0.60 | 0.65 |
|-----|-----------------------------|-----------------------|------|-------|-------|-------|-------|-------|-------|-------|
| | | ϕ_{THF} | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | ϕ_{water} | 0.90 | 0.80 | 0.70 | 0.60 | 0.50 | 0.45 | 0.40 | 0.35 |
| 1 | Acetophenone | — | — | 32.54 | 13.82 | 6.94 | 4.37 | 2.49 | 1.78 | 1.29 |
| 2 | Anethole | — | — | — | — | — | — | — | 22.38 | 13.28 |
| 3 | Aniline | — | — | 6.27 | 3.64 | 2.71 | 1.48 | 1.19 | 0.96 | 0.70 |
| 4 | Anisole | — | — | — | — | 38.84 | 9.02 | 5.42 | 3.97 | 2.71 |
| 5 | Anthracene | — | — | — | — | — | — | — | — | — |
| 6 | Benzaldehyde | — | — | 13.01 | 9.08 | 5.06 | 3.63 | 2.02 | 1.45 | 1.10 |
| 7 | Benzene | — | — | — | 21.76 | 13.86 | 8.40 | 6.12 | 4.17 | 2.94 |
| 8 | Benzonitrile | — | — | 41.40 | 20.61 | 9.90 | 5.14 | 2.83 | 2.00 | 1.44 |
| 9 | Benzophenone | — | — | — | — | — | 27.40 | 14.78 | 9.14 | 5.28 |
| 10 | Benzyl alcohol | — | — | 16.99 | 8.47 | 4.52 | 2.78 | 2.22 | 1.18 | 0.90 |
| 11 | Biphenyl | — | — | — | — | — | — | — | 30.68 | 17.96 |
| 12 | Chlorobenzene | — | — | — | — | — | 19.70 | 13.42 | 8.34 | 5.41 |
| 13 | <i>o</i> -Cresol | — | — | 22.83 | 12.80 | 6.44 | 3.96 | 2.50 | 1.73 | 1.26 |
| 14 | Diethyl phthalate | — | — | — | — | 34.76 | 13.58 | 6.92 | 4.26 | 2.70 |
| 15 | <i>N,N</i> -Dimethylaniline | — | — | — | — | — | — | 11.96 | 8.12 | 5.48 |
| 16 | 2,4-Dimethylphenol | — | — | — | 29.00 | 14.47 | 7.26 | 5.15 | 3.24 | 2.14 |
| 17 | Dimethyl phthalate | — | — | — | 22.38 | 8.45 | 4.04 | 2.25 | 1.64 | 1.06 |
| 18 | <i>m</i> -Dinitrobenzene | — | — | 14.60 | 10.95 | 6.58 | 4.82 | 2.81 | 2.00 | 1.48 |
| 19 | Diphenyl ether | — | — | — | — | — | — | — | 24.78 | 14.70 |
| 20 | Ethylbenzene | — | — | — | — | — | — | 23.48 | 14.41 | 9.35 |
| 21 | <i>N</i> -Methylaniline | — | — | — | — | — | 4.92 | 4.18 | 2.84 | 1.98 |
| 22 | Naphthalene | — | — | — | — | — | — | — | — | 37.88 |
| 23 | <i>p</i> -Nitroacetophenone | — | — | 20.82 | 13.08 | 6.83 | 3.70 | 2.48 | 1.74 | 1.29 |
| 24 | <i>o</i> -Nitroaniline | — | — | 13.22 | 9.63 | 5.42 | 2.86 | 1.96 | 1.40 | 1.05 |
| 25 | Nitrobenzene | — | — | 27.70 | 15.64 | 8.72 | 5.33 | 3.48 | 2.54 | 1.74 |
| 26 | <i>m</i> -Nitrophenol | — | — | 31.80 | 16.37 | 9.30 | 5.04 | 2.94 | 1.98 | 1.38 |
| 27 | Phenol | — | — | 13.40 | 7.66 | 4.61 | 2.76 | 1.64 | 1.22 | 0.95 |
| 28 | 1-Phenylethanol | — | — | — | 19.92 | 9.90 | 5.21 | 2.84 | 1.95 | 1.40 |
| 29 | 2-Phenylethanol | — | — | — | 18.57 | 9.15 | 4.97 | 3.09 | 1.95 | 1.39 |
| 30 | 3-Phenylpropanol | — | — | — | 51.56 | 23.00 | 11.03 | 6.27 | 3.48 | 2.35 |
| 31 | Quinoline | — | — | — | — | — | — | 9.08 | 5.78 | 3.64 |
| 32 | Toluene | — | — | — | — | — | — | 19.10 | 12.58 | 8.10 |

a given sample. However, mixtures of equal solvent strength will show variations in retention for certain solutes. These variations can be referred to as specific effects.

The specificity of ternary systems along one iso-elutropic line appears to vary quite regularly, and therefore can be expected to lie in between those of the limiting binary mixtures, at each end of the corresponding iso-elutropic line. Hence, some predictions as to the specific effects taking place in ternary mixtures can be made, if the specific effects in the limiting binaries can be classified. A sensible classification of specific effects can be obtained for binary mixtures of THF and water and acetonitrile and water, relative to binary methanol–water mixtures.

