

THE SEPARATION OF C_6F_{14} ISOMERS BY GAS CHROMATOGRAPHY AND THE EFFECT OF STATIONARY PHASE CONCENTRATION

T. M. REED, III

*Department of Chemical Engineering, College of Engineering,
University of Florida, Gainesville, Fla. (U.S.A.)*

(Received May 29th, 1962)

This paper describes the resolution of some of the isomers of C_6F_{14} , perfluorohexane, by gas-liquid partition chromatography.

An earlier report¹ discussed the partition chromatography of fluorocarbons on various stationary-phase liquids at temperatures near the boiling points of the compounds. The results showed that fluorocarbons may best be separated into molecular weight classes by partitioning on stationary media in which they form as nearly ideal solutions as possible. Such liquids as Kel-F oils and $(C_4F_9)_3N$ were used at concentrations of 0.1 to 0.2 c.c. per c.c. of total column volume. It has subsequently been found that at such high concentrations in the column fluorocarbon stationary phases do not separate the close-boiling isomers of fluorocarbon alkanes as well as do hydrocarbon stationary phases. Furthermore great improvement in the resolution of fluorocarbons by the hydrocarbon stationary phase is obtained by reducing the column temperature to room temperature. Since the activity coefficients of fluorocarbons in a hydrocarbon solvent are large, the capacity of the hydrocarbon partitioning column and the appearance times are unusually low, compared to that obtained on a stationary phase with which ideal solutions are formed. Thus, nonideal solutions possess some advantage in a GLPC of nonpolar molecules. At a column temperature of 30° it is possible to elute fluorocarbons up to C_6F_{14} from 2 meters of *n*-hexadecane (0.2 c.c. $C_{16}H_{34}$ /c.c. total column volume) in a few minutes at ordinary carrier gas flow rates (*ca.* 20 c.c./min in 0.2-in. i.d. tubes). However, a 2-m length is not sufficient for separating the isomers of C_6F_{14} .

EXPERIMENTAL

In the work with C_6F_{14} partitioned on *n*-hexadecane, a series of columns was investigated in which the thickness of the stationary phase on the supporting particles and the volume of stationary phase in the column were varied. Table I lists the information on these columns. In all columns, except 3A, the particles were acid-washed Chromosorb-P, 35 to 80 mesh. From these tests the ratio of *n*-hexadecane-to-solid support was selected that best resolved a mixture of the isomers of C_6F_{14} . This mixture was obtained in this laboratory as a fraction of the total material produced by the electrolysis of hexyl sulfide in anhydrous HF^2 . The best column was selected by noting the resolution of the C_6F_{14} material at room temperature. Various quantities ranging from 1 μ l to 30 μ l on the 0.197-in. i.d. tubes were charged. Carrier gas flow rates from 1 to 35 c.c./min were used.

TABLE I
COLUMNS WITH *n*-HEXADECANE SUBSTRATE

Column No.	Length (m)	Total packing (g)	g C ₁₆ H ₃₄ per g solid	c.c. packing per c.c. total at R.T.	c.c. C ₁₀ H ₂₀ per c.c. total at R.T.	i.d. tube (in.)
38 ^a	2	18.7	0.19	0.32	0.10	0.197
36 ^a	2	19.9	0.25	0.35	0.13	0.197
37 ^a	2	19.8	0.31	0.36	0.16	0.197
3A ^b	2	23.6	0.40	0.51	0.22	0.197
3C ^a	17	2047	0.40	0.72	0.352	0.50
40 ^c	8	104.3	0.40	0.49	0.248	0.197
37B ^a	2	22.8	0.51	0.46	0.26	0.197

^a Particle density of uncoated solid support = 1.85 g/c.c.

^b Particle density of uncoated solid support = 1.95 g/c.c.

^c Particle density of coated solid = 1.36 g/c.c.

It was found (a) that the resolution was best with 0.4 g of *n*-hexadecane per g of supporting solid; (b) that a maximum charge of about 5 μ l was possible without destroying the resolution; (c) that 12 to 16 m total length of column was sufficient to produce adequate resolution, and (d) that a carrier flow rate of 80 cm/min at the exit was near the optimum for this separation.

On the basis of these tests column 3C was prepared in 0.5-in. i.d. steel tubing for the preparative scale work. This column was arranged in the vertical plane. The resolution in this column was at least as good as that obtained in the smaller diameter tubes at the same total length. The use of nitrogen as carrier, rather than hydrogen used in the 0.197-in. i.d. tube, contributed to the better resolution in the 0.5-in. tube. The volume of *n*-hexadecane per unit total column was greatest in the larger tube even though the ratio of *n*-hexadecane to solid support was 0.40 g/g in both diameters.

