

# Dense Gas Chromatography at Pressures to 2000 Atmospheres

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## Abstract

We review here our chromatographic work with complex and nonvolatile solutes utilizing the solvent power of high density gases. Principal attention is given to biomolecules although several polymers have been migrated. We discuss the potential advantages of this approach over liquid chromatography, especially improved solvent power control, speed and detection. We also discuss the magnitude of the pressure needed to migrate species having various levels of complexity and molecular weight. This serves to establish the upper experimental pressure requirements of the apparatus as a function of the type of compounds to be separated.

At the Fifth Symposium of the GC Discussion Group, Institute of Petroleum, held in Brighton, England in September 1964, a potential of GC at elevated pressure was stated thusly (1):

"One of the most interesting features of ultra high pressure gas chromatography would be its convergence with classical liquid chromatography. A liquid is ordinarily about 1000 times denser than a gas; at 1000 atmospheres, however, gas molecules crowd together with a liquid-like density. At such densities intermolecular forces become very large, and are undoubtedly capable of extracting big molecules from the stationary phase. Thus in effect, nonvolatile components are made volatile."

Previous to this time Klesper, Corwin and Turner had migrated porphyrins at pressures up to 136 atmospheres (2). Since 1964 several groups have pursued a similar goal using pressures of the order of one hundred atmospheres. Recently a part of the earlier porphyrin team has reported additional studies (3). However the work of Sie, van Beersum and Rijnders at pressures to 80 atmospheres has been most promising; these authors have migrated polynuclear aromatics and other high molecular weight compounds using CO<sub>2</sub>, n-pentane and isopropanol at temperatures up to 245°C (4-6). They have developed both the adsorption (6) and partition (5) modes of this form of chromatography, and have illustrated their work with numerous separations. Their results were discussed in terms of the second virial coefficient between solute and gas molecules (4).

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2. Klesper, E., Corwin, A. H., and Turner, D. S., *J. Org. Chem.* **27**, 700 (1962).
3. Karayannis, N. M., Corwin, A. H., Baker, E. W., Klesper, E., and Walter, J. A., *Anal. Chem.* **40**, 1736 (1968).
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Pressures in the "ultra-high" region (which for GC are those above normal tank pressure, 150-200 atmospheres), of the magnitude suggested at Brighton, have been reported by this group (7-9). The original study dealt mainly with efficiency and speed, although attention was called to the pressure-induced shift in migration for small solute species (7). In subsequent work pressures to 2000 atmospheres were used to migrate over 80 polymers and biomolecules with molecular weights up to 400,000 (8,9).

The implementation of gas chromatography in the  $10^3$  atmosphere vicinity is certainly more demanding on equipment than is normal gas chromatography at 1-10 atmospheres, or even high pressure gas chromatography around  $10^2$  atmospheres. Sufficient data are not yet available to clearly discern the benefit of the  $>10^2$  atmosphere region. However the data of Sie and Rijnders well demonstrates the utility of  $10^1$ - $10^2$  atmosphere range. In this paper we will approach this question by 1) reviewing experimental results with large molecules of low volatility and 2) presenting some new theoretical equations along with both new and old data for comparison. We do not intend to present definite and broad conclusions at this time since our results are still tentative and specific in nature. However some of the suggested consequences of our treatment are undoubtedly relevant to the question of optimum experimental conditions at high pressures.

As stated previously, there are three potential advantages which dense gas chromatography has over its only competitor, liquid chromatography, for dealing with high molecular weight species (9). First, solvent power depends on a mechanical parameter, pressure, and can be varied precisely and quickly over a wide range to fit experimental requirements. An example of such variation will be shown later in terms of a stage-wise programmed pressure separation. Second, the speed of separation should be considerably greater than in liquid chromatography because of reduced viscosity and increased diffusivity. Third, the possibility exists that the high-sensitivity detector of normal gas chromatography can be applied to full advantage at high pressures. For instance, we have mainly employed flame ionization detectors in our work. These have required no special modification but are used, sometimes with splitting, directly after the decompression valve. At present noise and drift problems are hindering progress, but these can probably be corrected. Other sensitive detectors are perhaps equally applicable.

## Theory

In order to determine the experimental conditions needed for a particular separation, we must be able to describe the magnitude of the solubility of various substances in compressed gases over the range from ideal gases to those with liquid densities. The second virial approach describes well the initial departure from ideality; Sie, van Beersum and Rijnders found this approach valid to about 50 atmospheres for their systems (4). Theoretical description of gaseous solutions are very incomplete and laborious beyond this range (10).

In an effort to find some unifying scheme for the present phenomena—one which would relate the enhancement of volatility with the pressure, temperature, carrier gas and the size and nature of the solutes—we have suggested an examination of the Hildebrand solubility parameter.

