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Computer simulation as an aid in method development for gas chromatography

II. Changes in band spacing as a function of temperature

J. W. DOLAN, L. R. SNYDER* and D. E. BAUTZ
LC Resources Inc., 3182C Old Tunnel Road, Lafayette, CA 94549 (U.S.A.)
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ABSTRACT

Several different samples and three stationary phases of varying polarity have been examined for changes in band spacing as a function of temperature. The results of these studies have been expressed as a relative variability in the temperature coefficients of retention (S) for adjacent bands. A theoretical analysis suggests that useful changes in band spacing *vs.* temperature (or heating rate) can be expected when the difference in S values (ΔS) for two bands is larger than 1 to 2%. The samples studied exhibited variations in average values of ΔS of 0.6–6%. This suggests that optimizing the (isothermal) temperature or (programmed) heating rate of a gas chromatographic separation will often be advantageous.

INTRODUCTION

The preceding paper [1] describes software (DryLab GC) for the computer simulation of gas chromatographic (GC) separations as a function of isothermal temperature or temperature programming. Similar software exists (DryLab G) for the prediction of separations in high-performance liquid chromatography (HPLC) as a function of gradient conditions [2–8]. The fundamental theory of GC [9] and HPLC [10,11] suggests that temperature plays the same role in GC as mobile phase composition (%B) plays in HPLC. Therefore our detailed and comprehensive understanding of HPLC separation as a function of %B or gradient steepness [10-15] can be used to guide our development of GC separations as a function of temperature or programming rate. Many of the rules and generalizations that apply to gradient elution can be adapted directly to temperature-programmed GC.

Of major interest in this connection is the possible change in band spacing for a sample as the temperature is changed in a GC separation. Similar changes in band spacing as %B varies in HPLC are extensively documented [12–15], suggesting the usefulness of optimized multi-segment gradients [2–8, 13–15]. Several workers [16–18] have specifically noted changes in GC band spacing as temperature is varied, and similar results are reported elsewhere [19–22]. In this paper we will further explore

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these temperature-related changes in GC selectivity and relate them to the development of optimized temperature programs.

THEORY

Origins of temperature-related changes in GC band spacing

The capacity factor k_i of a solute i in GC is related to absolute temperature T as [23]

$$-T \ln k_i = -(\Delta H_{v,i}/R) + T[(\Delta S_{v,i}) + \ln \beta] \quad (1)$$

Here $\Delta H_{v,i}$ and $\Delta S_{v,i}$ refer to the partial molal enthalpy and entropy of vaporization from the stationary phase, respectively, R is the gas constant, and β is the phase ratio. Often the entropy of vaporization is roughly constant for different solutes and the same column (a variant of Trouton's rule [24]), or the enthalpy and entropy of retention for the components of a sample are related as

$$\Delta H_{v,i} \approx a\, \Delta S_{v,i} + b \quad (2)$$

where a and b are constants for the different solutes in a given sample. In either of these two cases, band spacing should not change with temperature, because it can then be shown that values of k are highly correlated with values of $\Delta H_{v,i}$ for a given separation temperature, and adjacent bands (with similar values of k) will then have similar values of $\Delta H_{v,i}$. Conditions that favor the applicability of Trouton's rule or eqn. 2 are (i) solute molecules that are similar to each in other in shape and size and (ii) non-polar solutes and/or stationary phases. Thus constancy in the entropy of retention requires solute molecules of similar shape, size and polarity; see also the discussion of ref. 25.

Similarly, eqn. 2 assumes either (i) solute–stationary phase interactions of the same "kind" for each solute in the sample, or no dependence of these interactions on temperature. Polar interactions (dipole–dipole or hydrogen bonding) decrease in strength with increasing temperature, while non-polar (dispersion) interactions do not. Thus if the overall polarity of the solute molecules in a given sample varies from one solute to the next, the dependence of k on temperature will also vary, and band spacing should change with temperature.

The basis of these changes in band spacing as a function of temperature (isothermal run) or heating rate (programmed run) is illustrated in Fig. 1 in terms of our linear-elution-strength (LES) model of GC retention. The LES approximation used in the present treatment (eqn. 4 of Part I) can be expressed as

$$\log k = \log k_o - S(T - T_o) \quad (3)$$

where S is a constant for a given solute, and k_o is the value of k at the starting temperature T_o. The slopes of the linear plots in Fig. 1 for solutes i and j are equal to the values of S (S_i and S_j) for each solute, and it is seen that $S_j > S_i$. As a result of this difference in S values, solute i elutes after j for temperatures $T < 180°C$, and before i for $T > 180°C$. At $T = 180°C$ the two solutes have the same retention time and are unresolved.

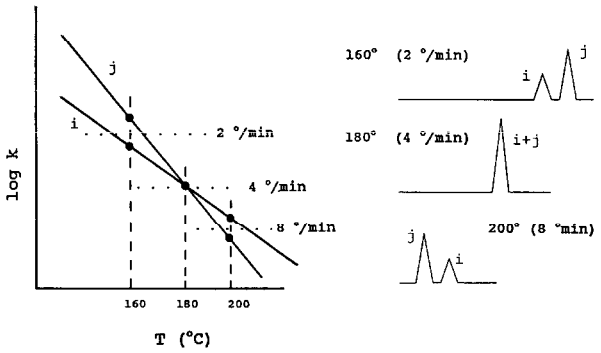

Fig. 1. Dependence of GC separation on isothermal plots of log k *vs.* temperature. See text for details.

