♦EPA **Project Summary**

Measurement of Hydrolysis Rate Constants for Evaluation of Hazardous Waste Land Disposal: Volume 1. Data on 32 Chemicals

J. Jackson Ellington, F. E. Stancil, Jr., and W. D. Payne

To provide input data for a mathematical model to estimate potential groundwater contamination from chemicals in land disposal sites, hydrolysis rate constants were determined for 26 regulated chemicals under carefully controlled conditions. Hydrolysis rates were measured under sterile conditions at precisely controlled temperatures and at three pH levels, 3, 7, and 11. Conditions were adjusted to provide sufficiently precise rate constants to meet modeling requirements determined through model sensitivity tests. In addition to close monitoring of temperature and pH, precautions were taken to minimize impact of adventitious processes. Chemical concentrations as a function of incubation time were measured by gas chromatography, liquid chromatography, or ion exchange chromatography. Identities and purities of the chemicals were determined by mass spectrometry supplemented, in some cases, by infrared spectrometry.

Hydrolysis rates for three standard reference compounds (chlorostilbene oxide for acid, 2,4-D methyl ester for base, and benzyl chloride for neutral conditions) were measured repetitively to assess the effect of undetected changes in experimental conditions. Pseudo-first order rate constants determined for benzyl chloride at 28.0°C over 8 months had a coefficient of variation (C.V.) of 9.0%. Values determined at higher temperatures (36.4, 45.0, and 52.9°C) and extrapolated back to 28.0°C had a C.V. of 18.0%. Second-order rate constants for the 2,4-D methyl ester and for 4-chlorostilbene oxide determined under similar conditions (28.0°C, 8 mo.) had C.V.'s of 14.7% and 14.0%, respectively.

Hydrolysis rate constants were determined experimentally for the following 26 compounds: warfarin, aldrin, brucine, dieldrin, disulfoton, endosulfan I, endosulfan II, fluoroacetic acid sodium salt, 2-methyllactonitrile, famphur, acrylamide, acrylonitrile, cis-1,4-dichloro-2-butene, trans-1,4-dichloro-2-butene, 4,4-methylene-bis-(2-chloroaniline), pentachloronitrobenzene, pronamide, reserpine, thiourea, uracil mustard, ethyl carbamate, 2,3-dichloropropanol, 1,3-dichloropropanol, 1,2,3-trichloropropane, 1,2,3-trichlorobenzene, and 1,2,4-trichlorobenzene. Rate data also were reported for: nitrobenzene, mitomycin C, chloromethyl methyl ether, 1,2-dibromo-3-chloropropane, and ethylene dibromide.

All compounds except thiourea were hydrolyzed to some extent under the varying conditions of pH and temperature employed. Hydrolysis rate constants reported at 25°C ranged from approximately 1 hr^{-1} to 1 x 10^{-7} hr^{-1}. Half-lives correspondingly ranged from a few minutes to centuries.

This Project Summary was developed by EPA's Environmental Research Laboratory, Athens, GA, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Background

The Hazardous and Solid Waste Amendments of 1984 to the Resource Conservation and Recovery Act (PL 98-616) stipulate that land disposal of hazardous waste is prohibited unless the EPA Administrator determines that prohibition of some wastes is not required to protect human health and the environment because those particular wastes are not likely to reach unacceptable levels in groundwater as a result of land disposal. The amendments define hazardous waste as any of 362 specific compounds (either part of or inclusive of Appendix VIII compounds). In compiling this list, major considerations were toxicity of the material and quantity of waste material generated annually.