| | | | | | | | | | | | | | | |
|-------|------|------|------|-------|-------|------|------|-------|-------|-------|-------|-------|------|------|
| 0.70 | 0.80 | 0.90 | 1.00 | 0.30 | 0.45 | 0.60 | 0.75 | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 |
| 0 | 0 | 0 | 0 | 0.10 | 0.15 | 0.20 | 0.25 | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 |
| 0.30 | 0.20 | 0.10 | 0 | 0.60 | 0.40 | 0.20 | 0 | 0.90 | 0.80 | 0.70 | 0.60 | 0.50 | 0.40 | 0.30 |
| 0.98 | 0.57 | 0.40 | 0.26 | 2.98 | 0.86 | 0.34 | 0.22 | 16.92 | 8.44 | 4.22 | 2.03 | 1.10 | 0.63 | 0.36 |
| 8.43 | 3.31 | 1.71 | 0.55 | — | 7.22 | 1.39 | 0.31 | — | — | — | — | 9.03 | 3.95 | 1.58 |
| 0.54 | 0.33 | 0.25 | 0.18 | 2.68 | 0.88 | 0.34 | 0.17 | — | — | — | — | 2.21 | 1.22 | 0.58 |
| 2.03 | 1.07 | 0.69 | 0.35 | 8.86 | 2.02 | 0.66 | 0.26 | — | — | 13.48 | 6.03 | 2.93 | 1.59 | 0.78 |
| — | — | 3.70 | 0.94 | — | 14.36 | 2.27 | 0.45 | — | — | — | — | 16.84 | 6.08 | 2.24 |
| 0.84 | 0.50 | 0.38 | 0.24 | 2.46 | 1.07 | 0.33 | 0.18 | 13.27 | 7.21 | 3.83 | 1.94 | 1.14 | 0.57 | 0.38 |
| 2.20 | 1.15 | 0.74 | 0.36 | — | 2.38 | 0.76 | 0.28 | 45.62 | — | 15.68 | 7.23 | 3.46 | 1.88 | 0.96 |
| 0.80 | 0.43 | 0.32 | 0.21 | 3.12 | 0.78 | 0.30 | 0.18 | 16.60 | 9.59 | 4.88 | 2.38 | 1.20 | 0.67 | 0.37 |
| 3.44 | 1.37 | 0.81 | 0.35 | 22.76 | 2.63 | 0.58 | 0.22 | — | — | — | 10.76 | 3.79 | 1.68 | 0.78 |
| 0.53 | 0.35 | 0.26 | 0.18 | 1.62 | 0.72 | 0.34 | 0.18 | 6.81 | 3.84 | 2.14 | 1.09 | 0.66 | 0.39 | 0.22 |
| 11.14 | 4.03 | 1.94 | 0.57 | — | 9.22 | 1.61 | 0.32 | — | — | — | — | 13.26 | 4.68 | 1.88 |
| 3.79 | 1.64 | 0.98 | 0.40 | 24.73 | 3.96 | 0.99 | 0.31 | — | — | — | 14.85 | 5.71 | 2.90 | 1.22 |
| 0.94 | 0.50 | 0.35 | 0.20 | 6.77 | 2.04 | 0.36 | 0.18 | — | — | 11.09 | 4.66 | 2.04 | 1.09 | 0.54 |
| 1.79 | 0.76 | 0.46 | 0.22 | 8.25 | 1.90 | 0.34 | 0.16 | — | — | 12.92 | 4.38 | 1.92 | 0.87 | 0.46 |
| 3.64 | 1.62 | 0.98 | 0.44 | 14.36 | 3.54 | 0.93 | 0.98 | — | — | — | 11.52 | 6.91 | 3.78 | 1.62 |
| 1.58 | 0.73 | 0.47 | 0.24 | 11.73 | 1.98 | 0.51 | 0.22 | — | — | 20.58 | 7.53 | 3.06 | 1.43 | 0.69 |
| 0.78 | 0.42 | 0.30 | 0.19 | 2.58 | 0.60 | 0.24 | 0.13 | 27.79 | 9.82 | 3.80 | 1.56 | 0.79 | 0.45 | 0.26 |
| 1.10 | 0.58 | 0.39 | 0.20 | 7.09 | 1.65 | 0.40 | 0.17 | — | — | 12.66 | 6.07 | 2.80 | 1.44 | 0.70 |
| 8.95 | 3.20 | 1.54 | 0.47 | — | 7.90 | 1.42 | 0.30 | — | — | — | — | 11.93 | 4.57 | 1.74 |
| 6.30 | 2.64 | 1.42 | 0.50 | — | 6.16 | 1.40 | 0.35 | — | — | — | — | 9.31 | 4.13 | 1.82 |
| 1.36 | 0.67 | 0.45 | 0.26 | 6.20 | 1.86 | 0.58 | 0.31 | — | — | — | — | 4.49 | 2.30 | 1.13 |
| 24.44 | 8.18 | 1.43 | 0.52 | — | 5.53 | 1.22 | 0.33 | — | — | — | 21.80 | 7.14 | 3.13 | 1.40 |
| 0.96 | 0.52 | 0.37 | 0.22 | 4.35 | 1.07 | 0.39 | 0.18 | — | 13.79 | 7.32 | 3.46 | 1.77 | 0.98 | 0.48 |
| 0.79 | 0.44 | 0.32 | 0.20 | 5.13 | 1.57 | 0.34 | 0.14 | — | — | 9.19 | 3.92 | 1.70 | 0.85 | 0.45 |
| 1.30 | 0.68 | 0.48 | 0.26 | 6.68 | 1.59 | 0.48 | 0.20 | — | — | 10.80 | 4.85 | 2.30 | 1.18 | 0.62 |
| 0.74 | 0.42 | 0.29 | 0.18 | 6.68 | 1.99 | 0.34 | 0.12 | — | — | 14.55 | 5.72 | 2.32 | 1.02 | 0.50 |
| 0.53 | 0.30 | 0.25 | 0.17 | 2.91 | 0.79 | 0.28 | 0.14 | 14.84 | 9.46 | 4.74 | 2.40 | 1.21 | 0.66 | 0.34 |
| 0.78 | 0.45 | 0.31 | 0.20 | 3.04 | 0.78 | 0.32 | 0.17 | 15.76 | 6.92 | 3.47 | 1.92 | 0.98 | 0.59 | 0.33 |
| 0.78 | 0.42 | 0.31 | 0.20 | 2.69 | 0.74 | 0.26 | 0.14 | 14.20 | 6.97 | 3.38 | 1.65 | 0.83 | 0.49 | 0.29 |
| 1.18 | 0.57 | 0.38 | 0.22 | 5.70 | 1.64 | 0.32 | 0.40 | — | 17.37 | 7.11 | 2.90 | 1.29 | 0.69 | 0.34 |
| 1.74 | 0.89 | 0.62 | 0.41 | — | 1.00 | 0.37 | 0.65 | — | — | — | — | 1.54 | 0.78 | 0.51 |
| 3.93 | 1.85 | 1.08 | 0.44 | — | 4.02 | 1.08 | 0.32 | — | — | — | 13.98 | 5.83 | 2.98 | 1.36 |

(Continued on p. 280)

APPENDIX I (continued)

Solute No.

