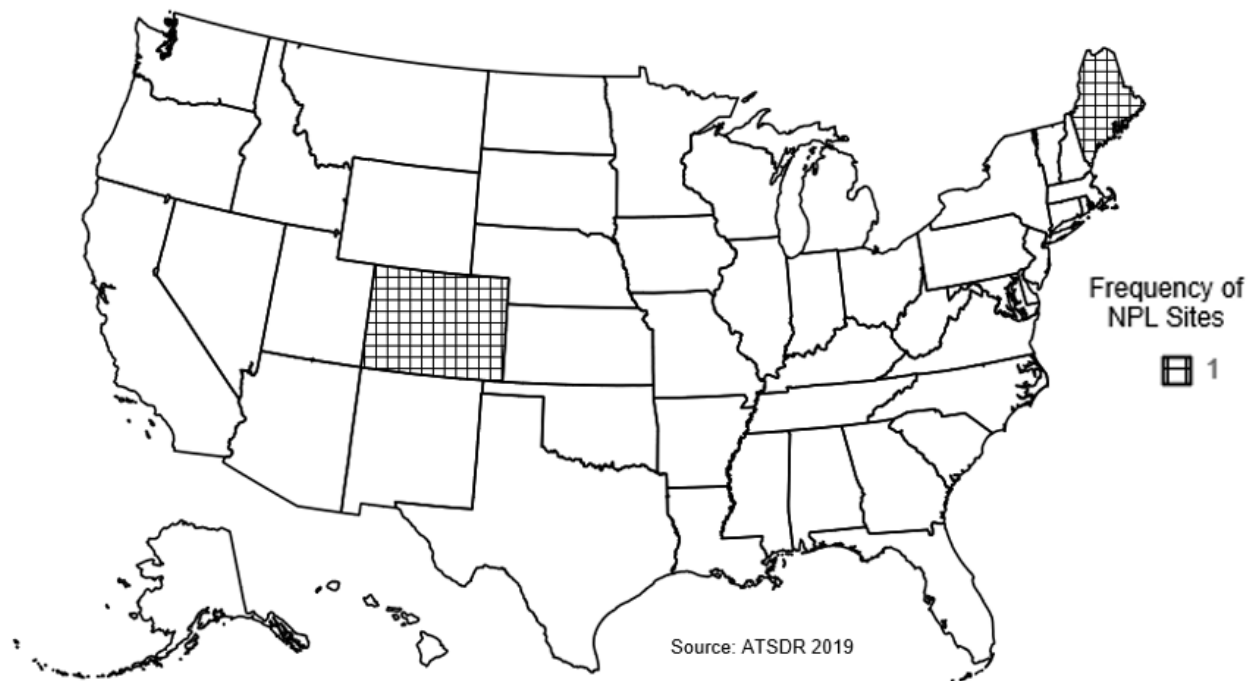


CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

5.1 OVERVIEW

Ethylene oxide has been identified in at least 2 of the 1,867 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (ATSDR 2019). However, the number of sites in which ethylene oxide has been evaluated is not known. The number of sites in each state is shown in Figure 5-1.

Figure 5-1. Number of NPL Sites with Ethylene Oxide Contamination



- People can be exposed to ethylene oxide through:
 - Inhalation of contaminated air near production and use facilities
 - Inhalation of contaminated air during sterilization/fumigation practices
 - Inhalation of tobacco smoke
 - Dermal contact during sterilization/fumigation practices
 - Use of medical devices and cosmetics sterilized with ethylene oxide
 - Preparation and ingestion of foods sterilized with ethylene oxide
 - During production of ethylene oxide and its involvement in the production of other chemicals
 - Following use of ethylene oxide in sterilization/fumigation operation
 - By breathing air contaminated with tobacco smoke

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- In the environment, ethylene oxide is expected to:
 - Oxidize in the atmosphere
 - Evaporate or hydrolyze from water
 - Volatilize from soil
 - React with nucleophilic groups such as carboxyl, amino, and phenolic groups, as well as strong acids

Ethylene oxide is man-made chemical used as a sterilant, a fumigant, or an intermediate in the production of other synthetic chemicals such as ethylene glycol. Gaseous releases of ethylene oxide to the environment are the result of uncontrolled industrial emissions (WHO 2003). Less than 1% of global production of ethylene oxide is used for the sterilization of biomedical equipment and foods or as a fumigant (WHO 2003).

Ethylene oxide degrades in both the air and natural water. In the air, oxidation via free radical formation is the most probable degradation pathway; the estimated half-life of this reaction ranges from 2 to 5 months. The half-life estimates for other degradation pathways for atmospheric ethylene oxide vary widely. In water, ethylene oxide would likely degrade via radical formation and hydrolysis, leading to the formation of glycols, and halogenated alcohols (in the presence of sodium chloride), which in turn degrade into simpler molecules such as carbon dioxide and water. The half-lives of these reactions range from a few hours to <15 days, depending on environmental conditions. Ultraviolet-catalyzed oxidation (in the presence of oxygen and nitrogen dioxide) may also account for some of the ethylene oxide lost in the atmosphere. Ethylene oxide also degrades in wastewater treatment systems with a half-life of about 20 days.

No data are available on the fate of ethylene oxide in soil. Nonetheless, this chemical is expected to either volatilize or be leached due to its high vapor pressure, infinite solubility in water, and reaction with mineral surfaces. Soil microorganisms may also convert it to glycols.

Data on the levels of ethylene oxide in the environment are very limited. There is a limited amount of ethylene oxide air monitoring data in the United States; EPA has begun to measure ethylene oxide at the National Air Toxics Trends Stations and the Urban Air Toxics Monitoring Program networks. There are no data to indicate that ethylene oxide is a common constituent of water sources of any type in any geographic location within the United States. Fumigated foods and sterilized hospital equipment may have initially high levels of ethylene oxide, which dissipate and/or degrade into other products within a few days. There are no data on ethylene oxide bioaccumulation in marine organisms.

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There are limited data to evaluate the general population's exposure levels to ethylene oxide. Environmental exposures may include ethylene oxide from tobacco smoke. The populations with potentially higher than average risk of exposure to ethylene oxide include sterilization technicians and industrial workers involved in the manufacture and/or use of ethylene oxide.

5.2 PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL**5.2.1 Production**

Ethylene oxide is primarily produced through ethylene oxidation with silver catalyst (Khan et al. 2002; Parod 2014). Ethylene and oxygen combine at 10–30 atmospheres and 400–500°F in a fixed bed catalytic reactor, which contains tubes with silver catalyst. The off-gas from the reactor is processed by CO₂ scrubbers followed by ethylene oxide scrubbers. Ethylene oxide is recovered from the resulting liquid by a desorber and then distilled (Khan et al. 2002). The EPA Chemical Data Reporting tool lists eight manufacturers of ethylene oxide in the United States at 11 different locations (EPA 2014, 2017a). Only two manufacturers (LG America and Shell Petroleum Inc.) reported actual production volume data with the other manufacturers declaring their production volumes confidential business information (CBI). In 2010 and 2011, LG Chemicals America reported production volumes of 3,368 and 26,479 pounds (1.5 and 12.0 metric tons), respectively. Shell Petroleum reported production volumes of 1,012,190,974, 925,329,789, and 1,012,190,974 pounds (0.45, 0.42, and 0.46 million metric tons) in 2009, 2010, and 2011, respectively. For 2015, the national domestic aggregate production of ethylene oxide was estimated to range from 5,000,000,000 to 10,000,000,000 pounds (2.3–4.6 million metric tons) (EPA 2014, 2017a). According to the American Chemistry Council (ACC) Economics and Statistics Department, in 2018, it was reported that there were 15 process plants in the United States that produced ethylene oxide with a total production volume of 2.92 million metric tons (6,400 million pounds) (ACC 2019). Total production capacity is about 3.5 million metric tons (7,700 million pounds) but is expected to increase by another 1.8 million metric tons (4,000 million pounds) by 2023 due to market demand (ACC 2019).

Ethylene oxide is produced naturally in negligible quantities by degradation of ethylene in certain plants and microorganisms. It can also emanate from water-logged soil, manure, and sewage sludge (WHO 2003).

