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Co-Occurrence of 1,4-Dioxane with Trichloroethylene in Chlorinated Solvent Groundwater Plumes at US Air Force Installations: Fact or Fiction

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ABSTRACT

Increasing regulatory attention to 1,4-dioxane has prompted the United States Air Force (USAF) to evaluate potential environmental liabilities, primarily associated with legacy contamination, at an enterprise scale. Although accurately quantifying environmental liability is operationally difficult given limited historic environmental monitoring data, 1,4-dioxane is a known constituent (i.e., stabilizer) of chlorinated solvents, in particular 1,1,1-trichloroethane (TCA). Evidence regarding the co-occurrence of 1,4-dioxane and trichloroethylene (TCE), however, has been heavily debated. In fact, the prevailing opinion is that 1,4-dioxane was not a constituent of past TCE formulations and, therefore, these 2 contaminants would not likely co-occur in the same groundwater plume. Because historic handling, storage, and disposal practices of chlorinated solvents have resulted in widespread groundwater contamination at USAF installations, significant potential exists for unidentified 1,4-dioxane contamination. Therefore, the objective of this investigation is to determine the extent to which 1,4-dioxane co-occurs with TCE compared to TCA, and if these chemicals are co-contaminants, whether or not there is significant correlation using available monitoring data. To accomplish these objectives, the USAF Environmental Restoration Program Information Management System (ERPIMS) was queried for all relevant records for groundwater monitoring wells (GMWs) with 1,4-dioxane, TCA, and TCE, on which both categorical and quantitative analyses were carried out. Overall, ERPIMS contained 5788 GMWs from 49 installations with records for 1,4-dioxane, TCE, and TCA analytes. 1,4-Dioxane was observed in 17.4% of the GMWs with detections for TCE and/or TCA, which accounted for 93.7% of all 1,4-dioxane detections, verifying that 1,4-dioxane is seldom found independent of chlorinated solvent contamination. Surprisingly, 64.4% of all 1,4-dioxane detections were associated with TCE independently. Given the extensive data set, these results conclusively demonstrate for the first time that 1,4-dioxane is a relatively common groundwater co-contaminant with TCE. Trend analysis demonstrated a positive log-linear relationship where median 1,4-dioxane levels increased between approximately 6% and approximately 20% of the increase in TCE levels. In conclusion, this data mining exercise suggests that 1,4-dioxane has a probability of co-occurrence of approximately 17% with either TCE and/or TCA. Given the challenges imposed by remediation of 1,4-dioxane and the pending promulgation of a federal regulatory standard, environmental project managers should use the information presented in this article for prioritization of future characterization efforts to respond to the emerging issue. Importantly, site investigations should consider 1,4-dioxane a potential co-contaminant of TCE in groundwater plumes. Integr Environ Assess Manag. © 2012 SETAC

Keywords: 1,4-Dioxane 1,1,1-Trichloroethane Trichloroethylene Groundwater Co-occurrence

INTRODUCTION

The United States Air Force (USAF) Emerging Issues Program has recently considered 1,4-dioxane as an emerging contaminant. Although relatively little is known about the occurrence, fate, and transport of 1,4-dioxane in the environment (Mohr 2001, Mohr and Jacobs 2005; DiGuiseppi and Whitesides 2007), numerous toxicity studies suggest that 1,4-dioxane has the potential to negatively impact human health (Stickney et al. 2003; ATSDR 2007; USEPA 2010). The United States Environmental Protection Agency's (USEPA) Integrated Risk Information System (IRIS) has recently developed oral noncancer and revised cancer toxicity assessments (USEPA 2010), which will likely be used to develop a federal maximum contaminant level (MCL) for drinking water and regulatory screening levels for groundwater and soil. Some states and other regulatory entities currently regulate 1,4-dioxane levels in environmental media (Mohr 2001; USEPA 2006; ATSDR 2007). Increasing regulatory attention has prompted the USAF to evaluate potential environmental liabilities posed by 1,4-dioxane contamination at an enterprise scale.

