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# Chemometric classification of the solvent properties (selectivity) of commonly used gas chromatographic stationary phases

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## Abstract

Abraham's solvation parameter model was used to characterize the solvent properties of 33 stationary phases in terms of their capacity for specific intermolecular interactions at 121.4°C. The capacity of the phases for dispersion, orientation, induction, and hydrogen-bond base interactions, combined with solvent cohesion (ease of cavity formation) were important in defining their behavior. The capacity for  $\pi$ - and  $n$ -electron pair acceptor interactions was less important and none of the phases possessed a significant capacity for solvent hydrogen-bond acid interactions. Principal component analysis and hierarchical clustering techniques were used to classify the phases by their similarity for specific intermolecular interactions. These methods provide a visual means of quantitatively comparing the properties of the stationary phases and a mechanism to develop a short list of phases able to represent the range of properties available in the larger data set.

## 1. Introduction

For many years chromatographers have sought a method to characterize the solvation properties of stationary phases used in gas chromatography with the goal of providing a rational approach for selection of an optimum phase for a given separation and to predict retention of solutes on different phases. Many researchers have contributed to this problem in the past and we will not attempt to review the voluminous literature on the topic in this report; instead we direct the reader to authoritative reviews on the subject [1–4]. If a similar understanding of retention could be developed as currently exists for the

kinetic properties of columns, then computer-aided optimization of separations would become a viable alternative to trial-and-error methods development.

Modern approaches to stationary phase characterization are based on the cavity model of solvation [5–8]. This model assumes that the transfer of a solute from the gas phase to solution in the stationary liquid phase involves three factors. Initially a cavity is formed in the stationary phase identical in volume to the solute. The solute is then transferred to the cavity with reorganization of the solvent molecules around the cavity and the set up of solute–solvent interactions. This process can be characterized by the individual free energy terms involved in the transfer process which can

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reasonably be assumed to be additive. The disruption of solvent–solvent interactions to form a cavity is energetically unfavorable for the transfer of a solute from the gas phase to solution and must be less important than the free energy gained from the formation of solute–solvent interactions otherwise the solute will not be retained. The free energy changes associated with reorganization of the solvent molecules around the cavity are likely to be small compared to the changes involved in the other two steps and to a first approximation can be ignored.

The solute in the gas phase can reasonably be assumed to be behaving ideally and solute–solute and solute–gas interactions are essentially negligible. Transfer of the solute to solution in the liquid phase occurs with the creation of additional intermolecular interactions which depend on properties of both the solute and solvent. The solution can reasonably be assumed to be infinitely dilute for the separation conditions employed in analytical gas–liquid chromatography and, therefore, all interactions that are formed in solution are of the solute–solvent type. These interactions can be characterized as dispersion, orientation, induction and complexation. Dispersion interactions are non-selective and are the binding forces that hold all assemblies of non-polar molecules together (they occur, of course, in assemblies of polar molecules were they are augmented by polar interactions). Molecules with a permanent dipole moment can interact with each other by the cooperative alignment of their dipoles (orientation interactions) and by their capacity to induce a temporary complementary dipole in a polarizable molecule (induction interactions). Complexation interactions are selective interactions involving the sharing of electron density or a hydrogen atom between molecules (hydrogen bonding and charge transfer, for example). In gas–liquid chromatography retention will depend on the cohesive properties of the solvent as represented by the energy required to form a cavity in the solvent, the formation of additional dispersion interactions of a solute–solvent type, and on selective solute–solvent polar interactions

which depend on the complementary character of the polar properties of the solute and solvent.

The above conceptual picture of retention in gas–liquid chromatography is intuitively sound but must be encoded in a mathematical form to establish the relative importance of the various contributing factors to solvation. As our knowledge exists today this is beyond the scope of computational chemistry. We must seek an empirical solution which combines experimentally accessible information with our overall goal of a quantitative model to express the relative contribution of cavity formation and solute–solvent interactions to the solution process. Two models have been proposed for this process. The solvation parameter model is discussed in this paper. In a companion paper [9] an alternative approach based on the separation of the free energy terms into cavity formation and non-polar and polar interactions with subsequent deconvolution into intermolecular interactions by multivariate analysis is evaluated.

The master retention equation in the solvation parameter model developed by Abraham [6,7,10,11] can be written as follows:

$$\log K_L = c + rR_2 + s\pi_2^H + a\alpha_2^H + b\beta_2^H + l \log L^{16} \quad (1)$$

where  $K_L$  is the gas–liquid partition coefficient,  $R_2$  the solute excess molar refraction [12],  $\pi_2^H$  the effective solute dipolarity/polarizability [13–16],  $\alpha_2^H$  the effective solute hydrogen-bond acidity [15,16],  $\beta_2^H$  the effective solute hydrogen-bond basicity [17], and  $L^{16}$  the solute gas–liquid partition coefficient on *n*-hexadecane at 25°C [13–15]. The explanatory variables listed above are solvation parameters derived from equilibrium constants or calculated from gas chromatographic measurements and are free energy-related parameters characteristic of the monomeric solute. Values of the solvation parameters for more than 1000 compounds are currently available and in many cases unknown values can be estimated using simple combining rules [7,11]. The solvent properties  $r$ ,  $s$ ,  $a$ ,  $b$  and  $l$  are unambiguously defined: the  $r$  constant refers to the ability of a solvent to interact with solute  $n$ -