| | 0.40 | 0.45 | 0.50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|-----------------------|------|------|------|-------|-------|-------|------|------|------|------|------|------|------|
| ϕ_{MeOH} | 0.40 | 0.45 | 0.50 | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 | 0.70 | 0.80 | 0.90 | 1.00 |
| ϕ_{THF} | 0.40 | 0.45 | 0.50 | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 | 0.70 | 0.80 | 0.90 | 1.00 |
| ϕ_{water} | 0.20 | 0.10 | 0 | 0.90 | 0.80 | 0.70 | 0.60 | 0.50 | 0.40 | 0.30 | 0.20 | 0.10 | 0 |
| 1 | 0.24 | 0.15 | 0.10 | 12.60 | 5.66 | 2.61 | 1.26 | 0.70 | 0.38 | 0.21 | 0.12 | 0.08 | 0.06 |
| 2 | 0.76 | 0.36 | 0.18 | — | — | — | 7.13 | 2.71 | 1.20 | 0.53 | 0.25 | 0.14 | 0.06 |
| 3 | 0.34 | 0.15 | 0.11 | 7.79 | 5.09 | 3.66 | 1.64 | 0.80 | 0.58 | 0.26 | 0.12 | 0.08 | 0.17 |
| 4 | 0.46 | 0.26 | 0.15 | — | 21.12 | 7.78 | 3.05 | 1.46 | 0.75 | 0.39 | 0.21 | 0.13 | 0.07 |
| 5 | 0.99 | 0.43 | 0.18 | — | — | — | 9.97 | 3.38 | 1.33 | 0.55 | 0.25 | 0.13 | 0.06 |
| 6 | 0.25 | 0.16 | 0.11 | 10.18 | 5.33 | 2.70 | 1.31 | 0.76 | 0.43 | 0.23 | 0.11 | 0.09 | 0.06 |
| 7 | 0.55 | 0.30 | 0.18 | — | — | 10.04 | 3.80 | 1.86 | 0.98 | 0.50 | 0.27 | 0.18 | 0.09 |
| 8 | 0.24 | 0.14 | 0.09 | 14.01 | 8.01 | 3.74 | 1.61 | 0.82 | 0.45 | 0.22 | 0.10 | 0.08 | 0.05 |
| 9 | 0.40 | 0.21 | 0.11 | — | — | 13.87 | 3.86 | 1.62 | 0.74 | 0.33 | 0.16 | 0.08 | 0.04 |
| 10 | 0.14 | 0.08 | 0.09 | 5.02 | 2.64 | 1.40 | 0.72 | 0.42 | 0.22 | 0.10 | 0.06 | 0.06 | 0.05 |
| 11 | 0.85 | 0.38 | 0.18 | — | — | — | 9.22 | 3.29 | 1.34 | 0.58 | 0.27 | 0.14 | 0.06 |
| 12 | 0.65 | 0.33 | 0.18 | — | — | 19.47 | 5.21 | 2.30 | 1.08 | 0.53 | 0.28 | 0.17 | 0.08 |
| 13 | 0.30 | 0.16 | 0.09 | — | 18.79 | 7.16 | 2.45 | 1.09 | 0.53 | 0.24 | 0.10 | 0.07 | 0.05 |
| 14 | 0.25 | 0.14 | 0.09 | — | 20.97 | 6.15 | 2.14 | 1.02 | 0.50 | 0.22 | 0.10 | 0.06 | 0.03 |
| 15 | 0.71 | 0.34 | — | — | — | 14.58 | 6.06 | 2.44 | 1.31 | 0.60 | 0.27 | 0.17 | 0.38 |
| 16 | 0.35 | 0.17 | 0.10 | — | — | 10.86 | 3.16 | 1.39 | 0.64 | 0.26 | 0.14 | 0.07 | 0.04 |
| 17 | 0.15 | 0.10 | 0.07 | 16.55 | 5.64 | 2.22 | 0.98 | 0.52 | 0.28 | 0.13 | 0.09 | 0.06 | 0.03 |
| 18 | 0.37 | 0.18 | 0.08 | — | — | 9.81 | 3.63 | 1.58 | 0.71 | 0.32 | 0.14 | 0.08 | 0.03 |
| 19 | 0.78 | 0.34 | 0.15 | — | — | — | 9.32 | 3.26 | 1.34 | 0.58 | 0.26 | 0.13 | 0.06 |
| 20 | 0.89 | 0.42 | 0.19 | — | — | — | 8.42 | 3.39 | 1.53 | 0.71 | 0.36 | 0.21 | 0.09 |
| 21 | 0.48 | 0.23 | — | — | 14.59 | 8.17 | 3.86 | 1.61 | 0.99 | 0.42 | 0.18 | 0.10 | 0.34 |
| 22 | 0.70 | 0.34 | 0.18 | — | — | 26.30 | 6.23 | 2.51 | 1.13 | 0.53 | 0.26 | 0.16 | 0.07 |
| 23 | 0.27 | 0.14 | 0.10 | — | 11.93 | 5.28 | 2.14 | 1.05 | 0.54 | 0.24 | 0.11 | 0.07 | 0.03 |
| 24 | 0.25 | 0.14 | 0.17 | — | 16.02 | 5.78 | 1.98 | 0.91 | 0.43 | 0.20 | 0.10 | 0.06 | 0.04 |
| 25 | 0.35 | 0.19 | 0.12 | — | 16.86 | 6.96 | 2.55 | 1.20 | 0.60 | 0.30 | 0.16 | 0.10 | 0.06 |
| 26 | 0.26 | 0.12 | 0.07 | — | — | 8.63 | 2.49 | 1.02 | 0.45 | 0.18 | 0.06 | 0.06 | 0.04 |
| 27 | 0.22 | 0.12 | 0.07 | 13.43 | 7.72 | 3.72 | 1.53 | 0.78 | 0.38 | 0.19 | 0.10 | 0.06 | 0.04 |
| 28 | 0.21 | 0.12 | 0.08 | 9.59 | 6.02 | 2.22 | 1.06 | 0.58 | 0.32 | 0.17 | 0.11 | 0.06 | 0.06 |
| 29 | 0.18 | 0.10 | 0.07 | 9.60 | 4.57 | 1.88 | 0.86 | 0.42 | 0.23 | 0.11 | 0.06 | 0.06 | 0.05 |
| 30 | 0.22 | 0.10 | 0.06 | — | 9.66 | 3.38 | 1.18 | 0.58 | 0.30 | 0.13 | 0.06 | 0.06 | 0.05 |
| 31 | 0.26 | 0.17 | — | 15.37 | 6.46 | 2.78 | 0.99 | 0.48 | 0.40 | 0.19 | 0.12 | 0.10 | 0.37 |
| 32 | 0.72 | 0.37 | 0.19 | — | — | 18.50 | 5.75 | 2.60 | 1.25 | 0.61 | 0.34 | 0.20 | 0.10 |