To provide a practical tool for determining which listed hazardous materials may be disposed of by land disposal and under what conditions, the use of a relatively simple model was suggested that would estimate potential groundwater contamination for each listed chemical. The model considers horizontal movement based on advection, dispersion, sorption, and transformation. Hydrolysis is the only transformation process specifically considered. Although other transformation processes, such as microbial degradation and chemical reduction, may take place, they are not presently included in the model. The model assumes no unsaturated zone for groundwater and assumes saturated groundwater "zones" ranging from 3 meters to 560 meters in depth. The mean depth of those considered is 78.6 meters Organic carbon contents used in the model will range from 1% to 0.1%. The point at which the groundwater must meet standards may vary but was originally set at 150 meters measured horizontally from the point of introduction

For each chemical considered, the maximum allowable concentration for the receiving groundwater, 150 meters "downstream," is entered into the model, which assumes environmental characteristics for selected subterrainian systems. The concentration of leachate leaving the disposal site is computed for various conditions of rainfall, soil type, pH, etc. A computed leachate concentration that would cause unacceptable groundwater conditions is selected by the Office of Solid Waste (OSW) maximum allowable concentration in leachates. A chemical may be disposed of by land only if treatment brings the leachate concentration down to the level selected that would not cause groundwater to exceed the acceptable concentration. The modeling approach applies to landfills, surface impoundments, waste piles, and land treatment operations. Land treatment operations may be addressed in a different manner to allow for reduction in concentrations resulting from the land treatment process.

It is necessary to acquire octanol/water partition coefficients and hydrolysis rate constants for each of the 362 chemicals except for solvents ("fast track" in the list), which will be treated as non-degrading, non-sorbing constituents and chemicals already banned by the State of California (listed as "California"). These two groups comprise 21 and 44 chemicals, respectively. The remainder of the 362 chemicals were separated into 3 groups by OSW: 81 in the "first third," 121 in the "second third," and 95 in the "third third." This report provides first- and second-order hydrolysis rate constants for those organic compounds in the first group for which satisfactory values were not developed in an earlier evaluation process and describes the laboratory experiments conducted to measure hydrolysis rate constants.

Hydrolysis Kinetics

Hydrolysis of organic compounds refers to reaction of the compound with water in which bonds are broken and new bonds with HO- and H- are formed. A common example is the reaction of an alkyl halide with the loss of halide ion (-X).

$$RX + HOH \longrightarrow ROH + HX \, (or \, H^+, X^-)$$
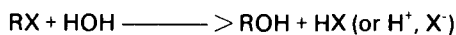
The rate of the reaction may be promoted by the hydronium ion (H^+, or H_3O^+) or the hydroxyl ion (OH^-). The former is referred to as specific acid catalysis and the latter as specific base catalysis. These two processes, together with the neutral water reaction, were the only mechanisms considered in this study. This allowed direct measurement of the H_3O^+ or OH^- concentration through accurate determination of solution pH.

Some chemicals show a pH dependent elimination reaction:

$$\begin{array}{cc} H & X \\ | & | \\ -C-C------> & C=C + HX \end{array} \quad \begin{array}{c} H^+ \, or \\ \\ OH^- \end{array}$$
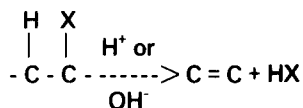
In this study, only the disappearance of substrate was monitored with no attempts to identify mechanisms.

All processes referred to above are included where the rate of hydrolysis is given by the equation,

$$-\frac{d[C]}{dt} = k_h[C] =$$
$$k_A[H^+][C] + k_B[OH^-][C] + k_N'[H_2O][C] \quad (1)$$

where [C] is the concentration of reactant and k_h is the pseudo-first-order rate constant at a specific pH and temperature, k_A and k_B are second-order rate constants and k_N' the pseudo-first-order rate constant for the acid, base, and neutral promoted processes, respectively. The water concentration is essentially not depleted by the reaction and is much greater than [C], thus $k_N'[H_2O]$ is a constant (k_N).

Equation 1 assumes each individual rate process is first order in substrate, thus k_h can be defined as:

$$k_h = k_A[H^+] + k_B[OH^-] + k_N \quad (2)$$

Using the autoprotolysis equilibrium expression

$$K_w = [H^+][OH^-] \quad (3)$$

equation 2 may be rewritten as

$$k_h = k_A[H^+] + \frac{K_B K_W}{[H^+]} + k_N \quad (4)$$

Equation 4 shows the dependence of k_h on [H^+] and on the relative values of k_A, K_B, and K_N.