or  $\pi$ -electron pairs; the  $s$  constant to the ability of the solvent to take part in dipole–dipole and dipole–induced dipole interactions; the  $a$  constant is a measure of the hydrogen-bond basicity of the solvent; the  $b$  constant is a measure of the hydrogen-bond acidity of the solvent; and the  $l$  constant incorporates contributions from solvent cavity formation and solute–solvent dispersion interactions, and more specifically in gas–liquid chromatography indicates how well the phase will separate members of a homologous series. For an uncharacterized phase the solvent properties  $r$ ,  $s$ ,  $a$ ,  $b$  and  $l$  are determined from the experimentally derived gas–liquid partition coefficient for a minimum of 15 to 30 varied solutes with known explanatory variables using the statistical analysis technique of multiple linear regression analysis. Abraham and co-workers have used Eq. 1 to characterize the 5 stationary phases in the Laffort data set [12], the 77 stationary phases in the McReynolds data set [18], the 24 stationary phases in the Poole data set [19], to identify impurities in two poly-(methylphenylsiloxane)s [20], to characterize a new stationary phase with hydrogen-bond acid properties [21], and to characterize surface interactions on carbonaceous adsorbents [22]. In an analogous fashion Poole and co-workers have used Eq. 1 to characterize the stationary phase properties of 46 liquid organic salts [23,24], to study the influence of temperature on the phase constants of 10 common stationary phases [25], and to estimate the breakthrough volume of a wide range of organic compounds in solid-phase extraction [26,27]. Non-chromatographic applications have included the characterization of chemically selective sensors, the solubility of gases and vapors in organic solvents, the effect of airborne chemicals on the upper respiratory tract irritation in mice, etc., and are reviewed elsewhere [7,17,28].

Carr and co-workers [29–34] have proposed an equation similar to Eq. 1 but different from it in that it uses an empirical polarizability correction factor  $\delta_2$  (used in solvatochromic models) in place of  $R_2$  and a new set of explanatory variables derived from chromatographic measurements:

$$\log K_1 = c + d\delta_2 + s\pi_2^{*c} + a\alpha_2^c + b\beta_2^c + l \log L^{16} \quad (2)$$

Since the explanatory variables are numerically different from those proposed by Abraham so are the characteristic phase constants derived from them. These differences, however, are generally small and both models yield the same qualitative conclusions [6,11,35]. It is not necessary to summarize the results using both equations for our current purpose and only Eq. 1 will be considered here.

## 2. Experimental

The name, abbreviation and composition of the stationary phases used in this study are summarized in Table 1. The gas–liquid partition coefficients at 121.4°C were taken from previous studies [23–25,36,37] and are corrected for interfacial adsorption. The experimental protocol for determining the partition coefficients is described in Ref. [38].

Principal component analysis and cluster analysis for data interpretation were performed using Pirouette V1.1 (Infometrix, Seattle, WA, USA) on a Epson Apex 200 computer (Epson America, Torrance, CA, USA). Multiple linear regression analysis was performed using the program SPSS/PC V3.1 (SPSS, Chicago, IL, USA) on an Epson Apex 200 computer. The explanatory variables used for multiple linear regression analysis were taken from the collection by Abraham and co-workers [11–16].

## 3. Results and discussion

Application of Abraham's solvation parameter model to the phases listed in Table 1 resulted in the characteristic phase constants summarized in Table 2. Initial evaluation reveals that the results are sensible. All coefficients are positive except for the  $c$  constant for all phases and the  $r$  constant for the fluorine-containing phases. The  $c$  constant contains, in part, the contribution from cavity formation, which is always unfavor-

able for solute transfer from the gas phase, so is expected to be negative. The  $r$  constant for fluorine-containing solvents is generally negative because of the method used to calculate  $R_2$  and is also reasonable [11,18]. None of the stationary phases are significant hydrogen-bond acids ( $b = 0$ ) at the measurement temperature. Small  $b$  constants were observed for the polyester phases EGAD and DEGS as well as for TCEP as shown below.

In each case the  $b$  constant is small but statistically significant. Based on the structure of these phases a significant contribution from hydrogen-bond acidity would not be anticipated. Polyester phases, however, are known to be thermally unstable yielding small amounts of the parent acid [1,39] and phases containing cyano groups are easily oxidized to the carboxylic acid [40] providing a possible explanation for the observed weak hydrogen-bond acidity while other phases in Table 1 containing more obvious hydrogen-bond acid functional groups are inert.

Force fitting the regression equation to the experimental data with  $b = 0$ , shown below the best fit to the data summarized above, provides a good fit, with only minor changes (except for  $b$ ) to the characteristic phase constants. It seems reasonable to conclude that the hydrogen-bond acidity of EGAD, DEGS and TCEP results from a low concentration of acidic impurities generated during use rather than a characteristic property of the stationary phase material itself. Since among common phases used in gas-liquid chromatography none can be identified as possessing significant hydrogen-bond acidity, this suggests an obvious target for the development of new phases with potential to have a significant impact on the practice of gas chromatography, especially since amongst functionalized molecules there are many hydrogen-bond bases. Hydroxyl groups are good hydrogen-bond acids, but as shown by the data in Table 2, hydroxyl groups on alkyl chains (THPED, QTAPSO and QBES) prefer to form solvent-solvent hydrogen-bond

