DRAFT FINAL REPORT

on

VALIDATION OF THE WATER SOLUBILITY TESTS
TECHNICAL DIRECTIVE 7

to

A. Leifer and D. L. Garin, Project Officers

OFFICE OF PESTICIDES AND TOXIC SUBSTANCES
U.S. ENVIRONMENTAL PROTECTION AGENCY

Contract No. 68-01-5043

February 28, 1981

by

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INTRODUCTION

The solubility of organic substances in water is one of the principal properties that determine the transport and accumulation of these substances in the environment. Furthermore, knowledge of water solubility is required for adequate design of many ecology and health related tests of the environmental impact of these chemicals.

Many methods for the determination of water solubility are suggested in the literature. Some of these are highly specialized methods, and others are very general. However, except for a few recent cases, there is usually little or no indication of the general precision or accuracy to be expected from use of these methods. In recognition of the importance of water solubility as a prime environmental variable, the USEPA has suggested several techniques for the determination of this property (Proposed Section 5 Guidelines, Federal Register 44:16240, 1979). The purpose of the current program has been to evaluate the methods suggested in the Section 5 Guidelines, with the goals of (1) determining the precision and accuracy to be expected; and (2) developing more precise statements of the techniques to be used and the precautions that need to be taken to achieve good results.

The specific plan of work followed on this program involved application of five different experimental methods to five groups of chemicals representing a wide divergence of solubilities and chemical character. During the course of the program, two of the approaches were dropped because

of technical faults with the approaches, and a more generally applicable technique was added to the evaluation scheme.

SUMMARY

The general objective of this program was to determine the applicability of water solubility tests outlined in the Section 5 Guidelines to five groups of organic chemicals encompassing a wide range of solubility and chemical functionality. The goals of this task were to develop information concerning (1) the precision and accuracy to be expected for each of the methods: (2) the precautions and special techniques needed to obtain good precision and accuracy; and (3) the general costs to be expected for determination of water solubility.

Early in the program, it became obvious that Method 1 (patterned after Method D in the Section 5 Guidelines) for solids was technically incorrect for oversaturation. Inasmuch as this method involved the use of specialized apparatus not generally available commercially, no further efforts were expended to refine the method to a useable status. During the course of the program, it was shown that the use of Method 2 (nephelometry, patterned after Method E in the Section 5 Guidelines) involves procedures that can seriously interfere with determination of the true water solubility. Therefore, investigation of this method was discontinued. In place of both of these methods, an investigation was made of the applicability of the "plating method" (Method 5). This latter method is relatively easy to apply, involves no special equipment, and can be applied to any solid organic chemical as long as no time constraints are imposed by technical factors (e.g. hydrolysis or general reactivity of the chemical).

The general results of this program are summarized in Table 1. Detailed descriptions of the methods and precautions to be observed are given in Appendix A. Estimated costs for determination of water solubility are shown in Appendix B.

Casual perusal of Table 1 suggests that with the exception of the very hydrophic chemicals (solubilities <1 ppm) precisions of 3-7 percent relative to the measured solubilities can be expected. With the very hydrophobic chemicals, the relative precisions found in this work average about 30 percent and generally range between 15 and 45 percent. This poorer precision is believed to be due to the ease with which the latter chemicals form suspensions and the difficulties associated with reliable removal of these suspensions. In both categories, there are examples of results lying well outside of the cited ranges.

Table 1. Summary of Solubility Data

Chemical	Method[a]	Solubility, mg/L 10°C	20°C	30°C	Relative Precision[b] 10°C	20°C	30°C	Literature Value 10°C	20°C	30°C	Reference
Benzoic Acid	5	2103	3030	4597	8.3	7.0	5.7		2700 @18°C		1
p-Hydroxybenzaldehyde	5	5065	7018	14,163	4.4	4.2	6.4			13,800	1
Benzene sulfonamide	5	4030	3990	6425	4.2	4.9	6.6		4000 @15°C		1
Trichlorophenol[c]	5	151	249	280	3.3	5.5	6.1		800		1
Trichlorophenol[d]											
Unbuffered sol'n.			494			1.5					
pH = 7.1			592			17					
pH = 8.9			2698			8.6					
Benzene	1	1780	1869	1712	3.9	3.4	1.3	1787	1777	1837	2
Diethylsulfide	1	3508	3704	3398	3.2	3.3	3.2		3130		3
Chloroform	1	6412	5319	5125	3.6	3.5	2.8		8000		3
Ethylbromide	1	5932	5546	5667	4.0	4.3	4.0		9100		3
Phenanthrene	3	0.61	0.91	1.46	17	24	7	0.61	0.92	1.46	4
	5	0.47	0.89	1.31	8.9	15	7.1				
Naphthalene	3	31.9	44.9	56.6	5.8	7.7	7.2	19.7	27.0	38.2	4,7
	2		48.1			12.2					
	5	27.9	40.6	57.9	5.5	3.6	6.2				
p-Dichlorobenzene	3	50.8	60.2	88.9	5.5	8.8	2.5	52.9	69.3	91.5	4
	5	55.3	66.5	91.4	4.0	3.6	6.4				

Table 1. (Continued)

Chemical	Method[a]	Solubility, mg/L 10°C	20°C	30°C	Relative Precision[b] 10°C	20°C	30°C	Literature Value 10°C	20°C	30°C	Reference
Ethylbenzene	4	206	210	215	4.0	2.0	2.1	209	207	213	2
Diphenylether	4	8.21 (solid)	18.2	19.9	3.8	3.6	2.2				
n-Octane	4	0.73	0.58	0.70	4.7	6.2	7.7	0.66 ±9% @25°C			5
2,4D, n-butylester	4	0.084	0.95	0.99	16	18	10				
Phosvel[c]	3	0.021	(0.04)	0.053	50	(85)	38	Unknown			
	5	0.025		0.021	49		36				
Anthracene	3	0.057	0.075	0.13	25	22	8.6	0.0569	0.0843	0.127	4
Methoxychlor	3	0.014	0.061	0.058	36	27	36	0.020@15	0.045@25°C		6
Methylphenanthrene	3	(e)	0.014	0.008	-	28	66	Unknown			

a. Related to Section 5 method designations D, E, F, G, and a "plating method", respectively.
b. Standard deviation expressed as a percentage of the indicated solubility.
c. Samples analyzed by gas chromatography.
d. Samples analyzed by HPLC.
e. Results not self-consistent - see text.

References

1. Chemical Rubber Handbook
2. R. L. Bohen and W. F. Claussen, J. Am. Chem. Soc., 73 1571 (1951).
3. Handbook of Environmental Data on Organic Chemicals ed. by Karel Verschuesen, Van Nostrand Reinhold Co., New York, 1977.
4. R. D. Wauchaup and F. W. Getzen, J. Chem. Eng. Data., 17 38 (1972).
5. C. McAuliffe, J. Phys. Chem. 70, 1267 (1966).
6. J. W. Biggar and R. L. Riggs, Hilgardia 42 383-391 (1974).
7. W. E. May, S. P. Wasik and D. H. Freeman, Anal. Chem., 50, 997-1000 (1978).

The accuracy of the results is difficult to define in the absence of consensus values for the true solubilities, and it should be noted that precision and accuracy can vary independently. For example, initial results with ethylbenzene yielded with good precision apparent solubilities that were 35 percent higher than the literature values, but correction of a sampling fault yielded results that differ by an average of only 1.3 percent from the literature values. In the case of naphthalene, there is a generally accepted solubility of about 30 mg/L at 20 C. However, our results obtained by two different methods using both G.C. and HPLC analyses, with two sets of gravimetrically prepared standards indicate a value about 25 percent high. We are confident that for the samples we ran the relative accuracy is no worse than 10 percent and is probably no worse than the indicated precision, and we are unwilling to accept the literature value as the true solubility for our set of chemicals. Another facet of the uncertainty of accuracy lies in the failure of most literature citations to include the precision of the measurements. Without such specification, comparison of independent results with respect to accuracy are meaningless.

In comparing the different methods, we find little or no significant differences between the results obtained with application of different methods to the same chemical. There may be however, significant differences in costs and manpower consumption. Methods 4 and 3 which involve sonication are rapid, and require equilibration times of no longer than 1-2 hours at most. However, they do require centrifugation of samples, and if sonication procedures are too severe, removal of suspended solute particles may be difficult except with extreme centrifugation procedures. On the other hand, the plating method (Method 5) may require equilibration times of days, but centrifugation is needed usually only as a final check on the results. The plating method is therefore less intensive with respect to manpower commitment. However, the plating method may not be applicable for the relatively few chemicals that hydrolyse rapidly or are otherwise relatively unstable.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this program, we concluded that Methods 1(liquids), 4, 3, and 5 are capable of yielding reasonable precisions of 3-7 percent for chemicals having solubilities greater than 1 ppm and 15-45 percent for the very hydrophobic chemicals. Definition of accuracy in quantitative terms is difficult, but, except for naphthalene, our results compare favorably with literature values for chemicals where seemingly good independent work has been conducted. Methods 1(solids) and 2 are unacceptable because of technical faults in these procedures. We recommend that methods 3 and 5 be given prime consideration for routine evaluation of water solubilities. Method 5 is simple, inexpensive and generally applicable to a variety of chemicals. We feel that a variation of Method 5 involving gentle occasional shaking of the samples could be considered identical to Method 1(liquids). Likewise, there is little fundamental difference between the operations involved in Methods 4 and 3. Thus, when considered in general terms, either Method 5 or Method 3 might be used for determination of water solubility. However, if the subject chemical is unstable with respect to hydrolysis or is otherwise reactive, method 3 should be used.

