



## Modeling the pH dependent hydrolysis of VX for aqueous releases

J.A. Cragan\*, M.C. Ward, C.B. Mueller

Applied Science Associates, South Kingstown, RI, USA

### ARTICLE INFO

#### Article history:

Received 29 January 2009

Received in revised form 30 April 2009

Accepted 1 May 2009

Available online 18 May 2009

#### Keywords:

VX

Nerve agent

Hydrolysis

Aqueous fate

### ABSTRACT

The fate of chemical warfare agents (CWAs) in aqueous environments is not well characterized. Limited physical and kinetic data are available in the open literature for this class of chemicals, in part due to the dangers associated with exposure to these compounds. As a result, the development of methods for determining the persistence and extent of impact of a waterborne chemical agent release remains largely unanswered. In this study a basic hydrolysis model was developed to track the fate of VX (O-ethyl S-(2-diisopropylaminoethyl) methylphosphonothiolate) from an instantaneous point source aqueous release. Hydrolysis product generation tracking was developed to determine the instantaneous pH within the local dispersive environment. Using instantaneous local pH values, the impact of pH on the persistence of VX hydrolysis rate was investigated for three different aqueous environments with varying dispersive conditions. Modeling results indicate that an accurate characterization of the pH dependence of the hydrolysis rate constant becomes more important in lower pH and lower turbulence environments. With this basic model, estimates of the time and extent of lethality of a VX release can be made.

© 2009 Published by Elsevier B.V.

### 1. Introduction

The fate of chemical warfare agents (CWAs) is an issue of national importance. Due to heightened awareness and sensitivity to the threat of terrorist activities at home and abroad, the need to develop tools for assessing the potential impact and extent of a CWA release is critical to minimizing injury and loss of life from a nerve agent release. The ambient environment of a chemical release is vital to understanding the fate and hazards associated with a release. Traditionally, the primary focus of CWA fate research has been on atmospheric fate. Inhalation based toxicity studies, atmospheric transport, and degree of toxicity persistence have understandably been at the forefront of human health-related research endeavors. A significant amount of research has also focused on determining the permeability of various materials to CWAs for developing effective personal protective equipment. The main thrust of aqueous experimental work has been exploring rapid and efficient decontamination and destruction methods at extreme pH and temperature [1–3]. However, the fate of CWAs in natural waters at ambient temperatures has received relatively little attention.

Investigating the fate of CWAs in natural waters is complicated by the fact that hydrolysis rates for these compounds exhibit significant dependence upon pH. For example, approximate reported

half-life values for VX (O-ethyl S-(2-diisopropylaminoethyl) methylphosphonothiolate) at 25 °C vary from 7 days at pH 8 to 30 days at pH 7 [4]. The need for characterization of the effective pH in the immediate environment of a CWA release is twofold: (1) pH is needed to determine the effective hydrolysis rate, and, (2) the speciation of the hydrolysis products, which are mainly organophosphorus acids, is a function of pH. An understanding of the speciation of the hydrolysis products generated is needed to calculate perturbations to the local pH, which in turn allows for the determination of instantaneous hydrolysis rates. A practical understanding of the potential for this pH dependence to alter CWA fate in a variety of environments is essential for developing appropriate response measures to a potential release.

The aim of this work was to develop a basic model which incorporates the impact of pH changes from hydrolysis products on the hydrolysis rate and overall persistence of VX. This was accomplished by developing a first-order estimate of the pH dependence of the hydrolysis rate based on available literature data. This derived equation was then used in combination with the hydrolysis products generated to determine the total amount of acid produced. Given this information, the impact of adding the calculated quantity of acid on the local pH was determined by taking into account an estimated natural buffering capacity from the ambient acids and bases that are found in natural waters. The change in pH is not a simple linear function of the acid introduced or produced, but depends on the alkalinity of the water. Alkalinity is rigorously defined by Dickson as “the excess of proton acceptors (bases formed from weak acids with a dissociation constant  $K \leq 10^{-4.5}$ , at 25 °C and zero ionic strength) over proton donors (acids with  $K > 10^{-4.5}$ ) in one kilogram

\* Corresponding author at: Applied Science Associates, Inc., 55 Village Square Drive, South Kingstown, RI 02879, USA. Tel.: +1 401 789 6224/340; fax: +1 401 789 1932.

E-mail address: [jcragan@asascience.com](mailto:jcragan@asascience.com) (J.A. Cragan).

**Table 1**  
Physical properties of VX. Unless otherwise noted, values are for 25 °C.

Parameter	Value
Molecular weight	267.37
Melting point	–50 °C
Boiling point	298 °C
Liquid density	1.008 g cm <sup>3</sup> (20 °C) <sup>a</sup>
Solubility	30 g/L (miscible)
Vapor pressure	0.00063 mmHg (25 °C)
Henry's law constant	3.5 × 10 <sup>–9</sup> atm·m <sup>3</sup> /mol <sup>a</sup>
log <i>K</i> <sub>ow</sub>	2.06 <sup>b</sup> , 3.08 <sup>c</sup>
log <i>K</i> <sub>oc</sub>	2.52 <sup>a</sup>
Viscosity	10.041 cP <sup>d</sup>
LD <sub>50</sub> (percutaneous)	0.01 g <sup>e,f</sup>

<sup>a</sup> From Munro et al. [4].

<sup>b</sup> This value has been reported in multiple literature sources, and is an estimate based on SRC techniques.

<sup>c</sup> EPA SPARC (Sparc Performs Automated Reasoning in Chemistry) model estimate.

<sup>d</sup> From Ref. [6].

<sup>e</sup> LD<sub>50</sub> is the exposure amount which results in 50% mortality in test subjects. The value presented here is for a 75 kg person.