In Table II are given the conditions of operation and appearance times on the preparative column and of two other hydrocarbon-coated columns of the smaller

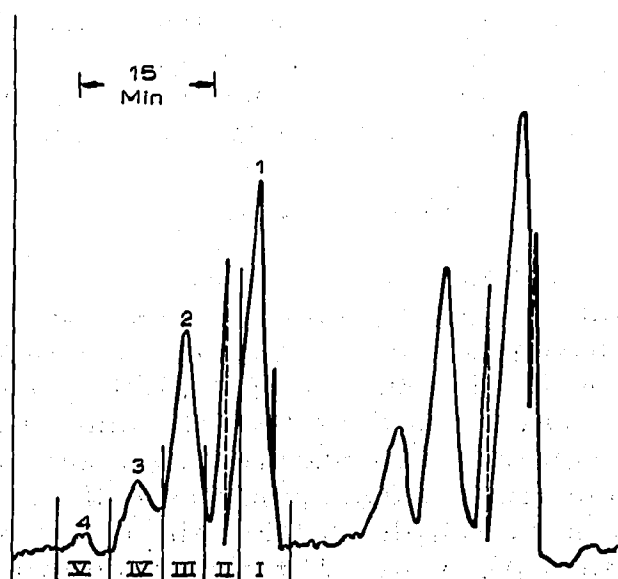


Fig. 1. C₆F₁₄ mixture on column 3C; 17 m of *n*-hexadecane. Roman numerals indicate cuts in preparative scale runs. Arabic numerals designate isomers.

TABLE II

CHROMATOGRAMS OF C₆F₁₄ MIXTURE ON *n*-HEXADECANE

Column 40: total length = 8 m; i.d. = 0.197 in.; $T = 28^\circ$; $P_t = 1$ atm; $P_o = 1$ atm. Void vol. = 85 c.c.; C₁₀H₃₄ vol. = 38.8 c.c. Hydrogen flow rate at exit = 16 c.c./min = 82 cm/min.

Compound	Peak app. time (min)	Corrected retention vol. (c.c.)	Partition coeff. K	K_{n-C_6}/K
Air	8.3	117	1.21	
<i>n</i> -C ₆ F ₁₄	22.0	314	0.170	1.0
2-CF ₃ -C ₅ F ₁₁	24.3	346	0.149	1.14
3-CF ₃ -C ₅ F ₁₁	25.5	364	0.139	1.22
(CF ₃) ₂ C ₄ F ₈	28.7	410	0.119	1.43

Column 40 + 3A + 37B in series: total length = 12 m; i.d. = 0.197 in.; $T = 28^\circ$; $P_t = 19.2$ p.s.i.a.; $P_o = 14.7$ p.s.i.a. Void vol. = 125 c.c.; C₁₀H₃₄ vol. = 57.5 c.c. Hydrogen flow rate at exit = 16 c.c./min = 82 cm/min.

Air	14	193	0.85	
<i>n</i> -C ₆ F ₁₄	37.5	520	0.145	1.0
2-CF ₃ -C ₅ F ₁₁	40.5	563	0.131	1.11
3-CF ₃ -C ₅ F ₁₁	42.5	590	0.124	1.17
(CF ₃) ₂ C ₄ F ₈	46	640	0.112	1.29

Column 3C: total length = 17 m; i.d. = 0.50 in.; $T = 28^\circ$; $P_t = 29.7$ p.s.i.a.; $P_o = 14.7$ p.s.i.a. Void vol. = 490 c.c.; C₁₀H₃₄ vol. = 760 c.c. Nitrogen flow rate at exit = 108 c.c./min = 85 cm/min.

<i>n</i> -C ₆ F ₁₄	77	5300	0.162	1.0
2-CF ₃ -C ₅ F ₁₁	84.5	5820	0.146	1.11
3-CF ₃ -C ₅ F ₁₁	90	6200	0.136	1.19
(CF ₃) ₂ C ₄ F ₈	96	6610	0.127	1.28

diameter. The auxiliary equipment used in the preparative separation has been described previously³. A typical chromatogram obtained during the quantity separation of the C₆F₁₄ mixture on column 3C is shown in Fig. 1. The vertical lines on the middle group of peaks show the cut points. The volume of each charge was approximately 0.05 c.c. and they were injected at 30-min intervals. Since complete resolution was not obtained in one pass, each cut was reprocessed on the 0.5-in i.d. column to obtain the pure isomers.

Each isomer was identified by nuclear magnetic resonance spectroscopy⁴ as follows:

Peak	Isomer
1	<i>n</i> -C ₆ F ₁₄
2	Perfluoro-2-methylpentane
3	Perfluoro-3-methylpentane
4	Perfluoro-dimethylbutane isomers

Because of the small quantity of dimethylbutane isomers, these two molecular species were not isolated separately. Pure perfluoro-2,3-dimethylbutane from another source⁵ established the appearance time of the fourth peak as that of this compound.

Analysis of the pure fractions on columns 40 + 3A + 37B in series, using hydrogen as carrier gas in a Perkin-Elmer Vapor Fractometer with thermistor detectors at 28°, showed no trace of peaks other than that of the particular isomer.

Perfluoropentane from the electrolysis of pyridine in HF has also been resolved into perfluoro-*n*-pentane and perfluoro-2-methylbutane by the same procedure.

WHY HYDROCARBON SUBSTRATES ARE BETTER

The hydrocarbon possesses the advantage over the more compatible fluorine-containing stationary phases primarily because the retention time of fluorocarbons in hydrocarbon is low at low temperatures. The greater relative partition coefficients found at lower temperatures, compared to higher temperatures, produces better resolution on thermodynamic grounds. Furthermore, the spreading of the peaks by diffusional processes is minimized by operation at low temperatures and low retention time.