APPENDIX II

EXPERIMENTAL CAPACITY FACTORS IN THE SYSTEM METHANOL-ACETONITRILE-WATER

| No. | Solute | ϕ_{MeOH} | ϕ_{ACN} | ϕ_{water} | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 | 0.70 | 0.80 |
|-----|-------------------------------|----------------------|---------------------|-----------------------|-------|-------|-------|-------|------|------|------|------|
| | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 0.90 | 0.80 | 0.70 | 0.60 | 0.50 | 0.40 | 0.30 | 0.20 | 0.10 | 0.00 | 0.00 |
| 1 | Acetophenone | — | — | 14.18 | 6.66 | 3.31 | 1.90 | 0.90 | 0.48 | | | |
| 2 | Anisole | — | — | — | 12.78 | 6.66 | 3.66 | 1.68 | 0.90 | | | |
| 3 | Benzaldehyde | — | 24.33 | 9.51 | 4.89 | 2.58 | 1.62 | 0.78 | 0.46 | | | |
| 4 | Benzene | — | — | — | 11.54 | 6.53 | 3.70 | 1.71 | 0.91 | | | |
| 5 | Benzonitrile | — | — | 10.60 | 5.26 | 2.73 | 1.55 | 0.74 | 0.42 | | | |
| 6 | Benzophenone | — | — | — | — | 22.01 | 8.04 | 2.91 | 1.28 | | | |
| 7 | Benzyl alcohol | — | 10.47 | 4.50 | 2.54 | 1.43 | 0.89 | 0.48 | 0.27 | | | |
| 8 | Biphenyl | — | — | — | — | — | 25.87 | 7.52 | 2.78 | | | |
| 9 | <i>n</i> -Butylbenzene | — | — | — | — | — | 45.65 | 11.67 | 4.10 | | | |
| 10 | <i>p</i> -Chlorobenzaldehyde | — | — | 7.54 | 3.39 | 1.67 | 1.48 | 0.90 | 0.72 | | | |
| 11 | Chlorobenzene | — | — | — | — | 15.42 | 7.62 | 2.87 | 1.33 | | | |
| 12 | <i>p</i> -Chlorophenol | — | — | 18.51 | 9.24 | 4.38 | 2.34 | 0.98 | 0.54 | | | |
| 13 | <i>p</i> -Chlorotoluene | — | — | — | — | — | 14.56 | 4.85 | 1.99 | | | |
| 14 | <i>o</i> -Cresol | — | — | 10.93 | 5.57 | 2.94 | 1.67 | 0.78 | 0.44 | | | |
| 15 | <i>o</i> -Dichlorobenzene | — | — | — | — | — | 14.04 | 4.58 | 1.94 | | | |
| 16 | Diethyl phthalate | — | — | — | 31.52 | 10.54 | 4.74 | 1.59 | 0.73 | | | |
| 17 | Dimethyl phthalate | — | — | 22.30 | 8.15 | 3.34 | 1.78 | 0.74 | 0.40 | | | |
| 18 | <i>m</i> -Dinitrobenzene | — | — | 13.15 | 7.27 | 3.97 | 2.38 | 1.12 | 0.60 | | | |
| 19 | <i>o</i> -Dinitrobenzene | — | — | 15.15 | 7.22 | 3.71 | 2.03 | 0.86 | 0.43 | | | |
| 20 | <i>p</i> -Dinitrobenzene | — | — | 10.49 | 5.97 | 3.04 | 1.82 | 0.87 | 0.47 | | | |
| 21 | 2,4-Dinitrotoluene | — | — | — | 15.42 | 7.14 | 4.02 | 1.61 | 0.82 | | | |
| 22 | 2,6-Dinitrotoluene | — | — | — | 14.73 | 6.97 | 3.53 | 1.42 | 0.72 | | | |
| 23 | 3,4-Dinitrotoluene | — | — | — | 14.33 | 6.28 | 3.09 | 1.19 | 0.58 | | | |
| 24 | Diphenyl ether | — | — | — | — | — | 23.52 | 6.45 | 2.32 | | | |
| 25 | Ethylbenzene | — | — | — | — | — | 12.23 | 4.43 | 1.89 | | | |
| 26 | <i>m</i> -Fluoronitrobenzene | — | — | — | 11.07 | 5.81 | 3.53 | 1.49 | 0.77 | | | |
| 27 | <i>o</i> -Fluoronitrobenzene | — | — | 16.01 | 8.28 | 4.35 | 2.49 | 1.11 | 0.58 | | | |
| 28 | <i>p</i> -Fluoronitrobenzene | — | — | 15.76 | 8.54 | 4.32 | 2.48 | 1.14 | 0.66 | | | |
| 29 | <i>p</i> -Fluorophenol | — | 13.26 | 6.41 | 3.50 | 1.89 | 1.10 | 0.53 | 0.27 | | | |
| 30 | <i>p</i> -Hydroxybenzaldehyde | 17.58 | 7.92 | 3.77 | 1.94 | 0.99 | 0.58 | 0.32 | 0.20 | | | |
| 31 | <i>p</i> -Methoxybenzaldehyde | — | — | 15.27 | 7.10 | — | 1.90 | 0.87 | 0.51 | | | |
| 32 | <i>p</i> -Methylbenzaldehyde | — | — | — | 10.61 | 5.07 | 2.01 | 1.26 | 0.74 | | | |
| 33 | Methyl benzoate | — | — | — | 15.35 | 6.83 | 3.58 | 1.50 | 0.82 | | | |
| 34 | Naphthalene | — | — | — | — | — | 13.31 | 4.54 | 1.96 | | | |
| 35 | <i>p</i> -Nitroacetophenone | — | — | 14.31 | 6.81 | 3.41 | 1.98 | 0.91 | 0.48 | | | |
| 36 | <i>p</i> -Nitrobenzaldehyde | — | 17.39 | 8.06 | 4.00 | 2.17 | 1.33 | 0.61 | 0.35 | | | |
| 37 | <i>p</i> -Nitrobenzaldehyde | — | 12.24 | 5.16 | 2.66 | 1.34 | 0.86 | 0.40 | 0.22 | | | |
| 38 | Nitrobenzene | — | — | 17.44 | 8.78 | 4.62 | 2.72 | 1.26 | 0.67 | | | |
| 39 | <i>m</i> -Nitrophenol | — | 19.18 | 9.42 | 5.00 | 2.65 | 1.48 | 0.71 | 0.38 | | | |
| 40 | <i>o</i> -Nitrophenol | — | — | 14.49 | 7.78 | 4.10 | 2.38 | 1.14 | 0.63 | | | |
| 41 | <i>p</i> -Nitrophenol | — | 17.06 | 8.62 | 4.43 | 2.28 | 1.34 | 0.62 | 0.35 | | | |
| 42 | Phenol | 12.72 | 7.72 | 4.25 | 2.50 | 1.39 | 0.94 | 0.46 | 0.26 | | | |
| 43 | 2-Phenylethanol | — | 18.30 | 8.84 | 4.62 | 2.34 | 1.36 | 0.65 | 0.37 | | | |
| 44 | <i>p</i> -Phenylphenol | — | — | — | — | 15.71 | 5.57 | 2.07 | 0.90 | | | |
| 45 | 3-Phenylpropanol | — | — | 21.02 | 9.25 | 4.32 | 2.22 | 0.97 | 0.52 | | | |
| 46 | <i>n</i> -Propylbenzene | — | — | — | — | — | 24.06 | 7.29 | 2.74 | | | |
| 47 | Toluene | — | — | — | — | 14.22 | 7.30 | 2.91 | 1.42 | | | |
| 48 | Trichlorotoluene | — | — | — | — | — | 24.74 | 6.93 | 2.55 | | | |
| 49 | 2,4-Dimethylphenol | — | — | — | 12.63 | 5.87 | 3.06 | 1.23 | 0.62 | | | |