<sup>f</sup> From Ref. [7].

of seawater” [5]. Until the alkalinity present in the ambient water is titrated with the addition of hydrolysis product acids, the result is a modulated change in pH when compared to an equal addition of acid to an unbuffered system.

### 1.1. Chemistry of VX

Table 1 summarizes some key physical properties of VX. VX has a consistency similar to motor oil and does not readily evaporate at ambient temperatures [6] and will not volatilize from water. The solubility of VX indicates it will exist in solution [6].

Fig. 1, modified from Munro et al. [4], presents the major hydrolysis pathways for VX and the pH dependent products formed from VX hydrolysis. In the work that follows, hydrolysis product generation was established according to the instantaneous pH value. Within the pH range of 6–7, product generation was split evenly between acidic and basic hydrolysis products for the purposes of product tracking.

Basic hydrolysis of VX produces EA 2192 [4], a solid at room temperature which is infinitely soluble. The toxicity of EA 2192 is reported to be similar to VX through oral, intravenous, or inhalation exposure depending upon the mechanism of contact [3], however a dermal toxicity LD<sub>50</sub> value of 1.4 mg/kg body weight is approximately 10 times less toxic than the VX LD<sub>50</sub> [8]. EA 2192 is described as “environmentally stable” [9], with one source reporting a hydrolysis rate for EA 2192 that is over 1000 times slower than the VX hydrolysis rate [10], which means EA 2192 would remain in the environment on timescales of the order of years in instead of days.

### 1.2. Temperature dependent hydrolysis

Eq. (1) presents the empirically derived temperature dependent hydrolysis rate constant from Demek et al. [11] for artificial seawater (pH 7.7) between 15 °C and 45 °C:

Eq. (1): VX hydrolysis as a function of temperature (in degrees Kelvin) for artificial seawater, pH 7.7

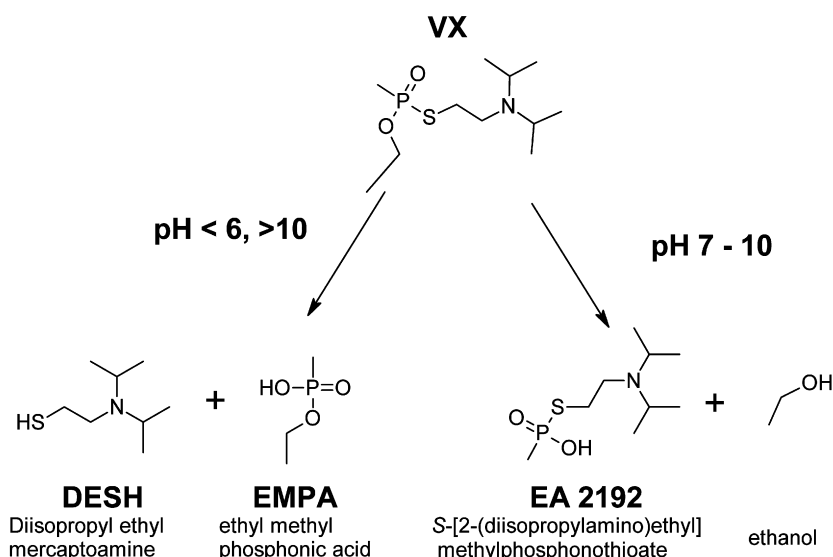
$$\log k_{\text{obs}} = 24.286 - \frac{7954}{T} \quad (1)$$

Focusing on environmentally relevant temperature values and extrapolating to a temperature outside of the experimental range, the calculated half-life values for VX ranged from 1.4 years (5 °C) to 7 days (25 °C).

### 1.3. pH dependent hydrolysis

Few sources were available for determining a pH dependent hydrolysis rate constant for VX in natural waters. Laboratory studies using buffered systems of strong acids and bases to catalyze the hydrolysis of VX provide only limited insight into the behavior of VX in the natural environment. More recently published works indicate that the concentration of dissolved organic matter plays a role in the rate on hydrolysis [12], however this impact is not quantified.

Epstein developed an equation for the pH dependent hydrolysis of VX [13]. The experimental work involved the addition of strong hydrochloric acid and sodium hydroxide solutions to alter pH. VX concentrations were tracked over time, and an empirical relationship between pH, hydroxide ion ([OH<sup>–</sup>]) concentration, the dissociation constant for water, the apparent dissociation constant



**Fig. 1.** Schematic of the major VX hydrolysis mechanisms for different pH values.

of VX, and a bimolecular reaction rate constant for OH was developed. Eq. (2) presents the empirical equation:

Eq. (2): VX hydrolysis rate as a function of pH, 25 °C

$$k_{\text{obsd}} = k_{\text{H}_2\text{O}} \frac{[\text{H}^+]}{K_a + [\text{H}^+]} + k \frac{K_a}{K_a + [\text{H}^+]} + k_{\text{OH}} [\text{OH}^-] \frac{K_a}{K_a + [\text{H}^+]} \quad (2)$$

where  $k_{\text{H}_2\text{O}}$  is the observed neutral hydrolysis rate ( $8.1 \times 10^{-8} \text{ s}^{-1}$ ),  $[\text{H}^+]$  is the hydrogen ion concentration,  $K_a$  is the apparent dissociation constant for VX ( $2.5 \times 10^{-9}$ ),  $k$  is acidic hydrolysis rate for VX ( $4.2 \times 10^{-6} \text{ s}^{-1}$ ),  $k_{\text{OH}}$  is the second order basic hydrolysis rate ( $8.3 \times 10^{-3} \text{ M}^{-1} \text{ s}^{-1}$ ), and  $[\text{OH}^-]$  is the hydroxide ion concentration (M). The validity of this equation to aqueous environments where the hydroxide ion is not the predominant nucleophile is difficult to ascertain. It has been suggested both calcium and copper act as catalysts to VX hydrolysis [14], however this has been refuted by other sources [3,15], and has not been explicitly included in any hydrolysis rate equation in the open literature.