Another effect contributing to the advantage of the hydrocarbon substrates for fluorocarbon separation is found in the work of GOLAY⁶ leading to the use of capillary columns. This work has shown that the spreading of peaks is low when the ratio of capacity in the gas phase to capacity in the stationary phase is high. Hydrocarbon stationary phases possess lower solubility of fluorocarbons and thus lower capacities at a given fluorocarbon partial pressure than do the same amounts of fluorocarbon liquid substrates. That is, for a given capacity (or partial pressure) in the gas phase the solubility (or capacity) in the liquid phase at a given temperature is inversely proportional to the activity coefficient of the gaseous component in that liquid phase. The relative partition coefficient of isomeric fluorocarbons are very similar, no matter what the nature of the solutions formed in the stationary phase, since the activity coefficients of isomeric fluorocarbons in a given solvent are essentially equal to one another. If this statement is true, merely reducing the quantity of fluorine-containing substrate per total column volume to a value which gives a ratio of capacities in the liquid and gas phases equal to that prevailing in the successful hydrocarbon substrate columns, should, by the GOLAY theory, produce resolutions comparable to those found in the hydrocarbon substrates. The following experiment demonstrates that this expectation is confirmed.

EFFECT OF SUBSTRATE CONCENTRATION ON RESOLUTION OF C₆F₁₄ ISOMERS

The chromatogram of the original mixtures of the C₆F₁₄ isomers on column 16 (Table III), 2 m long, (0.7 g of Cl(CF₂CFCl)₃CF₂COOC₂H₅ per g of Chromosorb) was one broad peak with no resolution of the isomers. Column 50 (Table III) was prepared with approximately one-fourth of this concentration of the ester on the solid support (0.22 g of ester per g of Chromosorb). The column length packed with this preparation was 7.35 m, approximately four times the length of column 16, so that approximately the same total quantity of stationary liquid phase was present in both columns 16 and 50. Operation of the 7.35-m column 50 at the same exit hydrogen gas velocity as in the

TABLE III

COLUMNS WITH FLUOROCARBON STATIONARY PHASES*

i.d. = 0.197 in.; particle density of uncoated support = 1.85 g/c.c.

Column No.	Length (m)	Total packing (g)	g stat. phase per g solid	c.c. packing per c.c. total at R.T.	c.c. stat. phase per c.c. total at R.T.
* <i>Kel-F acid 8114 ethyl ester</i>					
16	2.0	31	0.70	0.44	0.19
50	7.35	75.9	0.222	0.29	0.0565
* <i>Perfluorotributylamine</i>					
8A	2.0	33.6	1.71	0.46	0.288

2-m column 16 produced the chromatogram of 4 μ l of charge shown in Fig. 2A and Table IV. Fairly good resolution of isomers was thus obtained merely by spreading the liquid substrate over a greater solid supporting area. The substrate concentration ratio of approximately 4 to 1 was chosen on the basis of the known ratio of approximately 1 to 4 for the activity coefficients of C_6F_{14} in the Kel-F acid ester and in *n*-hexadecane, respectively¹.