For dense gases the solubility parameter,  $\delta$ , cannot be related to the energy of vaporization, as it ordinarily is for liquids since vaporization cannot occur under these conditions. Rather the cohesive energy density essential to  $\delta$ , is best obtained from the equation of state of the gas. Using the van der Waal's equation, and the assumed identity of  $\delta$ 's for liquids and for gases at liquid densities, we get (9).

$$\delta = 1.25 P_c^{1/2} [\rho/\rho_{liq}] \quad \text{Eq. 1}$$

where  $P_c$  is the critical pressure,  $\rho$  the gas density and  $\rho_{liq}$  the liquid density. A similar equation would result if we knew the liquid's solubility parameter,  $\delta_{liq}$ , from boiling point data at much lower temperatures. Here we must either correct for temperature or assume the correction to be unimportant. In either case

$$\delta = \delta_{liq} [\rho/\rho_{liq}] \quad \text{Eq. 2}$$

The contribution of  $\delta_{liq}$  to  $\delta$  has been ascribed to a "chemical effect," whereas the contribution of  $[\rho/\rho_{liq}]$  stems from a "state effect" (9).

The important point about either of the above equations is that  $\delta$  varies in proportion to gas density,  $\rho$ . This suggests that  $\rho$ , rather than other state variables, i.e.,  $P$  or  $T$ , is the parameter directly crucial to solubility. If one wants large  $\delta$ 's, one must choose  $P$ 's and  $T$ 's which will yield maximum density. Under ordinary supercritical conditions, a maximum  $\delta$  is obtained when  $P$  is at its largest possible value and when  $T$  is barely in excess of the critical temperature  $T_c$ . This can be seen by reference to Figure 1 which shows the dependence of  $\delta$  upon reduced temperature,  $T_r$ , and reduced pressure,  $P_r$ , assuming Equation 2 and assuming that the reduced density ( $\rho_r$ ) of the liquid is 2.66. Figure 1 also shows the regions in which the previous workers have obtained volatility enhancement.

From the viewpoint of solubility-parameter theory and the above equations, compressed gases present a versatile class of solvents. The solubility parameter, which measures roughly the power of the solvent to dissolve various substances, can vary from zero at low pressures up to liquid-like values ( $\sim 10$ ) at ultra high pressures. It thus spans continuously the range from dilute gases to normal liquids. Dense gases thus allow the use of some values (0-5) not available from liquids, and they provide superior transport properties over the entire range.

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9. Giddings, J. C., Myers, M. N., McLaren, L., and Keller, R. A. *Science* 162, 67 (1968).
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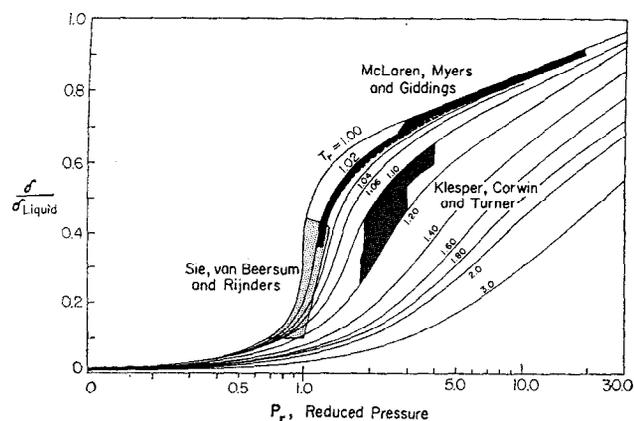


Figure 1. Dependence of solubility parameter,  $\delta$ , upon reduced temperature and pressure. The operating range of various workers is shown.

We have employed the van der Waal's equation as a vehicle for estimating the dependence of the solubility parameter on variables of state. This equation, as is widely recognized, fails to account accurately for P-V-T relationships over the full range of gas densities. However its use has several justifications: 1) it is simple; 2) it is widely understood; 3) its parameters are tabulated in many tables; 4) "it never predicts physically absurd results" (11); 5) it works unexpectedly well, even for liquids (11,12); and 6) van der Waal's equations and assumptions are undergoing a renaissance with regard to the modern theories of liquids (13).

In the earlier article where the use of the solubility parameter was suggested, no quantitative expressions were given for the magnitude of the volatility enhancement (9). Below we present several equations which stem from these concepts. A detailed discussion will appear elsewhere. The equations are admittedly very approximate. Mainly we wish at this stage a theory which is simple and yet presents an "order of magnitude" type estimate of dense-gas effects. The latter will hopefully suffice to formulate initial guidelines for the employment of dense gases in chromatography. At present this is our main goal. Refinements in the theory will follow.