(Continued on p. 282.)

APPENDIX II (continued)

| Solute No. | ϕ_{MeOH} | ϕ_{ACN} | ϕ_{water} | 0.90 | 1.00 | 0.15 | 0.225 | 0.30 | 0.375 | 0.45 | 0.525 | 0.60 | 0.675 | 0.75 | 0.25 | 0.30 | 0.35 |
|------------|----------------------|---------------------|-----------------------|-------|-------|-------|-------|------|-------|------|-------|-------|-------|------|------|------|------|
| 1 | 0.36 | 0.10 | 27.78 | 12.10 | 6.66 | 2.54 | 1.33 | 0.83 | 0.59 | 0.38 | 0.26 | 1.70 | 1.03 | 0.81 | | | |
| 2 | 0.68 | 0.28 | — | 27.84 | 11.75 | 4.74 | 2.14 | 1.26 | 0.84 | 0.48 | 0.28 | 2.53 | 1.66 | 1.26 | | | |
| 3 | 0.33 | 0.20 | — | 27.29 | 13.11 | 4.80 | 2.25 | 1.27 | 0.81 | 0.49 | 0.27 | 2.65 | 1.66 | 1.27 | | | |
| 4 | 1.14 | 0.41 | — | — | 15.12 | 4.87 | 2.20 | 1.34 | 0.93 | 0.45 | 0.29 | 3.03 | 1.76 | 1.32 | | | |
| 5 | 0.31 | 0.18 | 22.30 | 11.77 | 5.38 | 2.24 | 1.19 | 0.78 | 0.58 | 0.31 | 0.23 | 1.62 | 1.01 | 0.78 | | | |
| 6 | 0.76 | 0.33 | — | — | — | 12.91 | 4.23 | 2.06 | 1.12 | 0.57 | 0.32 | 6.94 | 3.22 | 2.14 | | | |
| 7 | 0.14 | 0.11 | 7.65 | 4.57 | 2.48 | 1.25 | 0.74 | 0.53 | 0.46 | 0.25 | 0.19 | 0.85 | 0.58 | 0.48 | | | |
| 8 | 1.40 | 0.50 | — | — | — | — | 9.76 | 4.25 | 1.96 | 0.82 | 0.40 | 16.79 | 6.69 | 4.04 | | | |
| 9 | 1.98 | 0.57 | — | — | — | — | 17.75 | 7.18 | 3.09 | 1.06 | 0.49 | 31.32 | 12.07 | 6.50 | | | |
| 10 | — | 0.49 | — | — | — | 11.90 | 4.17 | 2.15 | 1.30 | — | 0.32 | 5.65 | 3.21 | 2.22 | | | |
| 11 | 0.86 | 0.34 | — | — | 33.14 | 9.90 | 4.03 | 2.01 | 1.19 | — | 0.34 | 4.92 | 2.89 | 2.02 | | | |
| 12 | 0.32 | 0.15 | — | 20.90 | 8.38 | 2.94 | 1.49 | 1.00 | 0.61 | 0.34 | 0.21 | 1.68 | 1.10 | 0.82 | | | |
| 13 | 1.09 | 0.42 | — | — | — | 18.88 | 6.98 | 3.14 | 1.69 | 0.70 | 0.38 | 10.17 | 4.70 | 3.02 | | | |
| 14 | 0.31 | 0.18 | 21.88 | 11.77 | 5.59 | 2.18 | 1.18 | 0.74 | 0.51 | 0.31 | 0.21 | 1.46 | 0.94 | 0.71 | | | |
| 15 | 1.16 | 0.44 | — | — | — | 14.26 | 6.17 | 3.13 | 1.66 | 0.75 | 0.39 | 8.40 | 4.58 | 2.99 | | | |
| 16 | 0.50 | 0.19 | — | — | 25.86 | 5.00 | 2.70 | 1.30 | 0.77 | 0.41 | 0.23 | 4.34 | 2.12 | 1.39 | | | |
| 17 | 0.27 | 0.15 | — | 17.01 | 7.69 | 1.93 | 1.29 | 0.86 | 0.58 | 0.32 | 0.20 | 1.61 | 1.03 | 0.77 | | | |
| 18 | 0.38 | 0.17 | — | 17.36 | 8.17 | 2.88 | 1.54 | 0.93 | 0.65 | 0.31 | 0.21 | 2.19 | 1.26 | 0.92 | | | |
| 19 | 0.32 | 0.12 | — | 17.13 | 8.05 | 2.86 | 1.39 | 0.81 | 0.52 | 0.27 | 0.18 | 2.16 | 1.17 | 0.81 | | | |
| 20 | 0.31 | 0.13 | — | 15.16 | 6.84 | 2.84 | 1.39 | 0.86 | 0.55 | 0.28 | 0.20 | 2.07 | 1.20 | 0.88 | | | |
| 21 | 0.50 | 0.19 | — | — | 14.61 | 5.37 | 2.22 | 1.24 | 0.75 | 0.35 | 0.22 | 3.46 | 1.77 | 1.22 | | | |
| 22 | 0.43 | 0.18 | — | — | 14.58 | 4.31 | 2.10 | 1.14 | 0.75 | 0.34 | 0.21 | 3.38 | 1.69 | 1.15 | | | |
| 23 | 0.34 | 0.14 | — | 36.26 | 11.11 | 3.98 | 2.02 | 1.03 | 0.63 | 0.35 | 0.21 | 3.22 | 1.66 | 1.10 | | | |
