Ethylene Oxide

CAS No. 75-21-8

Known to be a human carcinogen

First listed in the *Fourth Annual Report on Carcinogens* (1985)

Also known as oxirane, EtO

Carcinogenicity

Ethylene oxide is *known to be a human carcinogen* based on sufficient evidence of carcinogenicity from studies in humans, including epidemiological studies and studies on mechanisms of carcinogenesis. Ethylene oxide was first listed in the *Fourth Annual Report on Carcinogens* in 1985 as *reasonably anticipated to be a human carcinogen* based on limited evidence of carcinogenicity from studies in humans and sufficient evidence of carcinogenicity from studies in experimental animals. The listing was revised to *known to be a human carcinogen* in the *Ninth Report on Carcinogens* in 2000.

Cancer Studies in Humans

An increased risk of cancer has been demonstrated in epidemiological studies of workers using ethylene oxide as a sterilant for medical devices and spices and in chemical synthesis and production (IARC 1994). The types of cancer most frequently reported to be associated with occupational exposure to ethylene oxide are lymphoma and leukemia. Several epidemiological studies reported an association between exposure to ethylene oxide and increased risk of leukemia and stomach cancer; however, other studies found no significantly increased risks of cancer. In most studies, information on the extent of exposure to ethylene oxide was limited. The likelihood of confounding occupational exposures to other chemicals generally is lower for sterilization workers than for chemical synthesis and production workers.

A meta-analysis of 10 distinct cohort studies of workers exposed to ethylene oxide found no association between exposure and risk of pancreatic or brain cancer; however, this analysis suggested associations with non-Hodgkin lymphoma (NHL) and stomach cancer (Shore *et al.* 1993). The largest study of U.S. workers exposed to ethylene oxide at plants producing sterilized medical supplies or spices found no excess mortality from any cause of death; however, male workers had excess mortality from all cancers of the hematopoietic system combined (especially lymphosarcoma, reticulosarcoma, and NHL) (Steenland *et al.* 1991). Risk of mortality from all lymphatic and hematopoietic cancer increased with increasing cumulative exposure to ethylene oxide, and this trend was strengthened when the analysis was restricted to cancer of lymphoid-cell origin (lymphocytic leukemia and NHL combined). Increasing cumulative exposure to ethylene oxide was associated with increased risk of leukemia, but this trend was not statistically significant (Stayner *et al.* 1993). Other studies reported elevated risk of leukemia in workers who had been exposed to ethylene oxide for more than 10 years (Teta *et al.* 1993) and elevated incidence of breast cancer in a cohort of workers who used ethylene oxide as a sterilant (Norman *et al.* 1995). Since the ethylene oxide profile was revised for the *Ninth Report on Carcinogens,* the International Agency for Research on Cancer has concluded that there is limited evidence in humans for a causal association with breast cancer (IARC 2012).

Studies on Mechanisms of Carcinogenesis

Evidence for a common mechanism of carcinogenesis in humans and experimental animals comes from studies that have found similar genetic damage in the cells of animals and workers exposed to ethylene oxide. The DNA-damaging activity of ethylene oxide explains its effectiveness as a sterilant, and this same property accounts for its carcinogenic risk to humans.

Ethylene oxide caused genetic damage in all species studied, including prokaryotic, lower eukaryotic, and *in vitro* and *in vivo* mammalian systems. Ethylene oxide caused gene mutations and heritable translocations in germ cells of rodents exposed *in vivo*. In occupationally exposed workers, ethylene oxide caused dose-related increases in the frequencies of chromosomal aberrations, sister chromatid exchange, *hprt* mutations in peripheral lymphocytes, micronucleus formation in erythrocytes, and DNA single-strand breaks in peripheral mononuclear blood cells (Fuchs *et al.* 1994, IARC 1994, Oesch *et al.* 1995, Schulte *et al.* 1995, Major *et al.* 1996). Similar genotoxic effects were observed in rodents exposed to ethylene oxide (IARC 1994). For direct-acting mutagenic chemicals, increases in chromosomal aberration frequency appear to be a good predictor of increased human cancer risk. Thus, all measurable genotoxic end points that are considered to be indicators of chemical carcinogenesis have been observed in both humans and experimental animals exposed to ethylene oxide.