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Table 5-1 summarizes information on U.S. companies that reported the manufacture or use of ethylene oxide in 2019 (TRI19 2021). Based on reported company names, seven of the companies were likely involved in sterilization processes; another nine companies were associated with medical devices. Toxics Release Inventory (TRI) data should be used with caution since only certain types of industrial facilities are required to report. This is not an exhaustive list.

Table 5-1. Facilities that Produce, Process, or Use Ethylene Oxide^a

State ^b	Number of facilities	Minimum amount on site in pounds ^c	Maximum amount on site in pounds ^c	Activities and uses ^d
AR	2	10,000	99,999	12
AZ	1	1,000	9,999	11
CA	1	1,000,000	9,999,999	6
CO	1	1,000	9,999	11
CT	1	1,000	9,999	12
DE	1	1,000,000	9,999,999	1, 3, 6, 7
GA	2	1,000	9,999	12
IA	5	1,000	9,999,999	6, 11, 12
IL	1	1,000,000	9,999,999	6
IN	4	100,000	9,999,999	6, 7
KS	2	100	9,999	9, 11, 12, 14
KY	1	1,000,000	9,999,999	6
LA	1	1,000,000	9,999,999	6
MD	14	100	49,999,999	1, 3, 4, 5, 6, 9, 10, 12
MI	2	1,000	9,999	12
MN	3	1,000	9,999,999	6, 11, 12
MO	2	10,000	9,999,999	6, 9, 12
MS	1	100,000	999,999	6
NC	4	1,000	49,999,999	6, 7, 11
NE	2	1,000	9,999	12
NJ	2	1,000	9,999,999	6, 11
NV	1	100	999	12
NY	1	10,000	99,999	9
OH	1	100	999	12
OK	1	10,000,000	49,999,999	6
PA	5	1,000	9,999,999	6, 9, 11, 12
PR	3	1,000	9,999	2, 3, 6, 12
SC	7	100,000	9,999,999	6, 9
TN	2	1,000	999,999	6, 12
TX	26	100	999,999,999	1, 2, 3, 4, 5, 6, 7, 9, 12, 13, 14
UT	2	1,000	9,999	2, 3, 11, 12

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Table 5-1. Facilities that Produce, Process, or Use Ethylene Oxide^a

State ^b	Number of facilities	Minimum amount on site in pounds ^c	Maximum amount on site in pounds ^c	Activities and uses ^d
VA	3	1,000	999,999	6, 11
WI	3	100,000	999,999	6
WV	6	1,000	9,999,999	6, 9, 14

^aPost office state abbreviations used.

^bAmounts on site reported by facilities in each state.

^cActivities/Uses:

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

Source: TRI19 2021 (Data are from 2019)

Estimated total production of ethylene oxide in the United States for the year 2004 was nearly 9 billion pounds (IARC 2008).

5.2.2 Import/Export

Due to its high reactivity, most ethylene oxide that is produced is also used onsite to create other products (ethylene oxide derivatives). There are little import or export volumes of ethylene oxide; however, there is substantial trade involving ethylene oxide derivatives such as monoethylene glycol (MEG) (ACC 2019). In 2018, approximately one-third of the MEG produced in the United States from ethylene oxide was exported to other nations. In 2018, the United States exported 0.831 million metric tons (1,800 million pounds) of ethylene oxide derivatives and also imported 1.2 million metric tons (2,600 million pounds) of ethylene oxide derivatives. Shell Petroleum exported 825,320 pounds of ethylene oxide in 2010; however, the other U.S. producers reported either zero export and import volumes or declared this as CBI (EPA 2014, 2017a).

5.2.3 Use

Greater than 97% of ethylene oxide production involves its use as a chemical intermediate for the production of other chemicals. The ACC reported the following consumption patterns of ethylene oxide in 2018: 34% to produce MEG; 28% in the production of ethoxylates; 16% used to produce

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ethanolamines; 6% in the production of glycol ethers; 4% to produce polyether polyols; and 12% for other uses, which includes sterilization of medical and surgical devices, microbial reduction in spices, and refining of corn (ACC 2019). At one time, ethylene oxide was used in the production of acrylonitrile, but that process was discontinued in 1966 (EPA 1984a, 1985; NIOSH 1981; WHO 1985). Ethylene oxide is used as a fumigant, a sterilant for food (spices) and cosmetics, and in hospital sterilization of surgical equipment and plastic devices that cannot be sterilized by steam (EPA 2017b; Parod 2014; Ribeiro et al. 1994; WHO 2003). Ethylene oxide is highly effective as a sterilant gas where it can penetrate packaging (such as cardboard, shrink wrap, paper, and other wrappings) and destroy bacteria and viruses (EPA 2004). Ethylene oxide is the primary fumigation/sterilization method for reducing bacteria levels in spices/herbs and black walnuts. According to the EPA (2008) RED, approximately 8.2 million pounds of ethylene oxide are used annually in the United States for commercial fumigation/sterilization. Of the 8.2 million pounds, approximately 7.4 million pounds are used annually for sterilization of medical and laboratory items/equipment; an estimated 800,000 pounds are used annually for fumigation of herbs and spices (EPA 2008).

5.2.4 Disposal

Because ethylene oxide is listed as a hazardous substance, disposal of wastes containing this compound is controlled by a number of federal regulations.

The production processes for ethylene oxide do not generate solid wastes, and the waste waters are treated or recycled. The production process is a closed system; however, vent gases and fugitive emissions may contain some ethylene oxide. Waste gases may be removed from the air by scrubbers. Wastes containing ethylene oxide may be incinerated by rotary kiln or fluidized bed incineration methods (EPA 1989; WHO 1985).

5.3 RELEASES TO THE ENVIRONMENT

The Toxics Release Inventory (TRI) data should be used with caution because only certain types of facilities are required to report (EPA 2005c). This is not an exhaustive list. Manufacturing and processing facilities are required to report information to the TRI only if they employ ≥ 10 full-time employees; if their facility is included in Standard Industrial Classification (SIC) Codes 10 (except 1011, 1081, and 1094), 12 (except 1241), 20–39, 4911 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4931 (limited to facilities that combust

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coal and/or oil for the purpose of generating electricity for distribution in commerce), 4939 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4953 (limited to facilities regulated under RCRA Subtitle C, 42 U.S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited to facilities primarily engaged in solvents recovery services on a contract or fee basis); and if their facility produces, imports, or processes $\geq 25,000$ pounds of any TRI chemical or otherwise uses $>10,000$ pounds of a TRI chemical in a calendar year (EPA 2005c).

5.3.1 Air

Estimated releases of 174,455 pounds (~79 metric tons) of ethylene oxide to the atmosphere from 114 domestic manufacturing and processing facilities in 2019, accounted for about 84% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2021). These releases are summarized in Table 5-2.

Table 5-2. Releases to the Environment from Facilities that Produce, Process, or Use Chemical Ethylene Oxide^a

		Reported amounts released in pounds per year ^b							
		Total release							On- and off-site
State ^c	RF ^d	Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	On-site ^j	Off-site ^k	
AR	2	9,173	0	0	0	0	9,173	0	9,173
AZ	1	308	0	0	0	0	308	0	308
CA	1	15	0	0	0	0	15	0	15
CO	1	325	0	0	0	0	325	0	325
CT	1	124	0	0	0	8	124	8	132
DE	1	1,293	0	0	0	0	1,293	0	1,293
GA	2	107	0	0	0	0	107	0	107
IA	5	2,415	380	0	0	0	2,415	380	2,795
IL	1	2,121	338	0	0	0	2,121	338	2,459
IN	4	1,035	0	0	0	0	1,035	0	1,035
KS	2	198	0	0	30,224	0	198	30,224	30,422
KY	1	612	0	0	0	0	612	0	612
LA	1	1,950	8	0	0	0	1,958	0	1,958
MD	14	40,723	120	0	5	0	40,843	5	40,848
MI	2	139	0	0	0	0	139	0	139
MN	3	356	2	0	5	0	363	0	363
MO	2	5,691	0	0	0	0	5,691	0	5,691

