ADDENDUM TO THE TOXICOLOGICAL PROFILE FOR VINYL CHLORIDE

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January 2016

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Supplement to the 2006 Toxicological Profile for Vinyl Chloride

Background Statement

This addendum to the Toxicological Profile for Vinyl Chloride supplements the profile that was released in 2006.

Toxicological profiles are developed in response to the Superfund Amendments and Reauthorization Act (SARA) of 1986 which amended the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA or Superfund). CERCLA mandates that the Administrator of ATSDR prepare toxicological profiles on substances on the CERCLA Priority List of Hazardous Substances. CERCLA further states that the Administrator will "establish and maintain inventory of literature, research, and studies on the health effects of toxic substances" [Title 42, Chapter 103, Subchapter I, § 9604 (i)(1)(B)].

The purpose of this addendum is to provide to the public and other federal, state, and local agencies a non-peer reviewed supplement of the scientific data that were published in the open peer-reviewed literature since the release of the profile in 2006.

Chapter numbers in this addendum coincide with the Toxicological Profile for Vinyl Chloride (2006). This document should be used in conjunction with the profile. It does not replace it.

3. HEALTH EFFECTS

3.1 INTRODUCTION

3.2 DISCUSSION OF HEALTH EFFECTS BY ROUTE OF EXPOSURE

3.2.1 Inhalation Exposure

3.2.1.2 Systemic Effects

Respiratory Effects. Pharyngeal irritation was observed in 138 out of 238 vinyl chloride-exposed workers compared with 63 out of 212 controls (relative risk [RR] 1.97; confidence interval [CI] 1.56–2.48) (Zhu et al. 2005a). This finding was significantly increased in workers with the highest cumulative exposure (>15,000 mg) compared to workers with a lower cumulative exposure (<15,000 mg).

Following the derailment of a train carrying vinyl chloride, a Centers for Disease Control and Prevention (CDC) team used a self-administered survey to evaluate health effects (Brinker et al. 2015); however, no breathing zone measurements of vinyl chloride were collected. Increased prevalences of lower (26%) and upper (22%) respiratory symptoms were reported; the odds ratios (ORs) were 14.1 (95% CI 3.0–135.0) and 3.9 (95% CI 1.3–13.9), respectively. It should be noted that 23% of the 92 responders reported that they did not wear personal protective equipment and 72 responders did report using respiratory protection.

Cardiovascular Effects. Abnormalities of microcirculation, as measured by capillaroscopy, were shown to persist in vinyl chloride workers 15 years after the cessation of exposure (21 male workers with average exposure duration of 30 years and 35 age-matched controls) (Lopez et al. 2013). Exposure duration was associated with enlarged capillaries, dystrophy, and augmented length. Symptoms of Raynaud's disease were also associated with exposure duration, but were not correlated with capillary abnormalities. Genetic polymorphisms of glutathione transfersase M1 and glutathione transfersase T1 were not significantly associated with the presence of Raynaud's disease in French vinyl chloride workers (58 with Raynaud's disease, mean age 66 years, mean duration of employment 24 years; 247 without Raynaud's disease, mean age 64 years, mean duration of employment 21 years) (Fontana et al. 2006).

Hepatic Effects. Liver biopsies of highly exposed vinyl chloride workers revealed 84% incidence (21/25 workers) of fatty liver disease and 80% incidence (20/25 workers) of steatohepatitis (i.e., inflammation with concurrent fat accumulation, also referred to as fatty liver disease) (mean age 45 years,

mean employment duration 19 years, mean cumulative exposure 11,391 ppm-year) (Cave et al. 2010). Liver fibrosis was present in 11 of 20 workers with steatohepatitis, and 4 of these workers also had hepatic angiosarcoma. Most serum clinical chemistry measures were within normal reference values in these workers (aspartate aminotransferase [AST], alanine aminotransferase [ALT], alkaline phosphatase, total bilirubin, and albumin). Total serum cytokeratine 18 levels were elevated in workers with steatohepatitis as compared to healthy control workers, suggesting that this may be an appropriate biomarker for this effect.

The prevalence of liver ultrasound abnormalities (not further defined) was increased by 19% in 238 vinyl chloride-exposed workers compared with 212 controls (RR 10.69; CI 4.38–26.12) (Zhu et al. 2005a). This effect was increased in workers with the highest cumulative exposure (>15,000 mg) and was associated with polymorphism of the CYP2E1 gene (c1c2/c2c2 genotype). A genetic polymorphism of CYP2E1 (increase in CYP2E1 c2c2 genotype) was also associated with liver fibrosis, diagnosed by ultrasonography in 13 of 320 workers employed in five polyvinyl chloride manufacturing plants (Hsieh et al. 2007). No association was found between liver effects and genetic polymorphisms of glutathione transferase or aldehyde dehydrogenase in the Zhu et al. (2005a) or Hsieh et al. (2007) studies. Increased CYP2E1 gene expression in peripheral blood lymphocytes in vinyl chloride-exposed workers was associated with increased risk of liver abnormalities, defined as ALT levels >40 units (U) and/or a defect observed by hepatic ultrasound (Wang et al. 2008).