	$c$	$r$	$s$	$a$	$b$	$l$
EGAD	-0.688 (0.035) $R = 0.999$	0.132 (0.024) S.E. = 0.026	1.394 (0.036) $F = 1935$	1.820 (0.063) $n = 24$	0.206 (0.048)	0.429 (0.005)
	-0.657 (0.047) $R = 0.998$	0.087 (0.030) S.E. = 0.035	1.471 (0.043) $F = 1291$	1.974 (0.071) $n = 24$		0.431 (0.007)
DEGS	-0.650 (0.004) $R = 1.000$	0.230 (0.003) S.E. = 0.004	1.572 (0.004) $F = 119240$	2.105 (0.007) $n = 34$	0.171 (0.005)	0.407 (0.001)
	-0.669 (0.031) $R = 0.999$	0.197 (0.020) S.E. = 0.027	1.668 (0.019) $F = 3045$	2.246 (0.041) $n = 34$		0.411 (0.005)
TCEP	-0.744 (0.029) $R = 0.999$	0.116 (0.017) S.E. = 0.025	2.088 (0.025) $F = 4177$	2.095 (0.038) $n = 39$	0.261 (0.031)	0.370 (0.005)
	-0.697 (0.049) $R = 0.998$	0.050 (0.026) S.E. = 0.042	2.215 (0.034) $F = 1742$	2.267 (0.055) $n = 39$		0.365 (0.008)

Table 1  
Identification and abbreviations for stationary phases

Number	Abbreviation	Name
1	SQ	Squalane
2	SE-30	Poly(dimethylsiloxane)
3	OV-105	Poly(cyanopropylmethyldimethylsiloxane)
4	OV-3	Poly(dimethylmethylphenylsiloxane) (10 mol% phenyl groups)
5	OV-7	Poly(dimethylmethylphenylsiloxane) (20 mol% phenyl groups)
6	OV-11	Poly(dimethylmethylphenylsiloxane) (35 mol% phenyl groups)
7	OV-17	Poly(methylphenylsiloxane)
8	OV-22	Poly(methylphenyldiphenylsiloxane) (65 mol% phenyl groups)
9	OV-25	Poly(methylphenyldiphenylsiloxane) (75 mol% phenyl groups)
10	OV-330	Poly(dimethylsiloxane)–Carbowax (CW) copolymer
11	OV-225	Poly(cyanopropylmethylphenylmethylsiloxane)
12	OV-275	Poly(dicyanoallylsiloxane)
13	QF-1	Poly(trifluoropropylmethylsiloxane)
14	DDP	Didecylphthalate
15	PPE-5	1,3-bis(3-phenoxyphenoxy)benzene
16	CW 20M	Poly(ethylene glycol)
17	U50HB	Poly(ethylene glycol) (Ucon 50 HB 660)
18	THPED	N,N,N',N'-Tetrakis(2-hydroxypropyl)ethylenediamine
19	EGAD	Poly(ethylene glycol adipate)
20	DEGS	Poly(diethylene glycol succinate)
21	TCEP	1,2,3-Tris(2-cyanoethoxypropane)
22	QMS	Tetra- <i>n</i> -butylammonium methanesulfonate
23	QFMS	Tetra- <i>n</i> -butylammonium trifluoromethanesulfonate
24	QBS	Tetra- <i>n</i> -butylammonium benzenesulfonate
25	QFBS	Tetra- <i>n</i> -butylammonium perfluorobenzenesulfonate
26	QTS	Tetra- <i>n</i> -butylammonium 4-toluenesulfonate
27	QACES	Tetra- <i>n</i> -butylammonium 2-(2-acetamido)aminoethanesulfonate
28	QTAPSO	Tetra- <i>n</i> -butylammonium 3-tris(hydroxymethyl)methylamino-2-hydroxy-1-propanesulfonate
29	QBES	Tetra- <i>n</i> -butylammonium N,N-(bis-2-hydroxyethyl)-2-aminoethanesulfonate
30	QPIC	Tetra- <i>n</i> -butylammonium picrate
31	QETS	Tetraethylammonium 4-toluenesulfonate
32	QPN	Tetra- <i>n</i> -butylphosphonium nitrate
33	QPC	Tetra- <i>n</i> -butylphosphonium chloride

complexes to the exclusion of solvent–hydrogen-bond acid solute–hydrogen-bond base interactions [24,36]. Abraham et al. [21] have shown that the phenol-containing phase, bis(3-allyl-4-hydroxyphenyl)sulfone has significant hydrogen-bond acidity. Likewise, Li et al. [31] have demonstrated significant hydrogen-bond acidity for the fluorinated alcohol phase, 4-dodecyl- $\alpha,\alpha$ -bis(trifluoromethyl)benzyl alcohol. Fluorinated alcohols have very low hydrogen-bond basicity which makes them particularly attractive as a structural entity to pursue in the preparation of new phases with hydrogen-bond acid properties

[11,21,28]. The magnitude of the characteristic phase constants in Table 2 is a measure of the capacity of a stationary phase for specific intermolecular interactions described by that constant. The various phase constants are only loosely scaled to each other so that changes in magnitude in any column can be read directly but changes in magnitude along rows must be interpreted cautiously. The magnitude of individual intermolecular interactions to the retention of specific compounds are represented by the solute–solvent product terms, some typical examples of which are summarized in Table 3.