Centrifugation of samples is necessary for the very hydrophobic chemicals and any chemical that, because of its chemical nature, tends to disperse readily as a colloid. If Method 3 is used, sonication periods should be no longer than about one minute because of the tendency for formation of very finely divided suspensions that may be difficult to remove by centrifugation. With the use of Method 5, centrifugation is recommended only as a final check after equilibration has been attained unless interim observations suggest the presence of suspended material. We recommend that all centrifugation be conducted using sealed centrifuge tubes in order to prevent loss of volatile organics.

Based on assumptions outlined in Appendix B, we estimate that routine determination of water solubility could be carried out at a cost of approximately (1979 bases) per chemical. This cost could be reduced through selection of samples to be analyzed such that a complete set of analyses would not be run until equilibration was apparent. It should be recognized however that this cost could be amplified severalfold by unforeseen difficulties associated with a given chemical. Because of the fact that the dissolution of liquid

organic chemicals does not involve a change of physical state, and hence does not consume energy for that process, the temperature dependence of dissolution of liquids is usually quite low. Therefore, it may not be necessary to run the complete matrix of samples as a function of temperature for organic liquids, and the cost of performance of the tests might be reduced. Decision as to whether or not the temperature dependence would be required could be based on a few preliminary measurements.

DISCUSSION

Generalized Approach to Solubility Measurements

Basic Elements

There are three basic functions that must be completed in any method for determining the solubility of an organic compound in water: (1) preparation of the solution, (2) sampling in preparation for analysis, and (3) analysis of the solution. As indicated in Table 2, these functions can be considered in terms of a set of laboratory operations, each of which may involve several options.

The various operations are frequently interactive however and free choice between the options may not always be appropriate. For example, sonication to effect rapid mixing and equilibration of the solution is apt to result in the formation of a finely divided suspension of solute that can interfere with determination of the true solubility. In such cases, centrifugation of the sample will be necessary for removal of excess solute before analysis. Filtration is useful for this purpose only if it can clearly be demonstrated that: (1) the process removes essentially all of the suspension, and (2) no appreciable amount of solute is lost from the solution by sorption on the filter. On the other hand, the use of mild agitation of the sample is apt to prolong the equilibration period, and analysis of the sample as a function of time must be required to verify approach to equilibrium.

Choice between the various options can also depend on such factors as the size of the sample being prepared and the nature of chemical being considered. For example, modern chemical analysis techniques such as HPLC or G.C. rarely require samples larger than 1-50 µL. Thus total solution volume does not have to be greater than 50 mL unless the solubility is less than 10-50 ppb. In such cases, extraction and concentration procedures may determine the need for larger initial solution volumes. The use of smaller solution

Table 2. Basic Elements of Solubility Measurements

Function	Operations	Options	Conditions or Considerations
Preparation	1. Mixing	Stir, Shake, Sonicate	Clean apparatus, pure substances, temperature control, prevention of solute loss by evaporation, etc
	2. Equilibration	Over/under saturation, Analyze as function of time	
	3. Separation of excess solute		
Sampling	1. Transfer for analysis	Pipette, Syringe, Decant	Maintain sample integrity, temperature
Analysis	1. Convert to suitable form for analysis	Extract, Concentrate, Derivatize	Preparation of standards, precision and accuracy of method, calibration and stability of response, Blank response, etc.
	2. Analyze	Chromatography (GC, GC-MS, LC, etc.), Spectrophotometry, Turbidimetry, Nephelometry, etc.	

volumes can facilitate mixing and equilibration. For example, if the plating method is used, the surface to volume ratio and hence the contact efficiency is greater for a small container than for a larger conainer having the same shape. Hence, a small container should lead to more rapid equilibration.

The chemical nature of the solute may limit the choice of options fartherif the solute is subject to hydrolysis or is otherwise unstable. In such cases there is a need to minimize the equilibration time and sonication followed by centrifugation may be the best choice.

In any case, the choice of options should be based on the following criteria, as suggested in Table 2:

1. Equilibration of excess solute with solution
2. Maintenance of constant temperature
3. Separation of excess solute
4. Maintenance of solution integrity
   a. prevention of loss by evaporation of solute
   b. prevention of loss by adsorption of solute
   c. prevention of contamination of solution
5. Assurance of analysis quality
   a. calibration of extraction and/or derivatization procedures
   b. appropriate calibration of analysis method
   c. use of system blanks and solutions of known concentrations

Precautions

Although execution of a solubility measurement is a relatively simple laboratory procedure, there are a number of problems that can arise because of the specific behaviors of individual chemicals.

Temperature Control. Temperature control can easily be achieved to $\pm 0.05^{\circ}C$ or better with commonly available commercial water baths, and the bath control will not usually be a limiting factor. However, it is relatively difficult to achieve good temprature control within a centrifuge. Most bench-top centrifuges capable of attaining g-factors of 1-3000 gs do not

have provision for temperature control. Medium-sized centrifuges in the 10-50,000 g range and ultracentrifuges (up to 200,000 g's) are refrigerated but control over the actual sample temperature is difficult. There is a significant amount of heat generated with these machines because of friction at the high speeds of operation. Actual temperature rises depend on the size of the rotor and the speed of operation. Although cabinet temperatures may be controlled to within a degree or less, the rotor and sample temperatures will generally be higher depending on the speed. Most manufacturers supply calibration charts for relating rotor speed and cabinet temperature to rotor temperature, but the accuracy and precision of these charts is questionable. In any case, the process of loading the centrifuge, running, and unloading the centrifuge is likely to subject the samples to temperature fluctuations of at least a few degrees. This variation may or may not have a significant effect on the measured solubility. Since solubility for hydrophobic compounds is generally slow, small changes in T for a short period of time may not affect results.

The temperature dependence for the solubility of most organic liquids is very slight (see F. W. Getzen, "Structure of Water and Aqueous Solubility" in Techniques of Chemistry ed. by M.R.J. Dack, John Wiley & Sons, Inc., New York, 1976), and many, e.g. benzene, exhibit a minimum solubility in the vicinity of 20°C. For these materials a temperature variation of a few degrees will probably have no appreciable effect on the apparent solubility. Thus temperature control would not be an important factor for liquids unless highly precise definition of the temperature dependence is needed. With solids however there is a change of state involved in the dissolution process, and the energy required for this change of state (the heat of fusion) can contribute to a significant temperature dependence for the solubility. A brief survey of the heats of fusion for 145 organic compounds indiciates an average value of 29.6 cal/g $\pm$33 percent. Assuming, as an example, a molecular weight of 100, we could expect a heat of fusion of 2.96 kcal/mole. Assuming this to be the principal contribution to the temperature dependence of solubility, the Clausius-Clapeyron equation can be used to estimate the effect of temperature variation on the solubility, viz.,

$$\ln \frac{S_1}{S_2} = \frac{-\Delta H}{R} \left(\frac{\Delta T}{T_1 T_2} \right)$$

Table 3 shows values of S_1/S_2 for several different ΔT's and ΔH's at a mean temperature of 20°C. These values indicate that uncertainties of 1-2 percent can be expected to result from a temperature variation of one degree and a 6-11 percent error is associated with changes of five degrees. Inasmuch as the error associated with temperature variation is only one of a number of sources of error in the solubility measurement, it is clear that care need be taken to minimize the temperature fluctuations with solid solutes and centrifugation should not be used unless it is necessary.

Table 3. Effect of Temperature on Solubility of Solids

		S_1/S_2		
ΔT°C	-ΔH, Kcal/mole	2	3	4
0.5		0.994	0.991	0.988
1		0.988	0.983	0.977
3		0.965	0.949	0.932
5		0.943	0.916	0.889

Changes of State. Choice amongst the various options to be performed in determining solubility sometimes depends on whether the chemical is liquid or solid. It is obvious that the normal melting point of a chemical may be within the desired range of temperatures for the solubility measurements. However, the mutual solubilities of the solute and water may be such that changes of state occur at temperatures other than the normal melting point. An excellent example of this behavior is found in the case of diphenylether. This compound has a normal melting point of 28°C, but in contact with water the ether-rich phase remains liquid at temperatures below 20°C. At 10°C the normal state in equilibrium with water is a solid, but transition to the solid state is very slow. (In our own experiments, one diphenylether sample remained liquid after nearly 30 hours at 10°C.) Thus considerable care needs to be taken to assure the fact that data are taken with the equilibrium states.

Another facet of this problem area arises with compounds that have appreciable volatility. Many organic compounds have equilibrium vapor concentrations that are significant with respect to their water solubilities. Thus it is clear that excess vapor space over the solution must be avoided and, more importantly, no ventilation of the sample should be allowed during the sampling and analysis procedures. Also, the analysis should be carried out as rapidly as possible using fresh samples for each analysis.

Sampling Procedures. The preferred sampling procedure is to transfer a sample directly from the solution to the analytical instrument. However, this is not always a straight forward procedure. With many organic chemicals that are more dense than water most of the organic will settle to the bottom of the container. Sometimes this allows direct sampling of the aqueous layer. Frequently, though, very small droplets or crystals of the organic can become supported on the surface of the aqueous layer. These "particles" cannot reliably be removed by centrifugation in many cases and care must be taken to avoid contamination of the syringe by these particles.