Calculated rate constants from Eq. (2) show limited agreement with empirical data for hydrolysis rates at different pH values. Furthermore, the calculated value from Eqs. (1) and (2) are roughly a factor of two different for 25 °C and pH 7.7. This difference is confirmed in the observations of Love et al. [12], where reported hydrolysis rates for buffered solutions were approximately a factor of two greater than the corresponding hydrolysis rate calculated from Epstein's equations. Because Eq. (2) was developed from laboratory experiments performed on pure water using strong acids and bases to control pH, it is difficult to extrapolate to natural environments, where other nucleophiles, dissolved ions, and organic matter potentially impact the hydrolysis rate [14,15].

## 2. Methods

### 2.1. Derivation of a new pH dependent hydrolysis rate for VX

Based on the limited available literature data, a half-life was derived for VX which included the two major studies. At pH 7.7 and 25 °C, Eq. (1) produces a half-life of 7.1 days for VX, while Eq. (2) results in a half-life for VX of 15 days. A linear regression of the calculated hydrolysis rate from Eq. (2) in the limited range pH range of 6–8.2 shows linear behavior ( $R^2 = 0.9664$ ). As mentioned previously, the use of high purity water and strong acids and bases for pH adjustments do not provide a reasonable analogue to natural waters, supported by the empirical results from Eq. (1) and experimental data from Love et al. [12]. Making the assumption that the data from slope of the hydrolysis rate as a function of pH is linear, and assuming that the difference between the calculated half lives for Eqs. (2) and (1) is a constant factor of 2.1 (15/7.1) throughout this range, roughly supported by the results of Love et al. [12], the calculated values from Eq. (2) as a function of pH at constant temperature were divided by 2.1 to get an estimate of half-life, and rate constant, as a function of pH for typical natural waters. A linear regression was then performed on the resultant values combined with additional published data within this pH range for 25 °C ( $R^2 = 0.9859$ ), producing the following equation:

Eq. (3): Derived VX half-life (days) as a function of pH for  $T = 25 \text{ °C}$

$$\text{half-life} = -18.0232 \times \text{pH} + 148.6943 \quad (3)$$

pH specific half-life values were converted to a hydrolysis rate constant using the assumption of first-order rate law kinetics.

### 2.2. Model development

Using the derived relationship between pH and hydrolysis rate, an instantaneous point source model was developed to track the fate, extent, and concentration of a 200 kg VX release in three different aqueous environments. The total dispersive distance as a function of time was calculated using Eq. (4):

Eq. (4): Dispersion distance ( $\sigma$ ) from release point as a function of time

$$\sigma = \sqrt{2K_x t} \quad (4)$$

where  $K_x$  refers to the dispersion coefficient for a given direction for a specific environment, and  $t$  is time. Dispersion coefficients for the  $x$  and  $y$  directions were assumed to be equal, and the vertical dispersion coefficient ( $K_v$ ) was set to accurately depict environmental conditions. These dispersive distances were in calculating instantaneous alkalinity changes for pH determination as a result of local perturbations as a result of the generation of hydrolysis products. The concentration at a prescribed distance from the initial point of release at a given time was determined according to the following equation, presented in Csanady [16].

Eq. (5): Concentration as a function of distance and time from the release point

$$\chi = \frac{Q}{(2\pi)^{3/2} 2K_v \sqrt{K_z}} \exp \left\{ -\frac{x^2}{4K_h t} - \frac{y^2}{4K_h t} - \frac{z^2}{4K_v t} \right\} \quad (5)$$

where  $\chi$  is concentration ( $\text{mol cm}^{-3}$ ),  $Q$  is the mass at the beginning of a time step (mol), and  $x$ ,  $y$ , and  $z$  are the locations in space from the initial starting point as a function of time. In solving for concentration at some distance  $x$  from the initial point of release,  $y$  and  $z$  were set equal to zero. Similarly,  $x$  and  $y$  were set to zero to determine the concentration at the maximum vertical dispersive distance,  $z$ , as a function of the total time at any given time step. For a given concentration, Eq. (5) can be rearranged to determine the horizontal or vertical distance at which that concentration is present. For this work, the  $\text{LD}_{50}$  value was used.

Beginning with an initial representative value for pH and solution alkalinity, the hydrolysis rate was determined using Eq. (3). The total vertical and horizontal dispersive distance was calculated as a function of time to determine a total dispersive volume, with the dispersion shape assumed to be approximately ellipsoidal. Hydrolysis product concentrations were recalculated at each time step, and mathematically added to the previous concentration (adjusted for the new dispersion volume) in order to determine speciation on a real-time basis. All dissociation reactions were assumed to be at equilibrium based on the pH at the beginning of the time step. The amount of acid from the dissociation of the hydrolysis products was then used to determine the local change in alkalinity, and then an iterative technique adapted from Follows et al. [17] was used to calculate the new pH as a result of the change in alkalinity. Using the new pH value, the hydrolysis rate for the next time step was calculated, and the change in total amount of VX was calculated for the next time step. These calculations were repeated for each time step in the model run. A general outline of the model architecture and data flow is presented in Fig. 2.