The solute properties which enter our considerations are molar volume,  $V_0$ , and solubility parameter,  $\delta$ . The relevant gas properties are  $\delta$  and the reduced solubility parameter,  $\Delta = \delta/\delta_0$ . For some applications we would need the solubility parameter,  $\Delta = \delta/\delta_0$ . For some applications we would need the solubility parameter of the stationary phase; here we consider relative changes in equilibrium and the liquid term cancels out. This, of course, assumes that stationary phase properties remain constant with changing pressure. This is difficult to justify, but also difficult to correct.

We use  $I_{12}$  to describe the volatility or solubility "enhancement" upon going isothermally from state 1 to state 2. We have

$$I_{12} = K_1/K_2 \quad \text{Eq. 3}$$

where  $K_1$  and  $K_2$  are the two distribution coefficients. Note that a large enhancement  $I_{12}$  requires a small

(relative)  $K_2$ ; this is because the  $K$ 's represent the ratio of (stationary/mobile) concentrations, and are thus reciprocally related to gas phase solubility.

Our approximate expression for  $I_{12}$  is

$$\ln I_{12} = (V_0\delta_0^2/RT) (\Delta_2 - \Delta_1) (2 - \Delta_2 - \Delta_1) \quad \text{Eq. 4}$$

If reference state 1 is an ideal gas, for which the solubility parameter is zero ( $\delta = \Delta = 0$ ), we have

$$\ln I_{1d} = (V_0\delta_0^2/RT) \Delta(2 - \Delta) \quad \text{Eq. 5}$$

or rearranged

$$(RT/V_0\delta_0^2) \ln I_{1d} = \Delta(2 - \Delta) \quad \text{Eq. 6}$$

This equation suggests that a plot of  $(RT \ln I_{1d})/V_0\delta_0^2$  versus  $\Delta$  will trace out a universal curve which is independent of the nature of the gas and solute, the temperature, etc. This hypothesis is difficult to check at present; we will discuss it in the light of known data later.

Finally we are concerned with the question of the threshold pressure—the lowest pressure at which a species becomes soluble enough to detect and measure. We assume that  $K$  must fall to a certain level,  $K^*$ , before the component becomes observable. While this threshold  $K$  depends upon detector sensitivity, etc., the rapid exponential dependence of  $I_{1d}$  (and thus  $K$ ) upon  $\Delta$  will make it unnecessary to specify the precise value of  $K^*$ .

Our approximate equation for threshold conditions are

$$\Delta^* = 1 - [(RT/V_0\delta_0^2) \ln K^*]^{1/2} \quad \text{Eq. 7}$$

where  $\Delta^*$  is the smallest value of  $\Delta$  leading to detectable migration. From  $\Delta^*$  we get  $\delta^*$  by using simply  $\delta^* = \Delta^* \delta_0$ ; from  $\delta^*$  we get threshold density  $\rho^*$  using Equation 1 or 2; and from  $\rho^*$  we get threshold pressure from a reduced states diagram such as Figure 1.

The foregoing equations will be compared with available experimental results in a later section.

## Previous Results

We summarize here some of the results of our earlier efforts to migrate and separate components of low volatility. The experimental results—and difficulties—are more fully described in the original reports (8,9).

Five gases have been examined in various degrees for their effect on migration rates. Very little influence was observed for the first two, He and  $N_2$ . These failed to migrate any of the nonvolatile species tested. However in the 1966 work, both  $N_2$  and a third gas, A, caused a significant shift in the migration rate of pro-

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12. Hildebrand, J. H., and Scott, R. L., "The Solubility of Nonelectrolytes" 3rd ed., Reinhold, New York, 1950.
13. Barker, J. A., and Henderson, D., J. Chem. Ed. 45, 2 (1968).

pane at 25°C and over the 200-1200 atmosphere range (7). Dense He failed to have any measurable influence.

The bulk of our efforts have revolved around the remaining two gases, CO<sub>2</sub> and NH<sub>3</sub>. These have been studied at temperatures only slightly above their critical values. Under these conditions one can reach the highest gas densities, and thus solubility parameters, for the least expenditure in pressure. Thus the operating and critical temperatures for CO<sub>2</sub> are 40°C and 31.1°C, and for NH<sub>3</sub> are 140° and 132.3°C, respectively.

We suggested earlier that the solvent power of a dense gas is a function of both a "state effect" and a "chemical effect." The former is determined by the degree of compression and related variables of state. The latter is fixed by the chemical nature of the gas and reflects its dipole and quadrupole moments, polarizability, electron sharing tendencies, etc. The latter, unfortunately, are not accurately reflected by the solubility parameter, especially when complimentary (e.g., acid-base) solute-solvent interactions occur.