Ethylene oxide is a direct-acting alkylating agent that forms adducts with biological macromolecules, including hemoglobin and DNA. Ethylene oxide caused dose-related increases in the frequency of hemoglobin adducts in exposed humans and rodents. Measurements of hemoglobin adducts (hydroxyethyl histidine and hydroxyethyl valine) have been used to monitor worker exposure to ethylene oxide (IARC 1994). The major DNA adduct of ethylene oxide is *N*7-(2-hydroxyethyl)guanine. Dose-related increases in this adduct, as well as smaller amounts of O^6-(2-hydroxyethyl)guanine and *N*3-(2-hydroxyethyl)adenine, were observed in rodents exposed to ethylene oxide. It has been suggested that background levels of hemoglobin and DNA adducts of ethylene oxide in humans and experimental animals arise from endogenous production of ethylene by intestinal flora or metabolism of unsaturated dietary lipids (Tornqvist 1996).

Cancer Studies in Experimental Animals

Inhalation exposure to ethylene oxide caused tumors at several different tissue sites in rodents, including the hematopoietic system in mice and rats; the lung, Harderian gland, mammary gland, and uterus in mice; and the brain and mesothelium in rats (NTP 1987, IARC 1994).

Properties

Ethylene oxide is the simplest epoxy compound, which at room temperature is a colorless gas with a sweet odor. It is miscible with water, alcohol, and most organic solvents and soluble in acetone. Ethylene oxide is flammable and explosive, and incomplete combustion releases carbon monoxide (IARC 1994). Physical and chemical properties of ethylene oxide are listed in the following table.

Property	Information
Molecular weight	44.0[a]
Specific gravity	0.882 at 10°C/10°C[a]
Melting point	–112°C[a]
Boiling point	10.6°C at 760 mm Hg[a]
Log K_{ow}	–0.3[a]
Water solubility	1,000 g/L at 25°C[b]
Vapor pressure	1,310 mm Hg at 25°C[a]
Vapor density relative to air	1.49[a]

Sources: [a]HSDB 2020, [b]ChemIDplus 2020.

Ethylene oxide is available commercially in the United States as a high-purity chemical containing no more than 0.03% water, 0.003% aldehydes as acetaldehyde, or 0.002% acidity as acetic acid. It has

been sold as a mixture with either carbon dioxide or fluorocarbon 12 to reduce its fire hazard (HSDB 2020).

Use

The major use of ethylene oxide in the United States (accounting for over 97% of production) is as an intermediate in the production of several industrial chemicals (IARC 1994, ATSDR 2020). The remainder is used in the gaseous form, either alone or combined with nitrogen, carbon dioxide, or dichlorofluoromethane, as a sterilizing agent, disinfectant, fumigant, or insecticide. The largest use (about 60%) is to produce ethylene glycol (antifreeze). Other chemicals produced from ethylene oxide include non-ionic surfactants (used in industrial applications, detergents, and dishwashing formulations), glycol ethers, ethanolamines (used in soaps, detergents, and textile chemicals), diethylene glycol, triethylene glycol, polyethylene glycol, and urethane polyols. Although a relatively small percentage of ethylene oxide is used as a fumigant or sterilizing agent, these uses involve a variety of facilities, products, and materials, including medical and dental clinics, research laboratories, hospital equipment, foods, furs, clothing, furniture, books, paper, leather, cosmetics, drugs, railroad cars, beehives, and tobacco. Facilities that manufacture sterile disposable medical supplies, and medical facilities, including hospitals, medical and dental clinics, and private medical and dental surgeries, account for about 95% of the ethylene oxide used as a fumigant or sterilant. In hospitals, ethylene oxide is used as a gaseous sterilant for heat-sensitive medical items, surgical instruments, and other objects and fluids coming in contact with biological tissues. Before 1966, ethylene oxide was used as an intermediate in the production of acrylonitrile.

Production

Ethylene oxide was first produced in the United States in 1921. Until 1937, it was produced by the chlorohydrin process, in which ethylene was treated with hypochlorous acid to produce ethylene chlorohydrin, and calcium hydroxide or sodium hydroxide was used to convert ethylene chlorohydrin to ethylene oxide. Essentially all U.S. production of ethylene oxide now uses the direct vapor phase oxidation process, by which ethylene is oxidized with air or oxygen in the presence of a silver catalyst to produce ethylene oxide. In addition, ethylene oxide is produced naturally as a metabolite of ethylene and has been identified in automobile and diesel exhaust and in tobacco smoke (IARC 1994).