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Table 5-2. Releases to the Environment from Facilities that Produce, Process, or Use Chemical Ethylene Oxide^a

Reported amounts released in pounds per year ^b									
State ^c	RF ^d	Air ^e	Water ^f	UI ^g	Land ^h	Other ⁱ	Total release		
							On-site ^j	Off-site ^k	On- and off-site
MS	1	1	0	0	0	0	1	0	1
NC	4	165	0	0	0	0	165	0	165
NE	2	40	0	0	0	0	40	0	40
NJ	2	402	0	0	0	0	402	0	402
NV	1	15	0	0	0	0	15	0	15
NY	1	8	0	0	0	0	8	0	8
OH	1	0	0	0	0	0	0	0	0
OK	1	1,456	0	0	0	0	1,456	0	1,456
PA	5	8,980	0	0	0	0	8,980	0	8,980
PR	3	340	0	0	0	0	340	0	340
SC	7	2,594	12	0	53	0	2,594	65	2,659
TN	2	202	0	0	0	0	202	0	202
TX	26	85,730	1,782	0	436	10	87,078	879	87,957
UT	2	42	0	0	0	0	42	0	42
VA	3	4,628	14	0	0	0	4,628	14	4,642
WI	3	314	9	0	0	0	314	9	323
WV	6	2,954	0	0	0	0	2,954	0	2,954
Total	114	174,455	2,665	0	30,723	18	175,938	31,923	207,861

^aThe 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.

^bData in TRI are maximum amounts released by each facility.

^cPost office state abbreviations are used.

^dNumber of reporting facilities.

^eThe sum of fugitive and point source releases are included in releases to air by a given facility.

^fSurface water discharges, waste water treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).

^gClass I wells, Class II-V wells, and underground injection.

^hResource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.

ⁱStorage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown.

^jThe sum of all releases of the chemical to air, land, water, and underground injection wells.

^kTotal amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI19 2021 (Data are from 2019)

Ethylene oxide is a synthetically produced gas used primarily in the production of other chemicals by the chemical industry. As a result, most of the releases of ethylene oxide to the atmosphere occur during its

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storage and handling in industrial settings. Industrial emissions of ethylene oxide are due to uncontrolled fugitive emissions or venting with other gases (EPA 1980, 2017b).

Other known sources of ethylene oxide air emissions include its production from combustion of hydrocarbon fuels and its release from commodity-fumigated materials, estimated to be about 10 million pounds annually (EPA 1980), and losses during disinfection of hospital equipment (EPA 2017b).

Ethylene oxide could be released to the atmosphere during catastrophic events. In 1987, an explosion in an ethylene oxide purification column in Antwerp, Germany occurred due to decomposition of ethylene oxide (Khan et al. 2002).

EPA's National Emission Inventory (NEI) database contains information regarding sources that emit criteria air pollutants (CAPs) and their precursors, and hazardous air pollutants (HAPs) for the 50 United States, Washington DC, Puerto Rico, and the U.S. Virgin Islands. This database documents and estimates emission data from multiple sources, including state and local environmental agencies; the TRI database; computer models for on- and off-road emissions; and databases related to EPA's Maximum Achievable Control Technology (MACT) programs to reduce emissions of HAPs. Ethylene oxide emissions estimated from the 2014 inventory are summarized in Table 5-3.

Table 5-3. Ethylene Oxide Emissions from the National Emissions Inventory

Emission sector	Amount of ethylene oxide emitted to air (pounds)
Fuel combustion, commercial/institutional, natural gas	17
Fuel combustion, commercial/institutional, oil	0.0009
Fuel combustion, electric generation, natural gas	45
Fuel combustion, industrial boilers, ICEs, natural gas	33
Fuel combustion, industrial boilers, ICEs, other	8
Industrial processes, chemical manufacturing	123,520
Industrial processes, not elsewhere classified	86,367
Industrial processes, petroleum refineries	0.040
Industrial processes, pulp and paper	125
Industrial processes, storage and transfer	6,707
Solvent, degreasing	1,368
Solvent, graphic arts	23

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Table 5-3. Ethylene Oxide Emissions from the National Emissions Inventory

Emission sector	Amount of ethylene oxide emitted to air (pounds)
Solvent, industrial surface coating and solvent use	2,502
Waste disposal	2,386

ICE = internal combustion engine

Source: EPA 2020a

Some older studies have suggested that ethylene oxide may be formed when fuels are burned in an engine or in other combustion conditions. However, these decades-old studies used methods that are considered outdated today and that contain significant uncertainties. No peer-reviewed studies are available that have used state-of-the-art analytic methods to measure ethylene oxide in emissions from combustion sources.

The World Health Organization (WHO 2003) reported that the estimated air emissions due to sterilization and fumigation operations, production, medical facility use, and ethoxylation resulted in 57, 31, 8, and 4% of total ethylene oxide emissions, respectively.

5.3.2 Water

Estimated releases of 2,665 pounds (~1.2 metric tons) of ethylene oxide to surface water from 114 domestic manufacturing and processing facilities in 2019, accounted for about 1.3% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2021). This estimate includes releases to waste water treatment and publicly owned treatment works (POTWs) (TRI19 2021). These releases are summarized in Table 5-2.

Although recent data were not located, historically, ethylene oxide discharges into water appeared to be primarily industry-related. WHO (1985) indicated that biological treatment of waste waters containing ethylene oxide appeared to be successful in removing and preventing this chemical from reaching waterways. Recent data concerning discharge of ethylene oxide to water were not located.

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5.3.3 Soil

Estimated releases of 30,723 pounds (~13.94 metric tons) of ethylene oxide to soil from 114 domestic manufacturing and processing facilities in 2019, accounted for about 14.8% of the estimated total environmental releases from facilities required to report to the TRI (TRI19 2021). These releases are summarized in Table 5-2.

No discharges of ethylene oxide into the soil are reported in the literature. Although ethylene oxide is a potent fumigant and will kill fungi, viruses, and insects, it is not approved as a soil fumigant. However, since ethylene oxide is infinitely soluble in water, it is likely that the soil environment is exposed to this chemical as a result of the atmospheric scrubdown of rainfall and some uncontrolled discharges of liquid wastes containing this chemical. Data concerning levels of ethylene oxide in soil were not found.

5.3.4 Other Sources

Solid or liquid wastes containing measurable amounts of ethylene oxide, as defined in Part 261 of CFR 40 (EPA 1984c), can be classified as hazardous with ignitable and toxic properties. However, according to EPA (1980), no specific wastes containing large amounts of ethylene oxide associated with the manufacture of ethylene oxide have been identified.

5.4 ENVIRONMENTAL FATE**5.4.1 Transport and Partitioning**

Air. The primary mode of transport of ethylene oxide is via air emissions into the atmosphere. At atmospheric pressure and room temperature, ethylene oxide exists as a gas due to its very high vapor pressure (1,095 mm Hg at 20°C) and low boiling point (51°F [10.6°C]) (NIOSH 2016). A fugacity model estimated that ethylene oxide will persist in the atmosphere over a densely populated area of Canada for approximately 3 days, localized to the area of discharge (WHO 2003).

Water. Although ethylene oxide dissolves in water in any proportion, it also has the tendency to volatilize due in part to its high vapor pressure. Conway et al. (1983) reported that about 95% of ethylene oxide mixed with water volatilizes within 4 hours (its half-life is about 1 hour), and thus is not prevalent in environmental water sources.

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Sediment and Soil. The reported log of the octanol/water partition coefficient (K_{ow}) for ethylene oxide is -0.30 (Hansch and Leo 1979), indicating that ethylene oxide is a very polar chemical. From its chemical and physical properties, it can be inferred that ethylene oxide in soil will volatilize as water evaporates, leach through the soil, or be removed by runoff during rainstorms. It is, therefore, unlikely that ethylene oxide will accumulate in soils or sediments (WHO 2003). No data on the accumulation and/or fate of ethylene oxide in the soil environment are available.

Other Media. EPA (1984b) indicated that there are no data on the bioaccumulation of ethylene oxide in animal tissue.