The gases NH<sub>3</sub> and CO<sub>2</sub> are complimentary with respect to their chemical effects, having unlike polarities and acid-base properties. They consequently exhibit different behaviors toward solutes, NH<sub>3</sub> being the best solvent for polar, hydrogen bonding substances like the sugars when compared at a similar degree of compression. Therefore we expect a lower threshold pressure (and thus a lower practical working pressure) when such polar substances are to be dissolved in gaseous NH<sub>3</sub>. While CO<sub>2</sub> was employed at pressures up to almost 2000 atmospheres, NH<sub>3</sub> was limited to 200 atmospheres by the earlier pumping system. Our present capability with NH<sub>3</sub> extends up to 2000 atmospheres.

In Figure 2 we show two chromatographic separations achieved in dense gases, one with NH<sub>3</sub> and the other with CO<sub>2</sub>.

Threshold pressures were also measured for several solutes in CO<sub>2</sub>. These, as we have explained, are the lowest pressures which yield a detectable signal. While threshold pressure will depend somewhat on detector sensitivity, the effect should be quite small here because all measurements were made on the same instrument. However our values are not yet highly reliable because of instrumental problems.

The rather abrupt threshold observed for most large molecules has suggested a pressure-programmed system whose purpose would be to increase the solvent power of the gas by degrees, thus eluting the compo-

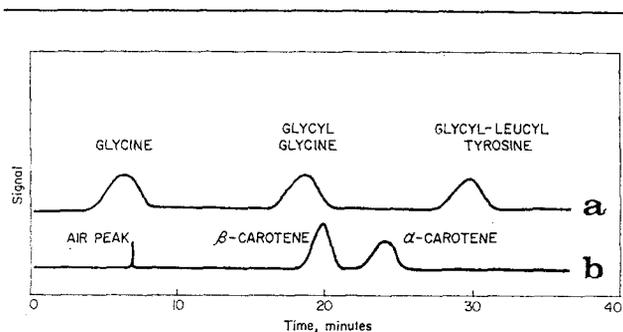


Figure 2. Chromatographic separations in a) dense NH<sub>3</sub> (200 atm) and b) dense CO<sub>2</sub> (500 atm). The former is on a 1.5 m Porasil B column; the latter on a 1.5 m, 15% Ucon column.

nents in turn as each became soluble. This concept is analogous to gradient elution in liquid chromatography, but has the advantage that pressure is changed instead of composition. The success of such a plan has been illustrated by the stagewise separation of squalane, DNP and SE-30, Figure 3. Each stage had an arbitrary duration of 40 minutes, toward the end of which sample vapor was introduced into the system. Clearly this approach could be extended to mixtures with many more components.

Much of our effort has been directed at determining those compounds which will "volatize" into a dense gas under fixed conditions. Volatilization is indicated by a detector response when the vapor above the sample was swept into the FID. It is confirmed by sample loss, occasional IR analysis, etc. Since there are many uncertainties (e.g., chemical reaction) remaining in such experimental systems, the confirmations are not yet absolute.

Table I provides a summary of our results in attempting to induce the migration of various substances in CO<sub>2</sub> and NH<sub>3</sub>.

## Experimental

Three new experimental programs were initiated in order to test the above conclusions relative to solubility enhancement and threshold pressures. The basic apparatus and methodology are those previously described (7,9). Carbon dioxide at 40°C was used throughout. The procedures are as follows.

**Threshold pressures.** The solute was dissolved in CS<sub>2</sub> and loaded on a support material (i.e., Chromosorb W or glass beads) in the same manner as stationary phase is deposited on column packing. This procedure is intended to provide a large interfacial area and a rapid equilibration between the condensed solute and its vapor. The loaded support was placed in the sample chamber, the chamber closed, and the pressure adjusted to the desired experimental value. Injections of the sample head-space were made at various pressures, each higher than the last, using identical electrometer settings. The pressure yielding the

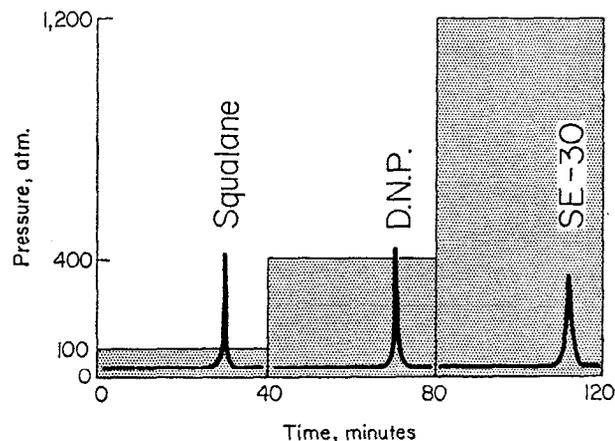


Figure 3. Stagewise pressure-programmed separation of squalane, DNP and SE-30 in CO<sub>2</sub> at 40°C.