A meta-analysis of seven studies including >40,000 vinyl chloride workers did not demonstrate increased mortality from liver cirrhosis (Frullanti et al. 2012).

Altered liver function was reported in polyvinyl chloride workers (52 males, 22–41 years old) compared with office workers from the same industrial complex in Iran (48 males, 23-43 years old) (Attarchi et al. 2007). Serum alkaline phosphatase and γ-glutamyl transferase levels (liver cholestasis tests) were increased by 10 and 29%, respectively, in workers exposed for at least 2 years to concentrations <1 ppm. In contrast, Maroni and Fanetti (2006) reported that abnormal liver function tests (i.e., serum chemistry) were not associated with current or past exposure to vinyl chloride (735 male and 22 female workers from four facilities in Italy; mean age 44 years, mean exposure duration 19 years), but instead were related to dietary and/or metabolic variables. The primary determinants of abnormal liver function in this study were high body mass index (i.e., overweight), alcohol intake, and high triglyceride levels.

Hematological Effects. Hemoglobin disorders (not further defined) were diagnosed in 46 out of 238 vinyl chloride-exposed workers compared with 22 out of 212 controls (RR 2.07; CI 1.20–3.57) (Zhu et al. 2005a).

3.2.1.3 Immunological and Lymphoreticular Effects

Proinflammatory cytokine levels (tumor necrosis factor-α, interleukin-1β, interleukin-6, and interleukin-8) were increased in the serum of vinyl chloride-exposed workers with steatohepatitis as compared with healthy control workers (Cave et al. 2010).

3.2.1.4 Neurological Effects

Neurasthenia (not further defined) was observed in 40 out of 238 vinyl chloride-exposed workers compared with 21 out of 212 controls (RR 1.74; CI 1.06–2.58) (Zhu et al. 2005a). This finding was significantly increased in workers with the highest cumulative exposure (>15,000 mg) compared to workers with a lower cumulative exposure (<15,000 mg).

Headaches were reported by 26% (prevalence OR of 3.6; 95% CI 1.2–11.8) of the first responders to a derailment of a train carrying vinyl chloride (Brinker et al. 2015).

3.2.1.7 Cancer

An association between vinyl chloride exposure and mortality from hepatobiliary cancer was observed in an updated study of 1,874 workers from a chemical manufacturing plant in New York (Carreon et al. 2014). A relationship with exposure duration was apparent, with an increase in hepatobiliary cancer mortality seen in workers exposed for ≥16 years. No association was observed between vinyl chloride exposure and mortality from pancreatic cancer or non-Hodgkin's lymphoma in this study. Gennaro et al. (2008) also confirmed a previously reported increase in mortality from liver and lung cancer in workers involved in the production of vinyl chloride and polyvinyl chloride in Italy (1,658 male workers). Mortality from liver and lung cancer was not elevated by vinyl chloride in a study of >12,000 industrial workers at two U.S. and two European sites; however, the cumulative exposure to vinyl chloride in these workers was relatively low (<2 ppm-year) (Marsh et al. 2007a, 2007b). A recent case report described a finding of adrenal epitheliodangiosarcoma in a male worker exposed to vinyl chloride for 15 years (Criscuolo et al. 2014). This is the first published report of this tumor type in vinyl chloride-exposed workers.

The National Toxicology Program (NTP) of the Department of Health and Human Services has classified vinyl chloride as "known to be a human carcinogen" (NTP 2011) and the U.S. Environmental Protection Agency (EPA) has classified vinyl chloride as a Group A carcinogen (human carcinogen) (EPA 2000). In addition, the International Agency for Research on Cancer (IARC) has concluded that sufficient evidence for carcinogenicity in humans and animals exists to classify vinyl chloride as a Group 1 carcinogen (carcinogenic to humans) (IARC 2008). The IARC Working Group (IARC 2008) concluded that vinyl chloride causes angiosarcomas of the liver and hepatocellular carcinomas, and found suggestive evidence of an increased risk of malignant neoplasia of soft and connective tissue. No association was found between vinyl chloride exposure and lung cancer, and the evidence for increased risk of brain cancer, lymphatic and hematopoietic cancers, and melanoma was characterized as weak.