The separation of the sample of Fig. 1 with a linear temperature program leads to similar results if the heating rate (instead of T) is varied. Thus in the analogous case of HPLC gradient elution, the linear-solvent-strength (LSS) approximation [10] predicts a value of k' that provides the same separation of a band pair in either isocratic or gradient elution. We will refer to this quantity as k' for isocratic separation and $\bar{k}$ for gradient elution. The value of $\bar{k}$ is determined by gradient steepness. A similar relationship for temperature-programmed GC can be assumed from the LES approximation of the present treatment (see later discussion of Figs. 4–6), with $\bar{k}$ given by[a]

$$\begin{aligned} \bar{k} &= 0.87\, t_P F/(V_m\, \Delta T\, S) \\ &= 0.87/(t_0\, r\, S) \\ &= 0.87/b \end{aligned} \tag{4}$$

Here t_P is the program time (run time for a linear program), F is the flow-rate, V_m is the column dead-volume, ΔT is the change in temperature during the program, S is defined by eqn. 3, t_0 is the column dead-time, and r is the heating rate (°/min); $b = (t_0\, r\, S)$ is another measure of the steepness of a linear temperature program.

For a given program steepness b, the separation of any pair of adjacent bands will be the same as in an isothermal separation with some temperature T, when k (isothermal) $= \bar{k}$; here, k' and k refer to the average value for the band-pair. Values of S will be similar (but not exactly constant) for different solutes[b], so that values of $\bar{k}$ will also be approximately the same for different bands in a temperature programmed run (linear program). This contrasts with the variation of k for different bands in isothermal separation. Thus in plots as in Fig. 1, isothermal runs can be represented by vertical lines (for the same temperature), whereas programmed separations are given by horizontal lines (for a given value of $\bar{k}$ or programming rate).

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[a] The quantity $\bar{k}$ in a temperature-programmed separation corresponds to the value of k for a band when it has migrated halfway through the column; see the related discussion of ref. 10 for gradient elution.

[b] The following discussion of Fig. 1 is deliberately simplified in order to give the reader a clearer picture of the interrelationship of isothermal and programmed-temperature separation. The approximations used here do not limit the accuracy of computer simulation as described in this and the preceding paper.

In the example of Fig. 1, it is assumed for purposes of discussion that k for an isothermal separation at 160°C is equal to $\bar{k}$ for a programmed run at 2°/min; similarly, isothermal separation at 180°C is equivalent to a programmed run at 4°/min, etc. In the GC system of Fig. 1, it is seen that i and j elute together for a 4°/min temperature program. For heating rates < 4°/min, j is retained more strongly, and *vice versa* for heating rates > 4°/min. This situation described in Fig. 1 is essentially similar to the liquid chromatographic separation of a sample, with %B varied rather than temperature (see the Discussion of refs. 12,14).

Correlation of values of S and k_o

During the application of DryLab GC to a given sample, values of log k_o and S are determined for each solute. If a plot of values of S *vs.* log k_o describes a single curve with little deviation of individual points from the curve (*e.g.*, Fig. 2A), there will be no changes in band spacing with change in temperature. Significant deviations of individual data points from such a curve (*e.g.*, Fig. 2B,C), on the other hand, will favor changes in band spacing as temperature is varied. It will prove useful to determine these average deviations in S for different samples —as an indication of the significance of band-spacing changes with temperature.

Dependence of separation on temperature (or heating rate) and values of S

A previous treatment for HPLC [12] has examined the necessary difference in solute S values that will allow the resolution of an initially unresolved band-pair by varying mobile phase composition (%B). Isocratic systems can be approximated by the LSS model, and the required fractional difference in S values for two adjacent bands ($\Delta S/S$) is (isocratic HPLC)

$$\Delta S/S = (8/2.3)\Delta R_s\, N^{-0.5}\, [(1+k')/k']/\log(20\, k_a/k_z) \qquad (5)$$

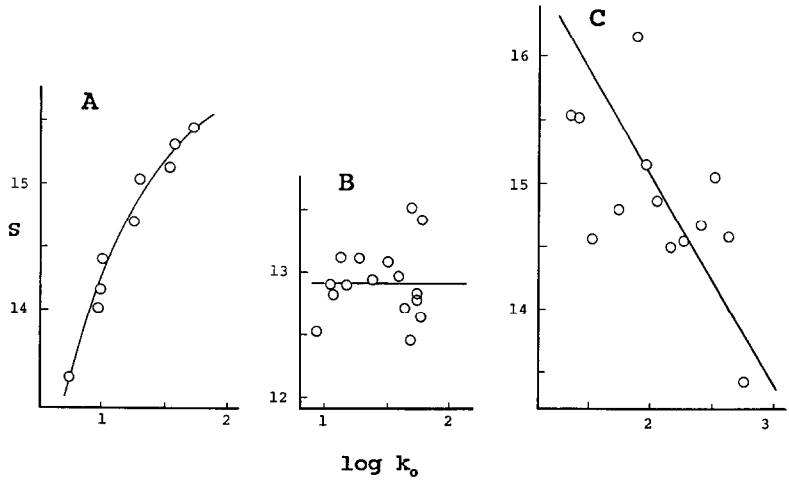

Fig. 2. Band-to-band variations in S for different samples. Conditions: DB-5 column; (A) rapeseed oil; (B) pesticides; (C) herbicides. See text for details.