As a good approximation, the second-order rate constants for acid hydrolysis and for base hydrolysis can be calculated by dividing the pseudo-first order rate constant obtained at the appropriate pH by the hydronium ion or hydroxyl ion concentration, respectively. The half-life of a chemical at a given pH and temperature can be calculated from equation 5, where k_h is the observed rate.

$$t_{1/2} = \frac{0.693}{k_h} \quad (5)$$

Contributing Factors in Determination of Hydrolysis Rate Constants

A typical hydrolysis experiment consisted of preparing a spiking solution of the compound of interest, preparing buffer solutions, transferring spiked buffer to individual "rate point tubes" (15-ml Teflon lined, screw cap, or sealed ampules), then monitoring degradation by sacrificing individual tubes and deter-

mining percentage of the substrate remaining.

Spiking solutions were prepared by dissolving the substrate in acetonitrile, methanol, or water. The concentration was such that 0 1 ml diluted to 100 ml with buffer gave a substrate concentration that was $1\times10^{-5}\underline{M}$ or was 50% of the water solubility or less

Initial hydrolysis runs were performed at pH 3, 7, and 11 Buffers were prepared at these pHs then measured at the temperature of the hydrolysis run. Each run consisted of five or six tubes. Immediate analysis of one tube established the 100% response peak (T_0). Analysis of a second tube within 3 to 6 hours gave a good estimate of sampling frequency for the remaining tubes.

The initial hydrolysis runs were used to set pH and temperature conditions for subsequent rate determinations. The rate determinations were normally performed in triplicate; however, some compounds required more replicates (aldrin, dieldrin) and some less (2-methyllactonitrile).

The EPA repositories at Research Triangle Park, NC, and Las Vegas, NV, were the first choice for chemicals on which hydrolysis rates were measured. Commercial chemical companies were the second sources The chemicals used for determining rate constants were analyzed by mass spectrometry for confirmation of the stated identity. The generated mass spectral data were used to confirm identities of chemicals. GC/FTIR was used to characterize the 1,2,3- and 1,2,4-isomers of trichlorobenzene.

Solvents used were "distilled in glass," Burdick and Jackson solvents either gas chromatograph of HPLC grade, as required by the method of analysis

An Orion Research EA920 pH meter equipped with an Orion Research Δ810300 Ross combination electrode was used for all pH measurements National Bureau of Standards (NBS) reference standards were used to calibrate and check the pH meter. The pH meter had a stated accuracy of ±0.02 units. The temperature compensation probe was used for all measurements. The pH was measured at the temperature of the hydrolysis rate measurement and adjusted with base or acid to obtain the desired pH.

Buffer stock solutions were prepared at 0 1 $\underline{M}$ using sterile water as described above. To prepare pH 3 buffer, 0.1 $\underline{M}$ potassium hydrogen phthalate was diluted to 0 005 $\underline{M}$ and final pH adjustment made with 0.1 $\underline{M}$ HCl. The pH 7 buffer was prepared from 0.1 $\underline{M}$ potassium dihy-

drogen phosphate diluted to 0.005 $\underline{M}$ with final pH adjustment using 0.1 $\underline{M}$ NaOH. Buffers for pHs 9 and 11 were made by diluting 0.1 $\underline{M}$ sodium phosphate heptahydrate to 0.005 $\underline{M}$ with final pH adjustment using 0.1 $\underline{M}$ NaOH.

Buffer stability was tested initially at 0.001 $\underline{M}$. Thus, pH 5 and pH 7 buffers held their respective pH's for the test period. The pH 9 buffer (0.001 $\underline{M}$) decreased to pH 8.07 after 24 hours and to pH 7.50 after 96 hours. Buffer at a concentration of 0.005 $\underline{M}$ remained constant at 9.10 ± 0.03 pH units for 25 days. Containers for the experiment were screw cap test tubes. Autoclaved (CO_2 free) water was used

Forma Scientific refrigerated and heated baths (Model 2095) were used for temperatures in the range of 2 to 70°C (±0.02°C) A lauda C-20 oil bath with a stated control accuracy of ±0.01°C and a fine control range of ±0.2°C was used for temperatures above 68°C. Temperatures were measured with American Society for Testing and Materials (ASTM) thermometers, calibrated by NBS procedures and NBS-certified master thermometers. The thermometers were calibrated in 0.1°C increments.