3.2.2 Oral Exposure

3.2.2.6 Developmental Effects

Ruckart et al. (2013) performed a case-control study to evaluate the relationship between exposure to solvents in contaminated drinking water during pregnancy and neural tube defects, oral clefts, and childhood hematopoietic cancers (524 controls, 15 cases of neural tube defects, 24 cases of oral clefts, 13 cases of cancer). No significant association was seen between vinyl chloride exposure and these effects.

3.2.3 Dermal Exposure

3.2.3.2 Systemic Effects

Ocular Effects. In the Brinker et al. (2015) study of first responders to a train derailment discussed in Section 3.2.1.2, an increased prevalence OR (5.8; 95% CI 1.1–58.6) of irritation, pain, or burning of eyes was reported.

3.2.4 Other Routes of Exposure

A single dose of 0, 200, 400, or 600 mg/kg vinyl chloride was given to pregnant Kumming mice (4–6/group) by intraperitoneal injection on day 6 of gestation (arachis oil vehicle). Embryos were evaluated for morphological development by histopathological examination 4 days following injection. Vinyl chloride administration produced a dose-related reduction in embryo survival (percent survival was 96,

86, 67, and 55% at doses of 0, 200, 400, and 600 mg/kg, respectively). The incidence of morphological abnormalities was 6, 51, and 71% at dose of 200, 400, and 600 mg/kg, respectively. Neural tube defects were the primary abnormality observed at doses of 400 and 600 mg/kg (Quan et al. 2014).

3.3 GENOTOXICITY

Genotoxicity studies in humans include several assays evaluating DNA damage, micronuclei, or chromosome aberrations in cultured human lymphocytes of occupationally exposed workers (see Table 3-1). DNA single-strand breaks were increased in lymphocytes from workers exposed to vinyl chloride concentrations >5 ppm (Kumar et al. 2013; Lei et al. 2004). The level of single-strand breaks was significantly associated with levels of the urinary biomarker thiodiglycolic acid (Lei et al. 2004). Micronuclei frequency was significantly increased in vinyl chloride workers compared to control workers (Ji et al. 2010; Jiao et al. 2012; Kumar et al. 2013; Wang et al. 2010a, 2011, 2013a, 2013b; Wu et al. 2013). The increase in micronuclei frequency was generally associated with cumulative exposure to vinyl chloride in these studies. Female workers were shown to be more susceptible than male workers to the increase in micronuclei frequency (Wang et al. 2013a). Total chromosome aberrations and chromatid type aberrations were increased in vinyl chloride workers with an exposure duration of >8 years, compared with workers exposed for a shorter time period and unexposed controls (Kumar et al. 2013).

Polymorphisms of genes involved in metabolism (CYP2E1, glutathione S-transferase pi 1 [GSTP1], aldehyde dehydrogenase 2 [ALDH2]), DNA repair (human 8-oxoguanine glycosylase 1 [hOGG1], O6-methylguanine-DNA methyltransferase [MGMT], X-ray repair cross complementing group 1 [XRCC1], xeroderma pigmentosum complement groups A, C, D, and E [XPA, XPC, XPD, XPF], thymine-DNA glycosylase [TDG], apurinic/apyrimidinic endonuclease 1 [APE1]), and cell cycle control (p53, p21) have been associated with increased micronuclei frequency in vinyl chloride workers (Ji et al. 2010; Qiu et al. 2008, 2011a; Wang et al. 2010a, 2010b, 2013b; Wen-Bin et al. 2009). Increased micronuclei frequency was also associated with altered promoter methylation of MGMT in vinyl chloride-exposed workers (Wu et al. 2013). Qiu et al. (2011b) showed an increase in p21 mRNA expression in workers exposed to vinyl chloride; however, there was no correlation with the frequency of micronuclei measured in these workers. Polymorphisms of CYP2E1, XRCC1, and XPD were also associated with susceptibility to DNA damage (single-strand breaks in lymphocyte DNA) of vinyl chloride-exposed workers (Zhu et al. 2005b, 2008).

Table 3-1. Genotoxicity of Vinyl Chloride *In Vivo*

Species (test system)	End point	Results	Reference
Human lymphocytes	DNA damage	+	Lei et al. 2004
	DNA damage	+	Kumar et al. 2013
	DNA damage	+	Zhu et al. 2005b
	DNA damage	+	Zhu et al. 2008
	Micronuclei	+	Ji et al. 2010
	Micronuclei	+	Jiao et al. 2012
	Micronuclei	+	Kumar et al. 2013
	Micronuclei	+	Qui et al. 2008
	Micronuclei	+	Qui et al. 2011a
	Micronuclei	+	Qui et al. 2011b
	Micronuclei	+	Wang et al. 2010a
	Micronuclei	+	Wang et al. 2011
	Micronuclei	+	Wang et al. 2013a
	Micronuclei	+	Wang et al. 2013b
	Micronuclei	+	Wen-Bin et al. 2009
	Micronuclei	+	Wu et al. 2013
	Chromosomal aberration	+	Kumar et al. 2013