Because of its solvent and stabilizing properties, many commercial products contain (or contained) 1,4-dioxane. Existing household products that contain 1,4-dioxane as a solvent include, but are not limited to, lacquers, paints, varnishes, resins, oils, waxes, dyes, and adhesives (USEPA 1995; Mohr 2001). Additionally, 1,4-dioxane is found currently in a wide range of industrial products including insecticides, fumigants, aircraft deicing fluids, and antifreeze (Mohr 2001; Surprenant 2002). Although recent production

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volume has decreased to between 1 and 10 million pounds annually, approximately 10 to 50 million pounds are reported to have been produced annually before the 1990s (USEPA 2006). Consequently, potential impacts to the USAF environmental restoration program posed by 1,4-dioxane are primarily associated with legacy contamination, with limited contribution from current sources mitigated by pollution prevention practices.

Quantifying the environmental liability associated with legacy contamination is operationally difficult given limited environmental monitoring data for 1,4-dioxane. 1,4-Dioxane is known to have been added as a stabilizer in chlorinated solvents such as 1,1,1-trichloroethane (TCA or methyl chloroform) at approximately 3.5% by volume (HSDB 1995; Doherty 2000; Mohr 2001; ATSDR 2007). Although the co-occurrence of 1,4-dioxane in TCA groundwater plumes is well documented (USEPA 1995; Mohr 2001; Zenker et al. 2003), evidence regarding the co-contamination of 1,4-dioxane and other chlorinated solvents such as trichloroethylene (TCE) has been heavily debated. For example, Mohr et al. (2010) reports that there is no data or patent information to confirm the use of 1,4-dioxane as a stabilizer in TCE, and that the physical properties of TCE and 1,4-dioxane suggest the contrary. As such, environmental project managers have largely discounted the prospect of co-contamination of 1,4-dioxane and TCE. Given that historic handling, storage, and disposal practices of chlorinated solvents have resulted in widespread soil and groundwater contamination at USAF installations, significant potential exists for concomitant 1,4-dioxane contamination. Co-occurrence of 1,4-dioxane at USAF sites contaminated with TCE remains uninvestigated at an enterprise scale.

Given that chlorinated solvents often drive remedial expenses at USAF installations, the objective of this investigation is to determine the extent to which 1,4-dioxane co-occurs with TCE independent of TCA contamination, and whether or not there is significant correlation. Significant co-occurrence between 1,4-dioxane with TCE does not necessarily prove that 1,4-dioxane was used as a stabilizer. However, quantifying the probability and magnitude of the association within groundwater plumes would provide environmental project managers with information regarding the likelihood that a previously identified TCE plume (without historic monitoring data for 1,4-dioxane) may contain 1,4-dioxane and the likely concentration, respectively. To accomplish these objectives, the USAF Environmental Resources Program Information Management System (ERPIMS) was queried for all relevant records on which both categorical and quantitative analyses were performed. Results are discussed within the context of potential impacts to the USAF Environmental Restoration Program.

METHODS

Database

ERPIMS, created in 1986 by the Air Force Center for Engineering and the Environment (AFCEE), is a relational Oracle® database designed to enable the USAF to centrally manage environmental restoration data. ERPIMS contains environmental sampling data including, but not limited to, geophysical data, hydrogeological data, and analytical chemistry data. For a comprehensive description of the tables, see http://www.afcee.lackland.af.mil/erpims/DLhandbook/html/index.html. Currently, there are over 100 million records, submitted by 176 distinct USAF installations, in ERPIMS. The vast majority of these data, approximately 95%, are composed of analytical results.

The ERPIMS web site contains comprehensive background information. All projects that generate analytical data, ultimately funded by the Defense Environmental Restoration Account (DERA), are required to submit data to ERPIMS. Contractors are required to submit this data to AFCEE through the ERPTools X software tool. The ERPTools X software contains over 1200 checks that are run against all data loaded into the program to ensure data integrity and comprehension. Once data have been submitted to AFCEE through the tool, an additional final review is conducted by the ERPIMS electronic data loading team. Only after the data has successfully passed all checks is it inserted into the production database and available for query.