Ethylene oxide is used as a fumigant for some food commodities. EPA has set tolerances of 7 ppm on herbs and spices, licorice roots, dried peppermint tops, sesame seeds, dried spearmint tops, and dried vegetables. A 50 ppm tolerance was set for walnuts (EPA 2018a).

Staples and Gulledge (2006) used a level III multi-media fate model to calculate ethylene oxide concentrations in air, water, soil, and sediment given an estimated annual emission rate using six different environmental scenarios meant to represent different climatic regions of the United States. Mass transport parameters such as the erosion and runoff mass transport velocities as well as rainfall rates and composition of the four main environmental compartments were varied in these six scenarios. The modeled output concentrations in air, water, and sediment were not highly sensitive to the changes in environmental parameters. However, modeled soil levels were shown to be fairly sensitive to changes in the input parameters, most likely the 10-fold changes in the soil erosion and runoff mass transport parameters. In all cases, hazard quotients calculated for target species were much lower than 1, suggesting low adverse risk to aquatic and terrestrial wildlife at the given emissions used in the model.

5.4.2 Transformation and Degradation

Ethylene oxide undergoes numerous reactions. It hydrolyzes in water and reacts with other nucleophiles with a half-life of approximately 10 days, forming ethylene glycol and ethylene chlorohydrin in saltwater (e.g., oceans). It also undergoes biodegradation, some of the measurable biological oxygen demand (BOD) is likely from the degradation of its reaction products. These rates have been measured in closed systems to prevent volatilization. Under most environmental conditions, volatilization from water or soil will be more rapid than hydrolysis, biodegradation, or reaction with other nucleophiles.

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Air. There is limited information on the fate of ethylene oxide in the atmosphere. EPA (1984b) reported that the most probable path of atmospheric degradation of ethylene oxide is oxidation via free-radical formation, and estimated its half-life in air at 25°C to range from 69 to 149 days, based on data (rate constants and the concentration of OH radicals) obtained by Fritz et al. (1982). Atmospheric half-lives based on reaction with hydroxyl radicals were also estimated as ranging from 38 to 382 days (WHO 2003).

According to EPA (1984b), measurements of the absolute rate constant, determined to be about 6×10^{-16} cm³/mole/second by Bogan and Hand (1978) for the reaction between oxygen and ethylene oxide at 27°C, indicate an ethylene oxide half-life of about 1,400 years, assuming an atmospheric oxygen concentration of 25,000 molecules/cm³. Bogan and Hand (1978) determined the final products of ethylene oxide oxidation to be hydrogen, water, carbon monoxide, carbon dioxide, and formaldehyde. Joshi et al. (1982) determined ethylene oxide to have a low reactivity with atmospheric nitrogen dioxide under W radiation and at 25°C. Using ethylene oxide:nitrogen dioxide ratios similar to those found in urban and rural air, these researchers reported the ethylene oxide half-life to be >53 hours.

In summary, the few available studies on the photodecomposition of ethylene oxide in the atmosphere suggest that it undergoes measurable rates of degradation into simpler products. However, laboratory estimates of the half-life of ethylene oxide in the atmosphere vary widely.

Water. If released to water, ethylene oxide would likely evaporate, hydrolyze, or biodegrade aerobically (and to a lesser extent, anaerobically) (WHO 2003). Ethylene oxide hydrolyzes in water to form glycols (Long and Pritchard 1956). EPA (1980) reported the hydrolysis rate constant (acid catalyzed) to be about 19.9×10^{-3} L/mol-second at 30°C. According to the same report, all epoxides, including ethylene oxide, can react with anions such as chloride and bromide in aqueous solutions, forming halogenated alcohols. The hydrolysis half-life of ethylene oxide ranges from 12 to 14 days in sterile, deionized, and natural river water (Conway et al. 1983; EPA 2017b; WHO 2003). Increased water salinity (up to 3% sodium chloride) was found to decrease the half-life of ethylene oxide to 9 days (Conway et al. 1983), producing ethanediol and chloroethanol. The volatilization half-life is estimated to be approximately 1 hour (WHO 2003). According to Anbar and Neta (1967), the degradation of ethylene oxide in water via hydroxyl radicals is very slow, with a computed half-life of about 50 years. Conway et al. (1983) reported that the half-life measurements for ethylene oxide in sterile and natural river water were not appreciably different.

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This may be because hydrolytic degradation of ethylene oxide is more rapid than biodegradation of this compound in aqueous media.

The estimated aerobic biodegradation half-life for ethylene oxide in water is expected to be 20 days to 6 months, while the anaerobic biodegradation half-life is estimated as 4 months to 2 years (WHO 2003). The aqueous aerobic biodegradation half-life from a BOD test was about 20 days. A 5-day BOD was 3% of the theoretical oxygen demand (1.82 g/g) (WHO 2003). With an initial concentration of 100 mg/L, ethylene oxide was found to hydrolyze in water over a 4-week period (J-CHECK 2019).

Sediment and Soil. No studies on the degradation of ethylene oxide in the soil environment have been located. However, it is likely that ethylene oxide would be found in both the water and vapor phases of the soil environment due to its high vapor pressure and very low octanol/water partition coefficient. Thus, ethylene oxide in the soil is likely to undergo at least some degradation via the same types of mechanisms as those that predominate in aquatic environments and via reactivity with mineral surfaces.

Ethylene oxide is expected to volatilize rapidly from soil, with estimated hydrolysis half-lives of 10.5 and 11.9 days for soil and groundwater, respectively. While volatilization is expected to be the predominant mechanism by which ethylene oxide is removed from soil, it may also undergo fairly rapid hydrolysis and biodegradation. It is not expected to be sorbed by soil or sediment (WHO 2003).

Other Media. While no reports of ethylene oxide in biota were located, bioaccumulation of ethylene oxide is not expected, based on the very low log K_{ow} (WHO 2003).

5.5 LEVELS IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to ethylene oxide depends, in part, on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of ethylene oxide in unpolluted atmospheres and in pristine surface waters are often so low as to be near the limits of current analytical methods. In reviewing data on ethylene oxide levels monitored or estimated in the environment, it should also be noted that the amount of chemical identified analytically is not necessarily equivalent to the amount that is bioavailable.

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Table 5-4 shows the lowest limit of detections that are achieved by analytical analysis in environmental media. An overview summary of the range of concentrations detected in environmental media is presented in Table 5-5.

Table 5-4. Lowest Limit of Detection Based on Standards^a

Media	Detection limit	Reference
Air	NA ^b	EPA 2019a
Drinking water	9 µg/L	EPA 2007

^aDetection limits based on using appropriate preparation and analytics. These limits may not be possible in all situations.

^bMethod detection limits are regularly updated.

Table 5-5. Summary of Environmental Levels of Ethylene Oxide

Media	Low	High	For more information
Outdoor air	0.4 µg/m ³ (0.22 ppb)	11 µg/m ³ (6.05 ppb)	Parod 2014
Surface water	Not applicable	2 mg/L	EPA 1984b
Food	<0.05 µg/g	1,800 µg/g	WHO 2003

Historical ambient air levels are shown in Table 5-6. The samples were collected in areas with no known industrial ethylene oxide sources and ranged from below the reporting level to 5.3 µg/m³ (2.92 ppb).

Table 5-6. Historical Ambient Air Monitoring Data from Selected States^a

Location (sampling time frame)	Number of valid samples ^b	Median(s) ^c	Range
California (1989–1990)	58	0.08 µg/m ³ (0.044 ppb)	0.03–0.54 µg/m ³ (0.017–0.30 ppb)
Colorado ^d	16	0.276 µg/m ³ (0.153 ppb) ^e	<RL–1.05 µg/m ³ (<RL–0.580 ppb)
Illinois (2018)	72	0.19–0.20 µg/m ³ (0.105–0.11 ppb) ^f	<RL–1.1 µg/m ³ (<RL–0.61 ppb)
Massachusetts (1999–2016)	1,433	0.15–0.18 µg/m ³ (0.083–0.099 ppb) ^g	<RL–5.3 µg/m ³ (<RL–2.92 ppb)
New Hampshire (2002–2008)	578	0.22–0.27 µg/m ³ (0.12–0.15 ppb) ^g	<RL–1.61 µg/m ³ (<RL–0.89 ppb)

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Table 5-6. Historical Ambient Air Monitoring Data from Selected States^a

Location (sampling time frame)	Number of valid samples ^b	Median(s) ^c	Range
Rhode Island (1999–2010)	11,280	0.14–0.20 µg/m ³ (0.077–0.11 ppb) ^g	<RL–1.68 µg/m ³ (<RL–0.92 ppb)

^aDifferent analytical methods with different detection limits were used.