| 24 | 1.18 | 0.41 | — | — | — | — | 9.38 | 3.96 | 1.78 | 0.70 | 0.37 | 15.64 | 6.29 | 3.71 | | | |
| 25 | 1.14 | 0.40 | — | — | — | 12.98 | 6.02 | — | 1.50 | 0.70 | 0.37 | 9.42 | 4.30 | 2.76 | | | |
| 26 | 0.54 | 0.22 | — | 20.10 | 11.32 | 4.42 | 2.05 | 1.33 | 0.78 | 0.41 | 0.25 | 2.84 | 1.56 | 1.15 | | | |
| 27 | 0.38 | 0.18 | — | 20.78 | 8.88 | 3.45 | 1.58 | 0.97 | 0.68 | — | 0.22 | 1.95 | 1.29 | 0.94 | | | |
| 28 | 0.38 | 0.18 | — | 20.68 | 8.94 | 3.56 | 1.65 | 0.94 | 0.70 | — | 0.22 | 2.09 | 1.39 | 1.02 | | | |
| 29 | 0.18 | 0.07 | 12.10 | 7.45 | 3.50 | 1.66 | 0.93 | 0.57 | 0.47 | 0.27 | 0.19 | 0.97 | 0.67 | 0.54 | | | |
| 30 | 0.17 | 0.06 | 7.37 | 3.38 | 1.87 | 0.91 | 0.58 | 0.42 | 0.36 | 0.22 | 0.18 | 0.66 | 0.45 | 0.38 | | | |
| 31 | 0.36 | 0.22 | — | — | — | 3.65 | 2.18 | 1.18 | 0.79 | 0.39 | 0.29 | 2.86 | 1.62 | — | | | |
| 32 | 0.18 | 0.25 | — | — | — | 6.43 | 3.44 | 1.78 | 1.11 | 0.54 | 0.32 | 5.01 | 2.48 | 2.07 | | | |
| 33 | 0.64 | 0.28 | — | 31.64 | 13.62 | 3.73 | 2.00 | 1.14 | 0.82 | — | 0.29 | 2.53 | 1.60 | 1.22 | | | |
| 34 | 1.13 | 0.44 | — | — | — | 17.20 | 5.70 | 3.27 | 1.49 | 0.72 | 0.38 | 9.09 | 4.19 | 2.76 | | | |
| 35 | 0.34 | 0.18 | — | 16.45 | 7.30 | 2.22 | 1.26 | 0.81 | 0.60 | 0.34 | 0.21 | 1.70 | 1.10 | 0.82 | | | |
| 36 | 0.23 | 0.11 | — | — | 17.18 | 5.85 | 2.34 | 1.36 | 0.89 | 0.44 | 0.25 | 3.12 | 1.92 | 1.38 | | | |
| 37 | 0.22 | 0.05 | — | 24.97 | 10.71 | 2.71 | 1.73 | 0.98 | 0.70 | 0.34 | 0.24 | 2.38 | 1.31 | 0.98 | | | |
| 38 | 0.46 | 0.23 | — | 17.70 | 8.73 | 3.14 | 1.70 | 0.99 | 0.70 | 0.40 | 0.26 | 2.42 | 1.42 | 1.04 | | | |
| 39 | 0.26 | 0.14 | 19.22 | 11.73 | 4.74 | 1.90 | 1.08 | 0.72 | 0.47 | 0.26 | 0.19 | 1.39 | 0.83 | 0.63 | | | |
| 40 | 0.50 | 0.21 | 15.54 | 12.75 | 5.87 | 1.91 | 1.42 | 0.87 | 0.63 | 0.34 | 0.25 | 1.99 | 1.21 | 0.90 | | | |
| 41 | 0.27 | 0.13 | 23.88 | 8.08 | 3.94 | 1.30 | 0.98 | 0.58 | 0.49 | 0.25 | 0.18 | 1.26 | 0.78 | 0.58 | | | |
| 42 | 0.19 | 0.11 | 8.30 | 5.03 | 2.59 | 1.21 | 0.78 | 0.51 | 0.41 | 0.26 | 0.18 | 0.97 | 0.62 | 0.49 | | | |
| 43 | 0.25 | 0.14 | 17.11 | 7.71 | 4.12 | 1.79 | 1.04 | 0.72 | 0.53 | 0.30 | 0.21 | 1.05 | 0.74 | 0.58 | | | |
| 44 | 0.57 | 0.20 | — | — | 27.14 | 7.07 | 3.44 | 1.45 | 0.81 | 0.42 | 0.24 | 4.67 | 2.14 | 1.40 | | | |
| 45 | 0.33 | 0.16 | — | 16.64 | 8.22 | 2.98 | 1.42 | 0.86 | 0.64 | 0.31 | 0.22 | 1.77 | 1.04 | 0.77 | | | |
| 46 | 1.38 | 0.48 | — | — | — | 16.94 | 9.88 | 4.54 | 2.07 | 0.86 | 0.41 | 16.75 | 7.18 | 4.23 | | | |
| 47 | 0.86 | 0.36 | — | — | 24.98 | 9.25 | 3.73 | 2.00 | 1.22 | 0.57 | 0.34 | 5.30 | 2.81 | 1.95 | | | |
| 48 | 1.38 | 0.43 | — | — | — | — | — | — | 2.02 | 0.87 | — | — | — | — | | | |
| 49 | 0.40 | 0.19 | — | 26.72 | 10.92 | 4.00 | 1.75 | 0.99 | 0.65 | 0.50 | 0.25 | 2.34 | 1.34 | 0.98 | | | |