Table 2  
Abraham's characteristic phase constants at 121.4°C

Stationary phase	<i>c</i>	<i>r</i>	<i>s</i>	<i>a</i>	<i>l</i>	Statistics for fit to Eq. 1 <sup>a</sup>	
						S.E.	<i>R</i>
SO	-0.222	0.129	0.011	0.000	0.583	0.017	1.000
SE-30	-0.194	0.024	0.190	0.125	0.498	0.022	0.999
OV-105	-0.203	0.000	0.364	0.407	0.496	0.024	0.999
OV-3	-0.181	0.033	0.328	0.152	0.503	0.021	0.999
OV-7	-0.231	0.056	0.433	0.165	0.510	0.025	0.999
OV-11	-0.303	0.097	0.544	0.174	0.516	0.029	0.999
OV-17	-0.372	0.071	0.653	0.263	0.518	0.025	0.999
OV-22	-0.328	0.201	0.664	0.190	0.482	0.034	0.998
OV-25	-0.273	0.277	0.644	0.182	0.472	0.042	0.997
OV-330	-0.430	0.104	1.056	1.419	0.481	0.051	0.995
OV-225	-0.541	0.000	1.226	1.065	0.466	0.025	0.999
OV-275	-0.909	0.206	2.080	1.986	0.294	0.036	0.998
QF-1	-0.269	-0.449	1.157	0.187	0.419	0.054	0.996
DDP	-0.328	0.000	0.748	0.765	0.560	0.025	0.999
PPE-5	-0.395	0.230	0.829	0.337	0.527	0.044	0.997
CW 20M	-0.560	0.317	1.256	1.883	0.447	0.032	0.999
U50HB	-0.184	0.372	0.632	1.277	0.499	0.013	1.000
THPED	-0.445	0.000	1.128	2.069	0.477	0.056	0.997
EGAD	-0.688	0.132	1.394	1.820	0.429		
DEGS	-0.650	0.230	1.572	2.105	0.407		
TCEP	-0.744	0.116	2.088	2.095	0.370		
QMS	-0.612	0.334	1.454	3.762	0.435	0.071	0.997
QFMS	-0.552	0.000	1.579	2.135	0.416	0.055	0.998
QBS	-0.924	0.121	1.756	3.507	0.464	0.050	0.996
QFBS	-0.723	-0.088	1.647	2.238	0.459	0.030	0.999
QTS	-0.686	0.156	1.582	3.295	0.459	0.033	0.998
QACES	-0.666	0.283	1.809	3.417	0.329	0.100	0.990
QTAPSO	-0.860	0.266	1.959	3.058	0.317	0.048	0.996
QBES	-0.805	0.253	1.760	3.368	0.382	0.046	0.997
QPIC	-0.542	0.100	1.557	1.424	0.445	0.061	0.994
QETS	-0.762	0.330	2.045	3.429	0.304	0.050	0.998
QPN	-0.758	0.183	1.829	3.538	0.421	0.051	0.996
QPC	-1.009	0.244	1.854	5.418	0.468	0.078	0.993

<sup>a</sup>S.E. = Standard error in the estimate; *R* = multiple correlation coefficient.

The product term  $rR_2$  is relatively small on all phases, including for iodobenzene, which has the largest  $R_2$  parameter value ( $R_2 = 1.188$ ) of the solutes in the data set. Many phases possess some capacity for  $\pi$ - and  $n$ -electron pair interactions, but selectivity for this interaction is all but non-existent amongst the stationary phases in Table 1. Phases containing metal co-ordination centers may have significant capacity for these interactions compared to the phases studied here, but for our present purposes we need not consider

the  $r$  phase constant further. It is clear from Table 3 that the product term  $l \log L^{16}$  is always significant. The contribution of cavity formation and dispersion interactions to retention involves at least part of the  $c$  constant as well [19,21,25,36]. The  $\sum(c + l \log L^{16})$  term is always favorable for transfer of a solute from the gas phase to the stationary phase indicating that the solute-solvent interactions formed by the transfer exceed the energy required to disrupt solvent-solvent interactions in preparing the

Table 3  
Contribution of specific solute–stationary phase interactions to retention ( $\log K_L$ )

Solute	Phase	$c$	$rR_2$	$s\pi_2^H$	$aa_2^H$	$b\beta_2^H$	$l \log L^{16}$
Nonan-2-one	OV-17	-0.372	0.008	0.444			2.453
	QF-1	-0.269	-0.053	0.787			1.984
	U50HB	-0.184	0.044	0.430			2.363
	TCEP	-0.744	0.014	1.420		0.133	1.752
	QTS	-0.686	0.019	1.076			2.173
	QPC	-1.009	0.029	1.261			2.216
Nonan-1-ol	OV-17	-0.372	0.014	0.274	0.097		2.654
	QF-1	-0.269	-0.087	0.486	0.069		2.147
	U50HB	-0.184	0.072	0.265	0.472		2.557
	TCEP	-0.744	0.022	0.877	0.775	0.125	1.896
	QTS	-0.686	0.030	0.664	1.219		2.352
	QPC	-1.009	0.047	0.779	2.005		2.398
Iodobenzene	OV-17	-0.372	0.083	0.535			2.332
	QF-1	-0.269	-0.533	0.949			1.886
	U50HB	-0.184	0.442	0.518			2.557
	TCEP	-0.744	0.138	1.712		0.031	1.896
	QTS	-0.686	0.185	1.297			2.066
	QPC	-1.009	0.290	1.520			2.107
Benzonitrile	OV-17	-0.372	0.052	0.725			2.092
	QF-1	-0.269	-0.333	1.284			1.692
	U50HB	-0.184	0.276	0.702			2.015
	TCEP	-0.744	0.086	2.318		0.086	1.494
	QTS	-0.686	0.116	1.756			1.854
	QPC	-1.009	0.181	2.058			1.890
4-Cresol	OV-17	-0.372	0.058	0.568	0.150		2.234
	QF-1	-0.269	-0.369	1.007	0.107		1.807
	U50HB	-0.184	0.306	0.550	0.782		2.152
	TCEP	-0.744	0.095	1.817	1.194	0.081	1.595
	QTS	-0.686	0.128	1.376	1.878		1.979
	QPC	-1.009	0.201	1.613	3.088		2.018