Water used in the experiments was unchlorinated ground water that was first processed through a high capacity reverse osmosis unit and a deionizer unit. This "house" deionized water was further purified by passage through a Barnstead Nanopure II deionizer, 4-module unit with Pretreatment, High Capacity, and Z-Ultrapure cartridges. Water obtained from this unit has a resistance of greater than 16 meg ohms This double deionized water was autoclaved for 30 min/liter and allowed to cool before use. The sterile water was stored in a sterile-cotton-plugged container until used. All hydrolysis runs were conducted in screw cap tubes. Data from smear plate counts on agar indicated growth as being less than 1 colony per milliliter through 9 days at 25°C and pH of 5, 7, and 9. Sterility checks on the water were performed intermittently.

Buffer solutions also were checked for bacterial growth. Buffer solutions, prepared as described above, were transferred at room temperature to screw cap test tubes. One-half were flame transferred, the other half without flaming. A sample (1 ml) from each tube was plated daily, for 9 concurrent days on TGE agar. After a 48-hour incubation, no growth was found. This confirmed sterility. Control checks during hydrolysis runs showed no growth.

Methods of Analysis

Generally gas chromatography was the first method of choice for four reasons:
1) instrument provided required sensitivity and specificity
2) solvent extraction stopped hydrolysis and allowed multiple injections over extended periods of time
3) solvent extraction also lessened problems caused by compound sorption to glass
4) methodology allowed direct aqueous injection of water soluble compounds that were not amenable to other methods of analysis

High performance liquid chromatography (HPLC) was used extensively; ion chromatography and the diode array UV-detector were used in the analysis of sodium fluoroacetate and thiourea, respectively. Hydrogen cyanide released by the decomposition of 2-methyllactonitrile was monitored by EPA Method 335.

Linearity of detector response in the concentration range of analysis for each chemical was established to ensure reliable concentration versus time plots.

Standard Reference Compounds

Standard reference compounds are compounds that are used as quality assurance standards and as references in inter-laboratory generation of hydrolysis data. Repetition of rate constant measurement for these compounds over the course of the reporting period established baseline information for evaluating experimental techniques and for all aspects of quality assurance. Three compounds were selected; one for each process: acid, base, and neutral hydrolysis. Each standard reference compound is also amenable to analysis by both gas chromatography and liquid chromatography. Reproduction of the hydrolysis constants of the SRCs at the established concentrations, pHs, and temperatures insured that the experimental conditions for each set of compounds were acceptable and that the rate constants for the OSW compounds could be determined with required precision and accuracy. A range of pseudo-first-order hydrolysis rates for all SRCs and second-order rate constants for the acidic and basic reference compound were established from these determinations. Hydrolysis data for the second and third set of compounds will be reported in subsequent volumes.

Hydrolysis Rate Constants

A summary sheet was prepared for each chemical. The summary sheet contained information pertinent to the

analysis of each chemical, and included source, purity, and analytical method. Also included on the sheet was information on pH, temperature, pseudo-first-order and second-order rate constants, half-lives, and correlation coefficients (r^2). Where a literature reference for the hydrolysis of a compound was obtained, the summary sheet contained the second-order rate constant if applicable and first-order rate constants at 25°C. For several of the compounds, lab data were generated in this study to fill in gaps in the literature.

Data from all the summary sheets were used to derive the values in Table 1. These values are the calculated rate constants at 25°C. The rate constants were assumed to increase a factor of 10 for each 20°C increase in temperature above 25°C. This corresponds to an activation energy of about 20 kcal/mole. When applicable, extrapolated values (25°C) were obtained using activation parameters. A temperature correction was applied to all calculations involving k_w or [OH⁻]. When statistical tests of the data indicated the hydrolysis was independent of pH, hydrolysis values from the extremes of pH (acid and/or base) were included in calculating the neutral hydrolysis rates reported in Table 1. Confidence limits were calculated from the mean and standard deviation values and are the values reported in Table 1.