When the organic-rich layer is less dense than the aqueous layer, a separatory funnel can be used to withdraw small samples of the aqueous layer, but the bulk of the solution should be left in contact with the excess solute.

When centrifugation is employed, it should be noted that the centrifuge tubes in most modern high speed machines are supported at only a small angle with respect to the vertical direction. Particles are therefore moved to the outer edge of the centrifuge tube. It is good practice to mark the outer side of such tubes and sample from the inner side of the tube. Also, care must be taken to avoid remixing of the particles through casual shaking or even thermal generation of convection currents caused by handling of the tubes.

Analysis Procedures. Analysis procedures are frequently quite specific for a given chemical. The preferred approach for analysis of solubility samples should involve direct analysis of the samples by some generally applicable technique such as HPLC or G.C.. Such an approach usually does not require intermediate workup of samples and hence avoids loss or contamination of the samples. Some solutes however because of their limited solubility or their

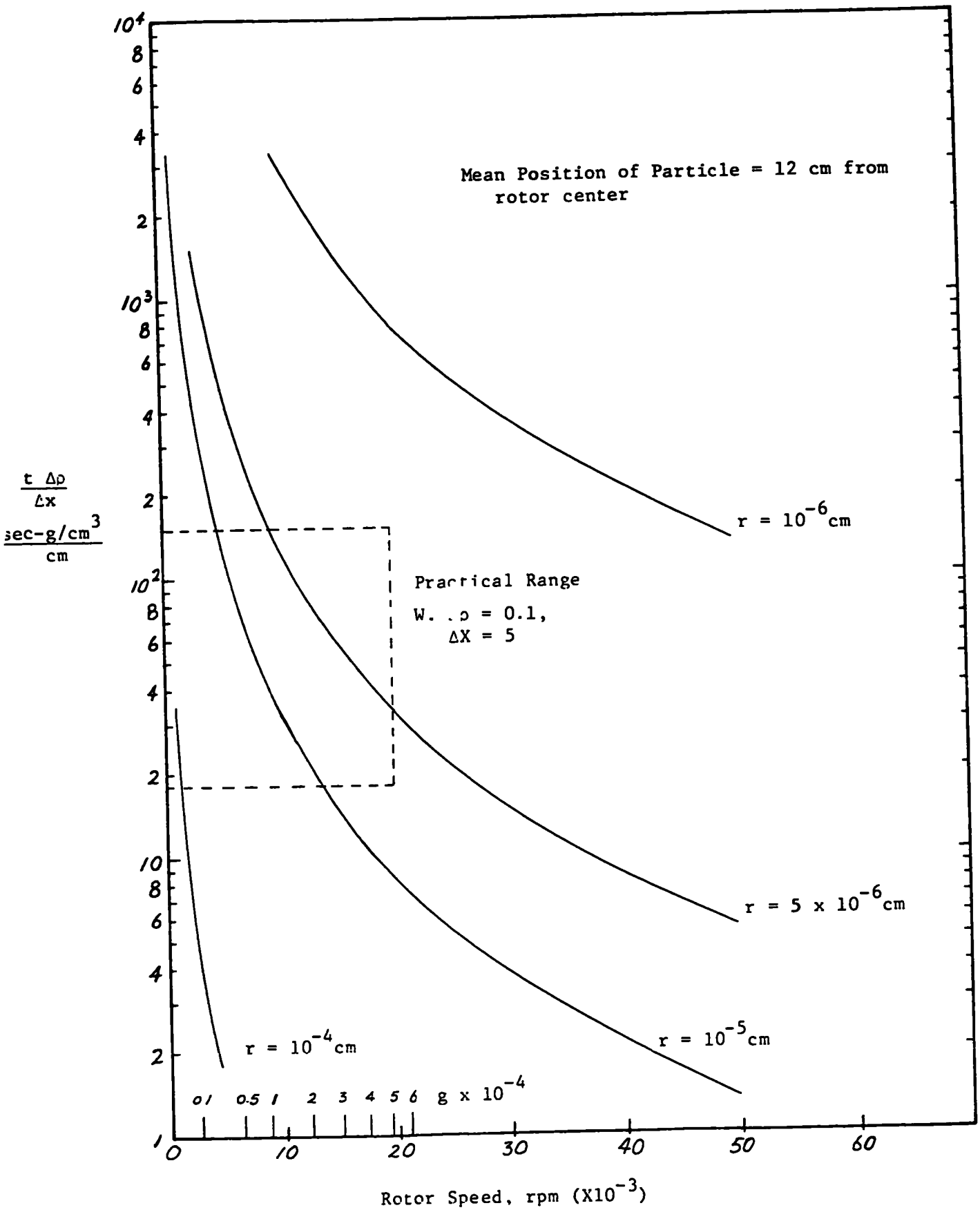
chemical nature may require pre-analysis preparation such as extraction and concentration or derivatization. In these cases, these intermediate steps should be calibrated carefully using duplication of the intended techniques with gravimetrically prepared samples having concentrations of the same strength as the solubility samples. Furthermore, the probable contribution of these extra steps to the overall uncertainty in the measured solubility should be documented.

Centrifugation. In addition to precautions already stated with respect to centrifugation and its interaction with other operations and options for solubility measurements, we offer a brief discussion of parameters that determine the efficacy of centrifugation. The settling rate of a suspended spherical particle depends on the size of the particle, its density, the density of the surrounding medium, the speed and size of the rotor, and the viscosity of the medium. If the position of a particle is specified in terms of its distance from the center of the rotor, its position as a function of time is given by

$$\ln \frac{x}{x_o} = \frac{2r^2\omega^2 (\rho-\rho_m) (t-t_o)}{9\eta}$$

where ω is the angular velocity in radians per second. For water ρ_m = 1.0 g/cc and $\eta = 10^{-2}$ poise. With one popular rotor $x_o \approx 12$ cm. Figure 1 shows g-factors and time per cm movement for a unit density difference as they vary with different particles sizes. As can be seen from this Figure it is reasonable to expect to remove particles of the order of 10^{-5} cm in size within time periods of about 1 hour using a medium-sized centrifuge. In any case it should be recognized that centrifugation does not "remove" particles from solution but rather enhances formation of a particle concentration gradient along the radius of the rotor. At any given speed of rotation this gradient will ultimately stabilize at a point when the diffusional spreading of the particles balances the centrifugally induced concentration effect. Thus, it is technically unfeasible to remove all particles and impractical to attempt to remove particles at sizes below about 10^{-5} cm.

Figure 1 . Practical Application of Centrifugation



EXPERIMENTS EVALUATION OF METHODS

Each of the water solubility methods outlined in the Section 5 Guidelines was examined, at least briefly, and one additional method, the plating method (Method 5), was evaluated. Detailed descriptions of these methods, except for Method 1 (solids) are found in Appendix A.

Results

Results of the solubility measurements made by each method are given in Appendix C. These data are summarized in Table 4.

Method 1 (solids)

It will be noted that no data were collected using Method 1 (solids). This method calls for the use of a special u-shaped vessel having a fritted-glass plug in one arm. The purpose of this design was to provide a built-in filter to separate undissolved solids from the solution. In use, the arms are alternately pressurized to effect pumping of the solvent back and forth across the frit. This device is not available commercially, but several were constructed and tried out. Use of the tubes proved very awkward:

1. Pressure drops across frits having the same nominal coarseness were too variable to permit operation of several tubes in parallel.
2. Very close control of pressure and the pressure switching mechanism is required for automatic operation.
3. The frits do not reliably exclude particles smaller than those that would normally either settle out or could be removed by mild centrifugation.
4. If an over/under saturation technique is used to judge approach to equilibrium, both sides of the frit automatically become supersaturated with respect to solute and the frit is useless.

Table 4. Summary of Solubility Data

Chemical	Method[a]	Solubility, mg/L			Relative Precision[b]			Literature Value			Reference
		10°C	20°C	30°C	10°C	20°C	30°C	10°C	20°C	30°C	
Benzoic Acid	5	2103	3030	4597	8.3	7.0	5.7		2700 @18°C		1
p-Hydroxybenzaldehyde	5	5065	7018	14,163	4.4	4.2	6.4			13,800	1
Benzene sulfonamide	5	4030	3990	6425	4.2	4.9	6.6		4000 @15°C		1
Trichlorophenol[c]	5	151	249	280	3.3	5.5	6.1		800		1
Trichlorophenol[d]											
Unbuffered sol'n.			494			1.5					
pH = 7.1			592			17					
pH = 8.9			2698			8.6					
Benzene	1	1780	1869	1712	3.9	3.4	1.3	1787	1777	1837	2
Diethylsulfide	1	3508	3704	3398	3.2	3.3	3.2		3130		3
Chloroform	1	6412	5319	5125	3.6	3.5	2.8		8000		3
Ethylbromide	1	5932	5546	5667	4.0	4.3	4.0		9100		3
Phenanthrene	3	0.61	0.91	1.46	17	24	7	0.61	0.92	1.46	4,7
	5	0.47	0.89	1.31	8.9	15	7.1				
Naphthalene	3	31.9	44.9	56.6	5.8	7.7	7.2	19.7	27.0	38.2	4
	2		48.1			12.2					
	5	27.9	40.6	57.9	5.5	3.6	6.2				
p-Dichlorobenzene	3	50.8	60.2	88.9	5.5	8.8	2.5	52.9	69.3	91.5	4
	5	55.3	66.5	91.4	4.0	3.6	6.4				

Table 4 (Continued)

Chemical	Method[a]	Solubility, mg/L 10°C	20°C	30°C	Relative Precision[b] 10°C	20°C	30°C	Literature Value 10°C	20°C	30°C	Reference
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Methoxychlor	3	0.014	0.061	0.058	36	27	36	0.020@15	0.045@25°C		
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a. Related to Section 5 method designations D, E, F, G, and A "plating method", respectively
b. Standard deviation expressed as a percentage of the indicated solubility.
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7. W. E. May, S. P. Wasik and D. H. Freeman, Anal. Chem., 50, 997-1000 (1978).