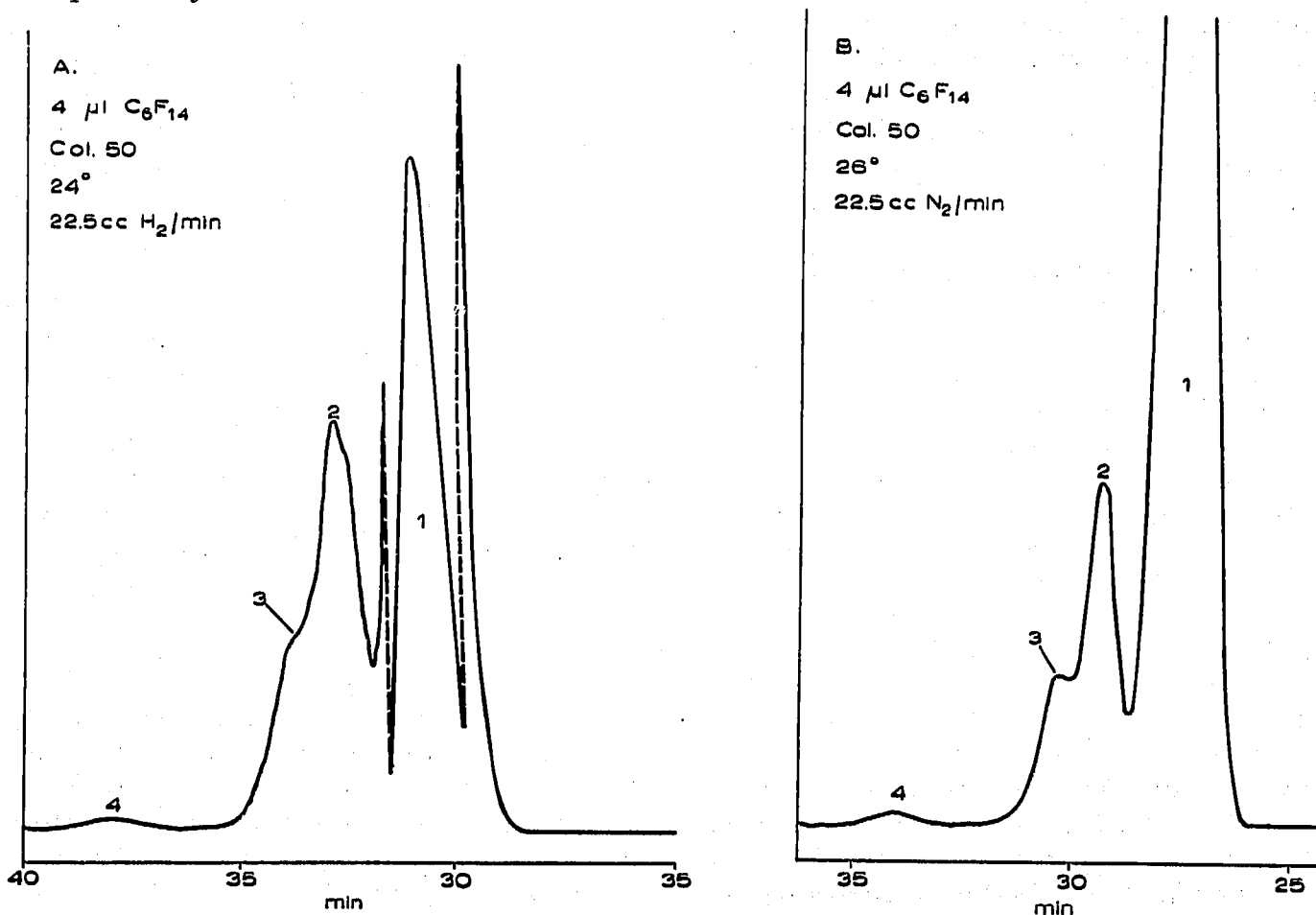


Fig. 2. C_6F_{14} mixture on 7.35 m of $Cl(CF_2CFCl)_3CF_2COOC_2H_5$. (A) Hydrogen carrier gas. (B) Nitrogen carrier gas.

On the basis of the GOLAY theory similar resolutions of C_6F_{14} isomers can be obtained on column 50 and column 40 (8 m of 0.4 g *n*-hexadecane per g of Chromosorb). The chromatogram of 4 μ l of the same C_6F_{14} mixture on *n*-hexadecane column 40 is shown in Fig. 3 and Table II. The resolution here is somewhat better than that

TABLE IV

CHROMATOGRAM OF C_6F_{14} MIXTURE ON KEL-F ACID ESTER

Column 50: total length = 7.35 m; i.d. = 0.197 in.; $T = 24^\circ$; $P_i = 1.2$ atm; $P_o = 1$ atm. Void vol. = 102 c.c.; $Cl(CF_2CFCl)_3CF_2COOC_2H_5$ vol. = 8.15 c.c. Hydrogen flow rate at exit = 22.5 c.c./min = 115 cm/min.

Compound	Peak app. time (min)	Corrected retention vol. (c.c.)	Partition coeff. K	K_{n-C_6}/K
Air	6.7	139	0.22	—
$n-C_6F_{14}$	30.8	630	0.0154	1.00
2- $CF_3-C_5F_{11}$	32.7	666	0.0145	1.06
3- $CF_3-C_5F_{11}$	34.2	700	0.0136	1.13
$(CF_3)_2C_4F_8$	37.8	770	0.0122	1.26

obtained on Kel-F ester column 50 using hydrogen carrier gas, but the approximate equivalence of the two columns is evident. The spreading of the peaks is greater on the Kel-F ester substrate even though the appearance times are lower. If the equivalence of the columns were strictly in accordance with GOLAY's theory, the Kel-F ester should be better than the hexadecane since the total volume of substrate per unit quantity of support is greater in the hexadecane column. GOLAY's theory indicates that the thinner substrate layer should give the better resolution. There must be other effects which counteract the deleterious effect of thicker liquid films in the hydrocarbon partitioning column.

An additional parameter that should be minimized according to the GOLAY theory is the void volume in the column. The hexadecane column has the advantage in this respect because of the greater liquid volume per unit solid support allowed by low liquid phase solution capacity.

A further consideration is the magnitude of gas phase diffusion coefficient. Fig. 2B shows the chromatogram of the C_6F_{14} mixture on column 50 under conditions identical with that of Fig. 2A except that nitrogen was used in Fig. 2B in place of hydrogen as carrier gas. The resolution is better with nitrogen. GOLAY's theory gives the spread per unit column length as:

$$2DS/F + [0.01 + 0.03 (C/C_1 + 1)] (F/D)$$

where S is the cross-section of the moving phase, F is the carrier volumetric flow rate, C is the capacity of the moving phase, C_1 is the capacity of the stationary phase, and D is the diffusion coefficient in the moving phase. The first term is spreading due to longitudinal diffusion in the gas phase. The second term, $0.01 F/D$, is the spreading due to finite time for transfer between moving and stationary regions of the carrier gas, and the third term is due to the finite time for transfer between phases. The first term is proportional to D ; the last two are inversely proportional to D . Depending upon which terms are the larger, the resolution can increase or decrease with decrease in

D. Because of the large molecular weight fluorocarbons, *D* is smaller with a given carrier gas than in the case of hydrocarbon molecules of the same number of carbon atoms. *D* with nitrogen is less than *D* with hydrogen, so that it appears for these fluorocarbons that the first term is more important than the others, since nitrogen gives better resolution than does hydrogen.