### 2.3. Assumptions

#### 2.3.1. Particulate interactions

Several assumptions were made in order to develop a test model for the fate of VX from an instantaneous waterborne release. Love et al. [12] performed experiments on the impact of particulate and dissolved organic material on the hydrolysis rate using activated charcoal and Suwannee River fulvic acid, a proxy for dissolved organic materials in aqueous environments. The research results reported that the amount of organic material present has an impact on the available VX concentration. Using activated charcoal, experiments of the partitioning between solution and the activated charcoal showed that between 70% and 90% of the VX in solution adsorbed onto the particulate material with a 5–10 min equilibration time. It is unclear, however, whether the impact of VX's affinity for particulate organic material acts to increase the half-life (and

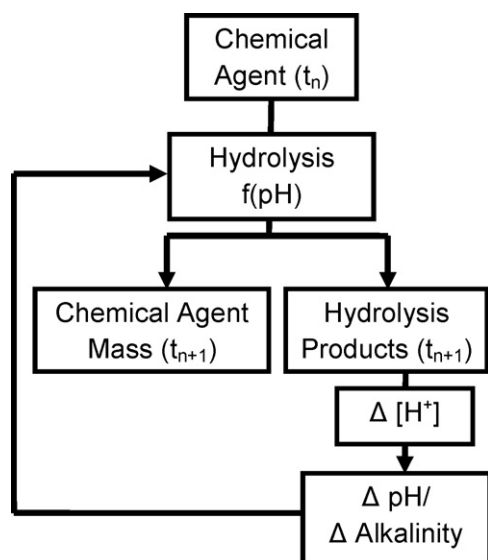


Fig. 2. Schematic of chemical model and pH feedback mechanism.

slow down the hydrolysis rate) by binding to a reactive center on VX, or if it only affects the partitioning of VX within solutions which contain organic material. Due to lack of conclusive information, particulate interactions were not included in the hydrolysis modeling of VX.

### 2.3.2. Percutaneous toxicity

VX is extremely effective via percutaneous exposure. There are numerous sources which report percutaneous  $LD_{50}$  [18], however the translation of percutaneous  $LD_{50}$  from a pure substance to an  $LD_{50}$  for contact with a dilute solution is unclear. Considering the lethality of VX and other CWAs, it is crucial to have accurate knowledge about toxicity and potential human health impacts. Determining the extent of the area which is lethal or can seriously impair a person who comes into contact with a VX solution is equally important. Typically,  $LD_{50}$  data is presented on a mass per unit body mass basis in order to scale laboratory results to a realistic human risk potential. In an aqueous environment, the application of this data becomes complicated by dispersion, dilution, and partitioning between organic and non-organic phases. Although soluble, the  $K_{ow}$  value for VX indicates that it easily partitions into the organic phase. As a result of this partitioning, VX poses a greater potential for risk through percutaneous contact than through inhalation as compared to other nerve agents. According to the CDC, any contact with VX poses the possibility to be lethal if the chemical is not washed off immediately [19].

In order to convert the  $LD_{50}$  value into a working aqueous concentration with equal impact, two methods were compared. One method involved simply taking the  $LD_{50}$  concentration for a 75 kg human, and generally assuming that this amount dissolved in 1 L of solution would impart the same lethality. The second method implemented the approach outlined in EPA's SWIMODEL (Swimmer Exposure Assessment Model), a model used to determine exposure rates of swimmers to commonly used pool chemicals. The potential dose rate for dermal exposure ( $PDR_{dermal}$ ) is calculated according to the following equation:

Eq. (6): Equation for the potential dose rate from dermal exposure

$$PDR_{dermal} = ET \times SA \times K_p \times C_w \times 10,000 \text{ cm}^2/\text{m}^2 \times 0.001 \text{ L}/\text{cm}^3 \times 1 \text{ mg}/1000 \mu\text{g} \quad (6)$$

where ET is the exposure time (h), SA is the total surface area ( $\text{cm}^2$ ),  $K_p$  is a chemical specific permeability coefficient ( $\text{cm}/\text{h}$ ), and  $C_w$  is aqueous concentration in the water (M). The permeability coefficient,  $K_p$ , is a function of the molecular weight of the compound and the octanol–water ( $K_{ow}$ ) partition coefficient. Uncertainties in this value arise from the fact that, although the  $K_{ow}$  is reported as experimental data, these authors were unable to locate the referenced data. Furthermore (see Table 1) the EPA SPARC (Sparc Performs Automated Reasoning in Chemistry) model estimates a  $\log K_{ow}$  value of 3.09 for VX. The range in aqueous concentration values that result from these two  $K_{ow}$  values are a factor of 5 different. The larger  $K_{ow}$  value in the equation provides the more conservative estimate of the water concentration for a given exposure time.

In order to determine exposure for the purposes of comparison, the  $LD_{50}$  value was substituted for a  $PDR_{dermal}$  value, and Eq. (6) rearranged to solve for  $C_w$ . As an example, a 1 h exposure time and an  $LD_{50}$  of 10 mg for a 75 kg person produces an equivalent aqueous concentration of  $2.73 \times 10^{-4}$  M VX. Using the same  $LD_{50}$  and calculating the equivalent concentration for a 10 mg/L VX solution results in a concentration of  $3.74 \times 10^{-5}$  M. These values differ by roughly one order of magnitude, however, given the dermal toxicity of VX and the lack of experimental data for dermal exposure in dilute solution, it was concluded that the more simplistic approach, although slightly more conservative, was a reasonable estimate for aqueous exposure to a human submerged in a solution of VX.

### 2.3.3. Chemical activity and hydrolysis product concentration

The thermodynamic activities of the hydrolysis products in solution were assumed to be equal to their concentration. All generated hydrolysis products were assumed to be uniformly mixed at any given time within the calculated dispersion volume, producing a homogenous hydrolysis product concentration within this volume. Due to the reported environmental stability of EA 2192, it was assumed to undergo no further chemical reaction, and the production of hydrogen was through dissociation in solution calculated from the published  $pK_a$  value of 11.05 [4]. EPA's SPARC model was used to estimate the second order hydrolysis rate for the hydrolysis of EMPA (ethyl methylphosphonic acid) to MPA (methylphosphonic acid), as well as the dissociation constants for MPA. The dissociation constant used for EMPA was that published by Munro et al. [4]. As mentioned previously, the hydrolysis rate was derived from a linear regression of empirical observations, the pH dependent hydrolysis rate published by Epstein [13], and the temperature dependent rate published by Demek et al. [11], similar to values observed by Love et al. [12].