Table I. Success in Inducing the Migration of Various Substances in dense NH<sub>3</sub> and CO<sub>2</sub>

Solute	Migration in NH <sub>3</sub>		Migration in CO <sub>2</sub> Pressure, atm
	at 200 atm and 140°C	at 40°C	
<i>Purines</i>			
Adenine	(-)	(+)	1300
Guanine	(-)	(-)	1300
Caffeine	(++)		
Xanthine	(-)		
<i>Nucleosides and Nucleotides</i>			
Adenosine, guanosine, uridine	(++)	(+)	1350
Adenylic acid	(++)		
<i>Cortical Steroids</i>			
Cortisone, hydrocortisone	(+)	(+)	1300
<i>Sterols</i>			
Cholesterol, ergosterol, lanosterol	(++)	(++)	510
<i>Sugars</i>			
Ribose, arabinose, xylose	(++)	(++)	1350
Glucose, fructose, mannose, sorbose	(++)	(++)	1350
Galactose	(+)	(-)	1350
Maltose	(++)	(++)	1350
Lactose	(++)	(-)	1350
<i>Terpenes</i>			
$\alpha$ -Carotene, $\beta$ -carotene, lycopene	(Decompose)	(++)	170
Squalene	(++)	(++)	510
<i>Amino Acids</i>			
Glycine	(++)	(+)	1350
Leucine, tryptophane, tyrosine arginine, lysine	(++)	(-)	1350
Glycylglycine, glycyl-L-leucyl-L-tyrosine	(++)		
Hippuryl-L-arginine	(-)		
<i>Proteins</i>			
Trypsin, lysozyme, apoferritin, $\gamma$ globulin	(-)		
Bovine albumin, bovine hemoglobin, gelatin	(-)		
Cytochrome C	(+)		
	(Decompose)		
<i>Silicone Oils and Gum Rubber</i>			
DC-200		(++)	700
OV-1	(-)		
OV-17	(++)		
SE-30	(-)	(++)	770*
<i>Alkanes</i>			
n-Octadecane, n-docosane, n-octacosane			
Squalene		(++)	136
<i>Carbowaxes</i>			
Carbowax 400	(++)	(++)	90*
Carbowax 1000		(++)	68*
Carbowax 4000		(++)	115*
Carbowax 20,000	(++)	(+)	190*
<i>Other Solutes</i>			
Quercitin	(++)		
Amygdaline	(-)		
Polysulfone	(-)		
Polyox	(-)		
Polystyrene 900	(-)		
Versamid 900	(-)		
Cellulose Acetate	(-)		
$\alpha$ -Glucose pentaacetate	(++)		
Polyvinyl chloride		(+)	1700
Polyethylene		(-)	1500
Dinonyl phthalate (DNP)		(++)	165*
Apiezon L	(-)	(++)	820*

++ = Strong migration (signal)  
+ = Marginal migration

- = Undetectable migration  
\* = Threshold pressures

first detectable peak was identified as the threshold pressure. No column was used; a column could increase the threshold pressure by excessive retention, but could not significantly lower it. The values are therefore close to the minimum practical working pressures.

**Enhanced solubility.** The procedure was much like that above. At each pressure a 10 second injection was made with an essentially constant flow rate in order to assure comparable sample volumes from the sample chamber. The peak area of the first, or threshold, peak was measured, as were the areas of subsequent peaks. Since these areas increased rapidly with pressure beyond  $p^*$ , only a small pressure range was covered.

**Enhanced migration.** Relative retention data were obtained from a 3 m long, 1 mm, i.d., column packed with 120-200 mesh Polypak 1. The sample was placed in the chamber as a liquid. The pressure in the sample chamber and column was raised to the desired pressure and the flow adjusted to a constant outlet (1 atmosphere) value for that solute. The retention time was observed. This was corrected for temperature and pressure, and the calculated air-peak time subtracted to provide a quantity proportional to the equilibrium distribution coefficient  $K$ . A porosity of 0.60 was assumed for the calculation of air-peak retention.

## Current Results

Initial results of sufficient number to critically study some qualitative and quantitative aspects of dense-gas chromatography have been obtained. These results fall into the same three categories as discussed in the experimental section. These are taken up in the same sequence below.

**Threshold pressures.** New threshold data were determined for a number of straight chain hydrocarbons and alcohols. The hydrocarbons and their threshold pressures in atmospheres are:  $C_{18}H_{38}$ , 87.5;  $C_{22}H_{46}$ , 89.8;  $C_{28}H_{58}$ , 98.6;  $C_{32}H_{66}$ , 100.8; and  $C_{36}H_{74}$ , 104.8. For the alcohols we have:  $C_{11}H_{23}OH$ , 61.2;  $C_{12}H_{25}OH$ , 78.2; and  $C_{18}H_{37}OH$ , 98.7.