^bSamples were reported be nonvalid by the instrument operators for reasons including, but not limited to, instrument malfunction or collection error.

^cNon-detect values and values below the RL may have been substituted with the detection limit/2.

^dPost-control samples only from background sites.

^eReported average assuming ½ MDL for non-detected samples.

^fRanges reflect 12-hour and grab sampling.

^gRanges reflect estimates at different sampling locations.

MDL = minimum detection level; NA = not applicable; RL = reporting level

Sources: CARB 1992; CDPHE 2018; EPA 2018a; Ramboll 2019

No data are available on levels of ethylene oxide in air, water, or soil at NPL sites (ATSDR 2019).

5.5.1 Air

The National Air Toxics Assessment (NATA) program is a comprehensive screening assessment released by EPA in 2018 (EPA 2018b). NATA uses emissions data compiled for a single year as inputs to air quality models; model outputs provide a snapshot of outdoor air toxic emissions. The data are used by public health officials to screen air toxic concentrations for further evaluation of public health risk and reduction activities in areas where concentrations are elevated. This assessment utilized emission estimates from the 2014 NEI discussed in Section 5.3.1 to calculate ambient concentrations of air toxics across the United States, Puerto Rico, and the Virgin Islands (EPA 2018c). A statistical breakdown of the calculated annual concentrations of ethylene oxide in ambient outdoor air at the census tract level is provided in Table 5-7. The mean calculated national concentration of ethylene oxide in ambient air was 2.92×10^{-4} µg/m³ (1.61×10^{-4} ppb) and the maximum level measured was 0.144 ug/m³ (0.079 ppb).

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Table 5-7. Ethylene Oxide Ambient Air Levels from NATA^a

Mean level	5 th percentile	25 th percentile	50 th percentile	75 th percentile	95 th percentile
2.9x10 ⁻⁴ µg/m ³ (1.0x10 ⁻⁴ ppb)	5.7x10 ⁻⁶ µg/m ³ (3.2x10 ⁻⁶ ppb)	4.0x10 ⁻⁵ µg/m ³ (2.2x10 ⁻⁵ ppb)	8.7x10 ⁻⁵ µg/m ³ (4.8x10 ⁻⁵ ppb)	1.5x10 ⁻⁴ µg/m ³ (8.2x10 ⁻⁴ ppb)	9.5x10 ⁻⁴ µg/m ³ (5.2x10 ⁻⁴ ppb)

^aAmbient levels were derived by arithmetically averaging census tract concentrations and are primarily from stationary point sources; emissions estimates from 2014 NEI.

NATA = National Air Toxics Assessment; NEI = National Emission Inventory

Source: EPA 2018b

EPA conducted a limited sampling of ethylene oxide in ambient air in both residential areas and locations in close proximity to the Sterigenics commercial sterilizing facility in Willowbrook, Illinois. The maximum 12-hour residential sample concentration was 2.1 µg/m³ (1.56 ppb) and the maximum 12-hour for a general workplace concentration was 9.09 µg/m³ (5.0 ppb). ATSDR reviewed the data to assess potential health risks to the surrounding community in a health consultation document (ATSDR 2018). The EPA Office of Air Quality Planning and Standards Office of Air and Radiation released a risk assessment report for this facility, which consisted of both monitoring data and modeled levels of ethylene oxide from the Gaussian dispersion model AERMOD (EPA 2019b). Sampling was conducted at eight locations in Willowbrook, two locations approximately 100 meters from the facility and six locations in the surrounding community, from November 2018 to March 2019. Ethylene oxide levels at the two locations near the facility reached maximum 24-hour values of 26.4 and 17.3 µg/m³ (14.5 and 9.5 ppb), respectively, for samples collected on February 5, 2019, while the background level 1.7 km away for this location was 0.174 µg/m³ (0.096 ppb) (EPA 2019b).

The Georgia Environmental Protection Division collected monitoring data from sites (September 2019–November 2020) located near three facilities that utilize ethylene oxide to sterilize medical equipment (Georgia EPD 2021). The average ethylene oxide air levels near the three facilities were 0.452, 0.489, and 1.149 µg/m³; the average levels at two “background sites” were 0.337 and 0.552 µg/m³. Recent monitoring data (samples collected in April–May 2020) from 12 sites in Lake County, Illinois reported air levels of 0.06–0.83 µg/m³ (0.0313–0.459 ppb) (LakeCounty 2020).

LaMontagne et al. (2004) studied the long-term trends in ethylene oxide worker exposures from 1984 to 2001 to document the effects that the Occupational Safety and Health Administration (OSHA) 1984 and 1988 standards had on workplace exposures. In this study, data from 87,582 8-hour personal samples and 46,097 short-term (15-minute) samples from 2,265 U.S. hospitals were analyzed. The number of

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hospitals that exceeded the 1 ppm permissible exposure limit (PEL) declined from roughly 20% in 1984 to about 1% in 2001. The number of hospitals that exceeded the 8-hour action level of 0.5 ppm decreased from about 40% in 1988 to about 5% in 2001. These results suggest that work shift exposures declined after the implementation of the new OSHA standards, continued to taper off, and have remained low and constant through 2001; however, the authors stated that since 1996, the probability of exceeding the short-term excursion limit has increased as enforcement of the standards decreased.

In 1993, it was estimated that the average ground-level ethylene oxide concentrations could be $>12 \mu\text{g}/\text{m}^3$ (>6.6 ppb) for 17 hours/year around a Canadian production facility, although no measured data were provided (WHO 2003). Ethylene oxide was detected in only 1 of 50 samples of indoor air in a study of residences by Health Canada; the concentration was determined to be $4 \mu\text{g}/\text{m}^3$ (2.2 ppb) in the 24-hour sample (WHO 2003). It was also detected at levels of $5 \mu\text{g}/\text{m}^3$ in 3 of 24 personal air samples collected from an occupant of each of the 50 residences.

Parod (2014) reported that mean and maximum concentrations of ethylene oxide in ambient air were <0.2 and 2 ppb (0.37 and $4.37 \mu\text{g}/\text{m}^3$), respectively, based on measured and estimated data. The average concentration may be slightly higher ($\leq 11 \mu\text{g}/\text{m}^3$ [≤ 6.05 ppb]) near production and sterilization facilities utilizing ethylene oxide (Parod 2014). Limitations of the report include lack of information regarding the number of samples evaluated, limit of detection, number of samples below the limit of detection, and whether the mean value was geometric or arithmetic.

EPA (2020b) reported ethylene oxide average concentrations from ambient air samples collected at 8 National Air Toxics Trends Stations (NATTS) and 10 Urban Air Toxics Monitoring Program (UATMP) sampling sites between October 2018 and March 2019. Results are summarized in Table 5-8. Measured average ethylene oxide concentrations ranged from $0.185 \mu\text{g}/\text{m}^3$ (0.103 ppb) in Grayson Lake, Kentucky to $0.397 \mu\text{g}/\text{m}^3$ (0.220 ppb) in Phoenix, Arizona. EPA has added ethylene oxide to pollutants to be measured at all existing, longstanding monitoring sites in the NATTS and the UATMP networks (a total of 34 sites).