Every analytical record that resides in ERPIMS is ultimately tied to a geographic location. Although the ‘‘SLX’’ table contains information that relates a particular GMW to a site (i.e., a release), the completeness of the records are generally insufficient to provide a basis for broad-scale applications (enterprise-wide queries). A join of the ‘‘Results,’’ ‘‘Samples,’’ ‘‘Test,’’ and ‘‘LDI’’ tables uniquely identifies every analytical record with the corresponding location. Attributes of the ‘‘LDI’’ table include fields that identify various logistical information including, but not limited to, the installation, sample date, sample depth, and coordinates.

The working data set used for these analyses was generated using minimal filters to ensure output captured all applicable records. Three independent tables, subsequently concatenated and cross-referenced to include only groundwater monitoring wells (GMWs) with records for all 3 analytes (1,4-dioxane, TCE, or TCA), were created to complete the query, with each output only varying by which analyte was specified. Additionally, the sample type was restricted to either a normal or field duplicate, but only the record reflecting the maximum concentration (including nondetects if no sample ever exceeded the reporting limit [RL] of the analytical laboratory) ever recorded for that particular GMW was retained. Thus, the final working data set consisted of 3 records (1 for each analyte regardless of the sample date) for each GMW. The RL rather than method detection limit (MDL) was used as the threshold for detection given historic uncertainties in the analytical detection capabilities for 1,4-dioxane. All units were standardized to $\mu\ L^{-1}$ (PPB).

In the context of this investigation, co-contamination is assumed to have originated from a similar source because information relating GMWs to a specific solvent release was limited in ERPIMS. Thus, temporal variation was omitted from evaluation, but also because of the inconsistency in measured analytes in any given sampling event. Also, depth of the GMW screen was not included in the assessment because of potential confounding with highly variable well screen intervals as well as combinations of high and low flow purge sampling techniques, which confound the assessment of potential density-dependent stratification of the respective chemicals within a plume. Given the inherent limitations of the available monitoring data in ERPIMS, this investigation is intended to provide insight into the empirical likelihood of co-occurrence rather than mechanistic details related to fate and transport.

Statistical evaluation

Query results for each GMW with records for all 3 analytes (1,4-dioxane, TCE, and TCA) were dichotomized in terms of detection (i.e., ≥RL) versus nondetection (i.e., <RL). Initial analysis included a $2 \times 2 \times 2$ contingency table to evaluate the association among all 3 analytes (Agresti 1996). In this context, counts of detections versus nondetections among the strata were tabulated and evaluated for independence using odds ratios (OR). General association was tested by χ^2 using Proc Freq in SAS® Version 9.2 for Windows® (SAS Institute 2008) and considered significant at $p \leq 0.05$.

The association between TCE and 1,4-dioxane was evaluated by a $2 \times 2 \times k$ contingency table where the conditional association was evaluated by installation (Agresti 1996). The conditional association was evaluated by installation because information relating GMWs to a specific solvent release was limited in ERPIMS. The Breslow-Day test for homogeneity of OR (calculated as the cross-product of the conditional contingency table) was used to test for conditional independence; conditional independence would imply that co-occurring contamination occurs randomly among installations. Because conditional independence was not observed (described below), tests for general association and the associated OR were evaluated for each installation where estimable. Although adjustment factors could have been applied to avoid undefined OR, for an extra layer of conservatism, estimability was subject to a requirement of at least 1 observation per cell of the contingency table (Argresti 1996). Evaluation of the quantitative trend between 1,4-dioxane and TCE was restricted to only those installations where significant association could be definitively determined. Conditional association was tested by χ^2 using Proc Freq in SAS Version 9.2 for Windows (SAS Institute 2008) and considered significant at $p \leq 0.05$.

Quantitative relationships between TCE and 1,4-dioxane levels were evaluated for installations where significant categorical association was observed. Trend analysis was carried out using quantile regression because heteroscedasticity was observed (discussed below) as described by Koenker and Bassett (1982); heteroscedasticity results in biased statistical inference for conventional regression methods predicated on the central tendency (i.e., the mean) of the relationship with constant variance assumption (Montgomery et al. 2001). By evaluating the trend at various distributional levels (i.e., quantiles) of the relationship (as opposed to the mean or ''central tendency''), quantitative trends can be tested with reliable inference when nonconstant variance is observed (Koenker and Bassett 1982; Buchinsky 1998). Quantile regression was performed using Proc Quantreg in SAS Version 9.2 for Windows (SAS Institute 2008), and results were considered significant at $p \leq 0.05$.