### 2.3.4. Alkalinity and dissolved inorganic carbon

For each time step, alkalinity was conservatively mixed within the dispersal volume in re-determining local alkalinity and pH. In oceanic waters, alkalinity has been found to be generally correlated with salinity [20]. Because real-time salinity and temperature data is more readily available than pH or alkalinity data, temperature and salinity were used to estimate the alkalinity using the general relationships presented in Lee et al. [20]. In order to calculate pH or alkalinity (or any parameter of the marine carbon dioxide system), knowledge of two of the four oceanic  $\text{CO}_2$  parameters (pH, alkalinity, total dissolved inorganic carbon (DIC), partial pressure of dissolved carbon dioxide gas) is necessary. For the purposes of model simulations, DIC was assumed to be constant (2000  $\mu\text{mol}/\text{kg}$  seawater). In fresh waters, the alkalinity is comprised of fewer chemical species, and speciation constant relationships with salinity dependence were used where available, with initial alkalinity and DIC modified to more typically observed values.

The fate of VX in natural waters was investigated for three different environments. Initial pH values of 8, 7, and 6 were used

**Table 2**  
 $K_H = 0.01 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.0001 \text{ m}^2 \text{ s}^{-1}$  Oceanic Scenario.

	Hydrolysis rate choice	$R_{MAX}$ (m)	$t_{MAX}$ (h)	$t_{TOTAL}$ (h)	$V_{MAX}$ ( $10^6$ L)
pH 8 data	No hydrolysis	19.99	5.35	7.56	3.34
	Epstein value	19.87	5.29	7.44	3.29
	Constant rate	19.85	5.28	7.41	3.27
	This work	19.75	5.22	7.31	3.23
	Maximum difference	0.23	7.6 min	14.8 min	0.12

**Table 3**  
 $K_H = 0.01 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.0001 \text{ m}^2 \text{ s}^{-1}$  Riverine Scenario.

	Hydrolysis rate choice	$R_{MAX}$ (m)	$t_{MAX}$ (h)	$t_{TOTAL}$ (h)	$V_{MAX}$ ( $10^6$ L)
pH 7 data	No hydrolysis	19.99	5.35	7.56	3.34
	Epstein value	19.97	5.34	7.54	3.33
	Constant rate	19.85	5.28	7.41	3.27
	This work	19.94	5.33	7.51	3.32
	Maximum difference	0.14	4.5 min	8.8 min	0.07

to approximate pH values for oceanic, riverine, and limnological environments, respectively. For each environment, model analyses were performed using horizontal dispersion coefficients which were an order of magnitude different. For a single horizontal dispersion coefficient, two vertical dispersion coefficient values were used for the simulations. The vertical dispersion coefficients were assigned a value two and three orders of magnitude smaller than the horizontal dispersion coefficient. The coefficients were varied in order to qualitatively assess the sensitivity to dispersive environment and assess the relative impact to VX fate for each simulated environment. For each pair of horizontal and vertical dispersion coefficients, four different hydrolysis cases were investigated: (1) no hydrolysis, (2) Epstein's pH dependent hydrolysis rate, (3) a constant VX hydrolysis rate employed in other CWA modeling work, and (4) the pH dependent hydrolysis rate derived in this work. For each case, the maximum radial distance with a concentration greater than or equal to the  $LD_{50}$  from the initial point of release, ( $R_{MAX}$ ) was determined, the time at this maximum ( $t_{MAX}$ ), the total time of persistence of a concentration level greater than the  $LD_{50}$  ( $t_{TOTAL}$ ), and the maximum volume of water ( $V_{MAX}$ ) which contained a concentration of VX that was at or above the  $LD_{50}$  were tabulated in order to compare the impact of the choice of hydrolysis rate constant on the fate of a 200 kg aqueous release of VX. No efforts were made to quantify low level toxicity.

### 3. Results and discussion

Model results for the  $K_H/K_V$  pair  $0.01 \text{ m}^2 \text{ s}^{-1}/0.0001 \text{ m}^2 \text{ s}^{-1}$  in three different pH environments are presented in Tables 2–4.

In the two lower pH environments, the no hydrolysis simulations show a smaller absolute difference in all four values presented to the derived hydrolysis rate. This is due to the fact that the derived

**Table 4**  
 $K_H = 0.01 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.0001 \text{ m}^2 \text{ s}^{-1}$  Lake Scenario.

	Hydrolysis rate choice	$R_{MAX}$ (m)	$t_{MAX}$ (h)	$t_{TOTAL}$ (h)	$V_{MAX}$ ( $10^6$ L)
pH 6 data	No hydrolysis	19.99	5.35	7.56	3.34
	Epstein value	19.98	5.34	7.55	3.34
	Constant rate	19.85	5.28	7.41	3.27
	This work	19.96	5.34	7.53	3.33
	Maximum difference	0.14	4.5 min	8.8 min	0.07

**Table 5**  
 $K_H = 0.01 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.00001 \text{ m}^2 \text{ s}^{-1}$  Oceanic Scenario.

	Hydrolysis rate choice	$R_{MAX}$ (m)	$t_{MAX}$ (h)	$t_{TOTAL}$ (h)	$V_{MAX}$ ( $10^6$ L)
pH 8 data	No hydrolysis	29.23	11.57	16.29	3.31
	Epstein value	28.86	11.28	15.72	3.19
	Constant rate	28.80	11.23	15.63	3.16
	This work	28.51	11.00	15.20	3.07
	Maximum difference	0.72	34 min	65 min	0.24

**Table 6**  
 $K_H = 0.01 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.00001 \text{ m}^2 \text{ s}^{-1}$  Riverine Scenario.