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Table 5-8. Ethylene Oxide Ambient Air Concentrations at National Air Toxics Trends Stations and Urban Air Toxics Monitoring Program Stations October 2018 to March 2019

Location	AQS Site ID	Station ID	Average concentration in $\mu\text{g}/\text{m}^3$ (ppb)
Phoenix, Arizona	04-013-9997	National Air Toxics Trend	0.397 (0.220)
	04-013-4003	Urban Air Toxics	0.345 (0.191)
Grand Junction, Colorado	08-077-0018	National Air Toxics Trend	0.261 (0.145)
Northbrook, Illinois	17-031-4201	National Air Toxics Trend	0.294 (0.163)
Chicago, Illinois	17-031-3103	Urban Air Toxics	0.365 (0.203)
Ashland, Kentucky	21-019-0017	Urban Air Toxics	0.286 (0.159)
Grayson lake, Kentucky	21-043-0500	National Air Toxics Trend	0.185 (0.103)
Smithland, Kentucky	21-139-0004	Urban Air Toxics	0.312 (0.173)
Calvert City, Kentucky	21-157-0014	Urban Air Toxics	0.363 (0.201)
Dearborn, Michigan	26-163-0033	National Air Toxics Trend	0.242 (0.134)
St Louis, Missouri	29-510-0085	National Air Toxics Trend	0.270 (0.150)
Camden, New Jersey	34-007-0002	Urban Air Toxics	0.350 (0.194)
E. Brunswick, New Jersey	34-023-0011	Urban Air Toxics	0.298 (0.165)
Chester, New Jersey	34-027-3001	Urban Air Toxics	0.361 (0.200)
Elizabeth, New Jersey	34-039-0004	Urban Air Toxics	0.305 (0.169)
Bountiful, Utah	49-011-0004	National Air Toxics Trend	0.338 (0.188)
Seattle, Washington	53-033-0080	National Air Toxics Trend	0.185 (0.103)
Lacey, Washington	53-067-0013	Urban Air Toxics	0.192 (0.107)

AQS = Air Quality System; ID = identification

Source: EPA 2020b

5.5.2 Water

There are very limited data on the presence or absence of ethylene oxide in water (drinking water supplies, groundwater, etc.) on a national scale. EPA (1984b) reported a survey showing ethylene oxide at a concentration of 2 mg/L in the effluent of a chemical plant in Bandenburg, Kentucky. The intake fraction (iF) is the modeled portion of chemical mass releases into the environment that will be inhaled, ingested, or absorbed by the population. The water iF for ethylene oxide is 1.32×10^{-5} compared to the air intake fraction of 1.99×10^{-5} , suggesting similar efficiency of population intake via water compared to air (Bennett et al. 2002).

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5.5.3 Sediment and Soil

No data are available on the presence or absence of any significant levels of ethylene oxide in soil. However, De Bont and Albers (1976) reported that ethylene oxide is produced by the metabolism of ethylene by an ethylene-oxidizing bacterium. Also, ethylene is a relatively common volatile hydrocarbon in wet soil, where it can be produced by several species of fungi, bacteria, and actinomycetes (Alexander 1977). Therefore, small but constant levels of ethylene oxide may be present in soils under wet conditions. No data are available on ethylene oxide in soils resulting from uncontrolled releases of ethylene oxide liquid waste or from atmospheric depositions of any kind.

5.5.4 Other Media

Ethylene oxide may be found in tobacco, some food and spices, skin care products, and medical devices as a result of its use as a fumigant and a sterilizing agent. Measurable amounts of ethylene oxide were detected in both fumigated and unfumigated tobacco and its smoke; the ethylene oxide concentration in smoke from unfumigated tobacco was 1 µg/g (EPA 1980). More recently, it was also detected in smoke from fumigated and unfumigated tobacco at 0.3 and 0.02 µg/mL (0.17 and 0.011 ppm), respectively (WHO 2003). Skin care products may contain up to 1 µg/g of ethylene oxide (WHO 2003). As a result of sterilization, medical devices have been found to contain ethylene oxide concentrations of 1–2%, which generally decrease rapidly upon aeration; however, levels >180 mg/m³ (>99 ppm) have been identified after aeration (WHO 2003). There is evidence that some foods such as flour and spices retain measurable ethylene oxide and byproducts several months after fumigation (NIOSH 1981; Parod 2014; EPA 2017b).

Residual ethylene oxide may be found in foods temporarily, following fumigation. The July 2006 Tolerance Reassessment and Risk Management Decision (TRED) for ethylene oxide required the use of sterilization methods that have been demonstrated to result in residue levels that are lower than those that result from sterilization using conventional sterilization methods (EPA 2006). All ethylene oxide product labels have been revised accordingly to require a single chamber sterilization process (where pre-conditioning and aeration occur in the same chamber as the sterilization) that yields less residues of ethylene oxide and its reaction products on spices. This was effective August 1, 2008. Based on product labels, the only food commodities that can be treated with ethylene oxide products in the United States are spices, dried vegetables, and seasonings. In addition, tolerances (the maximum amount of a pesticide allowed to remain in or on a food) are established in the Code of Federal Regulations for residues of

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ethylene oxide (and ethylene chlorohydrin) on commodities in the United States. The following commodities have established tolerances for ethylene oxide: dried herbs and spices (except basil), licorice roots, dried peppermint and spearmint tops, sesame seeds, dried vegetables, and walnuts. If any commodity other than those listed are found to have residues of ethylene oxide, it is considered to be adulterated and is subject to be seized and removed from the channels of trade. Scudamore and Heuser (1971) reported that ethylene oxide may react with water and inorganic halides (chloride and bromide) from foods and produce glycols and halohydrins. The same researchers concluded that the persistence or disappearance of ethylene oxide and its byproducts in fumigated commodities depends on the grain size, type of foods, aeration procedures, temperature, and storage and cooking conditions. According to Scudamore and Heuser (1971), most commodities experimentally fumigated (to kill microorganisms) had levels of ethylene oxide <1 ppm after 14 days in normal storage conditions. No residues of ethylene oxide were found in commercially fumigated flour or tobacco.

Rajendran and Muthu (1981) reported that concentrations of ethylene oxide in 24-hour aerated foods (wheat, rice, spices, dates, and peas), following a 24-hour fumigation period, ranged from 0 to 3.5 ppm. IARC (1976) indicated that food fumigated with ethylene oxide generally had negligible levels of ethylene oxide within a few hours after fumigation, due primarily to loss by volatilization. However, in spices, ethylene oxide levels of 53–116 mg/kg (ppm) and ~25 mg/kg (ppm) at 2 and 26 days after fumigation, respectively, have been reported (WHO 1985). As reported by EPA (2006), a 2005 study examining ethylene oxide residues in herbs and spices that were sterilized using an improved process that is used in all domestic spice sterilization work found that the ethylene oxide dissipated rapidly and would be unlikely to be found in spices available for consumption.

Food product samples obtained from retail stores in Denmark in 1985 were found to contain ethylene oxide in concentrations ranging from <0.05 to 1,800 µg/g (in 96 of 204 samples). Spice samples also contained ethylene oxide at a maximum concentration of 580 µg/g (mean: 84 µg/g) (WHO 2003).

5.6 GENERAL POPULATION EXPOSURE

The general population's exposure to ethylene oxide occurs primarily via inhalation and food ingestion. There is no information to indicate that ethylene oxide is a common contaminant of drinking water supplies.

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Some foods retain ethylene oxide after fumigation (EPA 2017b; NIOSH 1981; Parod 2014), thereby resulting in exposure to the general population. Ethylene oxide is naturally occurring in the body, as it is formed from ethylene conversion during metabolic processes (Bono et al. 2002; Parod 2014). WHO estimated that potential maximum exposure levels of ethylene oxide for the general population are about 0.34 and 0.17 $\mu\text{g}/\text{m}^3$ (0.19 and 0.094 ppb) for outdoor and indoor air, respectively. For those residing near point sources, the levels may be significantly higher (estimated as 2, 11, and 20.1 $\mu\text{g}/\text{m}^3$ [1.1, 6.05, and 11.06 ppb) near hospitals, sterilization facilities, and production facilities of ethylene glycol, respectively (WHO 2003).