Ethylene oxide is a major industrial chemical and is consistently ranked among the 25 highest-production-volume chemicals produced in the United States. The national aggregate production volume of ethylene oxide reported to the U.S. Environmental Protection Agency (EPA) for 2015 was between 5 billion and 10 billion pounds (ATSDR 2020). In 2018, 15 U.S. processing plants produced about 6.4 billion pounds of ethylene oxide, and market demands are expected to increase production capacity through 2023. U.S. imports were 3 million pounds in 2008, but fell to only about 500 lb by 2017 (USITC 2020). However, the United States imported about 2.6 billion pounds of ethylene oxide derivatives (other chemicals and products derived from ethylene oxide) and exported about 1.8 billion pounds of ethylene oxide derivatives (ATSDR 2020). In 2017, at least 106 facilities in 34 states produced, processed, or used ethylene oxide. As shown in the following table, U.S. production of ethylene oxide in recent years has greatly exceeded imports or exports.

Category	Year	Quantity (lb)
Production[a]	2015	5 billion to 10 billion
U.S. imports[b]	2017	505
U.S. exports[b]	2017	5.3 million

Sources: [a]ATSDR 2020. [b]USITC 2020; data are for "oxirane (ethylene oxide)."

Exposure

A significant number of people living in the United States are exposed to ethylene oxide, as evidenced by biological monitoring data and by data on occupational and environmental exposure and exposure through the use of consumer products. People are exposed to ethylene oxide in the workplace, in the environment, in tobacco smoke, and through use of products that have been sterilized with the compound, including medical products, food, clothing, cosmetics, and beekeeping equipment (NIOSH 1981, ATSDR 2020). The primary routes of potential human exposure to ethylene oxide are inhalation and ingestion. Exposure by dermal contact is expected to be low under most circumstances (IPCS 1985).

Biological Monitoring

In the 2015–2016 National Health and Nutrition Examination Survey (NHANES), the highest levels of ethylene oxide hemoglobin adducts were found in individuals who smoked cigarettes (as shown in the table below) (CDC 2020). Adduct levels also differed by race and ethnicity, being higher among Hispanic people and non-Hispanic black people than among non-Hispanic white people. Levels were also higher in men than in women, and in children (aged 6 to 11) than in adults (aged 20 or older). These hemoglobin adduct levels were similar to those reported in the 2013–2014 NHANES.

Sample	Mean (95% CI) (pmol/g of hemoglobin)	Sample size
Smokers	186 (155–223)	377
Non-smokers	27.0 (25.4–28.7)	1,896
Non-Hispanic white	25.4 (23.4–27.7)	569
Non-Hispanic black	31.0 (29.3–32.7)	340
All Hispanic	28.3 (27.0–29.6)	654

Source: CDC 2020. CI = confidence interval.

Occupational Exposure

Occupational exposure to ethylene oxide may occur among workers involved in ethylene oxide production, in the manufacture of its end products, or in its use in hospital and industrial sterilization (IARC 1994, ATSDR 2020). Industrial and health-care workers may be exposed to ethylene oxide during sterilization of a variety of products, such as medical equipment and products (e.g., surgical products or single-use medical devices), disposable health-care products, pharmaceutical and veterinary products, spices, and animal feed (IARC 1994).

In 2005, OSHA estimated that about 47,000 workers were employed in industrial sectors that used ethylene oxide and were therefore potentially exposed to ethylene oxide. These included 39,252 workers involved in hospital sterilization operations; 3,866 in chemical derivative manufacturing; 2,694 in commercial sterilization by manufacturers of medical and pharmaceutical products and food spices, contract sterilizers, and other sterilization and fumigation applications; and 1,151 in ethylene oxide production (OSHA 2005).

Because ethylene oxide is highly explosive and reactive, the equipment used for its processing generally consists of tightly closed and highly automated systems, which decreases the risk of occupational exposure (NCI 1985). A review of exposure data collected in 1987 from 11 U.S. ethylene oxide production facilities reported that the

highest mean 8-hour time-weighted-average (TWA) concentration was 1.6 ppm, with a range of 0.20 to 3.8 ppm; mean short-term exposure levels for maintenance workers were as high as 10.9 ppm (IARC 1994, 2012).