Because of these shortcomings Method 1 (solids) was not investigated further.

Method 1 (liquids)

Method 1 (liquids) has the unique feature of employing an over/under saturation technique to ascertain approach to equilibrium. With this method samples are paired, with one member of the pair being cooled to say 0-5°C and the other being warmed to 40-50°C. Both samples are then placed in a constant temperature bath at say 20°C and are periodically analyzed until results from the pair are within 5 percent of each other.

In principle, this is an excellent technique. An analysis of variance conducted on the raw data for this method showed little or no consistent dependence of the results on whether the samples had been initially cooled or warmed. However, this might well be expected regardless of the details of the technique. As indicated in a previous section of this report, the solubilities of many organic liquids show only very slight temperature dependencies. Thus for a liquid such as benzene which has a minimum solubility in the vicinity of 20°C, cooled and warmed samples have very similar initial concentrations and follow very similar "pathways" when they are changed to 20°C. Inasmuch as analyses as a function of time are still needed to determine the first result by this method, we feel that the use of over/under saturation offers only a redundancy that may not be justifiable.

Method 2

Attempts were made to apply Method 2 to naphthalene, p-dichlorobenzene, and phenanthrene. This method requires that a uniform and stable suspension of the solute be prepared at a level severalfold in excess of the solubility. This stock suspension is then diluted stepwise and measurements of the turbidity are made as a function of the known overall concentration. The solubility is determined as that concentration at which the solution is no longer turbid.

A crucial step in this method is in the quantitative preparation of the initial suspension. This cannot be accomplished by mechanical means such as sonication because of the uncertainties associated with uniform dispersal of all of the added solid. The preferred approach is therefore to dissolve a weighed quantity of solute in a minimum amount of organic solvent that is miscible with water. This solution is then added dropwise to the water with rapid stirring of the water. As the solubility limit is approached increasingly stable turbid zones are noted in the vicinity of the added drops, and at the solubility limit the entire solution becomes turbid.

This method offers an easy approach to estimating the solubility by treating the preparation as a turbidimetric titration. However, this estimated solubility will usually be greater than the true solubility. This latter fact is caused by the effect of the organic solvent on the water solubility. The use of mixed solvents to either enhance or limit solubility is a commonly used technique for HPLC and need not be discussed further here. The significance of this effect with respect to solubility measurements is very important. With even very small amounts of organic solvent, the overall solubility can be altered significantly. Results obtained with naphthalene by this method are appreciably greater than solubilities measured by either Method 3 or Method 5. With p-dichlorobenzene, we were not able to prepare turbid suspensions at levels 3 times the known solubility. With phenanthrene, similar difficulties were encountered. Furthermore, these suspensions were not always stable. In several cases, changes in turbidity due to coalescence of the suspensions were observed during the few minutes required for the turbidity measurement.

For these reasons, investigation of Method 2 was not pursued further.

Methods 3, 4, and 5

No particular problems were found with execution of Methods 3, 4, and 5. However, we do not feel that there are sufficient differences between Methods 3 and 4 to warrant separate definition. Both methods employ sonication for mixing and both methods require centrifugation. Further discussion of the

time and centrifugation variables for these methods is given below.

Time of Equilibration

Analysis of samples as a function of time was used with Methods 3, 4 and 5 as a means of judging when apparent concentrations were approaching equilibrium. With the two methods employing sonication, three samples were centrifuged and analysed after 1 hour, another three samples were analyzed after two hours, and the final set of samples was analyzed at four hours after the critical sonication. For the 26 chemical/temperature combinations done in this manner, with only two cases was the final result significantly different from results obtained after the first hour. This suggests that the sonication procedure is very effective as a means for dispersing the solute, and the additional samples beyond the first hour serve mainly to enhance the statistical confidence of the results.

With the plating method, the samples were allowed to stand at temperature for at least one day before the initial analysis, and subsequent analyses were carried out at 2-3 day intervals. During this period all samples were subjected to occasional gentle mixing. A convenient method for mixing in these cases was to simply manually roll the sample vials between the palms. For these samples, many of the first day results are close to the final result, but there are several cases where the apparent solubilities increase regularly over periods of 3-10 days. For example, p-hydroxybenzaldehyde at 30^{o}C took about 8 days, and trichlorophenol at pH=9 took about 8 days. Inasmuch as the mixing process for this method is a more casual procedure, some variation of equilibration time even with a given chemical is not unreasonable. We therefore recommend that the apparent solubilities for successive time periods be compared until such data become indistinguishable within the limits of precision. For most cases, we feel this will involve no more than three successive time periods. It should be noted however that the current results were obtained using standard 11-dram vials as sample containers. The use of other containers having smaller surface to volume ratios could very well lengthen the time required for equilibration.

Effects of Centrifugation

With Methods 3 and 4, centrifugation is required to remove excess suspended solute prior to analysis. With Method 5, centrifugation of the samples may not be necessary, but this can be ascertained by using centrifugation of one or more samples as a check on the final result. Alternatively, a measurement can be made of the turbidity of the final solutions to determine if centrifugation is needed. In this work, we have used the direct approach of centrifuging and re-analyzing one or more of the final samples for Method 5.

With Methods 3 and 4, g-factors were in the range of 17000-46000 and total centrifugation times were 25-120 minutes. The more extreme times and g-factors were necessary only for the very hydrophobic chemicals, i.e., those with solubilities of 1 mg/L or less. Usually, times of about 20-25 minutes at 17,000 g's were adequate to permit good solubility measurements. However, it was noted that the results were dependent on the sonication time. Sonication for periods of about one minute yielded good mixing and rapid equilibration; the use of longer sonication times resulted in formation of suspensions that were more difficult to remove by centrifugation.

With Method 5, results for the uncentrifuged samples were essentially the same as those obtained after centrifugation in all but two cases. Firstly, with trichlorophenol at pH=9, the samples were visibly turbid, and centrifugation did yield a slightly lower apparent solubility. The second case was with phosvel. Considerable difficulty was encountered in running this chemical by both methods 3 and 5. With both methods untreated or lightly centrifuged samples of phosvel had apparent solubilities 10-100 times the values listed in Table 4, and successive analyses of the same sample varied as much as tenfold. Centrifuged samples yielded lower and more consistent results, but these too are subject to more variation than generally found with other chemicals. Presumably this is due to the ease with which phosvel disperses in colloidal form.

Some examples of the effects of centrifugation are shown in Table 5.

Table 5. Examples of Centrifugation Effects

Chemical	Method	T°,C	Apparent Solubility, mg/L		Time, Min	g-Factor
			Untreated	Centrifuged		
Benzoic acid	5	10	2103 ±8%	2118 ±1%	30	3000
p-Hydroxybenzaldehyde	5	30	14163 ±6.4%	14433 ±1.3%	30	3000
Trichlorophenol (pH=9)	5	20	2698 ±8.6%	2548 ±1.2%	45	3000
Naphthalene	5	10	27.9 ±5.5%	30.3 ±9.1%	25	3000
	3	10	N.A.	31.9 ±5.8%	60	46000
p-Dichlorobenzene	5	30	91.4 ±6.4%	92.6 ±5.7%	25	3000
	3	30	N.A.	88.9 ±2.5%	60	46000
Phosvel	3	30	N.A.	0.21 ±102%	25	39000
	3	30	N.A.	0.04 ±35%	75	39000
Methylphenanthrene	3	20	N.A.	0.079 ±62%	25	39000
	3	20	N.A.	0.014 ±44%	75	39000

Precision and Accuracy

For all but the very hydrophobic chemicals, the results summarized in Table 4 show relative precisions of ±2-7 percent. For the very hydrophobic chemicals, precisions are of the order of 15-45 percent. In general, the precision of the analytical methods, based on repeated evaluations of standards, was of the order of 0.5-3 percent.

In general the measured solubilities compare favorably with values cited in the literature, but quantitative comparison is not warranted because of lack of consensus values of the solubilities of most of the subject chemicals.

APPENDIX A

SOLUBILITY METHODS

PLATING METHOD

General Approach:

This method is generally useful for solid organic compounds. In brief, the samples are prepared in triplicate by first dissolving the solute in a volatile organic solvent, placing the organic solution into a suitable vial, and allowing the solvent to evaporate while the container is rotated to coat the walls with solute. After the evaporation of the organic solvent, the container is filled with water, placed in a constant temperature bath for one day, and analyzed. The procedure is repeated for longer equilibration times and is performed at three temperatures (10, 20, 30°C). HPLC and G.C. are recommended for the analyses.

Specific Steps:

1. Determine or estimate approximate solubility by a convenient method.
2. Dissolve an amount of solute in an excess of the water solubility in a small quantity of a suitable volatile organic solvent (acetone, acetonitrile, etc.).
3. Place the organic solution in a suitable vial or flask and allow the solvent to evaporate while the container is gently rotated in such a way as to continuously wash the walls of the container with the remaining solution. This operation can be performed manually, or a rotating vacuum evaporator can be used.
4. After the organic solvent has evaporated, fill the container with high-purity water and attach a tight fitting top with a Teflon liner.
5. Place the container in a constant temperature bath.
6. Allow the samples to equilibrate for at least one day and then withdraw aliquots for analysis by G.C. or HPLC.