Exposure to ethylene oxide from environmental tobacco smoke and via maternal transfer has been demonstrated in several studies. In a study of 3–13-year-old children, the levels of HOEtVal (ethylene oxide hemoglobin adduct) was correlated to the number of cigarettes passively smoked by the children (Bono et al. 2005). The levels of HOEtVal were also correlated to urinary cotinine (a nicotine metabolite) levels. Similarly, studies of newborns of mothers have found correlations between HOEtVal levels in maternal blood and cord blood (Farmer et al. 1996; Von Stedingk et al. 2011) or newborn blood levels (Tavares et al. 1994). The cord blood levels were 5 times higher in smokers than nonsmokers (Farmer et al. 1996) and newborn blood levels were about 3 times higher in smokers (Tavares et al. 1994).

Monitoring data on ethylene oxide biomarkers (blood hemoglobin adducts, HEV) were collected during the 2013–2014 and 2015–2016 National Health and Nutrition Examination Survey (NHANES). The hemoglobin adduct levels for nonsmoking and smoking populations are presented in Tables 5-9 and 5-10, respectively. At occupational exposure levels, a relationship exists between exposure to ethylene oxide and increased levels of HEV. However, data to demonstrate that background HEV levels in nonsmoking populations are a direct indicator of internal exposures to ethylene oxide are not available.

Kirman et al. (2021) predicted air ethylene oxide levels that could result in the HEV levels observed in the NHANES 2013–2016 data. The prediction was based on an observed linear relationship between air exposure levels and HEV levels in workers (combined smokers and nonsmokers; slope: 10.9 pmol HEV/g Hgb per ppb ethylene oxide; Angerer et al. 1998). The arithmetic mean HEV level in nonsmokers was estimated to be 31.4 pmol/g Hgb (SD: 24.8, n=3841), and the mean level in smokers was estimated to be 236 pmol/g Hb (SD: 220, n=936). The corresponding equivalent air ethylene oxide levels were 2.9 ppb (SD: 1.3) in nonsmokers and 21.7 ppb (SD: 20.2) in smokers. Kirman et al. (2021) calculated HEV levels that would be associated with typical U.S. air levels of ethylene oxide. Based on a linear slope of 10.9 pmol HEV/g Hgb per ppb ethylene oxide, a concentration of 0.2 ppb in air would correspond to an

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Table 5-9. Geometric Mean and Selected Percentiles of Blood Ethylene Oxide Hemoglobin Adduct Levels (pmol/g hemoglobin) Among Nonsmokers in the U.S. Population from the National Health and Nutrition Examination Survey (NHANES) 2013–2016

	Survey years ^a	Geometric mean (95% CI)	Selected percentiles (95% CI)				Sample size
			50 th	75 th	90 th	95 th	
Total	2013–2014	28.5 (27.0-30.1)	29.1 (27.6-30.5)	37.5 (35.4-39.7)	50.1 (46.8-52.9)	60.8 (55.9-69.7)	1,945
	2015–2016	27.7 (26.1-29.5)	26.5 (25.2-27.7)	34.7 (32.7-36.6)	47.8 (44.0-53.4)	63.8 (54.0-80.1)	1,896
Age 6–11 years	2013–2014	33.9 (31.6-36.4)	33.2 (30.2-36.8)	42.9 (37.9-47.9)	52.6 (48.8-56.2)	62.9 (55.8-76.1)	321
	2015–2016	33.1 (31.8-34.4)	32.2 (30.7-33.7)	39.9 (37.8-42.0)	52.0 (46.6-58.6)	60.3 (56.0-64.2)	301
Age 12–19 years	2013–2014	29.3 (27.4-31.2)	29.6 (27.4-31.2)	36.4 (34.4-40.0)	49.0 (44.1-56.8)	60.3 (48.0-79.8)	358
	2015–2016	27.6 (25.1-30.3)	27.0 (25.2-29.3)	35.3 (31.3-39.1)	46.3 (40.7-53.9)	54.0 (46.3-60.4)	328
Age 20+ years	2013–2014	27.8 (26.2-29.5)	28.6 (26.9-30.1)	36.8 (34.6-38.8)	49.2 (44.5-54.1)	60.8 (54.1-69.7)	1,266
	2015–2016	27.2 (25.5-29.0)	25.7 (24.1-27.2)	33.7 (32.0-36.2)	47.5 (43.1-54.0)	65.8 (54.0-82.7)	1,267
Males	2013–2014	29.0 (27.2-31.0)	30.2 (28.3-31.3)	38.4 (35.9-40.4)	50.5 (45.3-52.9)	60.4 (52.9-71.1)	897
	2015–2016	29.1 (27.5-30.8)	27.3 (25.7-28.7)	36.4 (34.4-37.8)	51.2 (45.8-56.9)	80.1 (60.5-83.0)	882
Females	2013–2014	28.1 (26.5-29.8)	28.6 (26.9-29.7)	36.6 (34.9-38.6)	49.6 (45.7-55.6)	60.8 (54.7-69.7)	1,048
	2015–2016	26.6 (24.7-28.6)	25.8 (24.1-27.3)	33.2 (31.7-35.6)	46.6 (40.5-52.6)	56.9 (49.0-68.1)	1,014
Non-Hispanic blacks	2013–2014	31.3 (29.1-33.7)	30.8 (28.7-33.7)	43.9 (38.0-47.9)	58.3 (51.7-69.2)	78.4 (61.9-109)	376
	2015–2016	31.8 (30.1-33.6)	30.7 (28.0-33.6)	40.6 (38.0-44.4)	53.9 (47.6-63.7)	65.6 (55.2-79.2)	340
Non-Hispanic whites	2013–2014	27.2 (25.0-29.5)	28.1 (26.2-30.2)	35.9 (32.6-39.1)	48.0 (42.1-52.9)	59.2 (49.6-69.7)	680
	2015–2016	26.1 (24.0-28.4)	25.0 (23.6-26.6)	32.2 (29.7-34.3)	43.1 (39.9-48.9)	63.8 (46.4-83.1)	569
All Hispanics	2013–2014	30.2 (28.9-31.6)	30.0 (29.2-31.3)	37.2 (35.1-39.5)	49.1 (44.4-53.7)	59.2 (52.6-73.1)	585
	2015–2016	29.0 (27.7-30.4)	27.6 (26.4-29.4)	35.7 (34.1-37.4)	47.4 (42.0-58.3)	62.7 (49.4-95.4)	654

^aThe limits of detection (LODs) for survey years 2013–2014 and 2015–2016 were 13.13 and 13.13 pmol/g hemoglobin, respectively.

CI = confidence interval

Source: CDC 2022

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Table 5-10. Geometric Mean and Selected Percentiles of Blood Ethylene Oxide Hemoglobin Adduct Levels (pmol/g hemoglobin) Among Cigarette Smokers in the U.S. Population from the National Health and Nutrition Examination Survey (NHANES) 2013–2016

	Survey years ^a	Geometric mean (95% CI)	Selected percentiles (95% CI)				Sample size
			50 th	75 th	90 th	95 th	
Total	2013–2014	199 (177-224)	227 (208-244)	354 (325-391)	526 (464-612)	676 (610-894)	416
	2015–2016	192 (160-230)	228 (191-258)	374 (308-419)	533 (458-585)	675 (577-800)	377
Age 18–49 years	2013–2014	197 (175-221)	215 (177-250)	354 (314-399)	535 (439-649)	725 (535-926)	271
	2015–2016	151 (113-202)	180 (135-243)	296 (246-387)	464 (341-585)	585 (446-754)	220
Age 50+ years	2013–2014	204 (155-268)	243 (183-306)	345 (304-438)	510 (438-675)	657 (447-1250)	145
	2015–2016	290 (245-342)	300 (228-381)	444 (375-565)	606 (513-806)	806 (577-1530)	157
Males	2013–2014	200 (174-229)	214 (182-250)	383 (307-438)	578 (435-747)	742 (578-1060)	231
	2015–2016	176 (133-234)	227 (175-272)	360 (294-446)	540 (452-604)	606 (569-685)	231
Females	2013–2014	199 (159-248)	230 (185-264)	335 (290-388)	503 (404-649)	651 (490-926)	185
	2015–2016	214 (179-256)	228 (173-266)	383 (296-432)	531 (392-922)	763 (434-1530)	146

^aThe limits of detection (LODs) for survey years 2013–2014 and 2015–2016 were 13.13 and 13.13 pmol/g hemoglobin, respectively.