In industrial and health-care use of ethylene oxide sterilization, workers may be exposed during changing of pressurized ethylene oxide gas cylinders; from leaking valves, fittings, piping, and sterilizer door gaskets; from opening of the sterilizer door at the end of a cycle; from improper ventilation at the sterilizer door; from an improperly ventilated or unventilated air gap between the discharge line and the sewer drain; during removal of items from the sterilizer and transfer of the sterilized load to an aerator; from improper ventilation of aerators and aeration areas; from incomplete aeration of items; from inadequate general room ventilation; and from passing near sterilizers and aerators while they are operating. Health-care technicians can be exposed to short, concentrated bursts of the gas when the door of a sterilizing machine is opened (Sun 1986).

In a midwestern U.S. hospital's central supply department, short-term area ethylene oxide air concentrations were as high as 77 ppm, and TWA personal exposure concentrations ranged from 0.23 to 0.56 ppm (ATSDR 2020). Ethylene oxide concentrations in the air at two commercial sterilization facilities ranged from 0.7 to 32 ppm in 15-minute samples and from 0.5 to 1.6 ppm in 8-hour samples (ATSDR 2020). A survey of 21 companies involved in ethylene oxide sterilization (primarily of medical supplies and spices) conducted from 1976 to 1985 estimated that sterilizer operators were exposed to 8-hour TWA concentrations of 16 ppm before 1978 and 4 to 5 ppm after 1978 (IARC 1994). A set of nine air samples taken in 2019 and 2020 inside the scrubber room of a medical equipment sterilization facility had ethylene oxide concentrations ranging from 0.11 to 394 ppb (MDEGLE 2020). The maximum 12-hour ethylene oxide exposure for off-site workers in facilities near a commercial sterilization facility in Willowbrook, Illinois, was estimated to be 5.0 ppb (ATSDR 2020).

A study conducted in Massachusetts hospitals from 1990 to 1992 found that 23% of the hospitals exceeded the OSHA action level of 0.5 ppm at least once, 24% exceeded the short-term exposure limit of 5 ppm, and 33% reported accidental exposures to ethylene oxide in the absence of personal monitoring (LaMontagne and Kelsey 1997). TWA concentrations for sterilization-room workers in five hospitals ranged from less than 0.1 ppm to 4.3 ppm; peak exposure was 795 ppm (ATSDR 2020). However, other studies have shown that industrial hygiene measures can effectively control ethylene oxide exposure in hospitals and other places where it is used as a sterilant. An evaluation of nine sterilizer control systems in eight hospitals found that control technologies could reduce the average ethylene oxide concentration to less than 0.1 ppm for a full shift and the maximum concentration to within a ceiling limit of 5 ppm (Mortimer and Kercher 1989). Another evaluation found that standard industrial hygiene practices could result in nearly zero exposure to ethylene oxide in hospitals; peak levels were reduced from 500 ppm to less than 2.8 ppm through the use of engineering and administrative controls (Elias *et al.* 1993).

Environmental Exposure

People who live near industrial facilities that produce or use ethylene oxide may be exposed to emissions that occur during its storage and handling at those facilities, including uncontrolled fugitive emissions or venting with other gases (ATSDR 2020). Other sources of ethylene oxide emissions to air include its production during combustion of hydrocarbon fuel, its release from fumigated materials, and losses during disinfection of hospital equipment.

Releases of ethylene oxide to the environment have steadily decreased from about 5 million pounds per year in 1988 to about 280,000 pounds per year in 2018, according to EPA's Toxics Release Inventory (TRI 2020). The 2018 releases were primarily to air (99%). No specific solid wastes are produced in the manufacture of ethylene oxide (IPCS 1985). Ethylene oxide degrades in water and air with half-lives ranging from a few hours to five months, depending on the environmental conditions (ATSDR 2020). Conventional wastewater treatment, including biological treatment, is very effective in removing ethylene oxide from wastewater.

Ambient air monitoring data come from several sources, including the National Air Toxics Assessment (NATA), which uses data reported to the TRI emissions database; other EPA datasets; and state, local, and tribal air agencies. NATA estimated the mean national ethylene oxide ambient air concentration to be 1.61×10^{-4} ppb, with a measured maximum concentration of 0.079 ppb (ATSDR 2020). Average concentrations of ethylene oxide in national ambient air monitoring samples from EPA's National Air Toxics Trends Stations and Urban Air Toxics Monitoring Program between October 2018 and September 2019 ranged from 0.075 to 0.224 ppb (ATSDR 2020).