	Hydrolysis rate choice	$R_{MAX}$ (m)	$t_{MAX}$ (h)	$t_{TOTAL}$ (h)	$V_{MAX}$ ( $10^6$ L)
pH 7 data	No hydrolysis	29.23	11.57	16.29	3.31
	Epstein value	29.16	11.52	16.18	3.28
	Constant rate	28.80	11.23	15.63	3.16
	This work	29.09	11.46	16.07	3.26
	Maximum difference	0.43	20 min	40 min	0.14

hydrolysis half-life of VX increases from approximately 3 days at pH 8 to almost 19 days at pH 6, which is significantly longer than the time needed to disperse the VX to a concentration level below the  $LD_{50}$ . For the higher pH simulations, the faster hydrolysis rate translates to a greater absolute difference, indicating that utilizing a pH varying hydrolysis rate reduces overall persistence for the same dispersive conditions.

Results from employing a vertical dispersion coefficient which is one order of magnitude smaller than the simulations presented in Tables 2–4 are presented in Tables 5–7. As can be seen by comparison to the first group of results, reducing the vertical dispersion coefficient by a factor of ten increases the importance of using a pH dependent hydrolysis rate. The total time of persistence of VX at or above the  $LD_{50}$  concentration is more than twice that for the higher magnitude vertical dispersion coefficient. The maximum volume of water containing lethal concentrations of VX is slightly lower, while the maximum radial extent and total time of persistence are also nearly doubled. The magnitude of the differences between the hydrolysis rate derived in this work and the other hydrolysis rates also increases. This emphasizes the need for employing pH dependent hydrolysis rates to more accurately investigate the fate of a VX aqueous release.

Another interesting result is that the largest difference for this dispersion coefficient pair is observed between the conservative scenario and the constant hydrolysis rate simulations for the lower pH cases. The half-life value for a pH of 6 is approximately 540 h using the derived pH dependent rate, while it is greater than 1000 h using Epstein's equation. The constant hydrolysis rate value used produces a half-life of 175 h, which significantly overestimates initial VX hydrolysis for lower initial pH values. Employing a pH dependent hydrolysis rate constant not only takes the local environment pH changes into account, it more realistically encompasses

**Table 7**  
 $K_H = 0.01 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.00001 \text{ m}^2 \text{ s}^{-1}$  Lake Scenario.

	Hydrolysis rate choice	$R_{MAX}$ (m)	$t_{MAX}$ (h)	$t_{TOTAL}$ (h)	$V_{MAX}$ ( $10^6$ L)
pH 6 data	No hydrolysis	29.23	11.57	16.29	3.31
	Epstein value	29.19	11.54	16.23	3.29
	Constant rate	28.80	11.23	15.63	3.16
	This work	29.15	11.51	16.16	3.28
	Maximum difference	0.43	20 min	40 min	0.14

**Table 8** $K_H = 0.001 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.00001 \text{ m}^2 \text{ s}^{-1}$  River Scenario.

	Hydrolysis rate choice	$R_{\text{MAX}}$ (m)	$t_{\text{MAX}}$ (h)	$t_{\text{TOTAL}}$ (h)	$V_{\text{MAX}}$ ( $10^6$ L)
pH 7 data	No hydrolysis	19.99	53.50	75.60	3.35
	Epstein value	19.77	52.33	73.30	3.24
	Constant rate	18.80	47.19	63.87	2.79
	This work	19.57	51.26	71.26	3.14
	Maximum difference	1.19	6.3	11.7	0.56

**Table 9** $K_H = 0.001 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.00001 \text{ m}^2 \text{ s}^{-1}$  Lake Scenario.

	Hydrolysis rate choice	$R_{\text{MAX}}$ (m)	$t_{\text{MAX}}$ (h)	$t_{\text{TOTAL}}$ (h)	$V_{\text{MAX}}$ ( $10^6$ L)
pH 6 data	No hydrolysis	19.99	53.50	75.60	3.35
	Epstein value	19.87	52.88	74.38	3.29
	Constant rate	18.80	47.19	63.87	2.79
	This work	19.75	52.19	73.04	3.23
	Maximum difference	0.24	1.31	2.56	0.12

**Table 10** $K_H = 0.001 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.000001 \text{ m}^2 \text{ s}^{-1}$  River Scenario.

	Hydrolysis rate choice	$R_{\text{MAX}}$ (m)	$t_{\text{MAX}}$ (h)	$t_{\text{TOTAL}}$ (h)	$V_{\text{MAX}}$ ( $10^6$ L)
pH 7 data	No hydrolysis	29.23	115.7	162.9	3.31
	Epstein value	28.57	110.5	152.8	3.09
	Constant rate	25.95	90.9	119.0	2.33
	This work	28.00	106.1	144.7	2.91
	Maximum difference	3.3	24.8	43.8	0.97

the impact of the local pH changes. The change in hydrolysis rate (and half-life) at pH 8 is less than 0.05% throughout the simulation run time. The hydrolysis rate change within a model simulation starting at pH 7 using the Epstein equation ranged from 0.04% to 6.4% between the two groups of analyses. The same relative change in the hydrolysis rate was observed for the derived pH dependent hydrolysis rate. For the pH 6 simulations, Epstein's equation produced roughly the same relative variability, while the derived pH dependent rate showed an in-simulation variation of 0.1–11%.

Simulations for lower turbulent regimes are presented in Tables 8–11. Tables 8 and 9 present larger magnitude vertical dispersion coefficients than in Tables 10 and 11. Oceanic simulations (pH 8) were not included as the dispersion coefficients are outside the range of observed surface ocean turbulence.

Investigation of the uncertainty associated with an order of magnitude variation in the vertical dispersion coefficient can be done by comparing these results. Comparing the difference in maximum radial extent, time at this maximum radial extent, maximum lethal volume, and total time of persistence shows that the relative variability is constant regardless of the starting pH for the

**Table 11** $K_H = 0.001 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.000001 \text{ m}^2 \text{ s}^{-1}$  Lake Scenario.