Here S is the average of S values for the two bands, ΔR_s refers to the necessary increase in resolution (to be achieved by a change in %B), N is the column plate number, and k_a and k_z are the k' values of the first and last bands in the chromatogram. Because of the similarity of LC and GC separation in terms of the LSS and LEC approximations (see above discussion of eqn. 4), a relationship similar to eqn. 5 can be derived for GC separation as well. As a result of the wider range of k'–values (*ca.* 50-fold) that can be used in isothermal GC *vs.* isocratic LC, eqn. 5 must be modified to give (isothermal GC)

$$\Delta S/S = (8/2.3)\Delta R_s N^{-0.5}[(1+k)/k]/\log(50\ k_a/k_z) \quad (5a)$$

We can specify the necessary difference in S values for two unresolved bands such that a change in temperature will result in their separation with some required value of R_s. Assume (i) a required value of $\Delta R_s = 1.0$ (although smaller increases in resolution will often suffice), (ii) average value of $N = 100\,000$, (iii) the average value of k for a given band-pair = 5, and (iv) let the ratio $k_z/k_a = 10$. The necessary value of $\Delta S/S$ is then 0.019; *i.e.*, a 1.9% difference in the S values for the two solutes. If separation conditions can be selected that yield average differences in S of this magnitude, a change in temperature has a good chance of resolving an initially unseparated pair of bands.

The situation is somewhat more attractive for the case of a temperature-programmed GC run, as can be inferred from the similar discussion of ref. 12 for LC gradient elution. The corresponding equation for the required difference in solute S values is (temperature-programmed GC)

$$\Delta S/S = (8/2.3)\ \Delta R_s N^{-0.5}[(1+\bar{k})/\bar{k}]/\log(50) \quad (5b)$$

and the necessary value of $\Delta S/S$ is then only 0.008; *i.e.*, less than a 1% difference in S values.

A reviewer has asked whether the parameter S and related changes in band spacing with temperature are determined by the entropy or enthalpy of vaporization of the solute. S itself is more closely related to enthalpy than to entropy, but the related band spacing changes are determined by the *relationship* of entropy to enthalpy (deviations from eqn. 2).

EXPERIMENTAL

All experimental materials and procedures are discussed in the preceding paper [1].

RESULTS AND DISCUSSION

Part I [1] established that computer simulation (with DryLab GC) can be used in place of actual experimental runs to study GC separation as a function of conditions. A number of different samples were also described, any of which can be simulated in this fashion. In the following discussion we can therefore use simulated and experimental runs interchangeably, in order to gain increased insight into the effects of experimental conditions on band spacing and separation.

Similarity of separation by programmed-temperature and isothermal GC

In separations by HPLC, it has been shown [10] that the same separation of a group of adjacent bands can be achieved by either isocratic or gradient elution, provided that gradient conditions are adjusted so that the average k' value in the isocratic separation is equal to the average $\bar{k}$ value in gradient elution. Having specified the gradient conditions (%B/min, flow-rate, etc.), a corresponding value of gradient steepness b is defined[a], from which $\bar{k} = 1/1.15b$. A mobile phase composition (value of %B) can then be selected such that $k' = \bar{k}$.

We can proceed in the same way to show that a similar relationship exists for isothermal and temperature-programmed GC (as illustrated in Fig. 1). The value of this exercise will be more apparent in the following section, where we will examine changes in band spacing as a function of heating rate in temperature-programmed GC, *vs.* similar effects for isothermal separations. Fig. 3B shows a partial chromatogram of a spearmint oil, with one band-pair indicated by an asterisk. The values of S for these two bands are approximately equal (16.4 and 16.5, respectively), so that only