cavity. This we theorize is because cavity formation occurs by displacement retaining some of the solvent–solvent interactions, particularly dispersion interactions, since these are not directional, and the new solute–solvent interactions are simply added to these. The polar solvent–solvent interactions should be the most important in determining the energy required to form a cavity in the solvent. Abraham et al. [19] have shown that the  $l$  phase constant is directly proportional to the partial molar Gibbs free energy of solution for a methylene group,  $\Delta G(\text{CH}_2)$ . This conclusion is confirmed by the

results obtained in this study (Fig. 1 and Eq. 3).

$$\Delta G(\text{CH}_2) = -7.55 - 890 (l) \quad r^2 = 0.96 \quad (3)$$

Note, by definition that  $\sum(c + l \log L^{16})$  for the  $n$ -alkanes is also correlated to  $\Delta G(\text{CH}_2)$ . There is a reasonable correlation between the  $s$  phase constant and the  $c$  phase constant (Fig. 2 and Eq. 4). Those phases furthest removed from the best straight line generally have extreme values of the phase constants ratio  $a/s$ .

$$s = 4.91 \cdot 10^{-4} - 2.29 (c) \quad r^2 = 0.86 \quad (4)$$

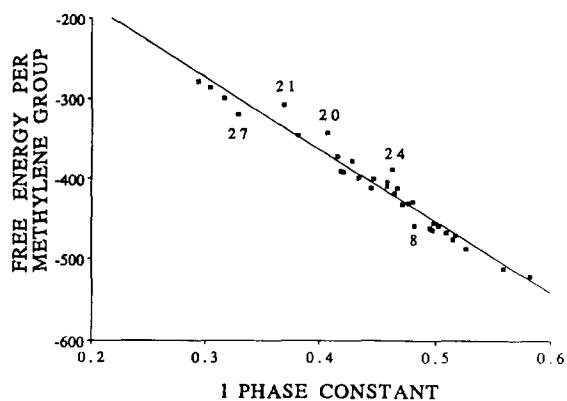


Fig. 1. Plot of the partial molar Gibbs free energy of solution for a methylene group (cal/mol; 1 cal = 4.184 J) against the  $l$  phase constant. Numbers refer to the phases identified in Table 1.

The magnitude of the  $c$  phase constant is largely determined by polar solvent-solvent interactions which must include other contributions ( $a$  phase constant in this case) besides those interactions of a dipole type. The general trend in the  $c$  and  $s$  phase constants, however, provides convincing evidence that the  $c$  phase constant is related to the energy required for cavity formation. Unfortunately, at the present time, we have no reliable method to dissect the product  $\sum(c + l \log L^{16})$  into precisely defined contributions of cavity formation and dispersion interactions. From an interpretive point of view the  $l$  phase constant indicates the spacing between members of a homologous series and contains useful information for phase selection. Retention, how-

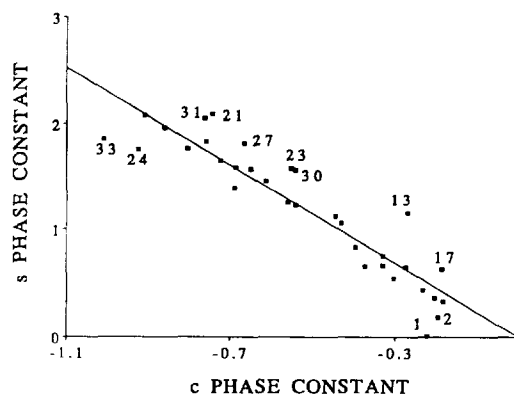


Fig. 2. Plot of the  $s$  phase constant against the  $c$  phase constant. Numbers refer to the phases identified in Table 1.

ever, is strongly dependent on the  $c$  phase constant as well, which is always in opposition to the  $l \log L^{16}$  term, so that phases with similar  $l$  phase constants exhibit significantly different absolute retention of solutes (Table 4). This is particularly striking in the case of certain of the liquid organic salts which have unusually large  $l$  phase constants compared to phases of similar polarity but also have characteristically large  $c$  phase constants. For example, QPC and OV-225 have virtually identical  $l$  phase constants but very different  $c$  phase constants, such that  $\log K_L$  (dodecane) on QPC is 1.657 and on OV-225, 2.113. A large  $l$  phase constant is desirable for general separations of polar and non-polar compounds. Phases with a small  $l$  phase constant and large  $c$  phase constant, such as OV-275, possess high selectivity for the separation of non-polar

Table 4  
Contribution of the phase constants to retention ( $\log K_1$ ) of dodecane