RESULTS

Overall, ERPIMS contained 5788 GMWs from 49 installations with records for 1,4-dioxane, TCE, and TCA analytes. The resulting data set was used for all analyses. Table 1 summarizes 1,4-dioxane records by co-occurrence with TCE and TCA. A total of 781 GMWs contained detectable levels (i.e., ≥RL) of 1,4-dioxane resulting in a detection frequency of 13.5%. Similarly, detection frequencies for TCE and TCA are 71.8% and 11.8%, respectively.

Table 1. 1,4-Dioxane records by co-occurrence with TCE and TCA[a]

		1,4-Dioxane		
TCE	**TCA**	**Nondetect**	**≥ RL**	**% ≥RL**
Nondetect	Nondetect	1543	49	3.08
	≥RL	36	2	5.26
≥RL	Non-Detect	3010	503	14.3
	≥RL	418	227	35.2

RL = reporting limit.

[a] Only groundwater monitoring wells that contained records for all 3 analytes were evaluated.

A total of 732 of 4196 GMWs (17.4%) that contained detectable levels of TCE and/or TCA also contained detectable levels of 1,4-dioxane, which accounted for 93.7% of all detections (732 of 781). However, controlling for detections of 1,4-dioxane, only 2 of 229 (0.873%) GMWs contained TCA without also containing TCE (Table 1), which corresponds to a conditional OR of 11.1. Assessment of the association between 1,4-dioxane and TCA is, therefore, almost completely confounded with TCE. Overall, 64.4% of all 1,4-dioxane detections were independently associated with TCE (503 of 781 GMWs).

Co-occurrence between 1,4-dioxane and TCE was observed across 27 installations. However, only 13 installations (48%) contained GMWs with combinations of detections (≥RL) and nondetects (<RL) for 1,4-dioxane and TCE to evaluate conditional independence (Table 2). The Breslow–Day test for homogeneity of the OR was significant ($p < 0.0001$), indicating significant heterogeneity among the OR (i.e., differential association between 1,4-dioxane and TCE among installations). Tests for general association and OR are summarized for each installation where estimable (Table 2). Significant (i.e., nonrandom) association was observed for 5 installations.

The quantitative relationship between 1,4-dioxane and TCE paired detections was evaluated among the 5 installations where significant categorical association was definitively determined (Table 2). A simple scatterplot of the raw data is presented in Figure 1, illustrating a positive log-linear relationship. Parameter estimates (i.e., slope and y-intercept values) and associated statistics from quantile regressions are presented in Table 3 for select quantiles. Slope parameters increased with increasing quantiles, reflecting heteroscedasticity. All slope parameters, except for the 0.10 quantile, were significant. Correspondingly, all y-intercept values were significant except for the 0.25 quantile.

DISCUSSION

The USAF Emerging Issues Program has considered 1,4-dioxane as an ''emerging contaminant'' due to changes in toxicity information and regulatory standards. The toxicity associated with 1,4-dioxane exposure has garnered increased federal regulatory attention; the USEPA IRIS program is finalizing revised toxicity values that may be used to develop a federal MCL for drinking water and regulatory screening levels for groundwater and soil contamination (USEPA 2010). Currently, however, various state governments and regional USEPA offices regulate 1,4-dioxane based on different

Table 2. 1,4-Dioxane records by TCE detections conditioned by installation[a]