**Enhanced solubility.** Results here were obtained by measuring peak areas at the threshold pressure and beyond. The relative enhancement above the threshold value,  $I^*$ , is equal to the ratio of the new area to the threshold area. A plot of these results against pressure  $p$  relative to threshold pressure  $p^*$  indicates the abruptness of the enhancement. Data for three compounds are shown on such a plot in Figure 4.

**Enhanced migration.** The retention time on the 3 m Polypack-1 column was measured for several small solute species over the pressure range 24-1560 atmospheres. Since outlet flows were adjusted to a constant value for each solute, independent of pressure, the flow velocities in the column decreased with increasing pressure. Nonetheless, due to enhancement, the retention times decreased dramatically; for benzene it changed from 173 minutes to 11 minutes between 26 and 380 atmospheres despite a manifold diminution in velocity. The highest observed enhancement,  $I_{id}$ , for both pentane and benzene was  $\sim 600$ , both found in the  $10^3$  atmospheres despite a manifold diminution in velocity.

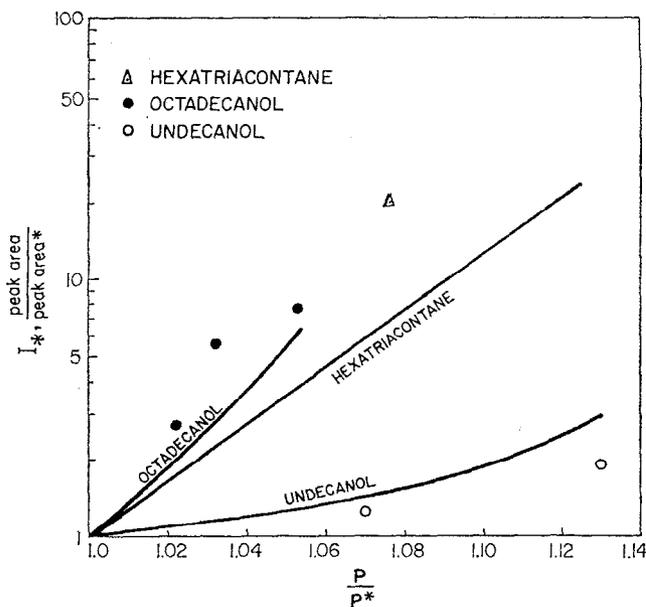


Figure 4. Solubility enhancement relative to threshold pressure  $p^*$ . See Equation 4.

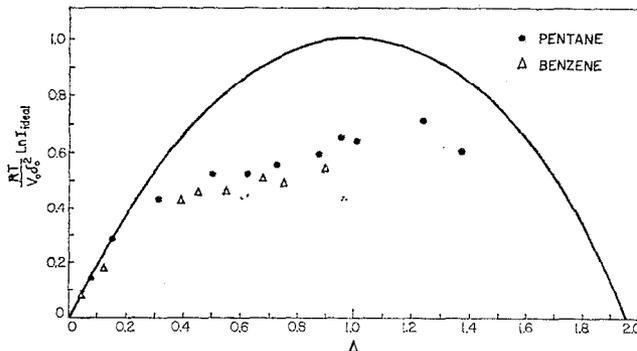


Figure 5. Enhanced migration results plotted in the form suggested by Equation 6.

Figure 5 in the form suggested by Equation 6. An extrapolation procedure was used to bring the curve into the origin at  $\Delta = 0$ , corresponding to the ideal gas.

## Discussion

Several qualitative conclusions arise from Equation 5 regarding the predicted dependence of the solubility enhancement,  $I_{id}$ , over its ideal-gas value. First,  $I_{id}$  is an exponential function of  $(V_0\delta_0^2/RT) \Delta(2 - \Delta)$ . Quantity  $V_0\delta_0^2/RT$  is strictly a function of solute parameters and temperature, while  $\Delta(2 - \Delta)$  reflects the relative density dependence of the gas ( $\Delta$  proportional to  $\rho$ ). At low densities (low  $\Delta$ ), the term  $\Delta(2 - \Delta)$  can be replaced by  $2\Delta$ , so that  $\ln I_{id}$  is initially proportional to gas density, a result consistent with the conclusions of Sie, van Beersum and Rijnders (4). At higher densities  $\ln I_{id}$  begins to level off, becoming flat at  $\Delta = 1$ . Since  $\Delta = \delta/\delta_0$ , this is the point where the solubility parameter of the gas has reached that of the condensed solute. As one continues beyond  $\Delta = 1$ , the

enhancement is predicted to lessen again. If one has a nonpolar solute with a low  $\delta_o$ , and chooses a gas with a large "chemical effect,"  $\delta_{11q}$ , it is not inconceivable to study the region well beyond  $\Delta = 1$  for its bearing on the nature of dense gas solution phenomena. More practically, we conclude that maximum enhancement at  $\Delta = 1$  can be approached at lower densities and pressures by using a gas with a large "chemical effect." If, however, the solute is highly polar ( $\delta_o$  high) it may be very difficult to approach this point.