– = negative result; + = positive result; DNA = deoxyribonucleic acid

Genetic polymorphisms of the XRCC1 DNA repair gene was also associated with an increase in the retention of etheno-DNA adducts in lymphoblast cell lines derived from vinyl chloride workers (Li et al. 2006, 2009a). The occurrence of the mutation biomarkers in serum was correlated with polymorphisms of the DNA repair genes XRCC1 (mutant p53) and excision repair cross complementation group 2 (ERCC2)/XPD (mutant p53 and ras-p21) in vinyl chloride workers (Li et al. 2006, 2009b). The presence of a polymorphism for CYP2E1 (variant c2 allele) was also associated with the occurrence of mutant p53 and ras-p21 serum biomarkers (Schindler et al. 2007). Polymorphisms of other genes involved in vinyl chloride metabolism (microsomal epoxide hydrolase [mEH], glutathione S-transferase mu 1 [GSTM1], glutathione S-transferase theta 1 [GSTT1]) were not associated with mutant p21 or p53 biomarkers in vinyl chloride workers (Li et al. 2005a, 2005b; Schindler et al. 2007).

The genotoxicity of vinyl chloride is also demonstrated in *in vitro* assays using mammalian or bacterial cell systems (see Table 3-2). Vinyl chloride produced chromosome aberrations in a gas exposure system using Chinese hamster lung cells (Asakura et al. 2008). DNA adducts of vinyl chloride were shown to be mutagenic following transfection into COS-7 mammalian cells (Fernandes et al. 2005). Chloro-

acetaldehyde, a metabolite of vinyl chloride, produced sequence specific mutations in the p53 gene region of human DNA (Kowalczyk et al. 2006). DNA repair kinetics, evaluated following transfection of human plasmid DNA into *Escherichia coli*, were also sequence specific with rapid repair occurring in some locations and delayed repair occurring at mutation hotspots (Kowalczyk et al. 2006). Repair of chloroacetaldehyde-induced mutagenesis in *E. coli* was shown to be mediated by the AlkB protein, which is produced as part of an adaptive response to alkylating agents in these bacteria (Maciejewska et al. 2009).

Table 3-2. Genotoxicity of Vinyl Chloride *In Vitro*

		Result		
Species (test system)	End point	With Activation	Without Activation	Reference
Chinese hamster lung cells	Chromosomal aberration	+	–	Asakura et al. 2008
African green monkey fibroblast cell line (COS-7)	Mutation spectra after transfection with DNA adducts of vinyl chloride	Not applicable	+	Fernandes et al. 2005
Human plasmid DNA	Mutation	Not applicable	+	Kowalcyzk et al. 2006
Escherichia coli transfected with human plasmid DNA	DNA repair	Not applicable	+	Kowalcyzk et al. 2006
E. coli transfected with plasmid DNA	Mutation and DNA repair	Not applicable	+	Maciejewska et al. 2009

– = negative result; + = positive result; DNA = deoxyribonucleic acid

3.4 TOXICOKINETICS

3.4.5 Physiologically Based Pharmacokinetic (PBPK)/Pharmacodynamic (PD) Models

3.4.5.3 Discussion of Models

Yoon et al. (2007) evaluated the impact of assuming extrahepatic metabolism by CYP2E1 in PBPK models for vinyl chloride inhalation. The study concluded that predictions for the rat and human models were not significantly affected by the inclusion of extrahepatic metabolism by CYP2E1 in the kidney and lung. Chiu and White (2006) described the development of a simplified steady-state solution of a generic PBPK model for volatile organic compounds. This steady-state analysis was shown to produce similar

results to the full PBPK model reported in the Environmental Protection Agency (EPA 2000) risk assessment for vinyl chloride.