	Hydrolysis rate choice	$R_{\text{MAX}}$ (m)	$t_{\text{MAX}}$ (h)	$t_{\text{TOTAL}}$ (h)	$V_{\text{MAX}}$ ( $10^6$ L)
pH 6 data	No hydrolysis	29.23	115.7	162.9	3.31
	Epstein value	28.87	112.9	157.4	3.19
	Constant rate	25.95	90.9	119.0	2.33
	This work	28.49	109.9	151.7	3.06
	Maximum difference	0.74	5.9	11.2	0.24

most turbulent regimes. Choosing a vertical dispersion coefficient 10 times greater than the in-situ value reduces the resulting radial distance by 40–50%, produces a total time of persistence which is approximately  $\frac{1}{2}$  of the lower turbulent value, but only slightly over-predicts the total lethal volume. The uncertainties are roughly the same when comparing any horizontal and vertical dispersion coefficient pair when there is an order of magnitude difference in vertical dispersion.

These results indicate that for higher turbulence environments, the assumption of a constant hydrolysis rate taken from a single experimental data point, or the assumption of a conservative constituent (no hydrolysis) introduces no significant error in the extent and duration of the lethal zone from a VX release. As turbulence decreases, the impact of the choice of hydrolysis rate plays a larger role. If the pH is unknown, making the assumption that VX, due to its long life, can be characterized as a conservative constituent overestimates the time of persistence by 7–50 min for the specified release parameters when compared to implementation of the derived hydrolysis rate equation. As the pH of the environment decreases and the hydrolysis rate decreases, the assumption of no hydrolysis introduces less uncertainty if the initial pH does not change dramatically. In environments where there is lower turbulence and the potential for pH changes on the order of 0.5 units (as in estuarine environments) the application of a constant or no hydrolysis rate to the VX fate determinations would introduce an uncertainty on the order of the difference between the oceanic and riverine systems: 15–50 min when compared to no hydrolysis or constant hydrolysis at an initial pH value of 8 out of a total persistence time out of 16 h (approximately 6% of the total time of persistence). Additionally, the areal extent would be roughly 0.5 m underestimated when compared to a pH dependent hydrolysis rate.

Additional simulations were also performed to evaluate the differences in the fate of VX in limnological environments at lower turbulence. For an initial pH of 6,  $K_H$  of  $1 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ ,  $K_V$  of  $1 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ , the assumption of no hydrolysis, despite the long half-life of VX, overestimates the total persistence for a 200 kg release by between 100 h and 433 h. This is due to the fact that the time scales of persistence for this level of turbulence approach the magnitude of the half-life for VX, and the value chosen makes a more significant impact on overall persistence. The results for this low turbulence simulation are presented in Table 12.

From these simulation results it is clear that in low turbulence environments, even with a low initial pH, the variability in the hydrolysis half-life results in significant variability for the four measures of release duration and extent. The potential variability in this environment highlights the need for an accurate understanding of the hydrolysis rate of VX as well as a thorough characterization of the factors that can impact it. Using a constant hydrolysis rate at pH 6 predicts the VX total time of lethality to be 77% of the conservative scenario. The hydrolysis rates derived in this work result in a total time of persistence which is 42% lower than the conservative scenario with the same initial conditions. Empirical evidence supports significant sensitivity to pH, making an appropriate choice of relationship for this dependence crucial to simulation results.

**Table 12** $K_H = 0.0001 \text{ m}^2 \text{ s}^{-1}$ ,  $K_V = 0.000001 \text{ m}^2 \text{ s}^{-1}$  Lake Scenario.

	Hydrolysis rate choice	$R_{\text{MAX}}$ (m)	$t_{\text{MAX}}$ (h)	$t_{\text{TOTAL}}$ (h)	$V_{\text{MAX}}$ ( $10^6$ L)
pH 6 data	No hydrolysis	19.99	535	756	3.35
	Epstein value	18.99	482	657	2.87
	Constant rate	14.17	439	582	2.51
	This work	18.14	265	323	1.25
	Maximum difference	5.8	270	433	2.10

Using the Epstein pH dependent rate calculation appears to introduce greater uncertainty in lower pH waters. The Epstein equation results in a 3% change in the hydrolysis rate, while the newly derived pH dependent hydrolysis rate equation produces a change of 11%, mainly due to a lower relative hydrolysis rate at low pH which results in a greater time of persistence. In the lowest turbulent regimes, the hydrolysis rate has the potential to introduce a significant degree of uncertainty into simulation results. The total persistence time using the hydrolysis rate derived in this work is 82% of the conservative scenario, with total persistence on the order of 24 days, as compared to a dilution time of 31.5 days when treating VX as a conservative constituent. From these results it can generally be stated that as the value of the dispersion coefficients decreases, the choice of hydrolysis rate constant has a greater impact on the time of persistence. This is largely due to the fact that the local pH changes as a result of more rapid VX hydrolysis are diluted through more vigorous mixing at higher dispersion rates, which acts to keep the hydrolysis rate essentially constant (a change less than 0.02% is observed). For a horizontal dispersion coefficient of  $0.1 \text{ m}^2 \text{ s}^{-1}$  the difference in the total time of persistence for the case of no hydrolysis as compared to the fastest hydrolysis rate at this pH (derived from this work) is less than 45 s. However, once the horizontal dispersion coefficient is reduced to  $0.01 \text{ m}^2 \text{ s}^{-1}$  or lower, the difference between the total time of persistence for the hydrolysis rate derived from this work as compared to the conservative no hydrolysis scenario is 15 min and 65 min for  $K_V = 1 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$  and  $K_V = 1 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ , respectively. Likewise, the total radial extent is 0.23–0.72 m less, and as a result the maximum radial extent is reached more quickly (8 min and 34 min, respectively) than the case where it is assumed that the hydrolysis rate is slow enough to be considered negligible.