Installation	TCE	1,4-Dioxane $\geq$RL	1,4-Dioxane Nondetect	OR	χ^2	*p* Value
A	$\geq$RL	100	19	5.26	0.754	0.385
	Nondetect	2	2			
B	$\geq$RL	3	1	3.00	0.533	0.465
	Nondetect	2	2			
C	$\geq$RL	5	5	4.67	3.16	0.075
	Nondetect	3	14			
D	$\geq$RL	4	51	1.25	0.039	0.843
	Nondetect	1	16			
E	$\geq$RL	59	640	7.68	16.1	$<$0.0001
	Nondetect	3	250			
F	$\geq$RL	3	76	1.01	$<$0.0001	0.994
	Nondetect	2	51			
G	$\geq$RL	1	16	4.63	1.35	0.245
	Nondetect	1	74			
H	$\geq$RL	191	134	11.9	44.2	$<$0.0001
	Nondetect	6	50			
I	$\geq$RL	53	38	5.58	5.31	0.0211
	Nondetect	2	8			
J	$\geq$RL	48	316	30.2	50.2	$<$0.0001
	Nondetect	2	398			
K	$\geq$RL	147	513	3.19	0.601	0.438
	Nondetect	7	78			
L	$\geq$RL	3	32	0.169	5.39	0.0202
	Nondetect	5	9			
M	$\geq$RL	11	824	1.74	0.523	0.470
	Nondetect	2	260			

OR = odds ratio; RL = reporting limit.

[a]Installations that contained a cell with a value of zero were not evaluated.

advisory levels, resulting in a wide range of standards between and within regulatory entities (Mohr 2001; USEPA 2006; ATSDR 2007). Consequently, investigation into the likelihood and magnitude of the association between 1,4-dioxane and TCE/TCA to better proximate USAF environmental liability from 1,4-dioxane is needed at an enterprise scale.

Using the available USAF environmental data from ERPIMS, the detection frequency of 1,4-dioxane in GMWs is approximately 13%. Although the detection frequency reflects insight (or lack thereof) into the likelihood of 1,4-dioxane contamination, historic analytical methods were fraught with relatively high RLs because of the high water solubility and poor purging efficiency. All 1,4-dioxane monitoring data before the late 1990s are limited by analytical methods, which have only recently permitted detection of 1,4-dioxane at concentrations less than $100\,\mu g\,L^{-1}$ (Draper et al. 2000; USEPA 2008). Although 1,4-dioxane detections in ERPIMS have been validated through an extensive quality assurance process (see *Methods* section), relatively insensitive analytical methods result in lower confidence in the nondetect records. The impact of more sensitive RLs, however, would only increase the number of detections and, thereby, increase the frequency of detection and co-occurrence with TCE/TCA, which are generally not detection-limited relative to 1,4-dioxane. Thus, the results presented herein should be considered conservative.

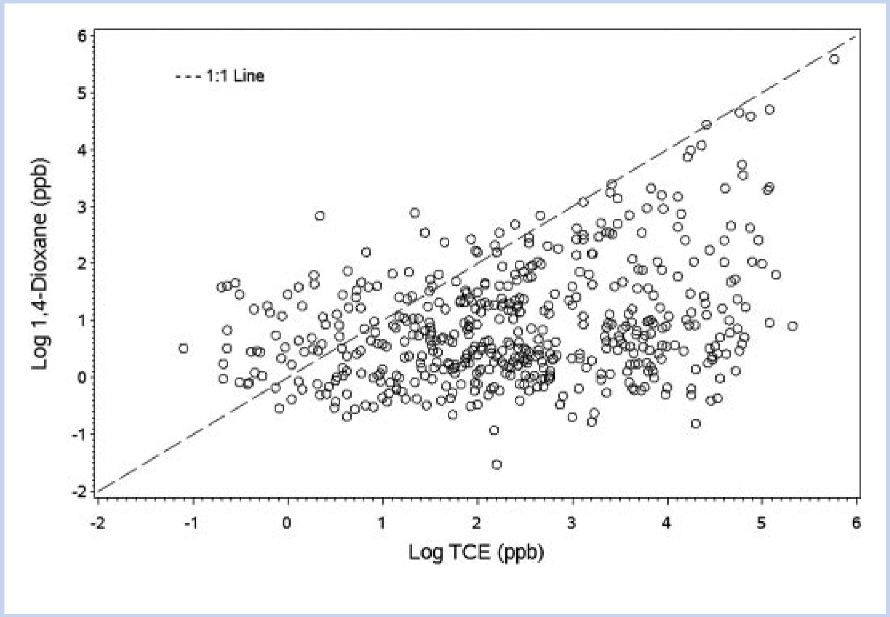

Figure 1. Log-log scatterplot of 1,4 dioxane and TCE levels paired by groundwater monitoring.