3.5 MECHANISMS OF ACTION

3.5.2 Mechanisms of Toxicity

The steatohepatitis observed in workers exposed to vinyl chloride is distinct from other forms of fatty liver disease because liver cell death is caused primarily by necrosis (not apoptosis). The molecular mechanism for hepatocellular necrosis was investigated in HepG2 cells exposed to increasing concentrations of chloroacetaldehyde (Beier et al. 2012). Depletion of protein thiols and inhibition of mitochondrial respiration preceded liver cell death and were suggested as the primary mechanism of toxicity in these cells. Metabolomics analysis of plasma samples from highly exposed vinyl chloride workers and healthy volunteers demonstrated an increase in plasma free fatty acids and lipid peroxidation products that may promote inflammation (Cave et al. 2012; Kirpich et al. 2013). Exposure of HepG2 cells to the lipid peroxidation products seen in the plasma of vinyl chloride workers produced mitochondrial dysfunction and endoplasmic reticulum stress (Kirpich et al. 2013). Experiments with primary rat hepatocytes exposed to chloroacetaldehyde suggested that effects on both lysosomes (decreased membrane integrity) and mitochondria (respiratory chain disruption) may contribute to liver cell toxicity (Pourahmad et al. 2012). Kaiser et al. (2012) further suggested that insulin resistance, impaired hepatic lipid secretion, and increased cytokine production may play a role in the induction of steatosis in vinyl chloride-exposed workers. Whole-genome mouse oligonucleotide microarray analysis was used to compare changes in gene regulation 3 days following oral administration of a single dose of a liver toxicant (vinyl chloride, aldrin, copper sulfate, or 2,4,5-thrichlorophenoxyacetic acid) (Eun et al. 2008). Different gene expression patterns were observed for carcinogenic and noncarcinogenic liver toxicants.

Vinyl chloride produced neural tube defects in the embryonic mouse brain following administration of a single dose of 400 or 600 mg/kg by intraperitoneal injection on day 6 of gestation (embryos were examined 4 days after dosing of dams) (Quan et al. 2014). The mechanism for this effect appears to be related to inhibition of neural epithelial cell proliferation and induction of caspace 3-mediated apoptosis.

3.8 BIOMARKERS OF EXPOSURE AND EFFECT

3.8.2 Biomarkers Used to Characterize Effects Caused by Vinyl Chloride

Cave et al. (2010) suggested that an elevation of the levels of total cytokeratin 18 levels in serum may be indicative of liver cell necrosis and may therefore be a useful biomarker of this effect in vinyl chloride-exposed workers.

Mocci and Nettuno (2006) evaluated the presence of plasma mutant-p53 protein and anti-p53 antibody as potential biomarkers for cancer in vinyl chloride workers. Seropositive results were found in 5 of 151 exposed workers. Each of these workers was exposed to cumulative vinyl chloride concentrations of >1,000 ppm-year. The presence of biomarkers for mutant ras-p21 and mutant p53 was associated with cumulative vinyl chloride exposure in occupational workers (Schindler et al. 2007).

3.10 POPULATIONS THAT ARE UNUSUALLY SUSCEPTIBLE

Vinyl chloride workers with genetic polymorphisms of genes related to metabolism, DNA repair, and cell cycle control may be more susceptible to liver toxicity and liver cancer. A polymorphism of the CYP2E1 gene was associated with an increase in liver abnormalities evaluated by ultrasound (Hsieh et al. 2007; Zhu et al. 2005a). Genetic polymorphisms of several genes were associated with increased micronuclei frequency, DNA damage, retention of DNA adducts, and an increase in tumor biomarkers in serum (Ji et al. 2010; Li et al. 2006, 2009a; Qiu et al. 2008, 2011a; Schindler et al. 2007; Wang et al. 2010a, 2010b, 2013b; Wen-Bin et al. 2009; Zhu et al. 2005b, 2008).

3.12 ADEQUACY OF THE DATABASE

3.12.3 Ongoing Studies

The following ongoing studies concerning the adverse health effects associated with vinyl chloride have been identified by the NIH Research Portfolio Online Reporting Tools (RePORTER 2014).

Dr. J.I. Beier at the University of Louisville is evaluating the interaction of the gut-liver-adipose axis in the enhancement of non-alcoholic fatty liver disease by vinyl chloride. This project aims to determine the minimal dose of vinyl chloride that contributes to the development of fatty liver disease in mice given a high fat diet and to explore the potential mechanisms for this effect using *in vitro* models. Specific experiments will characterize the effect of cytotoxic stimuli on hepatocytes, the response of macrophages

to inflammatory mediators, and the production of adipogenic mediators by fat cells. Studies in mice will evaluate the effect of vinyl chloride in combination with the high fat diet on intestinal permeability. Human intestinal epithelial cell (Caco-2 cells) will be used to investigate the expression of tight junction proteins and the role of SAPK signaling in response to vinyl chloride exposure and the high fat diet. The protective effect on probiotics on the intestine will also be evaluated. Findings from these studies are expected to assist in the identification of risk factors for the development of liver disease.

Dr. P.W. Brandt-Rauf is investigating the role of genetic polymorphisms of the gene for nucleotide excision repair (XPD) in vinyl chloride-induced genotoxicity using a combination of *in vivo*, *in vitro* and *in silico* approaches. These studies will identify workers who may be at high risk for liver cancer due to their inherited or acquired genetic defects and may help to target interventions for treating or preventing cancer in future studies.

4. CHEMICAL AND PHYSICAL INFORMATION

No updated data.

5. PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

5.1 PRODUCTION

Table 5-1 lists the facilities in each state that manufacture or process vinyl chloride, the intended use, and the range of maximum amounts of vinyl chloride that are stored on site. There are currently 40 facilities that produce, process, or use vinyl chloride in the United States. The data listed in Table 5-1 are derived from the Toxics Release Inventory (TRI13 2014). Only certain types of facilities were required to report. Therefore, this is not an exhaustive list.

5.2 IMPORT/EXPORT

Imports of vinyl chloride into the United States are negligible (ICIS 2006). Export volumes for 2004 and 2005 were 2.367 and 1.88 billion pounds, respectively (ICIS 2006).

Table 5-1. Facilities that Produce, Process, or Use Vinyl Chloride

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
AL	1	100,000	999,999	6
AR	1	1,000	9,999	9, 12
DE	1	1,000,000	9,999,999	6
IL	1	1,000,000	9,999,999	6
KY	4	10,000	49,999,999	1, 4, 6
LA	11	0	10,000,000,000	1, 3, 4, 5, 6, 12, 13
MI	1	1,000,000	9,999,999	6
MS	1	10,000,000	49,999,999	6
NC	1	0	99	1, 5
NE	1	1,000	9,999	12
NJ	2	1,000,000	49,999,999	6, 12
OH	3	1,000	99,999	12
TX	12	1,000	999,999,999	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14
UT	1	10,000	99,999	12

[a]Post office state abbreviations used.
[b]Amounts on site reported by facilities in each state.
[c]Activities/Uses:

1. Produce
2. Import
3. Onsite use/processing
4. Sale/Distribution
5. Byproduct
6. Reactant
7. Formulation Component
8. Article Component
9. Repackaging
10. Chemical Processing Aid
11. Manufacturing Aid
12. Ancillary/Other Uses
13. Manufacturing Impurity
14. Process Impurity

Source: TRI13 2014 (Data are from 2013)

6. POTENTIAL FOR HUMAN EXPOSURE

6.2 RELEASES TO THE ENVIRONMENT

According to the TRI, in 2013, approximately 447,049 pounds of vinyl chloride were released to the environment from 41 manufacturing or processing facilities (TRI13 2014). Table 6-1 lists the amounts released from these facilities to air, water, land, and publicly owned treatment works (POTWs).

Table 6-1. Releases to the Environment from Facilities that Produce, Process, or Use Chemical Vinyl Chloride[a]

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
AL	1	2,074	0	0	0	0	2,074	0	2,074
AR	1	0	0	0	0	0	0	0	0
DE	1	47,277	0	0	27	0	47,277	27	47,304
IL	1	22,300	0	0	0	0	22,300	0	22,300
KY	4	50,060	1	0	0	0	50,061	0	50,061
LA	11	208,994	1	0	45	0	208,995	45	209,040
MI	1	570	39	0	1	0	609	1	610
MS	1	19,118	0	0	0	0	19,118	0	19,118
NC	1	12	0	0	0	0	12	0	12
NE	1	37	0	0	0	0	37	0	37
NJ	2	17,510	16	0	27	0	17,526	27	17,553
OH	3	58	0	0	10	0	58	10	68
TX	12	78,835	14	5	4	0	78,851	8	78,859
UT	1	3	0	0	0	10	3	10	13
Total	41	446,848	71	5	114	10	446,921	128	447,049

[a]The TRI data should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list. Data are rounded to nearest whole number.
[b]Data in TRI are maximum amounts released by each facility.
[c]Post office state abbreviations are used.
[d]Number of reporting facilities.
[e]The sum of fugitive and point source releases are included in releases to air by a given facility.
[f]Surface water discharges, waste water treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).
[g]Class I wells, Class II-V wells, and underground injection.
[h]Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.
[i]Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown
[j]The sum of all releases of the chemical to air, land, water, and underground injection wells.
[k]Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI13 2014 (Data are from 2013)

6.2.1 Air

EPA's National Emission Inventory (NEI) database contains detailed information about sources that emit criteria air pollutants and their precursors, and hazardous air pollutants (HAPs) for the 50 United States, Washington DC, Puerto Rico, and the U.S. Virgin Islands. In 2011, there were 920,128 pounds of vinyl

chloride released to air from 15 different emissions categories, the most prominent being waste disposal and industrial processes accounting for roughly 30 and 60% of all of the emissions, respectively (EPA 2014a). Data from 2013 indicate that the vast majority of releases from the 41 facilities that reported to the TRI were to air; 446,848 pounds of vinyl chloride were released to air from these facilities, which represents over 99% of the total amount released in 2013 (TRI13 2014).

6.2.2 Water

Only 71 pounds of vinyl chloride were released to water from 41 facilities that reported vinyl chloride emissions in 2013 (TRI13 2014).