Precautions:

1. Check samples for suspended solute with a suitable turbidimeter, or by repeated centrifugation and analysis.
2. Extra care should be taken to avoid any excessive shaking or stirring of the contents in the vials after the samples have been prepared, but occasional mixing by gentle rotation of the vials is recommended.
3. Judgement of attainment of equilibration is made based on reproduction of analytical results after 2 or more successive time periods.

METHOD 1 LIQUID

General Approach:

This method is useful for liquid organic compounds having water solubilities 0.5 gm/L or greater. The method is patterned after the methods of Mader and Grady*. In brief, six samples are prepared and then divided into two groups. The first group is placed in a bath at about 0°C, and the second group is placed in a bath at about 50°C to obtain over and under saturation. After one hour, all samples are removed from their respective baths and placed in a constant temperature bath for one hour. The samples are then removed from the bath, centrifuged, returned to the constant temperature bath, and analyzed. This procedure is performed at three temperatures (10, 20, 30°C) with G.C. or HPLC being used as the analysis methods.

Specific Steps:

1. Determine or estimate the approximate solubility by any convenient method.
2. Add excess organic solute to six glass vials.
3. Add high purity water to the six glass vials and seal them with tight fitting tops having Teflon liners.
4. Divide the six samples into groups of three.
   a. place one group in a bath at about 0°C
   b. place the other group in a bath at about 50°C
5. Remove samples after one hour and place them in a constant temperature bath.
6. Occasionally agitate the samples to yield mixing of the organic with the water. (A low powered ultrasonic bath is useful for this purpose.)
7. After equilibration time of one hour, place samples in a centrifuge to remove any suspended droplets. As an alternative, any coarse suspension can be allowed to separate naturally but this process may take as long as several hours.

* Mader, W. J. and Grady, L. T., "Determination of Solubility", Chapter V, Techniques of Chemistry. Vol I - Physical Methods of Chemistry, Part V.

8. Replace the samples in the constant temperature bath.
9. Analyze samples by G. C. or HPLC.

Precautions:

1. Hydrolysis may interfere with analysis of some compounds.
2. Low molecular weight halocarbons may require washing to remove excess acid formed by hydrolysis.
3. If a separatory funnel is used to separate liquid phases, care should be taken to prevent volatization of solute from the aqueous phase.
4. If samples are taken directly from the mixture, care should be taken to avoid contamination of the pipette or syringe by the organic phase.

METHOD 2

General Approach:

Method 2 involves the use of nephelometry to determine the solubility of organic compounds in water. This method is based on the procedures of Parke and Davis*. The method requires the preparation of stable suspensions of the solute in water at several levels of concentration in excess of the solubility. The turbidity of each suspension is then determined and the data are extrapolated to zero turbidity to determine the solubility. Although this method was not investigated because of technical problems with its use, the precautions listed below are applicable for cases where turbidity may be used to ascertain the presence of suspended solids and/or the effectiveness of centrifugation.

Specific Steps:

1. Determine the approximate solubility of the solute by any convenient method, such as, turbidimetric titration.
2. Prepare a stock suspension of solute at a concentration of approximately 3 times the solubility (3S). For 1 liter:
   a) Dissolve the appropriate amount of solute in a minimum amount of acetone or other water miscible solvent.
   b) Add the organic solution to about 900 mL of water that is kept at the desired temperature. This addition should be carried out dropwise, with rapid stirring of the water.
   c) Add additional water to bring total volume to 1L .
3. Prepare individual samples by diluting the stock suspension to approximately 2.5S, 2.0S, 1.5S, 1.0S, and 0.5S.
4. Allow the samples to "age" at temperature for 1 hour.

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* Parke and Davis, J. Am. Chem. Soc., 64, 101 (1942).

METHOD E (cont'd)

5. Determine the percentage light transmission of pure water.
6. Determine the turbidities of the sample suspensions, using the blank correction determined in Step 5.
7. Plot turbidity as a function of concentration, and, using a least squares treatment of the data, determine the concentration at zero turbidity, and the probable error for the solubility.

Precautions:

1. Make sure solvent is free of any dust or contaminated particles. Scattering is strongly dependent on the size of the particles being tested and dust will greatly affect results.
2. Make sure the sample is placed in a light-tight box so that minimum background scatter is encountered.
3. Use photomultiplier in its most linear response region. This can be tested using neutral density filters.
4. Use matched cells or the same cell for all measurements to insure no difference in path length and reflection at interfaces occurs.
5. Keep solution at constant temperature to avoid thermodynamic fluctuation caused by rapid temperature shifts.
6. Keep all containers tightly closed and minimize air spaces to prevent loss of solute by volatization.

METHOD 4

General Approach:

This method is useful for hydrophobic liquids. The method is patterned after the methods of McAuliffe*. In brief, samples are prepared in triplicate by first placing an excess of solute in water, allowing the solution to equilibrate for 1 hour in a constant temperature bath, centrifuging the samples, and analyzing them. This procedure is performed at three temperatures (10, 20, and 30 C), with G.C. and HPLC being used as the analysis methods.

Specific Steps:

1. Determine or estimate the approximate solubility by any convenient method.
2. Add excess organic solute to three vials, using vigorous mixing or sonication to mix.
3. Fill vials with high purity water and seal the vials.
4. Place vials in a constant temperature bath for 1 hour.
5. Centrifuge samples.
6. Replace the samples into the constant temperature bath.
7. Analyze samples by G.C. or HPLC.
8. Repeat Steps 5 - 7 at high g-values and/or longer times.

Precautions:

1. Hydrolysis may interfere with analysis of some compounds.
2. For cases where the organic chemical is less dense than water, contamination of the pipette or syringe can be eliminated by gently transferring the sample to a separatory funnel after centrifugation, with subsequent removal of small quantities of the aqueous phase through the bottom of the funnel.
3. In cases where small droplets tend to remain supported on the water surface regardless of the centrifugation time, the droplets should be avoided during sampling.

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* McAuliffe, C., "Solubility in Water of Paraffin, Cycloparaffin, Olefin, Acetylene, Cycloolefin, and Aromatic Hydrocarbons", J. Phys. Chem., 70(4), 1267-1275 (1966).

METHOD 3

General Approach:

This method is generally useful for solid organic compounds. This method is patterned after the methods of Biggar and Riggs *. In brief, the samples are prepared in triplicate by first placing an excess of solute in water, dispersing the solute with a sonicator, allowing the solution to equilibrate for one hour in a constant temperature bath, centrifuging the samples, and analyzing them. The procedure is repeated for longer equilibration times and is performed at three temperatures (10, 20, 30°C). HPLC and G.C. are recommended for the analysis.

Specific Steps:

1. Determine or estimate the approximate solubility by a convenient method.
2. Add an excess of solute to three vials.
3. Fill the vials with high purity water.
4. Sonicate solutions for one minute using a Biosonic IV sonicator or its equivalent.
5. Seal vials and place them in a constant temperature bath.
6. Allow samples to equilibrate for a specified time.
7. Centrifuge samples in tightly sealed centrifuge tubes.
8. Replace samples in a constant temperature bath.
9. Analyze samples by HPLC or G.C.
10. Repeat steps 7-9 using higher g-factors and/or longer times

Precautions:

1. Sonication time should be limited to one minute to avoid formation of excessively fine particles.
2. Avoid excessive handling or shaking of centrifuged samples.

* Biggar, J. W. and Riggs, R. L., "Apparent Solubility of Organochlorine Insecticides in Water at VArious Temperatures", Hilgardia, 42 (10), 383-391 (1974).

General Conditions

Regardless of the method used, the procedures should incorporate methodology of good analytical technique. Glassware should be thoroughly cleaned and dried. If a detergent is used, the glassware should be rinsed with high purity water; be rinsed with dilute HCl; and be given a final rinse with high purity water. When transfers are made, all glassware involved should be given a preliminary rinse with the solution being transferred. All chemicals should be of the highest purity available, and initial purity checks on the solutes are advisable. Use of system blanks and gravimetric standards are preferred, and complete documentation of error (uncertainty) sources is desirable.

APPENDIX B

ESTIMATED COSTS FOR SOLUBILITY MEASUREMENTS

APPENDIX B

ESTIMATED COSTS FOR SOLUBILITY MEASUREMENTS

Projected Test Costs

Actual costs for performance of the solubility tests by industrial firms may be expected to vary considerably depending upon the availability of facilities, the size of the company and its extent of involvement in chemical analysis work, and the specific problems that may arise with a given chemical. For purposes of estimating such costs, we have assumed a case where chemical analyses are carried out on a more or less routine basis, with all necessary equipment already on site. Further, it is assumed that solubility tests might be conducted on a periodic basis with grouping of three chemicals per series. Table B-1 shows estimated costs (1979 basis) for such tests.

The costs shown in Table B-1 do not reflect BCL's costs associated with this task, but rather are directed at conduct of a service operation requiring little or no technique development for the test chemicals. By and large, the most significant contributions to the estimated costs are found in the manpower costs for the analytical work and in the burden for use of the analytical equipment. The latter cost will vary depending upon the depreciation rate and to some extent on the number of samples analyzed. The former depends primarily on the number of samples analyzed, and it could conceivably be minimized through selection of samples. For example, it might be possible to analyze only one sample of each chemical as a function of time until equilibrium appears to be reached. At that point, all three samples would be analyzed to verify the solubility. It is not expected that the costs would vary linearly with the number of samples, but overall costs might be minimized by this approach.