Phase	Phase constants		$l \log L^{16}$	$\sum(c + l \log L^{16})$
	$c$	$l$		
SQ	-0.222	0.583	3.321	3.099
OV-17	-0.372	0.518	2.951	2.579
QPC	-1.009	0.468	2.666	1.657
OV-225	-0.541	0.466	2.654	2.113
QTS	-0.686	0.459	2.614	1.928
CW 20M	-0.560	0.447	2.546	1.986
DEGS	-0.650	0.407	2.318	1.668
OV-275	-0.909	0.294	1.675	0.766



solutes from moderately polar solutes of similar volatility. The stationary phases in Table 2 differ significantly in their capacity for orientation and induction interactions, *s* phase constant, and solvent hydrogen-bond basicity, *a* phase constant. For solutes with complementary properties to the phase constants these interactions make significant contributions to retention (Table 3). The liquid organic salts are all dipolar, *s* = 1.4 to 2.0, and all hydrogen-bond bases, *a* = 1.4 to 5.4. In contrast the non-ionic phases have *s* phase constants from 0 to 2.1 and *a* phase constants from 0 to 2.1. The large *a* and *s* phase constants, and in some cases *l* phase constant as well, are the characteristic features that distinguish the liquid organic salts from non-ionic phases [24]. The identification of selective phases for specific dipolar and solvent hydrogen-bond base interactions will be dealt with subsequently. Principal component analysis and hierarchical clustering methods were applied to the data in Table 2 to classify the phases into groups with similar properties and to identify phases with unique characteristics. Principal component analysis performed with varimax rotation indicated that 99.9% of the variance in the data could be explained by four components (Table 5). The loadings for the principal components (Table 5) are equivalent to the coefficients of the linear equation defining how much each variable (phase constant) con-

tributes to the principal component (interaction) responsible for the solvation mechanism. The output from principal component analysis is displayed in the form of the score plots resulting from the projection of the data vector for the samples (phases) onto the principal components. Principal components (PCs) 1 and 2 are the most important and account for 95.9% of the variance in the data. The score plot, Fig. 3, shows three groups with QF-1, DDP, U50HB, OV-275, TCEP and QPC behaving independently (OV-275 and TCEP are tightly clustered and could be considered as a fourth group with a membership of 2). The loading for PC 1 is heavily weighted towards the *a* phase constant and can be considered as an axis of hydrogen-bond basicity. The loading for PC 2 is weighted towards the *s* phase constant with a significant contribution from the *c* phase constant. Given the approximate correlation of the *c* phase constant with the *s* phase constant (Eq. 4), it is reasonable to associate PC 2 with the capacity of the phases for orientation and induction interactions. That being the case, the phases identified in group 1 (SQ, SE-30, OV-105, OV-3, OV-7, OV-11, OV-17, OV-22, OV-25 and PPE-5) are weak hydrogen-bond bases differentiated by their capacity for modest orientation and induction interactions. QF-1 is loosely associated with this group and differs from them in having a greater capacity for

Table 5  
Summary of results from principal component analysis of 33 stationary phases

Principal component	Variance (%)	Cumulative variance (%)		
1	68.1	68.1		
2	27.8	95.9		
3	3.4	99.3		
4	0.7	99.9		
<i>Loadings for principal components</i>				
Phase constant	PC 1	PC 2	PC 3	
<i>r</i>	-0.002	-0.011	-0.008	
<i>s</i>	-0.007	0.961	-0.027	
<i>a</i>	0.999	-0.005	-0.004	
<i>l</i>	-0.004	-0.023	0.984	
<i>c</i>	-0.043	-0.274	0.175	

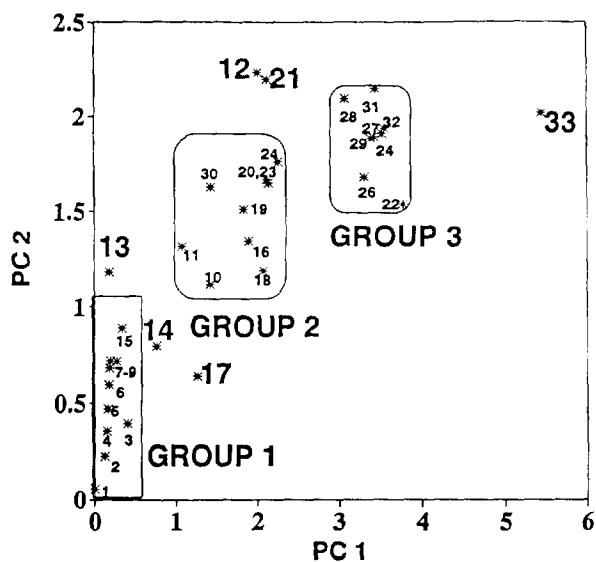


Fig. 3. Score plot for principal component 2 against 1. Numbers refer to the phases identified in Table 1.