6.2.3 Soil

According to the latest figures from the TRI, 114 pounds of vinyl chloride were released to land from the 41 facilities that reported to the TRI in 2013 (TRI13 2014). This amount accounted for less than 1% of the total vinyl chloride released to the environment from facilities that produce, process, or use vinyl chloride.

6.3 ENVIRONMENTAL FATE

6.3.2 Transformation and Degradation

Biodegradation of vinyl chloride typically occurs via three important pathways: (1) anaerobic reductive dechlorination producing ethene; (2) anaerobic oxidation to carbon dioxide under iron or manganese reducing conditions; and (3) aerobic ultimate biodegradation to carbon dioxide (SERDP/ESTCP 2012). The degradation of vinyl chloride under anaerobic conditions was studied using iron-enriched aquifer microcosms obtained from a site contaminated with various chlorinated compounds (Smits et al. 2011). Two separate microcosm columns were prepared in which one column was fed solely vinyl chloride while the second column had both vinyl chloride and acetate in the influent. Degradation of vinyl chloride and formation of ethene was noticeable in the column in which vinyl chloride and acetate was introduced into the influent, suggesting a reductive dechlorination pathway for vinyl chloride degradation; however, ethene was not produced in the column where vinyl chloride was the only substance in the influent, suggesting that oxidation to carbon dioxide was the important degradation pathway in this column.

6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

6.4.1 Air

Vinyl chloride levels in atmospheric samples collected across the United States in 2013 are available from the Air Quality System (AQS), which is the EPA's repository of ambient air quality data that has >5,000 active monitors nationwide (EPA 2014b). The 24-hour arithmetic means and maximum concentrations at sites where vinyl chloride were detected are shown in Table 6-2.

Table 6-2. Vinyl Chloride Levels (ppbC) in Air Samples Collected in the United States in 2013

Arithmetic mean (ppbC[a])	Maximum concentration (ppbC)	City	State
0.000492	0.02	Anchorage	Alaska
0.001148	0.016	Santa Rosa	California
0.000164	0.01	Grand Junction	Colorado
0.122857	0.9	New Castle	Delaware
0.032353	0.5	Wilmington	Delaware
0.031148	0.3	Washington	District Of Columbia
0.002542	0.03	Fort Lauderdale	Florida
0.001967	0.03	Davie	Florida
0.003833	0.06	Dania	Florida
0.001552	0.02	Valrico	Florida
0.000175	0.01	Winter Park	Florida
0.000364	0.02	Saint Petersburg	Florida
0.000862	0.02	Pinellas Park	Florida
0.000167	0.01	Schiller Park	Illinois
0.001967	0.06	Northbrook	Illinois
0.000339	0.02	Roxana	Illinois
0.000667	0.02	Lexington-Fayette (corporate name for Lexington)	Kentucky
0.138814	3.56	Smithland	Kentucky
0.226721	4.74	Calvert City (RR name Calvert)	Kentucky
0.088065	0.79	Calvert City (RR name Calvert)	Kentucky
0.464754	3.9	Calvert City (RR name Calvert)	Kentucky
0.027541	0.31	Calvert City (RR name Calvert)	Kentucky
0.052	0.67	Marshall	Kentucky
0.019444	0.1	Lewiston	Maine
0.0475	0.1	Presque Isle	Maine
0.023571	0.09	Portland	Maine
0.028966	0.16	Portland	Maine
0.031579	0.1	Rumford (census name for	Maine

Table 6-2. Vinyl Chloride Levels (ppbC) in Air Samples Collected in the United States in 2013

Arithmetic mean (ppbC[a])	Maximum concentration (ppbC)	City	State
		Rumford Compact)	
0.02449	0.13	Bangor	Maine
0.013333	0.1	Beltsville	Maryland
0.015686	0.3	Baltimore	Maryland
0.012903	0.2	Detroit	Michigan
0.004516	0.03	Dearborn	Michigan
0.002353	0.04	Blaine	Minnesota
0.000392	0.01	Rosemount	Minnesota
0.016	0.06	Inver Grove Heights (RR name Inver Grove)	Minnesota
0.003396	0.02	Rosemount	Minnesota
0.002264	0.02	Rosemount	Minnesota
0.003962	0.01	Apple Valley	Minnesota
0.003404	0.01	Richfield	Minnesota
0.004375	0.01	Minneapolis	Minnesota
0.003654	0.01	Minneapolis	Minnesota
0.004902	0.02	Minneapolis	Minnesota
0.004902	0.02	Minneapolis	Minnesota
0.004906	0.03	Minneapolis	Minnesota
0.004286	0.01	Minneapolis	Minnesota
0.003208	0.02	St. Louis Park	Minnesota
0.003077	0.02	St. Paul	Minnesota
0.003725	0.02	St. Paul	Minnesota
0.0018	0.02	Duluth	Minnesota
0.005577	0.03	St. Paul Park	Minnesota
0.004808	0.03	St. Paul Park	Minnesota
0.000577	0.01	Newport	Minnesota
0.001458	0.01	Bayport	Minnesota
0.010167	0.21	Columbus	Mississippi
0.009672	0.17	Columbus	Mississippi
0.004098	0.04	St. Louis	Missouri
0.00807	0.16	Camden	New Jersey
0.000656	0.02	North Brunswick Township	New Jersey
0.000656	0.02	Chester	New Jersey
0.001786	0.1	Tonawanda	New York
0.002222	0.1	Tonawanda	New York
0.002703	0.1	Tonawanda	New York
0.013462	0.2	Tonawanda	New York
0.008	0.2	New York	New York
0.001667	0.1	New York	New York