It should also be noted that the estimated costs do not reflect any problems that might arise with a given chemical. Any need for development of specialized procedures for a specific chemical could easily increase the costs severalfold.

TABLE B-1. ESTIMATED COSTS FOR SOLUBILITY TESTS[a,b]

	Direct Costs, $
I. MATERIALS	
A. Chemicals	30
B. Expendable Materials and Supplies	45
C. Use of Non-expendable materials[c] and Equipment, Lab Space, etc.	320
TOTAL $	$395

	Man-hours	
	Professional	Technician
II. LABOR		
A. Experimental Setup	2	20
B. Test and Laboratory Maintenance, Quality Assurance, etc.	-	10
C. Sample Preparation and Analytical Costs	16	48
D. Record Keeping/Reporting	8	-
TOTAL HR	26	78

Cost/Chemical: 9 prof hr + 26 tech hr + $135 = ~$1120[d]

(a) Assumes dedicated laboratory and no unusual analytical or materials handling problems.

(b) Test basis: three chemicals done in triplicate at three temperatures, with triplicate analyses; samples re-analyzed as a function of time over three 2-day intervals, or equivalent schedule.

(c) No purchases of major equipment (chromatographs, recorders, centrifuges, constant temperature baths, etc.).

(d) Estimated total cost per chemical using reasonable current charge-out rates and overhead rates, but with no allowance for inflation or extraordinary analytical or preparatory requirements for unusual chemicals.

APPENDIX C

SOLUBILITY DATA FOR INDIVIDUAL SAMPLES

TABLE C-1. BENZENESULFONAMIDE SOLUBILITY(a)--PLATING METHOD

Sample	Time, no. of days			Average	Lit. Value(b)
Precision for Std = ±2.8%					
T = 10°C					
	3	8	15		
1	4649 ± 6.6	4544 ± 6.8	4015 ± 4.8		
2	4844 ± 2.9	4156 ± 0.5	(sample destroyed)	4030 ± 4.2	
3	4956 ± 2.4	4405 ± 1.3	4072 ± 4.0		
Precision for Std = ±3%					
T = 20°C					
	1	2	6		
1	3732 ± 0.7	3994 ± 3.3	4267 ± 3.1		
2	1901 ± 5.5	2258 ± 3.2	2760 ± 0.7	3990 ± 4.9	4000 @ 15C
3	3565 ± 1.4	3875 ± 1.3	3865 ± 3.8		
Precision for Std = 2.8%					
T = 30°C					
	2	5	9		
1	4317 ± 6.9	5329 ± 6.9	6826 ± 3.4		
2	4466 ± 7.7	6025 ± 2.5	6444 ± 5.0	6425 ± 6.6	
3	5300 ± 9.0	5914 ± 12.4	6111 ± 6.1		

(a) mg/L ± percentage standard deviation.

(b) Chemical Rubber Handbook.

TABLE C-2. p-HYDROXYBENZALDEHYDE SOLUBILITY[b]--PLATING METHOD

Sample	Time, days 1	2	3	8	9	10	Average	Lit. Value[a]
T = 10°C; Precision for standard ±2.1%								
1		4205±15.0	4738±4.7	4830±1.8	5091±.47	4944±2.2		
2		5174±3.3	5129±1.1	4954±4.1	5173±4.5	5172±2.8	5065±4.4	
3		5044±7.0	4933±7.4	5033±5.0	5328±3.1	5397±.5		
	1	2	6					
T = 20°C; Precision for standard = ±1.4%								
1	6222±4.6	6871±1.5	5692±29					
2	6787±6.3	7436±1.3	6873±2.8				7018±4.2	
3	7546±6.7	7085±3.7	7151±3.9					
	1	2	3	6	8			
T = 30°C; Precision for standard = 1.6%								
1	11032±5.9	12653±4.9	12487±8.7	13357±3.4	14705±1.2			
2	11947±1.0	11867±2.5	13047±1.9	13655±2.3	14750±2.6		14,163±6.4	13800
3	7795±6.9	8894±8.7	10487±1.4	11070±4.9	13035±2.7			

a. Chemical Rubber Handbook

b. Mg/ℓ ± percentage standard deviation

TABLE C-3. BENZOIC ACID SOLUBILITY[b]--PLATING METHOD

Sample	Time, days 2	3	8	9	10	Average	Lit. Value[a]
T = 10°C; Precision for standard = 2.0%							
1	2072±19.4%	2100±1.7%	1881±1.7%	2436±10.8%	2189±12.6%		
2	2010±7.4%	2017±9.8%	1950±.6%	2481±4.3%	2140±3.3%	2103±8.3%	
3	2139±5.1%	2138±3.5%	1986±4.3%	2536±6.1%	2090±4.8%		
	1	2					
T = 20°C; Precision for standard = 2%							
1	3101±10.6%	3071±1.9%					
2	2937±9.8%	3133±3.6%				3030±7	2700 @18°C
3	2938±5.0%	3310±14.8%					
	2	3	6	8			
T = 30°C; Precision for standard = 2.4%							
1	5100±20.2	5127±9.5%	4445±15.3%	4356±17.9%			
2	5040±16.0	5247±5.0%	4646±8.2%	4642±3.5%		4597±5.7	
3	5133±15.9%	5353±.4%	4701±9.9%	4865±1.8%			

a. Chemical Rubber Handbook

b. mg/L ± percentage standard deviation

TABLE C-4. TRICHLOROPHENOL SOLUBILITY[a]--
PLATING METHOD (G.C. Analysis)

Sample	Time, no. of days			Average	Lit. Value[b]
Precision for Std = 1.7%					
T = 10°C	1	3	4		
1	182 ± 6.2	150 ± 7	155 ± 5.6		
2	180 ± 13.3	147 ± 2.8	158 ± 2.7	151 ± 3.3	
3	168 ± 7.0	148 ± 0.6	149 ± 4.5		
Precision for Std = 1.5%					
T = 20°C	1	2	7		
1	297 ± 6.0	294 ± 2.9	254 ± 8		
2	331	270 ± 2.2	254 ± 3.9	249 ± 5.5	800
3	307 ± 5.3	284 ± 2.7	239 ± 1.8		
Precision for Std = 2%					
T = 30°C	1	3	6		
1	282 ± 7.8	280 ± 11	280 ± 5.4		
2	290 ± 15	293 ± 13	283 ± 3.4	280 ± 6.1	
3	302 ± 15	283 ± 11	288 ± 2.4		

(a) mg/L ± percentage standard deviation.

(b) Chemical Rubber Handbook.

TABLE C-5. TRICHLOROPHENOL SOLUBILITY[a], pH EFFECT -- PLATING METHOD

Sample	Time, no. of days					Average
Precision for Std = 2.6% (all samples)						
T = 20°C (unbuffered)						
	1	4	7			
1	497 ± 2.5%	492 ± 1.8%	504 ± 0.67%			
2	491 ± 0.8	455 ± 11	496 ± 0.69			494 ± 1.5
3	490 ± 2.0	476 ± 3.5	489 ± 0.81			
T = 20°C (pH = 7.1)						
	1	2	3	6	8	
1	202 ± 6.8	315 ± 5.6	600 ± 0.7	676 ± 3	702 ± 8	
2	154 ± 3.3	265 ± 6.0	560 ± 1.3	571 ± 4.3	603 ± 17	592 ± 17
3	278 ± 9.6	364 ± 2.3	468 ± 1.5	509 ± 12	574 ± 7.9	
T = 20°C (pH = 9.0)						
	1	3	6	8		
1	1406 ± 4.2	3688 ± .48	3092 ± 5.6	2874 ± 6.9		
2	499 ± 3.8	2401 ± 4.6	1934 ± 0.7	1888 ± 1.3		2900 ± 14
3	734 ± 1.8	4016 ± 3.4	2565 ± 2.7	2523 ± 1.9		

(a) mg/L ± percentage standard deviation.

NOTE: No reference value found.

TABLE C-6. BENZENE SOLUBILITY[a]--METHOD 1

T, °C	Sample[b] 1-0	1-u	2-0	2-u	3-0	3-u	Average	Lit. Value
10	1774 ± 2.6	1797 ± 0.9	1741 ± 0.2	1826 ± 3.9	1724 ± 8	1788 ± 1.0	1780 ± 3.9	1787[c]
20	1926 ± 1.9	1949 ± 3.1	1847 ± 0.33	1874	1841 ± 0.3	1815 ± 2.7	1869 ± 3.4	1777[c]
30	1708 ± 0.5	1683 ± 0.2	1700 ± 0.04	(sample lost)	1730 ± 0.5	1734 ± 0.85	1712 ± 1.3	1837[c]

(a) mg/L ± percent standard deviation.
(b) Sample Designation: 1-0, vial from 1st pair pretreated by exposure to temp. of about 50°C;
1-u, vial from 1st pair pretreated by exposure to temp. of about 0°C; same for 2 and 3.
(c) Bohon, R. L. and Claussen, W. F., J. Am. Chem. Soc., 73, 1571 (1951).