| 0.40 | 0.45 | 0.50 | 0.15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|------|------|------|-------|-------|-------|-------|-------|-------|------|------|------|------|------|
| 0.40 | 0.45 | 0.50 | 0.45 | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 | 0.70 | 0.80 | 0.90 | 1.00 |
| 0.20 | 0.10 | 0 | 0.40 | 0.90 | 0.80 | 0.70 | 0.60 | 0.50 | 0.40 | 0.30 | 0.20 | 0.10 | 0 |
| 0.57 | 0.40 | 0.30 | 1.26 | — | 13.58 | 6.32 | 2.95 | 1.78 | 1.03 | 0.66 | 0.44 | 0.31 | 0.25 |
| 0.80 | 0.51 | 0.34 | 2.10 | — | — | 14.10 | 5.89 | 3.34 | 1.78 | 1.04 | 0.66 | 0.42 | 0.30 |
| 0.81 | 0.52 | 0.34 | 1.14 | 28.68 | 10.25 | 5.72 | 2.74 | 1.68 | 1.00 | 0.65 | 0.42 | 0.30 | 0.22 |
| 0.83 | 0.53 | 0.36 | 2.16 | — | — | 13.94 | 6.26 | 3.51 | 1.90 | 1.14 | 0.70 | 0.45 | 0.30 |
| 0.53 | 0.37 | 0.25 | 1.17 | — | — | 7.46 | 3.38 | 1.97 | 1.11 | 0.70 | 0.42 | 0.28 | 0.21 |
| 1.15 | 0.65 | 0.39 | 4.51 | — | — | — | 15.02 | 6.69 | 3.09 | 1.74 | 0.94 | 0.56 | 0.36 |
| 0.36 | 0.29 | 0.23 | 0.49 | 8.85 | 3.72 | 1.99 | 1.06 | 0.67 | 0.46 | 0.32 | 0.22 | 0.18 | — |
| 1.92 | 0.94 | 0.50 | 9.59 | — | — | — | 36.28 | 14.34 | 5.79 | 2.98 | 1.54 | 0.82 | 0.46 |
| 2.86 | 1.24 | 0.61 | 14.94 | — | — | — | — | 24.31 | 9.55 | 4.66 | 2.37 | 1.25 | 0.68 |
| 1.23 | 0.70 | 0.42 | 1.43 | — | 24.22 | 8.57 | 3.11 | — | — | 0.99 | 0.62 | 0.40 | 0.31 |
| 1.16 | 0.68 | 0.42 | 3.69 | — | — | 33.67 | 11.82 | 5.88 | 2.94 | 1.67 | 0.98 | 0.59 | 0.41 |
| 0.53 | 0.36 | 0.27 | 1.10 | — | 19.78 | 8.22 | 3.22 | 1.69 | 0.92 | 0.54 | 0.30 | 0.22 | 0.25 |
| 1.56 | 0.82 | 0.47 | 6.17 | — | — | — | 21.38 | 9.78 | 4.46 | 2.35 | 1.36 | 0.78 | 0.50 |
| 0.49 | 0.34 | 0.26 | 0.95 | — | 11.82 | 5.76 | 2.74 | 1.48 | 0.82 | 0.51 | 0.31 | 0.22 | 0.22 |
| 1.60 | 0.88 | 0.50 | 5.94 | — | — | — | 19.94 | 9.25 | 4.30 | 2.29 | 1.38 | 0.80 | 0.50 |
| 0.79 | 0.47 | 0.28 | 2.54 | — | — | 28.14 | 8.89 | 4.22 | 2.02 | 1.09 | 0.64 | 0.39 | 0.27 |
| 0.52 | 0.34 | 0.24 | 1.74 | — | 21.15 | 8.42 | 3.41 | 1.88 | 1.03 | — | 0.39 | 0.25 | 0.18 |
| 0.57 | 0.36 | 0.22 | 1.69 | — | — | 11.34 | 4.66 | 2.51 | 1.29 | 0.71 | 0.39 | 0.23 | 0.17 |
| 0.50 | 0.32 | 0.21 | 1.41 | — | — | 13.43 | 4.94 | 2.48 | 1.22 | 0.68 | 0.36 | 0.22 | 0.14 |
| 0.54 | 0.34 | 0.21 | 1.66 | — | 22.02 | 11.42 | 4.86 | 2.58 | 1.30 | 0.71 | 0.38 | 0.22 | 0.16 |
| 0.70 | 0.41 | 0.24 | 2.47 | — | — | 21.86 | 7.73 | 3.62 | 1.70 | 0.91 | 0.52 | 0.28 | 0.16 |
| 0.66 | 0.39 | 0.23 | 1.98 | — | — | 22.13 | 7.88 | — | 1.74 | 0.91 | 0.49 | 0.27 | 0.18 |
| 0.62 | 0.38 | 0.22 | 2.18 | — | — | 25.47 | 8.07 | 3.66 | 1.73 | 0.88 | 0.49 | 0.27 | 0.19 |
| 1.73 | 0.83 | 0.43 | 8.30 | — | — | — | 35.34 | 13.70 | 5.49 | 2.66 | 1.40 | 0.74 | 0.42 |
| 1.48 | 0.79 | 0.46 | 5.66 | — | — | — | 19.58 | 8.90 | 4.14 | — | — | 1.10 | 0.49 |
| 0.70 | 0.43 | 0.29 | 2.06 | — | — | 14.20 | 5.97 | 3.07 | 1.60 | 0.94 | 0.54 | 0.31 | 0.24 |
| 0.60 | 0.38 | 0.26 | 1.66 | — | 22.96 | 11.43 | 4.78 | 2.53 | 1.33 | 0.76 | 0.45 | 0.27 | 0.21 |
| 0.65 | 0.42 | 0.26 | 1.77 | — | — | 12.85 | 5.26 | 2.85 | 1.51 | 0.84 | 0.50 | 0.30 | 0.20 |
| 0.38 | 0.27 | 0.22 | 0.65 | 15.93 | 7.60 | 3.77 | 1.74 | 1.03 | 0.59 | 0.34 | 0.20 | 0.14 | 0.16 |
| 0.29 | 0.25 | 0.21 | 0.40 | 8.18 | 3.04 | 1.60 | 0.79 | 0.50 | 0.30 | 0.19 | 0.11 | 0.10 | 0.25 |
| 0.77 | 0.50 | 0.30 | 1.15 | — | 13.98 | 6.30 | 2.80 | 1.68 | 0.96 | 0.60 | 0.40 | 0.28 | 0.22 |
| 1.06 | 0.63 | 0.40 | 0.90 | — | 24.11 | 10.94 | 4.78 | 2.51 | 1.43 | 0.86 | 0.57 | 0.38 | 0.27 |
| 0.77 | 0.50 | 0.34 | 1.90 | — | — | 13.34 | 5.34 | 2.89 | 1.62 | 0.97 | 0.62 | 0.42 | 0.32 |
| 1.46 | 0.81 | 0.47 | 6.18 | — | — | — | 19.89 | 8.63 | 4.05 | 2.22 | 1.22 | 0.70 | 0.46 |
| 0.54 | 0.35 | 0.24 | 1.79 | — | 19.20 | 8.80 | 3.77 | 2.06 | 1.12 | 0.67 | 0.39 | 0.24 | 0.19 |
| 0.81 | 0.48 | 0.30 | 1.22 | — | 23.26 | 6.48 | 3.15 | 1.82 | 1.00 | 0.58 | 0.34 | 0.22 | 0.18 |
| 0.63 | 0.41 | 0.26 | 0.75 | 22.62 | 7.94 | 4.53 | 2.25 | 1.37 | 0.70 | 0.47 | 0.30 | 0.19 | 0.14 |
| 0.67 | 0.43 | 0.30 | 1.71 | — | — | 11.32 | 5.06 | 2.78 | 1.47 | 0.84 | 0.52 | 0.33 | 0.22 |
| 0.42 | 0.30 | 0.24 | 0.94 | 27.57 | 11.48 | 5.10 | 2.21 | 1.24 | 0.66 | 0.38 | 0.22 | 0.14 | 0.27 |
| 0.58 | 0.39 | 0.28 | 1.45 | — | 16.38 | 8.28 | 3.74 | 2.10 | 1.17 | 0.73 | 0.44 | 0.29 | 0.38 |
| 0.38 | 0.27 | 0.22 | 0.72 | 23.03 | 9.09 | 4.15 | 2.95 | 1.08 | 0.58 | 0.33 | 0.19 | 0.13 | 0.17 |
| 0.37 | 0.28 | 0.22 | 0.56 | 10.16 | 4.90 | 2.70 | 1.45 | 0.89 | 0.52 | 0.34 | 0.21 | 0.15 | 0.17 |
| 0.42 | 0.32 | 0.26 | 0.68 | 12.86 | 6.73 | 3.20 | 1.49 | 0.90 | 0.54 | 0.36 | 0.29 | 0.22 | 0.31 |
| 0.78 | 0.46 | 0.30 | 2.66 | — | — | 31.76 | 8.26 | 3.52 | 1.61 | 0.88 | 0.49 | 0.30 | 0.32 |
| 0.51 | 0.36 | 0.26 | 0.98 | — | 15.26 | 6.11 | 2.42 | 1.34 | 0.80 | 0.50 | 0.35 | 0.29 | 0.40 |
| 2.05 | 0.99 | 0.53 | 9.45 | — | — | — | 36.18 | 14.45 | 6.26 | 3.17 | 1.74 | 0.94 | 0.52 |
| 1.14 | 0.67 | 0.42 | 3.70 | — | — | 30.67 | 11.31 | 5.76 | 2.80 | 1.66 | 0.98 | 0.60 | 0.22 |
| 2.06 | 0.97 | 0.54 | 9.55 | — | — | — | 40.03 | 15.68 | 6.44 | 3.29 | 1.72 | 0.91 | 0.55 |
| 0.62 | 0.39 | 0.29 | 1.45 | — | 25.84 | 10.63 | 4.20 | 2.30 | 1.18 | 0.70 | 0.43 | 0.29 | 0.30 |