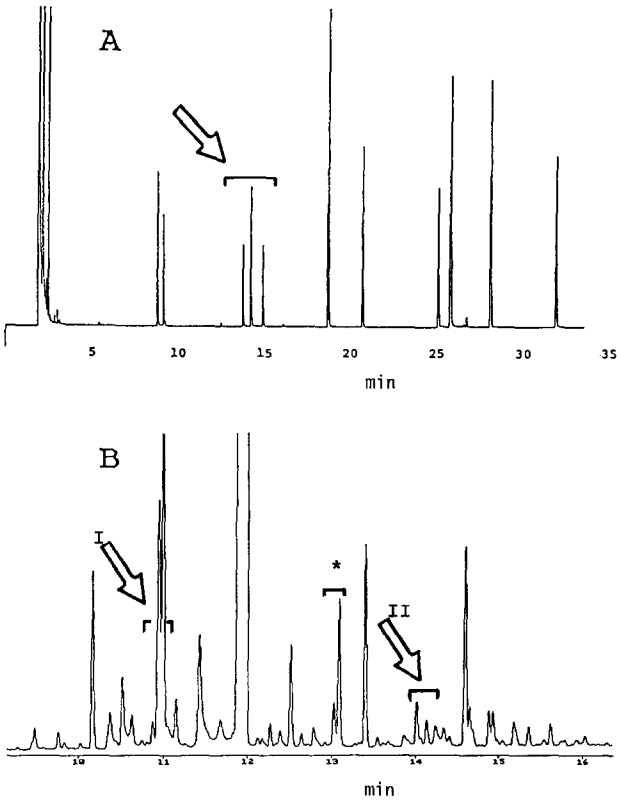

Fig. 3. Separation of phenol (A) and spearmint oil (B) samples by GC. Conditions: DB-5 column, 1 ml/min; (A) 50–200°C at 4.6 °C/min; (B) 50–300°C at 8 °C/min.

[a] For gradient elution, $b = V_m \Delta\varphi S/t_G F$, where $S = -\mathrm{d}(\log k')/\mathrm{d}\varphi$; see ref. 4; φ is the volume fraction of strong solvent B in a binary mobile phase A–B.

minor change in band spacing with change in temperature or heating rate is expected (for a moderate change in k or $\bar{k}$). This example will therefore serve as a reference case for comparison with the separation (as a function of temperature) of band pairs having different values of S.

Fig. 4 shows the change in separation (and resolution) of this band-pair (asterisk in Fig. 3B) as a function of heating rate (programmed separations, top; iso-

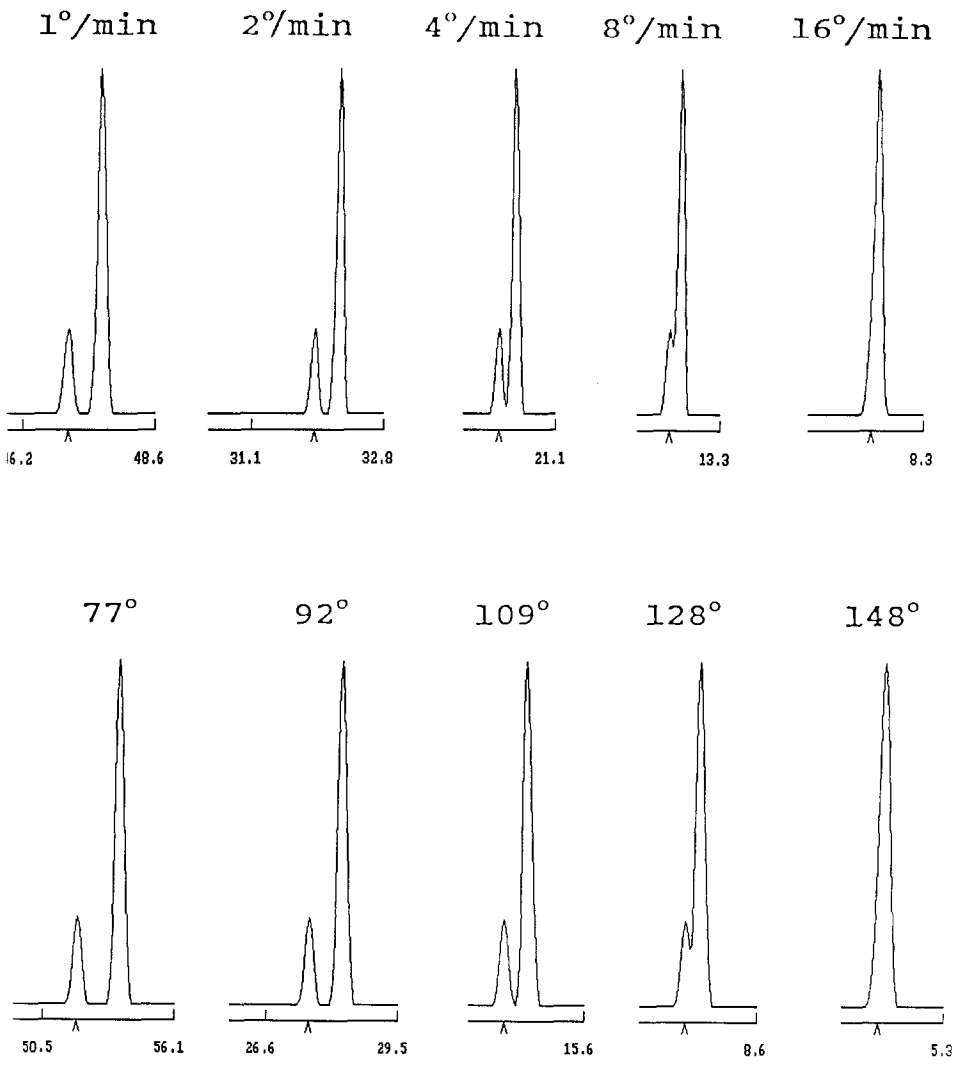

Fig. 4. Corresponding separations of band-pair marked by an asterisk in Fig. 3B (spearmint oil); temperature-programmed (top) *vs.* isothermal (bottom). Computer simulations based on experimental runs used as input for DryLab GC (2 and 8 °C/min, 50–300°C). Isothermal temperatures (bottom) chosen to give $k = \bar{k}$ for corresponding runs (*e.g.* 1°C/min and 77°C).