#### 4. Conclusions

From these simple model simulations, it is clear that the appropriate relationship of pH dependence for the VX hydrolysis rate can have a significant impact on the prediction of extent and persistence for an aqueous release of VX. With a more complete set of empirical observations of the hydrolysis rates in natural waters at several temperatures and pH values, methods for investigating the question of VX persistence can be refined and improved. Environmental variability plays a significant role in this type of simulation, however the inclusion of instantaneous local pH and hydrolysis rate calculations are important refinements. More refined values for hydrolysis allows for the investigation of questions regarding cumulative toxicity of VX and EA2192 from a waterborne release. Validation of  $K_{ow}$  estimates with experimental data will allow for the possibility of addressing the impact of particulate materials. The most serious result of an aqueous release without more accurate knowledge of the fate of VX in the water column would be to underestimate the half-life, and determine a location non-lethal prematurely. It is not unfeasible to think that adsorption to suspended particulate materials would prolong the time a VX release remained lethal by potentially sustaining a concentration above the  $LD_{50}$  adsorbed

to particle material which acted to inhibit hydrolysis. A thorough understanding of aqueous fate also allows for the development of toxicity estimates. Finally, the determination of the impact of dissolved ions typically found in natural waters needs to be empirically determined in order to fully characterize VX's hydrolytic fate.

#### Acknowledgements

This research was supported by Defense Threat Reduction Agency's Contract #CA07MSB035 and SBIR #DTRA05-013.

#### References

- [1] Commission on Engineering and Technical Systems, Alternative Technologies for the Destruction of Chemical Agents and Munitions, National Academies Press, Washington, DC, 1993.
- [2] Y.C. Yang, J.A. Baker, J.R. Ward, Decontamination of chemical warfare agents, *Chem. Rev.* 92 (1992) 1729–1743.
- [3] Y.C. Yang, Chemical detoxification of nerve agent VX, *Acc. Chem. Res.* 32 (1999) 109–115.
- [4] N.B. Munro, S.S. Talmage, G.D. Griffin, L.C. Waters, A.P. Watson, J.F. King, V. Hauschild, The sources, fate, and toxicity of chemical warfare degradation products, *Environ. Health Perspect.* 107 (1999) 933–974.
- [5] DOE, Handbook of Methods for the Analysis of the Various Parameters of the Carbon Dioxide System in Sea Water, Version 2, in: A.G. Dickson, C. Goyet (Eds.), ORNL/CDIAC-74, 1994.
- [6] United States Army Medical Management of Chemical Casualties Handbook, 2nd edition, Chemical Casualty Care Office, Aberdeen Proving Ground, MD 21010-5425, September 1995.
- [7] Army Field Manual No. 3-9, Potential Military Chemical/Biological Agents and Compounds, Department of the Army, Department of the Army, Washington, DC, December 1990.
- [8] SBCCOM, Online: <http://dhmh.md.gov/labs/pdf/Terrorism/MSDS%20-%20All%20chemical%20agents-SBCCOM.pdf>.
- [9] J. Ware, Environmental Team Leader, Assembled Chemical Weapons Assessment, Design, Construction and Operation of One or More Pilot Test Facilities for Assembled Chemical Weapons Destruction Technologies at One or More Sites: Final Environmental Impact Statement, Aniston Army Depot, AL, Pine Bluff Arsenal, AR, Blue Grass Army Depot, KY, Pueblo Chemical Depot, CO US Department of Defense.
- [10] Y.C. Yang, L.L. Szafraniec, W.T. Beaudry, C.A. Bunton, Perhydrolysis of nerve agent VX, *J. Org. Chem.* 58 (1993) 6964–6965.
- [11] M.M. Demek, G.T. Davis, W.H. Dennis Jr., et al., Behavior of chemical agents in seawater, Edgewood Arsenal, Department of the Army Edgewood Arsenal, MD, AD-873242, 1970.
- [12] A.H. Love, A.L. Vance, J.G. Reynolds, M.L. Davisson, Investigating the affinities and persistence of VX nerve agent in environmental matrices, *Chemosphere* 57 (2004) 1257–1264.
- [13] J. Epstein, *J. Am. Water Works Assoc.* 66 (1974) 31–37.
- [14] J.A.A. Ketelaar, H.R. Gersmann, M.M. Beck, Metal-catalyzed hydrolysis of thiophosphoric esters, *Nature* 177 (1956) 392–393.
- [15] J.M. Albizo, J.R. Ward, Hydrolysis of GD and VX by 0.05 M/0.10 M Copper(II)-N,N,N',N'-tetramethylethylenediamine (TMEN), in Proceedings, Army Science Conference (16th), vol. 1, 25–27 October 1988, AD-A203101, pp. 33–37.
- [16] G.T. Csanady, *Turbulent Diffusion in the Environment*, D. Reidel Pub. Co., Dordrecht, Boston, 1973.
- [17] M.J. Follows, T. Ito, S. Dutkiewicz, On the solution of the carbonate chemistry system in ocean biogeochemistry models, *Ocean Model.* 12 (2006) 290–301.
- [18] N.B. Munro, K.A. Ambrose, A.P. Watson, Toxicity of the organophosphate chemical warfare agents GA, GB, and VX: implications for public protection, *Environ. Health Perspect.* 102 (1994) 18–38.
- [19] Department of Health and Human Services, Center for Disease Control and Prevention Fact Sheet. Facts about VX, last reviewed March 23, 2005.
- [20] K. Lee, L.T. Tong, F.J. Millero, C.L. Sabine, A.G. Dickson, C. Goyet, G.H. Park, R. Wanninkhof, R.A. Feely, R.M. Key, Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans, *Geophys. Res. Lett.* 33 (2006) L19605.