TABLE C-7. ETHYL BROMIDE SOLUBILITY[a]--METHOD 1

T, °C	Sample[b] 1-0	1-u	2-0	2-u	3-0	3-u	Average	Lit. Value
10	5677 ± 1.2	5890 ± 0.4	5532 ± 7.3	5815 ± 0.95	6106 ± 3.8	6249 ± 5.7	5932 ± 4.0	
20	5254 ± 1.5	5856 ± 3.8	5704 ± 2.3	5626 ± 1.8	5349 ± 1.2	5481 ± 3.4	5546 ± 4.3	9100[c]
30	5750 ± 3.6	5809 ± 0.8	5390 ± 0.6	5712 ± 2.8	5420 ± 0.5	5925 ± 1.9	5667 ± 4.0	

(a and b)--Same as above.
(c) Verschuesen, Karel, HANDBOOK OF ENVIRONMENTAL DATA ON ORGANIC CHEMICALS, Van Nostrand Reinhold Co., NY (1977).

TABLE C-8. CHLOROFORM SOLUBILITY[a]--METHOD 1

T, °C	Sample[b] 1-0	1-u	2-0	2-u	3-0	3-u	Average	Lit. Value
10	6323 ± 2.9	6602 ± 3.1	6446 ± 5.0	9549 ± 4.6	7511 ± 5.3	6340 ± 3.3	(6412) ± 3.6[d]	
20	7135 ± 0.13	5340 ± 0.46	5385 ± 3.1	5259 ± 1.4	5338 ± 5.1	5259 ± 5.5	5319 ± 3.5	8000[c]
30	5344 ± 0.29	5014 ± 2.4	4966 ± 2.2	5138 ± 2.8	5147 ± 1.8	5134 ± 0.3	5125 ± 2.8	

(a) mg/L percentage standard deviation.
(b) Sample Designation: 1-0, vial from 1st pair pretreated by exposure to temp. of about 50°C;
1-u, vial from 1st pair pretreated by exposure to temp. of about 0°C; same for 2 and 3.
(c) Verschuesen, Karel, HANDBOOK OF ENVIRONMENTAL DATA ON ORGANIC CHEMICALS, Van Nostrand Reinhold Co., NY (1977).
(d) Based on selected values to form most consistent set.

TABLE C-9. DIETHYL SULFIDE[a]--METHOD 1

T, °C	Sample[b] 1-0	1-u	2-0	2-u	3-0	3-u	Average	Lit. Value
10	3475 ± 3.5	3561	3505 ± 5.2	3975 ± 0.23	3310 ± 1.5	3518 ± 0.64	(3508) ± 3.2[d]	
20	3617 ± 0.68	3657 ± 1.6	3656 ± 1.5	4125 ± 5.4	3887 ± 1.6	(sample lost)	3704 ± 3.3	3130[c]
30	3609 ± 3.6	3980 ± 16.6	3441 ± 4.1	3287 ± 0.65	3351 ± 0.44	3294 ± 16	(3398) ± 3.2[d]	

(a - d)--Same as above.

TABLE C-10. PHENANTHRENE SOLUBILITY
(mg/L)

(METHOD 3)

Sample	Time, hr. 1	2	4	Average	Lit. Value[a]
T = 10°C; Precision for standard = ± 0.3%					
1	.64 ± 5.3[b]	.66	.82		
2	.41 ± 15	.57 ± 7	.84	(0.61 ± 17)[c]	0.61
3	.63 ± 36	.68	(4.5)		
T = 20°C; Precision for standard = ± 0.6%					
1	0.70 ± 17	0.65	1.23 ± .9		
2	0.81 ± 15	0.88 ± 12	1.20 ± 1.7	0.91 ± 24	0.92
3	0.79 ± 38	.83 ± 17	0.85 ± 2.6		
T = 30°C; Precision for standard = ± 0.9%					
1	1.45 ± 6	1.49 ± 4	2.00 ± 10		
2	1.56 ± 5	1.31 ± 5	2.21 ± 7.7	(1.46 ± 7)[c]	1.46
3	1.43 ± 11	1.46 ± 3	2.13 ± 10		

(a) R. D. Wauchaup and F. W. Getzen, J. Chem. Eng. Data, 17 38 (1972).

(b) Solubility ± percentage standard deviation.

(c) Selected "best" value.

TABLE C-11. PHENANTHRENE SOLUBILITY[a]--PLATING METHOD

Sample	Time, no. of days			Average
Precision for Std = 0.1%				
T = 10°C				
	1	2	3	
1	0.51 ± 6.7	0.46 ± 9.1	0.55 ± 12	
2	0.49 ± 11	0.44 ± 13.1	0.42 ± 1.6	0.47 ± 8.9
3	0.44 ± 4.0	0.46 ± 8.9	0.46 ± 9.7	
Precision for Std = 0.4%				
T = 20°C				
	1	2	7	
1	0.83 ± 18	0.89 ± 6.4	0.919 ± 12	
2	0.88 ± 14	0.803 ± 15	0.852 ± 14	0.89 ± 15
3	0.88 ± 22	0.706 ± 21	0.888 ± 21	
Precision for Std = 2.0%				
T = 30°C				
	1	3	6	
1	1.38 ± 4.8	1.37 ± 5.3	1.31 ± 2.9	
2	--	1.14 ± 24	1.20 ± 12	1.31 ± 7.1
3	--	1.32 ± 11	1.13 ± 11	

(a) mg/L ± percentage standard deviation.

NOTE: No reference value found.

TABLE C-13. NAPTHALENE SOLUBILITY
(mg/L)
(METHOD 3)

Sample	Time, hr. 1	2	3	Average	Lit. Value[a]
T = 10°C; Precision for standard = ± 4.5%					
1	38.3 ± 8.0[b]	35.6 ± 5.6	31.1 ± 4		
2	38.0 ± 2.0	30.7 ± 5.3	30.8 ± 2.6	(31.9 ± 5.8)[c]	19.7
3	39.0 ± 2.4	33.1 ± 3.7	31.8 ± 5.2		
T = 20°C; Precision for standard = ± 3.2%					
1	57.1 ± .9	42.8 ± 6	43.4 ± .5		
2	41.8 ± 1	49.1 ± 3.5	43.3	(44.9 ± 7.7)[c]	27.0
3	49.8 ± 6	46.4 ± 3	39.6		
T = 30°C; Precision for standard = ± 2.9%					
1	56.6 ± 6	52.7 ± 3.7	72.1 ± 1.9		
2	61 ± 6.8	58.3 ± 1.2	36.2 ± 6.1	(56.6 ± 7.2)[c]	38.2
3	64.4 ± 3.7	52.9 ± 1.7	48.9 ± 7.7		

(a) R. D. Wauchaup and F. W. Getzen, J. Chem. Eng. Data, 17 38 (1972).

(b) Solubility ± percentage standard deviation.

(c) Based on "best" data.

TABLE C-13 NAPHTHALENE SOLUBILITY
(METHOD 2)

Sample Set	r^{2}[a]	Solubility, mg/L[b]
1.	0.97	a. 42.5 ± 6.4%
	0.97	b. 39.0 ± 8.2%
2.	0.94	a. 50.8 ± 7.5%
	0.92	b. 53.3 ± 7.5%
3.	0.99	a. 50.8 ± 3.0%
	0.99	b. 52.1 ± 3.1%

(a) The square of the correlation coefficient.

(b) Solubility measured at 546 and 436 nm respectively with probable error in the intercept.

TABLE C-14. NAPHTHALENE SOLUBILITY[a]--PLATING METHOD

Sample	Time, no. of days			Average
Precision for Std = 3%				
T = 10°C				
	1	2	3	
1	28.2 ± 5.7	27.5 ± 8.2	27.7 ± 1.7	
2	27.1 ± 9.4	28.6 ± 4.4	27.3 ± 4.2	27.9 ± 5.5
3	29.3 ± 12	26.6 ± 3.0	28.3 ± 2.1	
Precision for Std = 3%				
T = 20°C				
	1	2	8	
1	36.5 ± 1.9	36.2 ± 6.2	41.7 ± 2.0	
2	38.8 ± 6.8	36.3 ± 3.8	40.5 ± 2.9	40.6 ± 3.7
3	36.0 ± 2.7	37.8 ± 5.3	39.2 ± 3.9	
Precision for Std = 1.0%				
T = 30°C				
	1	5	7	
1	58.2 ± 11	59.1 ± 8.9	57.1 ± 7.7	
2	57.7 ± 4.1	57.4 ± 7.5	59.6 ± 8.0	57.9 ± 6.2
3	58.2 ± 6.8	56.4 ± 3.0	57.3 ± 9.6	

(a) ng/L ± percentage standard deviation.

TABLE C-15. p-DICHLOROBENZENE SOLUBILITY
(mg/L)

(METHOD 3)

Sample	Time, hr. 1	2	4	Average	Lit. Value[a]
T = 10°C; Precision for standard = ± 5.9%					
1	48 ± 16[b]	43.9 ± 11	30 ± 18		
2	49 ± 2.1	35.6	36 ± 20	(50.8 ± 5.5)[c]	52.9
3	43 ± 13	44 ± 20	30 ± 24		
T = 20°C; Precision for standard = ± 1.8%					
1	64 ± 14	63 ± 5	54 ± 5		
2	63 ± 11	60 ± 9	61 ± 4.3	60.2 ± 8.8	69.3
3	59 ± 12	67 ± 11	56 ± 5.4		
T = 30°C; Precision for standard = ± 4.6%					
1	81.3 ± 7.3	85.5 ± 7	87.9 ± 4.4		
2	78.9 ± 9.2	69.8 ± 6.6	89.5 ± 2.0	88.9 ± 2.5	91.5
3	88.0 ± 5.8	81.7 ± 8.4	89.0 ± 1.5		

(a) R. D. Wauchaup and F. W. Getzen, J. Chem. Eng. Data, 17 38 (1972).