TABLE I

SUMMARY OF SEPARATIONS OF FIG. 4

Heating rate (°C/min)	b	$\bar{k}$	T^a (°C)	R_s	
				Prog[b]	Iso[b]
1	0.0295	29	77	2.1	2.7
2	0.059	14	92	1.8	2.1
4	0.110	7.2	109	1.4	1.5
8	0.236	3.6	128	1.0	0.9
16	0.472	1.8	148	0.5	0.4

[a] Temperature for isothermal separation where $k = \bar{k}$.
[b] Programmed-temperature ("Prog") and isothermal ("Iso") values.

thermal temperature bottom). The isothermal temperatures were selected[a] to give $k = \bar{k}$ for each set of corresponding runs (1°C/min, 77°C; 2°C/min, 92°C; etc.). It is readily seen that corresponding programmed and isothermal separations are generally similar, as predicted by analogy from the case of isocratic *vs.* gradient elution in HPLC. Table I provides a quantitative assessment of the comparisons of Fig. 4. Here it is seen that the resolution of corresponding runs (where $k = \bar{k}$) is about the same, as expected; the only exceptions are for large values of k, where the isothermal resolution tends to be a little higher (this minor discrepancy is a consequence of the LES approximation). The concept (embodied in Fig. 1) of corresponding temperature-programmed and isothermal separations is nevertheless confirmed.

Variability of values of S for different solutes

Values of S and k_0 were obtained for the components of several samples that were separated on the three columns described in ref. 1. Plots of S *vs.* $\log k_0$ were made for each sample/column combination, as illustrated in Fig. 2. The average deviation of values of S from the best-fit curve was determined and expressed as a "deviation in S" (%). Table II summarizes these results. Returning to Fig. 2A, we see that the relatively non-polar rapeseed-oil sample separated on the slightly polar DB-5 column shows only minor deviations of data points from the solid curve ($\pm 0.4\%$, see Table II). The more polar herbicide sample of Fig. 2C, however, exhibits a considerably greater scatter of data points, and the average deviation in S is correspondingly larger ($\pm 2.5\%$, Table II). The pesticide sample of Figure 2B exhibits an intermediate scatter of data points ($\pm 1.6\%$ in S, Table II).

As noted in the Theory section, deviations of S as in Fig. 2 (for a given GC system) should be smaller for non-polar samples separated on less polar stationary phases. Systems 1–3 of Table II are examples of "non-polar/non-polar" separations of this type, and moderate deviations in S are found[b] (1.6–2.3) as expected. The

[a] That is, given a heating rate r (*e.g.*, 2°C/min), eqn. 4 defines a value of $\bar{k}$, and eqn. 1 ($k = \bar{k}$) results in a corresponding value of the temperature T (*e.g.*, 92°C in the present example).

[b] The deviations in S for the gasoline samples (Nos. 1,2) of Table II are known to arise mainly from differences in molecular shape [25]; *e.g.*, *n*-alkanes *vs.* branched alkanes *vs.* cyclic hydrocarbons of various kinds. Similar differences in shape exist for the pesticide sample (No. 3) of Table II.

TABLE II

SUMMARY OF BAND-TO-BAND VARIATIONS IN S AS DETERMINED FROM PLOTS OF S *VS.* LOG k_0 FOR VARIOUS SAMPLES AND COLUMNS

See text and Fig. 2.

No.	Sample	Column	Deviations in S^a (%)	$\Delta S/S^b$
1	Gasoline A	SPB-1	1.8	0.025
2	Gasoline B	SPB-1	2.3	0.032
3	Pesticides	DB-5	1.6	0.022
4	Lime oil	DB-5	2.2	0.031
5	Lemon oil	DB-5	2.5	0.035
6	Rapeseed oil	DB-5	0.4	0.006
7	Barbiturates	DB-5	1.0	0.014
8	Herbicides	DB-5	2.5	0.035
9	Phenols	DB-5	4.8	0.067
10	Spearmint oil	Nukol	4.2	0.059
11	Peppermint oil	Nukol	4.4	0.062

[a] Average absolute deviation of values of S from best-fit curves as in Fig. 2.

[b] Average difference in S values (ΔS) for two adjacent bands, divided by S [ΔS is equal to $(2)^{0.5}$ times the "deviation in S"].

separation of moderately polar samples on less polar columns should also yield smaller deviations in S, when the solutes have a similar shape and functionality; examples of such separations are provided by systems 4–7 of Table II (deviations in S of ± 0.4–2.5%). Larger deviations of S from "best-fit" values are expected (and found) for (i) polar samples of varying functionality (systems 8 and 9 of Table II: ± 2.5–4.8%) and (ii) separations of moderately polar samples of similar functionality on polar columns (systems 10 and 11 of Table II: ± 4.2–5.9%).