TCE and TCA were almost always found within the same GMW for corresponding 1,4-dioxane records; only 2 of 229 GMWs contained TCA without also containing TCE where 1,4-dioxane was detected (Table 1). The confounding of TCA with TCE illustrated in these analyses does not necessarily provide evidence that TCE and TCA were released concurrently. Given the long operational time period of many of the USAF installations, it is highly likely that several different solvents were used at a given installation. For example, TCE was the predominant solvent used before the 1970s (Mohr 2001). Subsequently, TCE was replaced with TCA when TCE was attributed to increasing smog and worker-exposure illnesses and was identified as a carcinogen to animals (Mohr 2001). However, in the 1980s, TCA was associated with ozone depletion, and many installations then switched to dichloromethane (DCE), perchloroethylene (PCE), or back to TCE (Mohr and Jacobs 2005; Mohr et al. 2010). Although the environmental fate and transport properties of TCA and TCE are sufficiently different such that environmental releases of TCA should attenuate (e.g., biotic decomposition, abiotic oxidation, dilution, etc.) relatively more rapidly, the working data set used for these analyses queried the maximum concentration of each analyte by GMW without restricting the sample date. Consequently,

Table 3. Linear quantile regression estimates and corresponding CI[a] for the regression of 1,4-dioxane on TCE for paired log-transformed concentrations among installations where significant categorical association was observed[b]

Quantile	Parameter	95% lower CI	Estimate	95% upper CI	*p* Value
0.10	Slope	−0.0123	0.0793	0.1709	ns[c]
	Y-intercept	−0.5459	−0.3334	−0.1208	0.0022
0.25	Slope	0.0679	0.1228	0.1777	<0.0001
	Y-intercept	−0.1841	−0.0584	0.0674	ns
0.50	Slope	0.0602	0.1296	0.1989	0.0003
	Y-intercept	0.4462	0.2625	0.6299	<0.0001
0.75	Slope	0.1606	0.2843	0.4081	<0.0001
	Y-intercept	0.5365	0.8304	1.1243	<0.0001
0.90	Slope	0.3476	0.4259	0.5043	<0.0001
	Y-intercept	1.0715	1.2781	1.4848	<0.0001

CI = confidence interval.

[a] Confidence intervals were determined by bootstrap resampling with replacement.

[b] See Table 2.

[c] Not significant at $\alpha = 0.05$.

confounding TCA with TCE was somewhat expected given historic handling, storage, and disposal practices of chlorinated solvents at USAF installations.

1,4-Dioxane was observed in 17.4% of the GMWs with records for TCE and/or TCA detections, which accounted for 93.7% of all 1,4-dioxane detections (Table 1). This supports the assumption that the source of 1,4-dioxane in groundwater may be linked to chlorinated solvent contamination, but does not imply the direct use of 1,4-dioxane as a chlorinated solvent stabilizer. Furthermore, 64.4% of 1,4-dioxane detections were associated with GMWs with TCE, independent of TCA, firmly establishing 1,4-dioxane as a probable TCE groundwater co-contaminant. However, significant (i.e., nonrandom) association between 1,4-dioxane and TCE could only be determined for 5 installations (Table 2). Co-occurrence of 1,4-dioxane and TCE among the remaining installations evaluated in these analyses, should not be regarded as independent, necessarily. Because of the inherent limitation of the available data in ERPIMS that associates a given GMW to a specific site (i.e., release), co-occurrence was evaluated by GMW. Conditioning the assessment by site would have resulted in more informative conclusions. Nonetheless, significant co-occurrence was definitively demonstrated between 1,4-dioxane and TCE in these analyses.