(b) Solubility ± percentage standard deviation.

(c) Based on "best" 1 hr. data.

TABLE C-16. p-DICHLOROBENZENE SOLUBILITY[a]--PLATING METHOD

Sample	Time, no. of days			Average
Precision for Std = 0.9%				
T = 10°C				
	1	3	4	
1	56.1 ± 1.8	54.1 ± 4.6	55.6 ± 3.1	
2	53.0 ± 2.7	53.8 ± 3.3	56.2 ± 7.8	55.3 ± 4.0
3	56.3 ± 4.6	55.8 ± 1.9	56.8 ± 0.9	
Precision for Std = 1.0%				
T = 20°C				
	1	2	8	
1	64.9 ± 3.8	67.3 ± 1.2	66.3 ± 3.2	
2	65.3 ± 5.2	66.3 ± 2.3	65.8 ± 4.2	66.5 ± 3.6
3	65.2 ± 6.0	66.4 ± 1.4	69.8 ± 1.1	
Precision for Std = 1.5%				
T = 30°C				
	1	5	7	
1	90.2 ± 5.4	90.3 ± 10	93.6 ± 4.8	
2	87.4 ± 8.0	90.4 ± 8.2	92.3 ± 14	91.4 ± 6.4
3	97.9 ± 1.7	89.2 ± 5.2	90.3 ± 6.6	

(a) mg/L ± percentage standard deviation.

NOTE: No reference value found.

TABLE C-17. ETHYLBENZENE SOLUBILITY[a]--METHOD 4

T, °C	Sample Number 1	2	3	Average	Lit. Value[b]
10	203 ± 5	198 ± 2	211 ± 2.6	206 ± 4	209
20	(sample lost)	206 ± 1.9	212 ± 1.2	210 ± 2	207
30	204 ± 0.2	214	215 ± 2.5	215 ± 2.1	213

(a) mg/L ± percentage standard deviation.
(b) Bohen, R. L. and Claussen, W. F., J. Am. Chem. Soc., 73, 1571 (1951).

TABLE C-18. DIPHENYL ETHER SOLUBILITY[a]--METHOD 4

T, °C	Sample Number 1	2	3	Special[b]	Average
10 (solid)	8.22 ± 2.1	8.19 ± 7	(c)		8.21 ± 3.8
20 (liquid)	18.7 ± 0.2	18.0 ± 2.9	17.9 ± 5.7		18.2 ± 3.6
30 (liquid)	20.2 ± 0.2	20.1 ± 2.7	16.6 ± 4.7	19.4 ± 0.3	19.9[d] ± 2.2

(a) mg/L ± percentage standard deviation.
(b) Sample mixed by gentle rotation of flask and equilibrated for 72 hr.
(c) Sample remained liquid for 29 hr, and was not equilibrated.
(d) Average based on selected samples.

TABLE C-19. n-OCTANE SOLUBILITY
(mg/L)
(METHOD 4)

T°C	Precision for Standard	Sample 1	Sample 2	Sample 3	Average	Lit. Value[a]
10	± 0.8%	0.72 ± 6.8[b]	0.73 ± 3.7	0.73 ± 1.3	0.73 ± 4.7	0.66 ± 9 @ 25°C
20	± 0.4%	0.60 ± 4.7	0.58 ± 5.4	0.56 ± 7.0	0.58 ± 6.2	
30	± 0.4%	0.69 ± 5	0.71 ± 7.7	0.68 ± 11	0.70 ± 7.7	

(a) C. McAuliffe, J. Phys. Chem. 70, 1267 (1966).

(b) Solubility ± percentage standard deviation.

TABLE C-20. 2,4-DICHLOROPHENOXYACETIC ACID-n-BUTYL ESTER SOLUBILITY[b]--METHOD 4

Sample	Time, hr. 1	2	4	Average	Lit. Value[a]
T = 10°C; Precision for standard = ±1.3%					
1	0.078±14[b]	0.096	0.144±9.4		
2	0.087±18	0.080±31	0.082±12	0.084±16	
3	0.089±28	0.096±20	0.10±27		
T = 20°C; Precision for standard = ±0.4%					
1	1.0±22	1.0±23	0.91±21		
2	1.0±9.6	0.99±22	1.14±23	0.95±18	
3	0.88±33	1.09±20	1.04±44		
T = 30°C; Precision for standard = ±0.7%					
1	1.05±3.9	1.0±11	0.88±0.3		
2	0.99±17	0.95±28	1.05±6	0.99±10	
3	1.15±26	0.99±18	1.03±28		

a. Unknown

b. mg/L ± percentage standard deviation.

TABLE C-21. PHOSVEL SOLUBILITY[a]--METHOD 3

Sample	Time, no. of hours 1	2	4	Average
Precision for Std = 2.1% T = 10°C				
1	.024 ± 100	.020 ± 49	.027 ± 85	
2	.051	.024 ± 63	.041 ± 69	.021 ± 50
3	.035	.041	.017 ± 30	
Precision for Std = 1.3% T = 20°C				
1	(2.2 ± 73)	(.048 ± 80)	(.05 ± 106)	(.04 ± 85)
2	(b)			
3				
Precision for Std = 2.7% T = 30°C				
1	.055 ± 8.3	.065 ± 49	.058 ± 4.9	
2	.008 ± 40	.114 ± 2.5	.029 ± 60	.053 ± 38
3	.029 ± 71	.058 ± 29	.007 ± 37	

(a) mg/L ± percentage standard deviation.
(b) Blanks in table: data widely scattered and not reproducible.

NOTE: No reference value found.

TABLE C-22. PHOSVEL SOLUBILITY[a]--PLATING METHOD

Sample	Time, no. of days			Average
Precision for Std = ±3%				
T = 10 C				
	3	8		
1	(b)	.032 ± 62		
2	.023 ± 22	.019 ± 34		.025 ± 49
3				
T = 20 C[b]				
Precision for Std = ±3%				
T = 30 C				
	4	7	8	
1	.024 ± 36	.020 ± 64	.036 ± 39	
2	.015 ± 24	(sample lost)		.021 ± 36
3	.018 ± 35	.018 ± 15	.025 ± 26	

(a) Mg/ℓ ± percent standard deviation.
(b) Blanks in table: data widely scattered and not reproducible.

NOTE: No reference value found.

TABLE C-23. ANTHRACENE SOLUBILITY
(METHOD 3)

Sample	Time, Hr. 1	2	4	Average	Lit. Value[a]
T = 10°C; Precision for Standard = ±0.77%					
1	.097±2.9[b]	.062±21	.081±17		
2	.071±55	.068±3.1	.080±16	.057±25	0.0569
3	.058±27	.076±13	.070±38		
T = 20°C; Precision for Standard = ±1.2%					
1	0.10±7.9	0.064±5.5	0.094±32		
2	0.075±20	0.074±37	0.069±26	0.075±22	0.0843
3	0.092±35	0.11±16	0.074±38		
T = 30°C; Precision for Standard = ±1.4%					
1	0.15±16	0.089±1.3	0.15±12		
2	0.15±12	0.23±19	0.13±7.6	0.13±8.6	0.127
3	0.13±4	0.25±1.1	(.3)		

(a) R. D. Wauchope and F. W. Getzen, J. Chem. Eng. Data, 17 38 (1972).

(b) Solubility (mg/L) ± percentage standard deviation.

TABLE C-24. METHOXYCHLOR SOLUBILITY[b]--PLATING METHOD

Sample	Time, hr. 1	2	4	Average	Lit. Value[a]
T = 10°C; Precision for standard = ±2.2%					
1	0.015±49[b]	0.015±24	0.009±11		
2	sample lost	0.016±25		0.014±36	
3	0.017±39	0.017±47	0.007±13		0.020 @15 C
T = 20°C; Precision for standard = ±1.5%					
1	0.068±20	0.062±32	0.060±54		
2	0.065±32	0.068±36	0.071±51	0.061±27	
3	0.070±27	0.062±27	(0.13)		0.045 @25 C
T = 30°C; Precision for standard = ±2.4%					
1	0.078±42	0.052±17	0.061±78		
2	0.032±55	0.11±11		0.058±36	
3	0.064±16	0.077±18	0.094±56		

a. J. W. Biggar and R. L. Riggs, Hilgardia, 42 383 (1974).

b. mg/L ± percentage standard deviation

TABLE C-25. METHYLPHENANTHRENE SOLUBILITY[b]--METHOD 3

Sample	Time, hr. 1	2	4	Average	Lit. Value[a]
T = 10°C; Precision for standard = ±0.4%					
1	0.15±98[b]	0.044±16	0.027±02		
2	0.17±41	0.018±40	0.010±96	?	
3	0.13±69	0.024±3	0.23±43		
T = 20°C; Precision for standard = ±0.3%					
1	0.017±31	0.009±8.3	0.014±24		
2	0.022	(0.063±51)	0.018	0.014±28	
3	(0.057±23)	(0.056±18)	0.014±18		
T = 30°C; Precision for standard = ±0.7%					
1	0.015±17	sample lost	-		
2	0.010±69	0.014±66	0.006±51	0.008±66	
3	0.010±98	0.005±20	0.004±48		

a. Unknown

b. mg/L ± percentage standard deviation