The dependence of GC band-spacing on deviations in S and temperature

We have seen (Fig. 1) that differences in S for adjacent bands lead to changes in relative retention (band spacing) when the temperature is changed in isothermal separations, or when the heating rate is varied in temperature-programmed runs. Eqn. 5a and b of the Theory section describe the necessary difference in solute S values for a change in temperature or programming-rate to enable the resolution of a previously unresolved band pair. The values of $\Delta S/S$ are 0.008 (temperature programming) and 0.019 (isothermal), respectively. The average values of $\Delta S/S$ for the systems of Table II are in almost every case large enough to assure significant changes in band spacing as a result of varying the column temperature or heating rate. That is, the optimization of temperature or heating rate should be useful for the separation of most samples. A collaborative study of six randomly selected samples by five different laboratories has since found this to be true in every case [26].

The preceding discussion can be summarized as follows. A change in isothermal temperature or in the heating rate of a temperature-programmed GC separation will often lead to useful changes in band spacing and resolution. The likelihood of such changes in separation will increase for more polar stationary phases, for more polar

sample molecules, and for solutes of varying functionality or molecular shape. Some of these generalizations have been pointed out by other workers [17], and examples of these effects can be clearly seen in a number of published studies.

Examples of changes in band spacing with changes in heating rate or isothermal temperature

The various samples studied by us offer many examples of changes in band spacing with experimental conditions; *i.e.*, a change in the steepness of the temperature program or a change in isothermal temperature. Fig. 3 shows chromatograms of the phenol (A) and spearmint oil (B) samples, with specific band-triplets indicated (arrows) for further discussion.

Phenol sample. The band-triplet noted in Fig. 3A (arrow) consists of 2-nitrophenol, 2,4-dimethylphenol and 2,4-dichlorophenol. Fig. 5 shows the separation of this group of solutes as a function of heating rate in temperature-programmed separation (top) or isothermal temperature (bottom). The isothermal runs are selected to provide $k = \bar{k}$ (corresponding conditions) for the matched runs (1°C/min *vs.* 51°C, 4°C/min *vs.* 83°C, etc.). As in the examples of Fig. 4, corresponding separations are in each case quite similar in terms of resolution. However these separations show band spacing changing with heating rate or temperature, due to significant differences in S values for the compounds in question (Table III). In this case, the middle band (No. 2) has a larger value of S (15.6) *vs.* the values (14.6 and 14.7) of the first and last

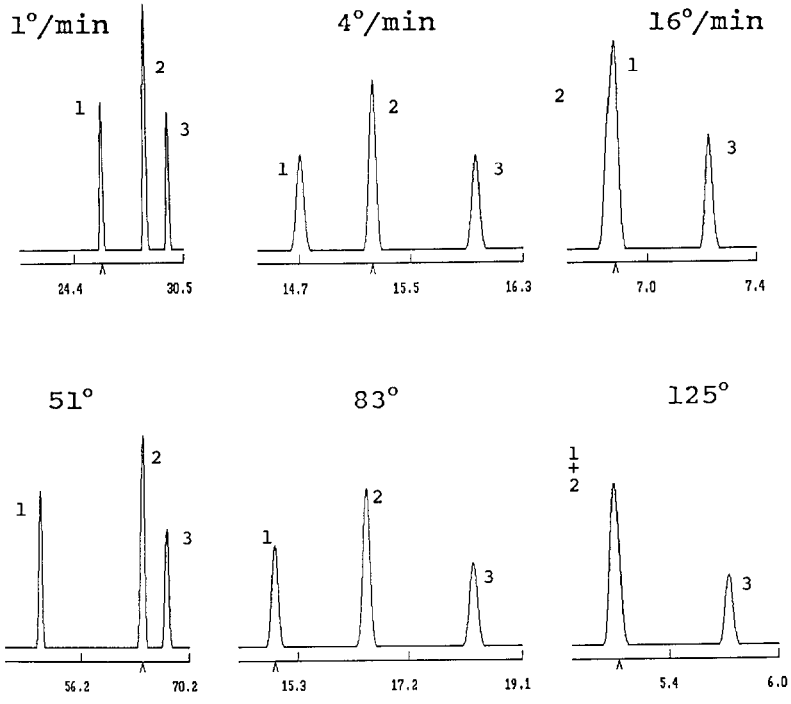

Fig. 5. Corresponding separations of phenol triplet from Fig. 3A (computer simulation). Conditions as in Fig. 3A, except as noted. Bands: 1 = 2-nitrophenol; 2 = 2,4-dimethylphenol; 3 = 2,4-dichlorophenol.

TABLE III

VALUES OF S FOR SELECTED COMPOUNDS IN THE SEPARATIONS OF FIG. 3

Solute group[a]	S^b			$\Delta S/S$	
	1	2	3	2/1	3/2
Phenols	14.6	15.6	14.7	0.066	−0.060
Spearmint-I	16.4	16.3	16.6	−0.008	0.024
Spearmint-II	16.1	16.7	16.1	0.031	−0.031

[a] Indicated by arrows in Fig. 3; phenols (A) and spearmint oil (B).
[b] Values of S for indicated band (see Figs. 5 and 6).

bands. This means (see Fig. 1) that as k or $\bar{k}$ is increased, band 2 should move toward band 3. Examination of the examples of Fig. 5 shows this effect quite clearly. Thus for a slow heating rate (1°C/min) or a lower temperature (51°C), band 2 lies closer to band 3 than to band 1. As the heating rate or isothermal temperature is increased,