CI = confidence interval

Source: CDC 2022

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HEV level of 2.2 pmol/Hgb. This level of HEV was approximately 7% of the arithmetic mean level in the U.S. nonsmoking population, based on NHANES 2013–2016 (31.4 pmol/g Hgb).

5.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Occupational groups exposed to ethylene oxide include workers in ethylene oxide manufacturing or processing plants, sterilization technicians, workers involved in the fumigation of foods, clothing, and cosmetics, and indoor fumigators (EPA 2017b; OSHA 1988;). Reported odor threshold concentrations of ethylene oxide in air are in the range of 430–700 ppm (786.9–1,281 mg/m³) (Amoore and Hautala 1983; OSHA 2018a), which is well above the OSHA permissible exposure limit (PEL) of 1 ppm (1.83 mg/m³) (OSHA 2018a, 2018b, 2018c). Thus, odor does not provide adequate warning of hazardous concentrations. Worker exposure to ethylene oxide can be determined through routine air monitoring and biomonitoring (see Sections 3.3.1 and 3.3.2 for additional details). The TWA concentration for ethylene oxide exposure in hospital settings near sterilization equipment was determined to be around 90 mg/m³ (49.5 ppm) (WHO 2003).

Hospital workers and patients may be exposed to residual levels of ethylene oxide during procedures where medical supplies that have been sterilized with ethylene oxide are used. During sterilization, plastics can absorb ethylene oxide and release it when the product is used, resulting in exposure by inhalation, dermal contact, or direct release to the blood stream (Chien et al. 2009). Some sterilized plastics may retain concentrations of ethylene oxide ranging from 3 to 443 mg/kg (ppm) even after 7 days of aeration (WHO 1985). Medical equipment such as adhesive dressings and cotton wool pads may also retain ethylene oxide at ≤ 2 mg/kg (ppm) for 7–8 days after sterilization (Dauvois et al. 1982).

Technicians involved in routine disinfection of medical equipment in hospitals may be exposed to relatively high levels of ethylene oxide. The temporal trends in U.S. hospital settings have indicated that exposure to hospital workers has shown a steady decline since implementation of OSHA standards in 1984 and 1988 (see Section 5.5.1) (LaMontagne et al. 2004). The number of hospitals that exceeded the 1-ppm PEL declined from roughly 20% in 1984 to about 1% in 2001 and the number of hospitals that exceeded the 8-hour action level of 0.5 ppm decreased from about 40% in 1988 to about 5% in 2001.

Short-term area concentrations of ethylene oxide were detected in the air of a central supply department of a Midwestern U.S. hospital at levels up to 77 ppm (141 mg/m³) (measured at breathing zone height). TWA personal exposure concentrations in this proximity were determined to be 0.23–0.56 ppm (0.42–1.0 mg/m³). Adjustment of the ventilation system, added exhaust hoods, and addition of an ethylene

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oxide monitoring system mitigated the elevated air levels of ethylene oxide (Zey et al. 1994). Similarly, an intervention study conducted in 10 medical supply manufacturing facilities in Taiwan found that worker exposure to ethylene oxide was reduced by increasing the number of post-sterilization purge cycles and increased ventilation (Chien et al. 2007). A study of 9 hospital workers and 15 factory workers exposed to ethylene oxide during sterilization of medical equipment showed that elevated concentrations typically occurred in short bursts. Concentrations ranged from 22 to 72 ppm (40–132 mg/m³) for hospital settings and from 14 to 400 ppm (26–732 mg/m³) in factories (Tates et al. 1991). Instantaneous environmental air concentrations from the breathing zone near a hospital sterilizer unit ranged from 0.4 to 22.5 mg/m³ (0.22–12.38 ppm) (Brugnone et al. 1986). An analysis of historical data pertaining to occupational exposure in various United Kingdom industries concluded that ethylene oxide concentrations ranged from <0.1 to 16 mg/m³ (<0.055–8.8 ppm), with a mean concentration of 2.0 mg/m³ (1.1 ppm) for 17 measurements (Cherrie et al. 2001).

Air samples collected at two commercial sterilization facilities contained ethylene oxide in concentrations ranging from 0.7 to 32 ppm (1.3–59 mg/m³) and from 0.5 to 1.6 ppm (0.9–2.9 mg/m³) for 15-minute and 8-hour durations, respectively (Cummins et al. 1993). A composite study presented airborne ethylene oxide concentrations in hospital sterilization facilities in various countries, with data collection ranging from 1977 to 1987. TWAs ranged from not detectable to 72 mg/m³ (39.6 ppm), with peak levels ranging from not detectable to 1,431 mg/m³ (787 ppm). The study also reported 8-hour TWAs and peak levels, measured in 1987 for six Dutch and Belgian hospitals, ranging from not detectable to 28 mg/m³ (15.4 ppm) and from not detectable to 700 mg/m³ (385 ppm), respectively (Florack and Zielhuis 1990). Air concentrations, measured in seven Swiss hospitals with sterilization units from March 2003 to March 2004, ranged from not detectable to 0.59 ppm (1.08 mg/m³) (Haufroid et al. 2007).

In facilities utilizing ethylene oxide in sterilizing applications, concentrations in air are typically high for very short time periods (i.e., after opening a sterilizer), thereby resulting in low TWA exposures despite high initial concentrations. A survey of 26 exposure scenarios at 18 hospitals with ethylene oxide sterilizers determined that air concentrations peak within 20 seconds of opening portable sterilizers and within 78 seconds of opening built-in sterilizers. In a confined space, a peak ethylene oxide value of 24 ppm (43.9 mg/m³) was reported following the opening of a built-in sterilizer (Yoshida et al. 1989). A 2005 study by the Taiwan Institute of Occupational Safety and Health of the medical supplies manufacturing industry monitored ethylene oxide concentration and exposure at 10 factories. Ethylene oxide concentrations in air were determined by collecting samples on hydrobromic acid (HBr)-coated charcoal tubes, followed by analysis with gas chromatography/mass spectrometry (GC/MS). It was

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determined that workers operating sterilizers were exposed to short-term ethylene oxide air concentrations of 27.61 ppm (50.53 mg/m³), with mean TWA workshift exposures of 7.35 ppm (13.45 mg/m³). Additional measurements were obtained near the aeration, sterilizer, and warehouse areas of the facility, where mean ethylene oxide air concentrations were 10.19, 5.75, and 8.78 ppm (18.65, 10.52, and 16.07 mg/m³), respectively (Chien et al. 2007).

A study of an Egyptian facility using ethylene oxide for sterilization of medical products found concentrations ranging from 4.20 to 7.10 ppm (7.87–12.9 mg/m³) in the sterilization and aeration room and from 0.70 to 2.50 ppm (1.3–4.58 mg/m³) in the final inspection room. The mean concentration in the assembly and injection room was reported as 0.21 ppm (0.38 mg/m³) (Kamel et al. 2011).

Studies of worker exposures in five hospital sterilization rooms in the United States indicate that the time-averaged exposures range from <0.1 to 4.3 ppm (<0.183–7.87 mg/m³), with peaks as high as 795 ppm (1,455 mg/m³) (Hansen et al. 1984). In New Zealand fumigators and workers handling container cargo, the maximum 8-hour exposure levels (personal breathing zone) were 0.13 ppm (0.23 mg/m³) and 0.005 ppm (0.009 mg/m³), respectively (Hinz et al. 2020). Brugnone et al. (1985) reported alveolar concentrations of ethylene oxide to be about 75% of the environmental concentrations of ethylene oxide in a hospital sterilizing unit (0.1–7.8 ppm or 0.183–14.27 mg/m³).

Ethylene oxide concentrations were monitored in a facility in Brazil that utilizes the chemical in the production of polyethylene glycol. Ambient air concentrations, determined using passive air sampling pumps with activated charcoal tubes, were analyzed for over a 3-month period. TWAs for an 8-hour working day were determined to be 2–5 ppm (4–10 mg/m³) (Ribeiro et al. 1994).