orientation and induction interactions with similar hydrogen-bond basicity. DDP and U50HB have a similar capacity for orientation and induction interactions as the group 1 phases but are stronger hydrogen-bond bases. The phases identified in group 2 (OV-330, OV-225, CW 20M, THPED, EGAD, DEGS, QFMS, QPIC and QFBS) are distinguished from the phases in group 1 by their greater capacity for orientation and induction interactions and hydrogen-bond base interactions. They are towards the center of the scale defined by the two principal components so their properties have to be considered as intermediate (this is a diffuse group with respect to orientation and induction interactions and a tight group with respect to hydrogen-bond basicity). Loosely associated with this group are OV-275 and TCEP, which have similar hydrogen-bond basicity but a significantly greater capacity for orientation and induction interactions. OV-275 and TCEP have to be considered as exhibiting unique selectivity. Group 3, which contains only liquid organic salts (QMS, QTS, OBS, QACES, QTAPSO, QBES, QETS and QPN), is characterized by having a strong capacity for orientation and induction interactions and strong hydrogen-bond basicity. QPC to the right of the figure has to be considered exceptional in that it

has the largest capacity for solvent hydrogen-bond base interactions with a similar capacity to the other members of group 3 for orientation and induction interactions. The liquid organic salts are unique solvents whose properties cannot be duplicated by any of the non-ionic solvents. The score plot of PC 1 against PC 3, Fig. 4, accounts for 71.5% of the variance in the data. The loading for PC 3 is weighted towards the *l* phase constant with a significant contribution from the *c* phase constant. This component is dominated by the contribution from cavity formation and dispersion interactions to the solvation process. In this plot the phases in group 1 and group 2 in Fig. 3, remain largely intact. Squalane is removed from group 1 as it is significantly easier to form a cavity in this solvent than for the other phases in group 1 (assuming that dispersion interactions are approximately constant as a function of size for all solvents). The group 2 phases have similar cavity forming requirements to the group 1 phases but are more basic. DEGS and QFMS are now removed from group 2 and are distinguished from them by the greater energy required in forming a cavity in the solvent. PC 3 has most influence on group 3 phases which are now widely dispersed on the right-hand side of the figure corresponding to

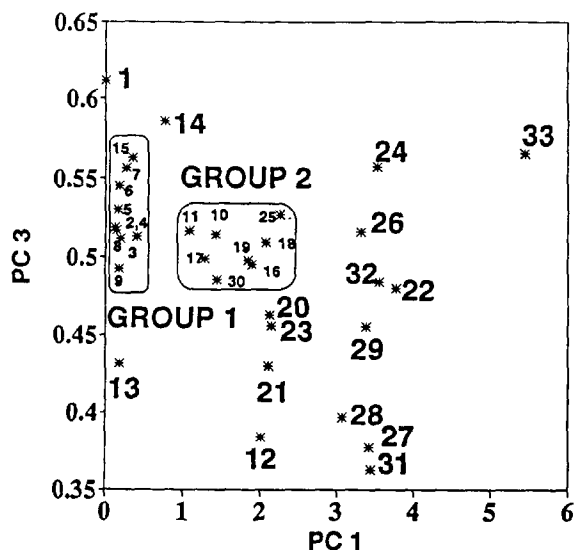


Fig. 4. Score plot for principal component 3 against 1. Numbers refer to the phases identified in Table 1.

similar hydrogen-bond basicity but significantly different requirements for cavity formation. TCEP and OV-275 are similarly separated. Fig. 4 accents an important selection requirement for the group 3 solvents; some of the liquid organic salts provide general retention properties similar to the less basic phases while others can be expected to discriminate against non-polar solutes and yield very low retention (this is true of OV-275 as well). The score plot of PC 2 against PC 3 accounts for 31.2% of the variance in the data. In this plot, Fig. 5, there is a rough general correlation between the capacity of a phase for orientation and induction interactions and for cavity formation and dispersion interactions as demonstrated by the diagonal relationship and the large area of the principal component space that is left empty. The group 1 phases, with the exception of OV-22, OV-25 and SQ lie across the diagonal. Within this group, the poly(siloxane) phases with a high methyl group content have a low capacity for orientation and induction interactions combined with ease of cavity formation while replacing methyl groups with phenyl groups increases both the capacity for orientation and induction interactions and the energy required for cavity formation. The group 2 phases are aligned approximately diagonally in-

dicating that for these phases the increasing energy required to form a cavity is associated with the capacity of the solvent for orientation and induction interactions. The group 3 phases are widely distributed parallel to the horizontal axis as all these phases have a significant capacity for orientation and induction interactions as well as a significant range of energy requirements to form a cavity in the solvent. An alternative classification method to principal component analysis is cluster analysis. In this technique a distance matrix in multivariate space is formed and the Euclidean distance between samples or groups of samples (phases) to each other is used as a measure of the similarity of the samples for all the properties contained in the data matrix. A number of distance metrics can be used as the basis of the cluster algorithm with the final output as a connection dendrogram. The data in Table 2 were analyzed by a number of cluster algorithms with the complete link (farthest neighbor) approach deemed the most appropriate (there was a great deal of similarity in the results obtained for all methods with the single link method showing the greatest variation, but even in this case the differences were small). The complete link dendrogram is shown in Fig. 6. Descendants with a similarity of 1 would be identical and those with a similarity of 0 possessing no properties in common. The major groupings in Fig. 6 agree with the group membership for Fig. 3 with minor differences. The paired descendants indicate the level of similarity between two phases. For example, OV-22 and OV-25 are very similar in their properties and so are OV-275 and TCEP. As a group the liquid organic salts in group 3 have the least in common with the remaining phases. Phases which are singular descendants have properties that differ most of all from the other phases. This includes DEGS, QPIC, THPED, U50HB, PPE-5, DPP, QF-1, SE-30, OV-105, SQ, QMS, QTS, QTAPSO, QETS and QPC. The interesting phases are those that have no descendants and little similarity to their nearest neighbor, as these are the phases that it is most difficult to duplicate their properties by using another phase represented in the data collection. In this sense the most unique solvents are U50HB, QF-1, QMS and QPC. The