Using ethylene oxide emissions data to model risk estimates, NATA found that in 2014, 58 U.S. census tracts had elevated cancer risks (defined as greater than 100 in 1 million) from long-term exposure to ethylene oxide (EPA 2018a,b, 2019). (The threshold ethylene oxide concentration associated with elevated cancer risk = 0.011 ppb.) EPA, state, and local agencies conducted follow-up air monitoring and modeling for eight sites near specific industrial sources of ethylene oxide. Four sites (in Colorado, Georgia, and Illinois) were located near 5 of the 58 census tracts identified as having potential excess cancer risk, and four sites (in Georgia, Illinois, and Michigan) were located near 11 census tracts that had not been identified as having excess cancer risk. The results of this sampling are summarized in the table on the next page.

The highest exposure levels were reported for the facility at Willowbrook, Illinois (mean = 1.68 ppm); this site was associated with a lifetime cancer risk of 6.4 per 1,000 residents. Approximately 19,000 people lived within a mile of the plant boundaries (ATSDR 2018).

Most of the monitoring was conducted within one mile of the facilities (Lakewood, Colorado, and Willowbrook) or within less than half a mile (three sites in Georgia). At three sites, ethylene oxide levels decreased with distance from the facilities. At the Covington, Georgia, site, the levels within a mile of the facility were over 10 times the levels at greater distances (median of means = 2.28 vs. 0.135 ppb) (Montrose 2019). The maximum levels in 24-hour samples taken at two locations about 100 meters (109 yards) from the Willowbrook facility were 14.5 and 9.5 ppb, compared with 0.096 ppb in a sample taken 1.7 km (about a mile) from the facility (ATSDR 2020). In Waukegan, Illinois, a biomonitoring survey (N = 93) found that residents of a neighborhood about half a mile from a medical equipment sterilization facility had average levels of ethylene oxide hemoglobin adducts about 50% higher than those of residents living unreported distances farther from the facility (50.1 vs. 29.8 pmol/g of hemoglobin) (Goodman and Miller 2019).

Because of potential cancer hazards resulting from environmental exposure to ethylene oxide, EPA issued a final rule under the Clean Air Act to address emissions of ethylene oxide from storage tanks, process vents, and equipment leaks and to reduce ethylene oxide emissions from covered facilities by approximately 0.76 tons per year (see Regulations and Guidelines).

Other methods to lower ambient ethylene oxide concentrations and decrease cancer risk include closing facilities and installing emission-control measures. Following an order by the State of Illinois

Location	Sampling agency (no. of samples)	Dates of sampling (duration)	Ethylene oxide (range) (ppb) median or mean across sampling sites or dates
Census tracts with potential excess cancer risk (>100 in 1 million)			
Lakewood, CO	CO (28)	2018 (7 days)[a]	1.19 (0.471–1.716)[b] median of means
Covington, GA	GA (121)	2019–2020 (5 mo)	0.21 (0.16–0.48)[c,d] median of means
Waukegan, IL[e]	Lake Co. (100)	2019–2020 (11 mo)[f]	0.0963 (ND–2.39)[g] median
Willowbrook, IL	EPA (18)	2018 (2 days)[h]	1.68 (0.19–5.05)[c,i] mean
	EPA (265)	2018–2019 (3 mo)[a]	0.145 (0.12–0.99)[c,j] median of medians
	Willowbrook (40)	2019 (10 days)[a]	2.0 (0.13–180)[k,l] median
Census tracts not identified as having potential excess cancer risk			
Atlanta, GA	GA (31)	2020 (4 mo)	0.62 (0.24–1.59)[c,m] median of means
Smyrna, GA	GA (90)	2019–2020 (5 mo)	0.19 (0.033–0.55)[c,n] median of means
Gurnee, IL	Lake Co. (343)	2019–2020 (11 mo)[f]	0.088 (ND–4.91)[g] median
Waukegan, IL[e]	Lake Co. (146)	2019–2020 (11 mo)[f]	0.086 (ND–5.6)[g] median
Grand Rapids, MI	MI (7)	2019–2020 (7 mo)	0.214 (0.0656–1.82)[o] median

ND = Not detected.
[a]Before emission controls were installed (Lakewood) or before closure (Willowbrook). [b]CDPHE 2018. [c]Reported in µg/m^3; 1 ppb = 1.8 µg/m^3. [d]GAEPD 2020b.
[e]Facility was associated with 4 census tracts: 2 with elevated risk and 2 without.
[f]Not consecutive. [g]Lake County 2020. [h]12-hour sampling. [i]ATSDR 2018.
[j]Colledge and Johnson 2019. [k]Willowbrook 2019b.
[l]Median and range before plant closure calculated using closure dates provided by EPA.
[m]GAEPD 2020c. [n]GAEPD 2020a. [o]MDEGLE 2020.