Table 6-2. Vinyl Chloride Levels (ppbC) in Air Samples Collected in the United States in 2013

Arithmetic mean (ppbC[a])	Maximum concentration (ppbC)	City	State
0.387097	0.4	Columbus	Ohio
0.000333	0.01	Yukon	Oklahoma
0.003704	0.1	Pittsburgh	Pennsylvania
0.001695	0.1	Philadelphia	Pennsylvania
0.014754	0.2	Philadelphia	Pennsylvania
0.011475	0.2	Philadelphia	Pennsylvania
0.005	0.1	Philadelphia	Pennsylvania
0.031667	0.26	Clute (corporate name for Clute City)	Texas
0.000339	0.02	Denton	Texas
0.003704	0.2	Texas City	Texas
0.0016	0.04	Harris	Texas
0.043793	0.24	Channelview	Texas
0.0075	0.34	Galena Park	Texas
0.01451	0.24	Baytown	Texas
0.001667	0.06	La Porte	Texas
0.006296	0.2	Houston	Texas
0.043051	0.3	Harris	Texas
0.061	0.74	Houston	Texas
0.048	1.16	Deer Park	Texas
0.057297	1.24	Deer Park	Texas
0.008333	0.06	Pasadena	Texas
0.075833	0.2	Kaufman	Texas
0.000333	0.02	Austin	Texas
0.000192	0.01	Bountiful	Utah
0.000357	0.01	Rutland	Vermont
0.008475	0.1	Groveton	Virginia
0.008475	0.1	Hopewell	Virginia
0.006557	0.2	Virginia Beach	Virginia
0.000526	0.03	Seattle	Washington
0.011111	0.2	Wheeling	West Virginia

[a]ppbC is equivalent to ppbv multiplied by the number of carbons of the compound.

6.4.2 Water

Vinyl chloride was detected in 6 out of 518 monitoring wells sampled in 19 urban land-use watersheds in the United States during a U.S. Geological Survey (USGS) analysis of groundwater contaminants conducted from 1996 to 2002 (Squillace et al. 2004). The median level was reported as 0.2 µg/L and the

maximum concentration was 8.1 µg/L. Vinyl chloride was detected in 1 out of 1,208 samples of domestic wells used for drinking water during another USGS survey (Rowe et al. 2007).

Vinyl chloride was detected at levels ranging from 11 to 23 ng/L in water samples collected from 12 homes located in Ithaca, New York (Walter et al. 2011). Most of the samples obtained from the homes tested negative for vinyl chloride, but each of the positive detections occurred from homes using municipal water and chlorinated polyvinyl chloride (CPVC) type pipe.

During an assessment of groundwater in the United States from 1985 to 2001, vinyl chloride was detected at a median concentration of 1.1 µg/L (positive detections only) in samples obtained from >50 of the nation's most important river basins and aquifers (USGS 2006). It was also detected in 0.083% of 2,401 samples of domestic wells at an assessment level of 0.20 µg/L and in 0.042% of samples at an assessment level of 1 µg/L. Vinyl chloride was not detected in any samples at assessment levels >5 µg/L. The median level of vinyl chloride in these domestic wells (positive detections only) was 0.74 µg/L (USGS 2006).

6.4.4 Other Environmental Media

Vinyl chloride was detected at levels ranging from 6.31 to 18.0 ng per cigarette in a test using seven different brands of cigarettes (Zenzen et al. 2012).

7. ANALYTICAL METHODS

7.2 ENVIRONMENTAL SAMPLES

A method to determine the levels of vinyl chloride in textile materials that employed solid-phase micro extraction (SPME) and gas chromatography–mass spectrometry (GC/MS) was developed (Zhu et al. 2009). The detection limit was reported as 0.08 mg/m^2 and the quantification limit was 0.25 mg/m^2.

8. REGULATIONS AND ADVISORIES

No updated data.

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