Table 1. *Hydrolysis Rate Constants at 25° C*

	Rate Constants		
	Acid $M^{-1}hr^{-1}$	*Neutral* hr^{-1}	*Base* $M^{-1}hr^{-1}$
Warfarin	1.4×10^{-4}	4.9×10^{-6}	0.026
Aldrin		$(3.8 \pm 2.3) \times 10^{-5}$	
Brucine	5.9×10^{-3}		0.21
Dieldrin		$(7.5 \pm 3.3) \times 10^{-6}$	
Disulfoton		$(2.8 \pm 0.4) \times 10^{-4}$	5.99
Endosulfan I	$(8.1 \pm 2.7) \times 10^{-3}$	$(3.2 \pm 2.0) \times 10^{-3}$	$(1.0 \pm 0.7) \times 10^{4}$
Endosulfan II	$(7.4 \pm 3.9) \times 10^{-3}$	$(3.7 \pm 2.0) \times 10^{-3}$	$(1.5 \pm 0.9) \times 10^{4}$
Fluoroacetic Acid Sodium Salt		$<1.7 \times 10^{-6}$	
2-Methyllactonitrile		4.47	
Nitroglycerine[a]			77 ± 11
Famphur		$(2 5 \pm 9) \times 10^{-4}$	5.0
Acrylamide	$<3.6 \times 10^{-2}$	$<(2.1 \pm 2.1) \times 10^{-6}$	
Acrylonitrile[b]	$(4.2 \pm 0.3) \times 10^{-2}$		$(6.1 \pm 6.5) \times 10^{-1}$
Mitomycin C[a]		3.7×10^{-4}	3.0 ± 1.7
Chloromethyl methyl ether[a]		21	
1,2-Dibromo-3-chloropropane[a]			20.6
Ethylene Dibromide[a]		9.9×10^{-6}	
cis-1,4-Dichloro-2-butene		$(9.1 \pm 1 1) \times 10^{-3}$	
trans-1,4-Dichloro-2-butene		$(9.0 \pm 0.5) \times 10^{-3}$	
4,4-Methylene-bis-(2-chloroaniline)	$(2.9 \pm 3) \times 10^{-4}$	$<9 \times 10^{-8}$	
Pentachloronitrobenzene		$(2.8 \pm 0.7) \times 10^{-5}$	
Pronamide	4.3×10^{-3}	$<1.5 \times 10^{-5}$	7.4×10^{-2}
Reserpine	0.82	$(4.5 \pm 1.8) \times 10^{-5}$	9.8 ± 10.9
Thiourea		$<5.3 \times 10^{-7}$	
Uracil Mustard		0.57 ± 0.08	$(2.05 \pm 0.2) \times 10^{5}$
Ethyl Carbamate		$<2.6 \times 10^{-7}$	1.1×10^{-1}
2,3-Dichloro-1-propanol		$(5.3 \pm 0.8) \times 10^{-5}$	20.6 ± 2.2
1,3-Dichloro-2-propanol		$(3.1 \pm 0.2) \times 10^{-3}$	854 ± 87
1,2,3-Trichloropropane		$(1.8 \pm 0.6) \times 10^{-6}$	9.9×10^{-4}
1,2,3-Trichlorobenzene		$(1.6 \pm 1.3) \times 10^{-5}$	
1,2,4-Trichlorobenzene		$(2.3 \pm .9) \times 10^{-5}$	

[a] *Values were extracted from literature references in Section 1. The second-order alkaline hyrolysis rate constant for Mitomycin C was determined a Athens ERL.*

[b] *Calculated from alkaline second-order rate constant assuming zero neutral contribution.*

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

BULK RATE
POSTAGE & FEES PAID
EPA
PERMIT No G-35

Official Business
Penalty for Private Use $300

EPA/600/S3-86/043