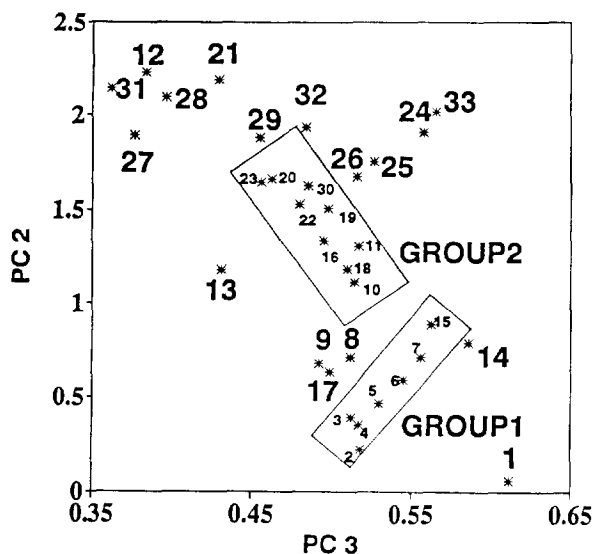


Fig. 5. Score plot for principal component 2 against 3. Numbers refer to the phases identified in Table 1.

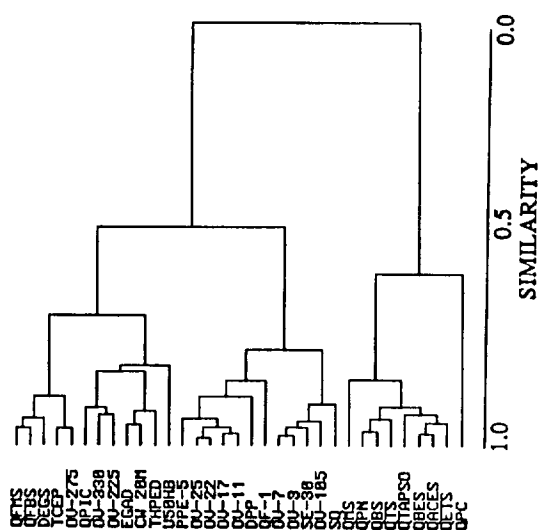


Fig. 6. Complete link dendrogram obtained by cluster analysis of the data in Table 2.

dendrogram is very useful for indicating similarity in a simple visual format but must be used with the group classification to indicate the most useful phases for method development. For example, the fact that OV-275 and TCEP are similar in properties does not mean that neither phase has desirable solvent properties for method development. Rather, either of them is a good candidate as a preferred phase for methods development since they belong to a group whose membership is significantly different to the properties of their neighboring group to which they have most similarity. Thus, it would be sensible based on their solvent properties to select one of the phases QFMS, QFBS, DEGS, TCEP and OV-275 as a preferred phase (the top group in Fig. 6) but a better choice could be made for the next phase to select than to take a second phase from this group.

#### 4. Conclusions

The data in Table 2 combined with the interpretation in Figs. 3–6 allow 9 phases to be identified as representative of the collection of phases studied. This includes phases characteristic of a

group as well as phases characteristic of themselves. The list would include squalane (case of cavity formation and dispersion interactions), OV-17 (weak orientation, induction, and hydrogen-bond basicity and ease of cavity formation), QF-1 (intermediate orientation and induction interactions with low hydrogen-bond basicity and ease of cavity formation), U50HB (intermediate hydrogen-bond basicity with weak orientation and induction interactions and ease of cavity formation), CW 20M (intermediate orientation, induction, and hydrogen-bond basicity and ease of cavity formation), QMS (large contribution from hydrogen-bond basicity, intermediate orientation and induction interactions, and intermediate ease of cavity formation), QTS (large orientation, induction and hydrogen-bond basicity, and intermediate ease of cavity formation), QPC (as for QTS except that this phase is an exceptionally strong hydrogen-bond base and is more cohesive with respect to the difficulty of cavity formation), and OV-275 (very cohesive solvent with unfavorable cavity formation, strong orientation and induction interactions, intermediate hydrogen-bond basicity). As discussed previously this list does not contain any phases with a significant capacity for solvent hydrogen-bond acid interactions or strong electron pair donor–acceptor interactions. These interactions are not well represented among the liquid phases commonly used in gas chromatography today. The above discussion has only concerned solvent properties while other practical considerations such as the useful liquid temperature range, coating characteristics, etc., are equally important as selection criteria. Also, those phases characteristic of a group could justifiably be substituted by other phases within the same group. Committees should be left to ponder the question of selecting preferred phases given that other phases than those studied here should also be considered. The above work, we believe, supplies a rational approach for the work of these committees and for those interested in the development of new stationary phases with an expectation of providing different separation characteristics to existing phases. It is important to note that the data in Table 2 were acquired at a common temperature of 121.4°C. It should

provide a reasonable guide to the selection of phases for particular applications in the neighborhood of the reference temperature. Little is known about the change in phase constants as a function of temperature [11,25,33] and what information is available is in conflict. Selectivity changes with temperature, however, are likely to be phase dependent, and it cannot be assumed that the ranking order produced at one temperature will hold at all temperatures. When using Eq. 1 to predict retention on different phases it should be remembered that this equation refers to a gas–liquid partition model and that predictions will be less reliable for separation conditions and phases where interfacial adsorption is a significant retention mechanism [1,2,41].

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