The results in Figure 5 are in rough accord with the theory, the latter shown by the top, dome-shaped curve. The dependence of  $\ln I_{1d}$  (times the constant) is linear at first, and then flattens as  $\Delta = 1$  is approached. We have been able to go to  $\Delta = 1.37$  with pentane since  $\text{CO}_2$  has a fairly large chemical effect. However the range is not sufficient and the precision not adequate to determine if a maximum actually exists. Some error in these curves near the maximum may result from an uncertain estimate of air peak time, since in this region the peaks are close on the heels of the hypothetical air peaks.

The steepness in the rise of exponential  $I$  curves depends on the magnitude of the coefficient  $V_o\delta_o^2/RT$ . The latter is essentially the reduced cohesive energy of the solute,  $\Delta E_o/RT$ . This quantity varies from 9.0 for a small molecule like pentane at  $40^\circ\text{C}$  to many hundred for high polymers. The maximum enhancement in solubility for a component is therefore of the order of  $\exp(V_o\delta_o^2/RT)$ , a sizeable number even for small molecules. Both maximum enhancement and its initial steepness of rise increase roughly with molecular size (i.e., volume  $V_o$ ).

For large, nonvolatile molecules it is difficult or impossible to measure  $I_{1d}$  because no signal can be obtained at low pressures. Under these circumstances we can observe only the enhancement relative to threshold,  $I^*$ .

Theoretical and experimental values of  $I^*$  appear in Figure 4. Equation 4 was used for the theoretical curves. There is a trend to increasing steepness with molecular size. However octadecanol and hexatriacontane have similar slopes because the slightly larger threshold pressure of the latter (104.8 vs. 98.7) puts it into a less compressible region with a resulting relative decrease in the  $\Delta$  increment,  $\Delta_2 - \Delta_1$ , for a given  $p$  increment. The theoretical curves are highly uncertain because the pressure range is small and increments in  $\delta$  and  $\Delta$  were difficult to determine accurately.

The trends in threshold values themselves are shown in Figure 6. This is a display of current data plus some of the earlier results. The plots are made in line with Equation 7. The negative slope of the line is therefore  $\ln K^*$ .

We see that the various points cluster fairly well around the dashed line, whose slope was determined from the data, and are thus reasonably consistent with each other and with theory. This is gratifying since the plot involves different molecular types and covers nearly a twentyfold molecular weight range.

The theory, from Equation 7, requires an approach to  $\Delta^* = 1$  at  $(RT/V_o\delta_o^2) = 0$ . Actually for flexible polymers, as opposed to rigid molecules, a better intercept would be about  $\Delta^* = 0.9$ .

From the slope of the dashed line we find that

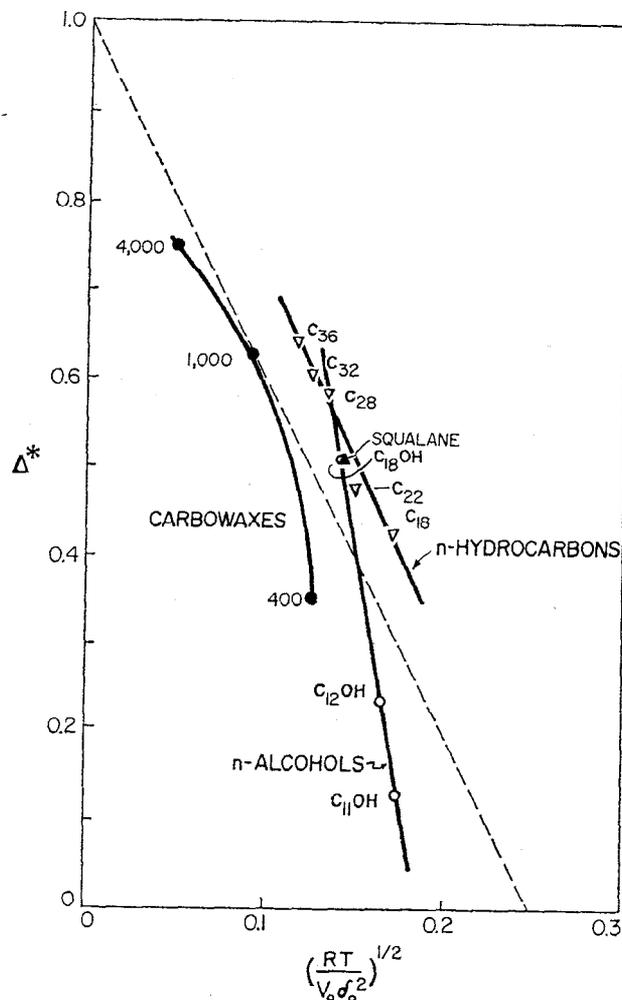


Figure 6. Reduced threshold solubility parameters,  $\Delta^* = \delta^*/\delta_o$ , versus  $(RT/V_o\delta_o^2)^{1/2}$  for a variety of substances. The dashed curve has its intercept fixed by theory and its slope fixed by the experimental points. See Equation 7.