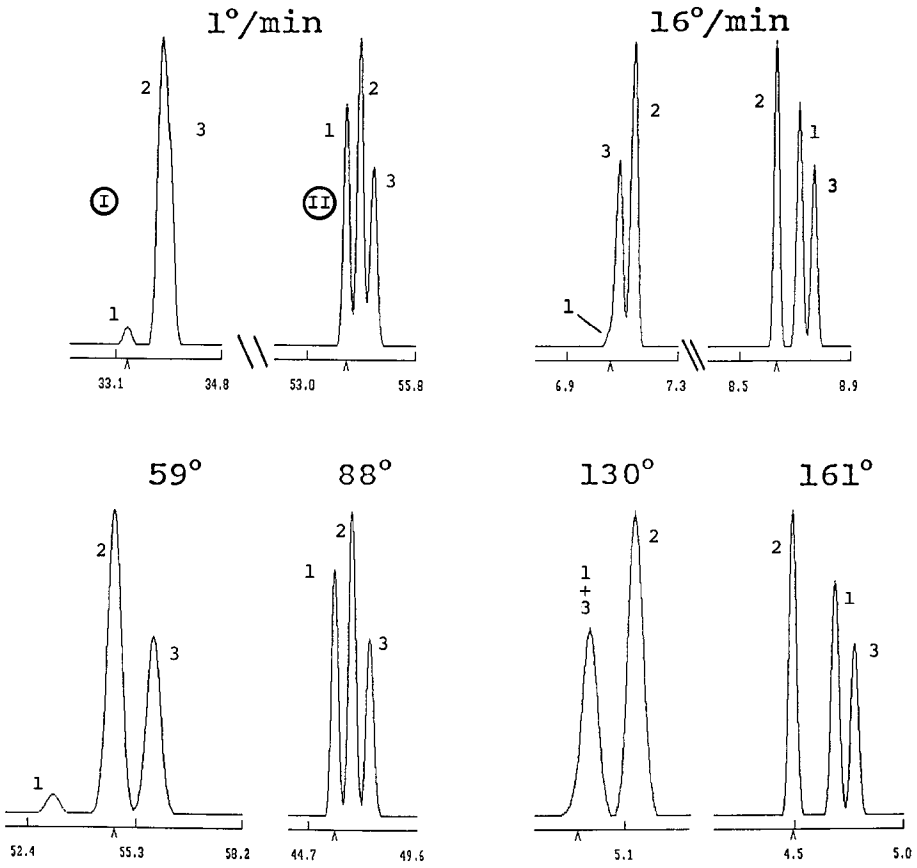

Fig. 6. Separation of band groups I and II of the spearmint oil sample (Fig. 3B, arrows) as a function of heating rate or isothermal temperature. Conditions as in Fig. 3B, except as noted.

band 2 moves toward band 1, and for the separations on the right of Fig. 5 (16°C/min or 125°C) bands 1 and 2 have merged together.

Conditions for the optimized separation of the sample of Fig. 5 would yield an equal spacing of the bands in temperature-programmed separation, corresponding to a heating rate $r = 3$°C/min. This example also emphasizes the importance of optimizing temperature-programmed or isothermal conditions for obtaining the best separation of a given sample.

Spearmint oil sample. Two groups of bands (I and II) are noted in the separation of Fig. 3B, each of which exhibits change in band spacing when heating rate or isothermal temperature is varied (Table III summarizes the relevant S values). For band-group I the last band (No. 3) has a higher value of S than the other two bands, therefore band 3 should migrate toward bands 1 and 2 as the heating rate or isothermal temperature is increased. For band-group II the second band (No. 2) has a higher value of S, so it should move toward band 1 as the heating rate or temperature is increased.

Fig. 6 shows the separation of these two band groups as a function of increase in heating rate or isothermal temperature. The vertically matched runs in Fig. 6 are for corresponding conditions ($k = \bar{k}$), and there is again a general similarity[a] in resolution for these matched runs. The general trends predicted by the S values of Table III are confirmed in these examples, and it is seen that these changes in band spacing even result in reversals of retention order: for band-group II, an increase in heating rate or temperature results in the inversion of the elution order of bands 1 and 2.

Fig. 7 shows the corresponding resolution maps for each band-group (I, 7A; II, 7B) of the spearmint sample, as well as the separation for an optimized heating rate (arrow). These examples again illustrate the potential dependence of separation on heating rate in temperature-programmed GC runs. Similar maps could be constructed for the isothermal separations, but these are not shown.

Change in column length or flow-rate

Once a temperature program has been designed for optimum band spacing (and resolution), it may be desirable to change the column length or flow-rate as a means of either increasing resolution or decreasing run time. It is important to recognize that a change in column length or flow-rate will generally change the band spacing, according to eqn. 4. That is, *if it is desired to maintain the same band spacing when varying column length or flow-rate, the value of b (or $\bar{k}$) in eqn. 4 must be maintained constant.* For example, if column length is increased by a factor x, or flow-rate is decreased by the same factor, then run time must be increased by x-fold. Otherwise b (and $\bar{k}$) changes, and band spacing can change as well; as seen in Fig. 1.