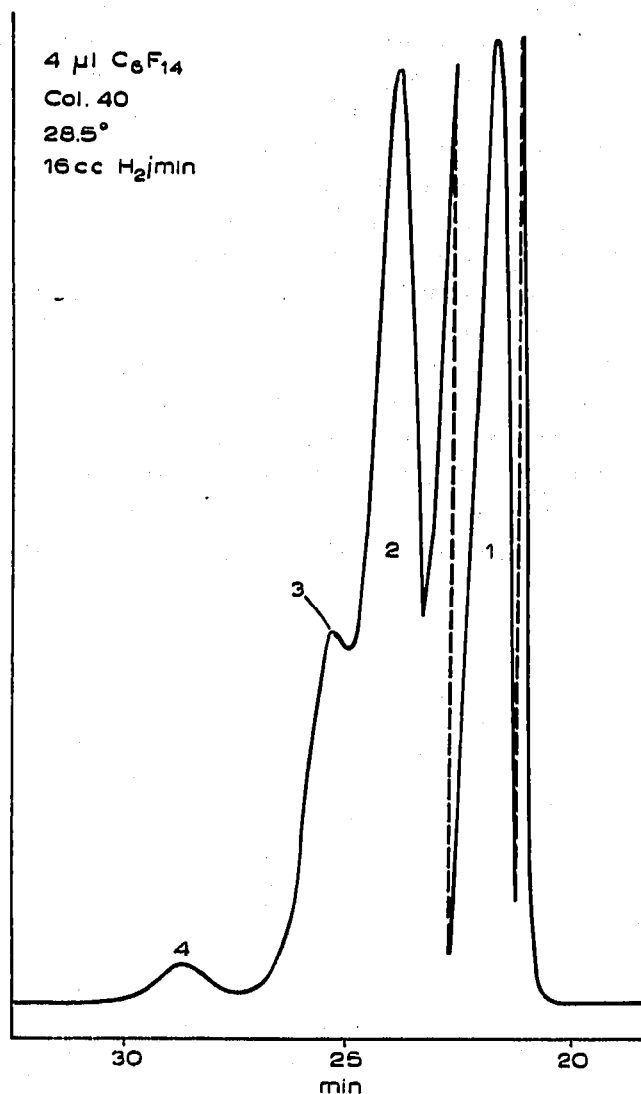


Fig. 3. C_6F_{14} mixture on 8 m of *n*-hexadecane.

Comparison of the data for the various C_6F_{14} isomers on *n*-hexadecane (Table II) with those on the Kel-F ester (Table IV) confirms the expectation that the relative partition coefficients of these fluorocarbons are essentially independent of the nature of the stationary phase, even though the partition coefficients themselves are ten times larger in the hexadecane than in the Kel-F ester.

REMARKS ON HYDROCARBON RESOLUTION IN NONIDEAL SOLUTION SUBSTRATES

For analysis of hydrocarbon mixtures the use of fluorocarbon stationary phases was studied to determine if the nonideal solution possesses any advantages over ideal solu-

tions. Experimental explorations in this direction are described below which indicate that nonideal solution chromatography of C_6H_{14} isomers is not quite as attractive as that for fluorocarbons. It is to be expected at the start from thermodynamic studies of solution that each hydrocarbon isomer will have a different activity coefficient in solution with a given solvent. Even in the absence of such evidence, the fact that the boiling points of hydrocarbon isomers differ considerably from one another would lead one to expect different solution behavior of the isomers one from the other. The boiling points of fluorocarbon isomers all lie within a small temperature range of a few degrees or tenths of a degree, and thus, are essentially equivalent in solution behavior. The condition holding for fluorocarbon isomers demonstrated above, namely that the relative partition coefficients are essentially independent of the type of solution behavior encountered, does not hold for hydrocarbon isomers in fluorocarbon solvents. Nonideal solution behavior may thus destroy or enhance the ideal solution resolution, depending upon the relative magnitudes of the individual activity coefficients of each hydrocarbon isomer when dissolved in a particular nonideal solution substrate. It is desirable that in a given solvent the activity coefficients of isomeric hydrocarbons should decrease with increase in normal boiling point. Actually, they probably increase with increase in boiling point when the substrate is a fluorocarbon. A typical behavior is illustrated by Figs. 4 through 7, which are chromatograms of a mixture containing predominantly three hexane isomers and one heptane isomer.