Last, trend analysis demonstrated a positive log-linear trend between 1,4-dioxane and TCE. However, increasing variability in 1,4-dioxane levels was also observed with increasing TCE levels (Figure 1), which approach the upper limit of the solubility for TCE. Although the magnitude of the association depends on the quantile evaluated, results for the 0.5 quantile (i.e., the median relationship) indicate that 1,4-dioxane levels increase between approximately 6% and 20% of the increase in TCE levels (Table 3); coupled with the slope estimate or estimates, practitioners can predict 1,4-dioxane levels from measured TCE levels using the following equation

$$10^{Y_{\mathrm{Int}}+\mathrm{Slope}(\mathrm{LogTCE})}.$$

Subunity slope estimates suggest greater attenuation of 1,4-dioxane relative to TCE if, indeed, both contaminants were released concurrently; greater environmental attenuation of 1,4-dioxane relative to other organic contaminants has been reported (Nyer et al. 1991; Mohr 2001; Zenker et al. 2003). Nonetheless, as previously stated, these results do not support the assertion that 1,4-dioxane was used as a stabilizer in commercial chlorinated solvents (Doherty 2000; Mohr 2001; ATSDR 2007). Rather, these results are intended to inform environmental project managers as to the most probable 1,4-dioxane levels at groundwater sites with chlorinated solvent plumes where 1,4-dioxane is anticipated to co-occur (~17% of cases according to our results).

On finalization of a federal promulgated standard for 1,4-dioxane (i.e., a drinking water MCL), necessary enterprise-wide characterization of 1,4-dioxane within groundwater at USAF installations may have significant impact on the USAF Environmental Restoration Program. Although derivation of remedial action objectives and cleanup strategies will vary according to site-specific conditions and exposures, given the probable low screening levels, consideration of 1,4-dioxane as a contaminant of potential concern during human health risk assessments will likely be required at all sites and installations regardless of the regulatory authority. The promulgation of a federal cleanup standard for 1,4-dioxane may also require additional sampling to further characterize closed sites or sites currently in various remedial phases. Discoveries of 1,4-dioxane contamination may delay completion of site cleanup and require expensive revisions to existing remedial infrastructure to address new or lower standards and/or additional volume of contaminated groundwater; there is strong evidence, both from the laboratory and field, that suggests 1,4-dioxane will migrate much further than chlorinated solvents (Roy and Griffin 1985; Priddle and Jackson 1991; Nyer et al. 1991; Mohr 2001). Mohr et al. (2001) report 1,4-dioxane plumes measuring up to 6 times greater in area than the associated solvent plumes. Moreover, groundwater treatment systems designed for chlorinated solvents are generally unsuccessful treating 1,4-dioxane due to limited partitioning to organic C and volatility (Mohr and Jacobs 2005; USEPA 2006). In general, 1,4-dioxane is not efficiently removed in most groundwater treatment methodologies including air stripping, C adsorption, precipitation-coagulation, and biological treatment. However, advanced oxidation methods using hydrogen peroxide, ozone, and/or UV photograph-oxidation have been shown successful (Zenker et al. 2003). Unfortunately, operational costs for many of the advanced oxidation processes are substantial and the efficiency is moderate to low (Zenker et al. 2003). The development of modified biological treatment options to reduce 1,4-dioxane are being explored (USEPA 2006).

In conclusion, where TCE and/or TCA have been detected in groundwater, the presence of 1,4-dioxane was observed with a probability of co-occurrence at approximately 17%. Moreover, 64.4% of all 1,4-dioxane detections were observed to co-occur with TCE independently. Thus, in an effort to minimize redundant future field efforts, current site investigations should consider 1,4-dioxane a potential co-contaminant of TCE proactively. Given the persistence, mobility, and treatment challenges associated with 1,4-dioxane, environmental project managers are faced with difficult obstacles to ensure protection of human health. Nonetheless, improved (and continuously improving) characterization and remedial technologies coupled with the knowledge of the liability presented in this article should promote a steadfast response to the emerging issue.

Disclaimer—The views expressed in this article are those of the authors and do not necessarily reflect the official policy or position of the Air Force, the Department of Defense, or the US Government.

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