CONCLUSIONS

Previous workers have recognized that changes in band spacing (values of α) are possible when the column temperature is changed in GC, especially for mixtures of

[a] The similarity of corresponding separations in Figs. 5 and 6 is less pronounced than in Fig. 4, because eqn. 4 is strictly correct only for the case of band-groups that have equal S values.

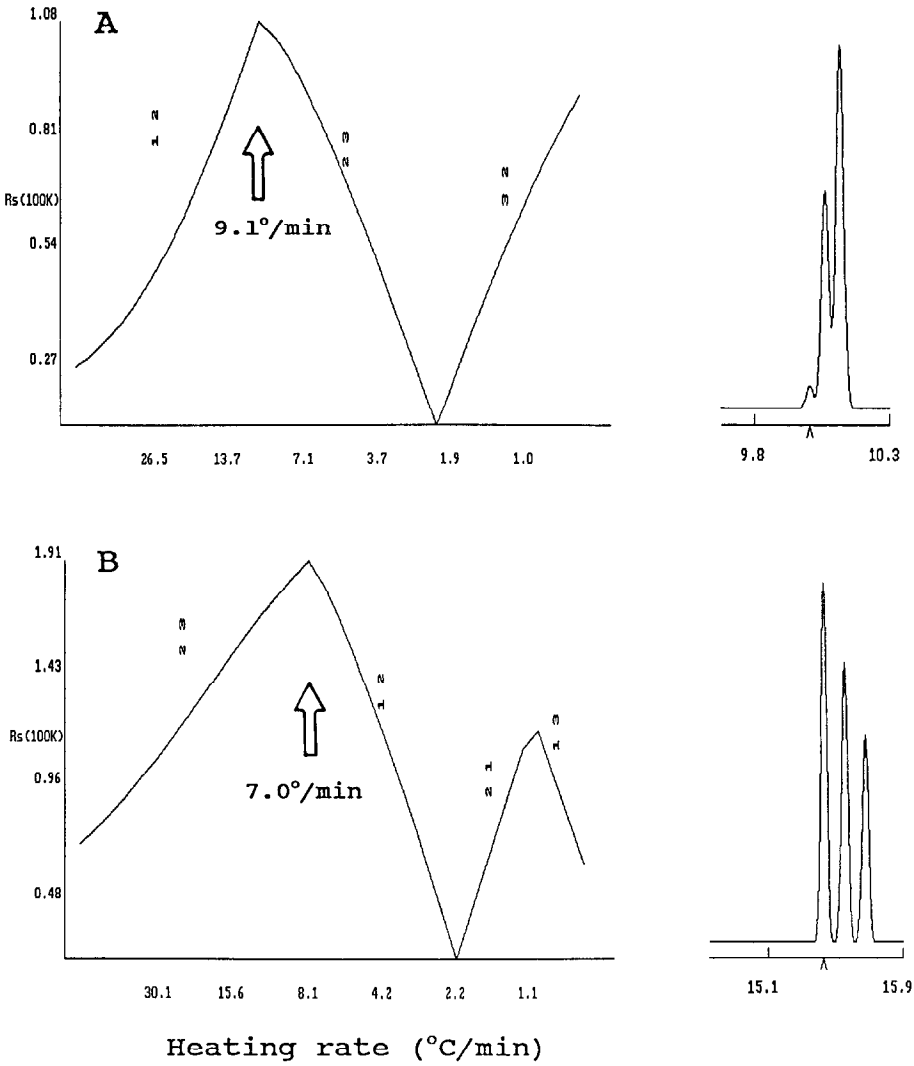

Fig. 7. Resolution maps and optimized separations (arrows) for the temperature programmed separations of band groups I (A) and II (B) of the spearmint oil sample; see Fig. 6.

polar and non-polar compounds separated on a polar column. This suggests that there is often an optimum (intermediate) isothermal temperature for such separations. In the present study, several sample/column combinations that involved hundreds of individual solutes of varying polarity were studied experimentally, in order to better understand this phenomenon. While the present study confirms the possible change of retention order for mixtures of polar plus non-polar compounds separated on polar columns, it appears that useful changes in separation with temperature are not limited to this case. Thus non-polar samples (*e.g.*, hydrocarbons) separated on

non-polar columns can also exhibit significant changes in band spacing (due primarily to differences in molecular shape).

A general treatment (based on a linear-elution-strength or LES model) is also presented for the dependence of band spacing on both heating rate or isothermal temperature in the GC separation of a sample. It is shown that similar separations of adjacent sample bands can be achieved by either temperature-programmed or isothermal elution, when "corresponding" conditions are used; *i.e.*, such that the average retention in isothermal (k) or programmed ($\bar{k}$) runs is made equal. This means that changes in heating rate will often result in changes in band spacing (and resolution) for the case of temperature-programmed GC separation.

On the basis of the present study, it appears that temperature-related changes in band spacing are generally large enough to be worth exploiting —in order to maximize sample resolution. Some examples of temperature-programmed GC method development based on this approach (including computer simulation) are described in ref. 26 and the following paper [27].

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