Fig. 4 illustrates a chromatogram of the C_6H_{14} mixtures in the conventional

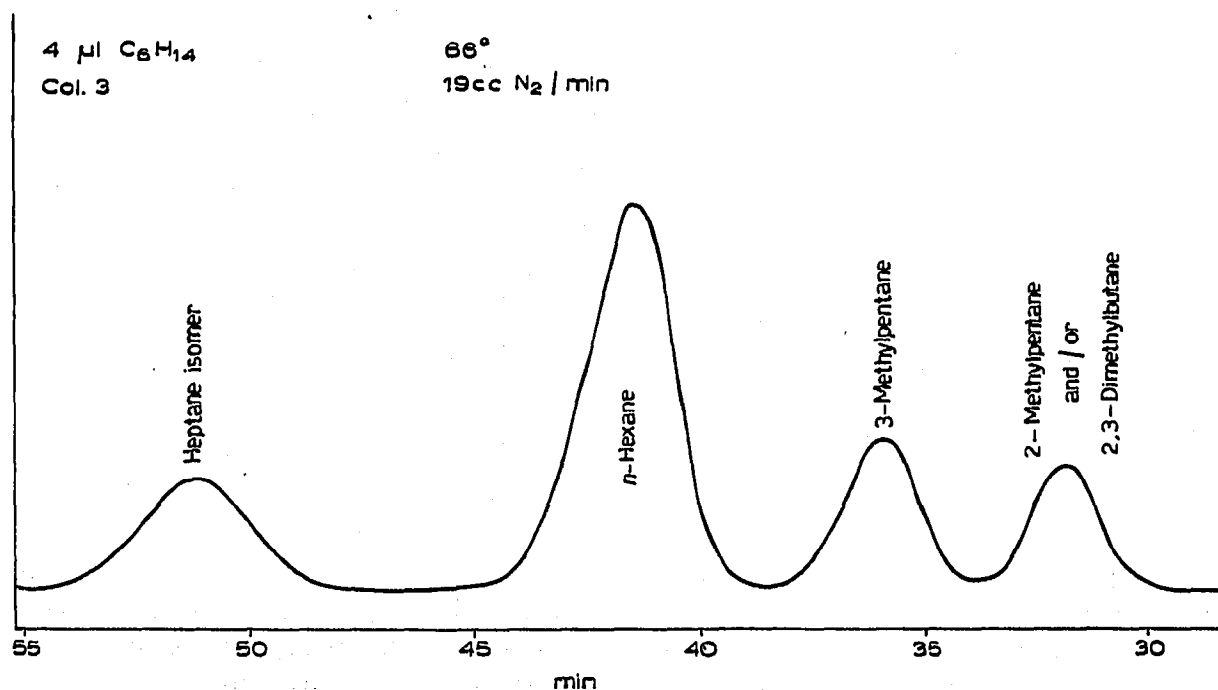


Fig. 4. C_6H_{14} mixture on 2 m of *n*-hexadecane.

manner on *n*-hexadecane (column 3, ref. 1) at 66° with a 4- μ l charge. Fig. 5 is the same material at 20° on column 16, the 2-m Kel-F ester packing of high substrate concentration, using hydrogen carrier gas. The resolution is relatively poor in the latter case.

As shown in Fig. 6A, when the C_6H_{14} mixture is run with hydrogen carrier gas on the 7.35-m column 50 containing essentially the same total amount of Kel-F ester as column 16, the resolution is greatly improved over that obtained in the two preceding columns. When nitrogen is substituted for hydrogen as carrier at otherwise identical conditions (Fig. 6B), the hydrocarbon peaks are more widely spread out. This behavior

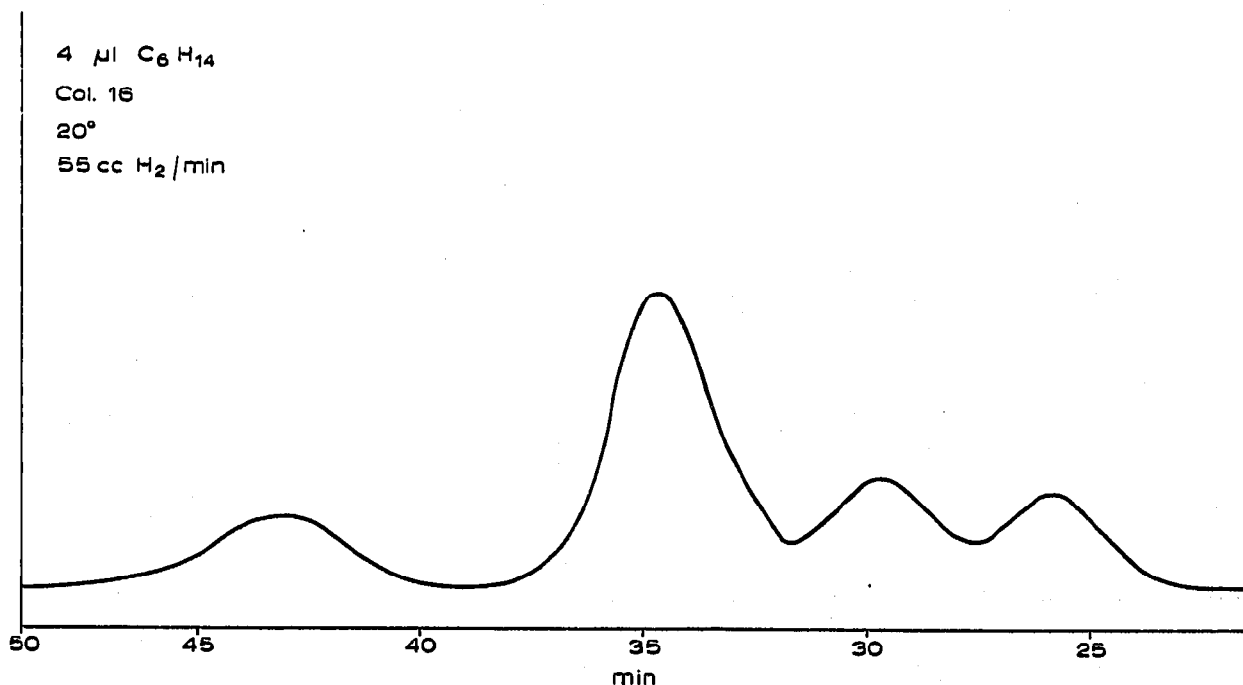


Fig. 5. C_6H_{14} mixture on 2 m containing 12.8 g $Cl(CF_2CFCl)_3CF_2COOC_2H_5$.

with respect to carrier gas molecular weight is the opposite to that found for the fluorocarbon mixture above. The resolution of the hydrocarbon is decreased by decreasing the diffusion coefficient, D , indicating that the second and third terms of the GOLAY theory are the more important for the hydrocarbon C_6H_{14} mixture.