ACKNOWLEDGEMENT

The assistance of ir. Anton Drouen in constructing some of the figures in this publication is gratefully acknowledged.

REFERENCES

- 1 P. J. Schoenmakers, H. A. H. Billiet and L. de Galan, *J. Chromatogr.*, 185 (1979) 179.
- 2 P. J. Schoenmakers, H. A. H. Billiet and L. de Galan, *Anal. Chem.*, submitted for publication.
- 3 P. J. Schoenmakers, H. A. H. Billiet and L. de Galan, *J. Chromatogr.*, 205 (1981) 13.
- 4 S. R. Bakalyar, R. McIlwrick and E. Roggendorf, *J. Chromatogr.*, 142 (1977) 353.
- 5 N. Tanaka, H. Goodell and B. L. Karger, *J. Chromatogr.*, 158 (1978) 233.
- 6 R. Spatz and E. Roggendorf, *Z. Anal. Chem.*, 299 (1979) 267.
- 7 E. Roggendorf and R. Spatz, *J. Chromatogr.*, 204 (1981) 263.
- 8 J. L. Glajch, J. J. Kirkland, K. M. Squire and J. M. Minor, *J. Chromatogr.*, 199 (1980) 57.
- 9 P. J. Schoenmakers, H. A. H. Billiet, R. Tijssen and L. de Galan, *J. Chromatogr.*, 149 (1978) 519.
- 10 R. Tijssen, H. A. H. Billiet and P. J. Schoenmakers, *J. Chromatogr.*, 122 (1976) 185.
- 11 R. P. W. Scott and P. Kucera, *J. Chromatogr.*, 142 (1977) 213.
- 12 R. M. McCormick and B. L. Karger, *Anal. Chem.*, 52 (1980) 2249.
- 13 G. E. Berendsen, P. J. Schoenmakers, L. de Galan, Gy. Vigh, Z. Varga-Puchony and J. Inczedy, *J. Liq. Chromatogr.*, 3 (1980) 1669.
- 14 P. J. Schoenmakers *et al.*, to be published.
- 15 E. H. Slaats, *Ph. D. Thesis*, University of Amsterdam, Amsterdam, 1980.