$K^* \sim 8 \times 10^6$ . An earlier crude estimate from low pressure experiments in another laboratory had led to  $K^* \sim 10^6$ , in rough agreement. The value of  $K^*$  could vary up to two orders of magnitude (depending on experimental circumstances) without greatly altering the slope in Figure 6.

Figure 6 should have utility in correlating the required  $\Delta^*$  with solute volume,  $V_o$ , solubility parameter,  $\delta_o$ , and with temperature  $T$ . From  $\Delta^*$  we can determine the minimum working pressure for chromatographic separation. Note that when  $(RT/V_o\delta_o^2)^{1/2}$  reaches about 0.25, the molecule is small enough or the temperature high enough to use normal, low pressure gas chromatography.

In order to check our work against independent, nonchromatographic data, we have employed the results of Diepen and Scheffer (14) for the solubility of naphthalene in compressed ethylene, and the results of

14. Diepen, G. A. M., and Scheffer, F. E. C., J. Am. Chem. Soc. 70, 4085 (1948).

Gamburg (15) for the solubility of compressor oil in compressed nitrogen. The latter data were kindly made available in the form of a translation from the Russian by A. Beerbower of Esso Research and Engineering Company. Plots analogous to those for our data in Figure 5 are shown for these data in Figure 7. While of limited range on the  $\Delta$  scale, these results agree with ours in being somewhat below the curve predicted by Equation 6. Empirically the left hand side of Equation 6 appears to average about half the value given, i.e.,  $\Delta(2 - \Delta)/2$ , a form that might be useful for correlating data. Note that the nitrogen data are for high reduced temperatures, so that the results altogether cover a wide range of state and chemical parameters.

In conclusion, we find that the theoretical guidelines provided by the application of solubility-parameter concepts are in rough accord with the data. Some numerical results can be predicted reasonably, and others disagree a great deal. Because of the rapid exponential increase in solubility with pressure, it is difficult to pin point enhancement with reliability. We can more accurately, on the other hand, predict the pressure (e.g., threshold pressure) at which enhancement reaches a certain level. The latter, fortunately, is of more practical significance, because it tells us the rough magnitude of pressures and temperatures needed to accomplish the desired goals.

Perhaps the greatest value of these concepts is in providing qualitative guidelines. One can predict the effect of variation in molecular size and polarity on enhancement, and the possibility for increasing or decreasing that enhancement through the control of pressure, temperature and carrier gas. This, alone, is an important goal for the chromatographer faced with the necessity for separating complex systems.

#### Acknowledgment

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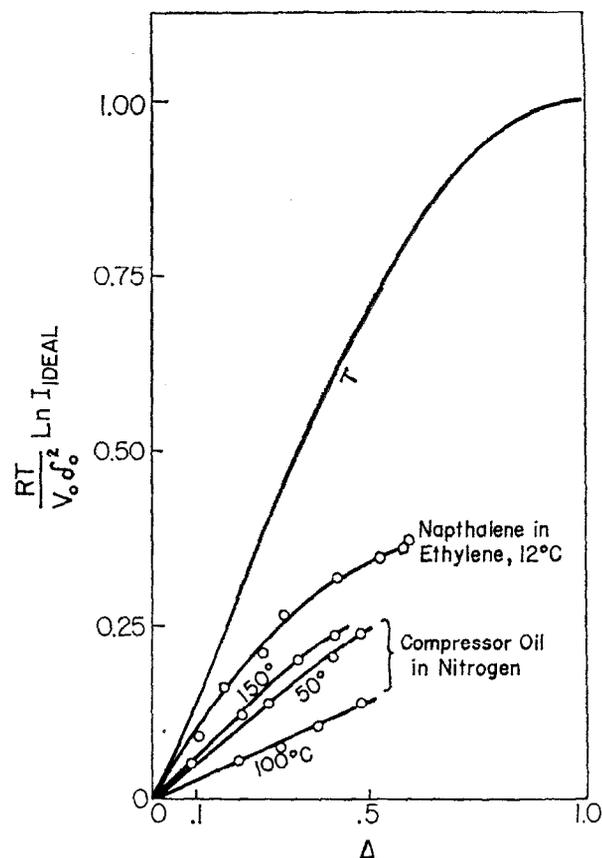


Figure 7. Enhanced solubility data from nonchromatographic studies plotted in the form of Equation 6.

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15. Gamburg, D. Iu., *Neft. Khoz.* 25, 46 (1947).