Although the hydrocarbons form rather nonideal solutions in the Kel-F ester substrates they are not sufficiently different in their behavior to alter the relative appearance times appreciably from those observed using a hydrocarbon substrate (*e.g.*, *n*-hexadecane). This is probably due to the fact that a large part of the nonideal behavior in the Kel-F ester substrate arises from dipole-induced-dipole effects which are not as dependent upon the structure of the hydrocarbon isomer as would be purely induced-dipole-induced-dipole effects encountered in a purely nonpolar substrate.

When a nonpolar substrate (perfluorotributylamine) is used to resolve the C_6H_{14} mixture, the result is the chromatogram of Fig. 7. Here the very different activity coefficients of the C_6H_{14} isomers in this solvent cause the isomers to appear very close together. The activity coefficient of the *n*- C_6H_{14} is larger than that of the isomeric structures⁷, and since the vapor pressure of the *n*- C_6H_{14} is lower than that of the other isomers, it appears in a relatively shorter time than that corresponding to its vapor pressure. In this instance all the isomers appear close together.

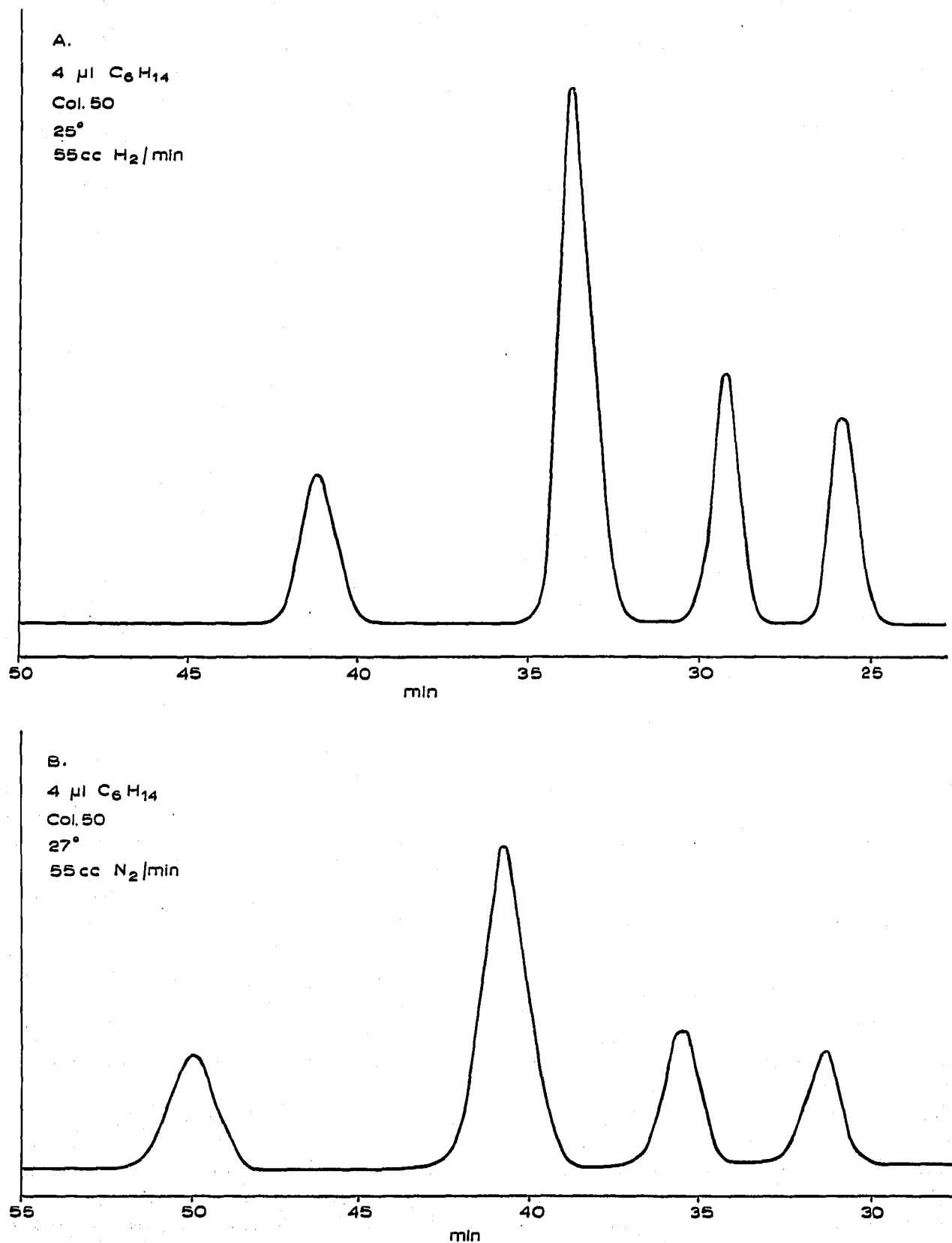


Fig. 6. C_6H_{14} mixture on 7.35 m containing 13.8 g of $Cl(CF_2CFCl)_3CF_2COOC_2H_5$. (A) Hydrogen carrier gas. (B) Nitrogen carrier gas.

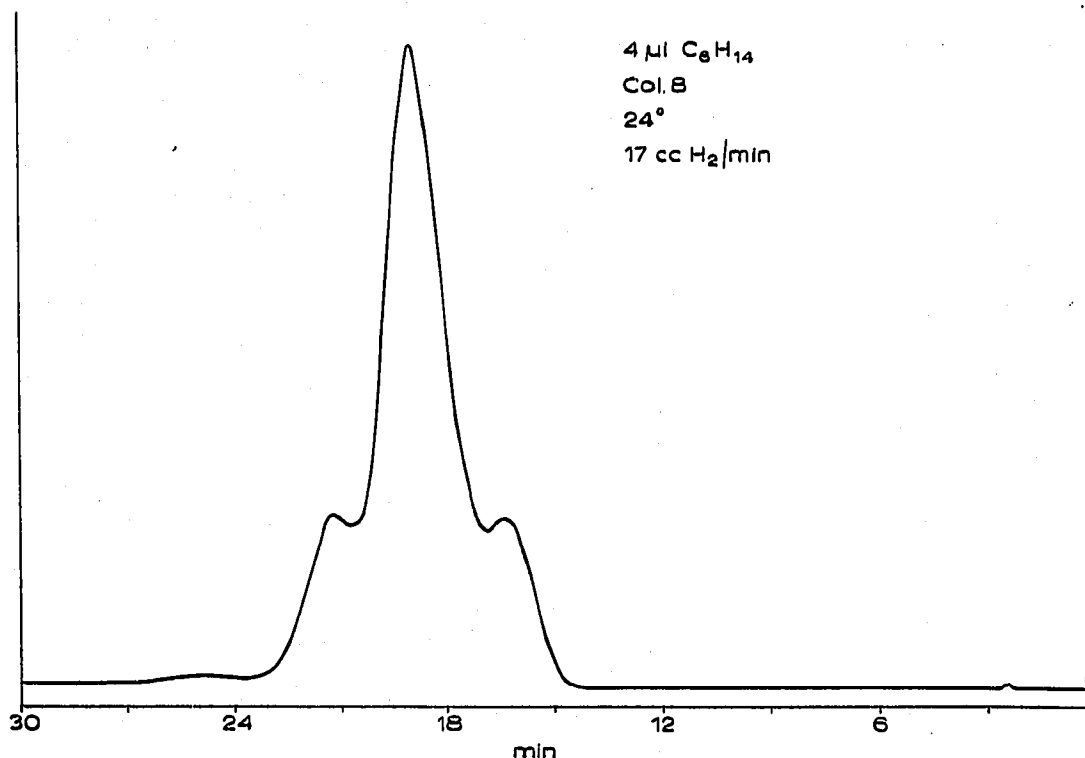


Fig. 7. C_6H_{14} mixture on 2 m of perfluorotributylamine.

CONCLUSIONS

(1) The Kel-F ester column 50, in which the substrate concentration is 0.0565 c.c./c.c. total column volume on 35 to 80 mesh Chromosorb is rather versatile. It allows good resolutions of both hydrocarbon and of fluorocarbon mixtures in column lengths of several meters. To obtain equivalent resolutions longer columns are required for fluorocarbon isomers than for hydrocarbon isomers.

(2) The *n*-hexadecane substrate at ordinary concentration in the column (0.2 to 0.4 c.c./c.c. total) on 35 to 80 mesh Chromosorb-P provides fairly good resolution of C_6F_{14} fluorocarbon isomers at room temperature when the column length is 8 to 16 m. This is the best type of column obtained so far for fluorocarbon isomer mixtures in that it produces the sharpest peaks and adequate resolution.

ACKNOWLEDGEMENTS

Messrs. T. E. TAYLOR and G. W. VINING carried out most of the separations in this work, and were supported in part by the Minnesota Mining and Manufacturing Company and in part by the National Science Foundation, Grant GI4591.

SUMMARY

The separation of the isomers of perfluorohexane by gas-liquid chromatography is difficult for two reasons: (1) the isomers have similar vapor pressures in that they all boil within a range of one or two degrees, and (2) they all show essentially identical

thermodynamic behavior in any given solvent. The latter behavior precludes the existence of selective solvent effects, so useful in hydrocarbon systems, to aid in the separation. Satisfactory stationary phases for this isomer separation are hydrocarbons at concentrations of 0.3 c.c. per c.c. of column or chlorofluorocarbons at 0.05 c.c. per c.c. of column volume. Approximate retention volumes for $n\text{-C}_6\text{F}_{14}$ are 8 c.c. per c.c. of n -hexadecane at 28° , and 77 c.c. per c.c. of $\text{Cl}(\text{CF}_2\text{CFCl})_3\text{CF}_2\text{COOC}_2\text{H}_5$ at 24° . The relative behaviors of the partitioning media are explained on the basis of the GOLAY theory. The resolution of the hydrocarbon hexanes is poor on perfluorocarbon substrates because of large differences in the thermodynamics among the hydrocarbon isomers in these solvents.

REFERENCES

- ¹ T. M. REED, *Anal. Chem.*, 30 (1958) 221.
- ² R. D. DRESDNER, T. M. REED, T. E. TAYLOR AND J. A. YOUNG, *J. Org. Chem.*, 25 (1960) 1464.
- ³ T. M. REED, J. F. WALTER, R. R. CECIL AND R. D. DRESDNER, *Ind. Eng. Chem.*, 51 (1959) 271.
- ⁴ W. BREY, personal communication, 1960.
- ⁵ F. N. TLUMAC, personal communication, 1961.
- ⁶ M. J. E. GOLAY, in V. J. COATES, H. J. NOEBELS AND I. S. FAGERSON, *Gas Chromatography*, Academic Press, New York, 1958.
- ⁷ M.R. CINES, *U.S. Pat.* 2,692,227, October 19, 1954.

J. Chromatog., 9 (1962) 419-430