suspending operations at the Willowbrook facility in February 2019, regulatory and community concerns about environmental exposure resulted in the facility's permanent closure in September 2019 (Willowbrook 2019a), which resulted in substantial decreases in exposure levels. Preliminary data from the Village of Willowbrook indicated that median exposure levels were 2.0 ppm (range = 0.13 to 180 ppm) prior to closing, 0.38 ppm (range = 0.09 to 3.3 ppm) after the facility's suspension, and less than 0.040 ppm (range <0.040 to 5.0 ppm) after the facility's closure (Willowbrook 2019b). EPA also reported decreases in exposure levels after the facility closed, though the monitoring period, sample numbers, and measured concentrations differed from the Village's measurements (Colledge and Johnson 2019). The medical equipment sterilizing facility in Grand Rapids, Michigan, also agreed to cease sterilization activities in January 2020 in response to a consent order. The other sites for which monitoring data are available continued operating into 2020. The Lakewood facility installed emission-control devices, which reduced median ethylene oxide concentrations by 70% (median of means = 0.36 ppb, range = 0.23 to 0.55 ppb) (CDPHE 2018).

Exposure from Consumer Products

Ethylene oxide has been detected in tobacco smoke, automobile exhaust, and some foods and spices; however, few data are available that can be used to estimate exposure levels. Fumigated products may initially contain high levels of ethylene oxide, but it degrades or disperses within a few days. One study found that ethylene oxide levels in most experimentally fumigated commodities were less than 1 ppm after 14 days under normal storage conditions. Concentrations of ethylene oxide in fumigated grains, spices, dates, and peas ranged from 0 to 3.5 ppm after 24 hours. Another study reported concentrations in spices ranging from 53 to 116 ppm after 2 days and about 25 ppm after 26 days (ATSDR 2020).

Regulations

Coast Guard (Dept. of Homeland Security)

Minimum requirements have been established for safe transport of ethylene oxide on ships and barges.

Department of Transportation (DOT)

Ethylene oxide mixtures are considered hazardous materials, and special requirements have been set for marking, labeling, and transporting these materials.

Environmental Protection Agency (EPA)

Clean Air Act

National Emission Standards for Hazardous Air Pollutants: Listed as a hazardous air pollutant. On May 29, 2020, EPA finalized amendments to the Miscellaneous Organic Chemical Manufacturing NESHAP that include estimated ethylene oxide emission reductions of 0.76 tons per year.
New Source Performance Standards: Manufacture of ethylene oxide is subject to certain provisions for the control of volatile organic compound emissions.
Prevention of Accidental Release: Threshold quantity (TQ) = 10,000 lb.
Urban Air Toxics Strategy: Identified as one of 33 hazardous air pollutants that present the greatest threat to public health in urban areas.

Comprehensive Environmental Response, Compensation, and Liability Act

Reportable quantity (RQ) = 1 lb.

Emergency Planning and Community Right-To-Know Act

Toxics Release Inventory: Listed substance subject to reporting requirements.
Threshold planning quantity (TPQ) = 1,000 lb.
Reportable quantity (RQ) = 10 lb.

Federal Insecticide, Fungicide, and Rodenticide Act

The tolerances for residues of ethylene oxide when used as a fumigant on certain herbs and spices, dried vegetables, and walnuts range from 7 to 50 ppm.

Resource Conservation and Recovery Act

Listed Hazardous Waste: Waste code for which the listing is based wholly or partly on the presence of ethylene oxide = U115.
Listed as a hazardous constituent of waste.

Food and Drug Administration (FDA, an HHS agency)

Regulations for ethylene oxide and polymers and copolymers of ethylene oxide used as direct or indirect food additives are prescribed under 21 CFR 172, 173, 175, 176, and 178.

Occupational Safety and Health Administration (OSHA, Dept. of Labor)

While this section accurately identifies OSHA's legally enforceable PELs for this substance in 2018, specific PELs may not reflect the more current studies and may not adequately protect workers.
Permissible exposure limit (PEL) = 1 ppm.
Acceptable peak exposure = 5 ppm (15-min excursion).
Comprehensive standards for occupational exposure to ethylene oxide have been developed.

Guidelines

American Conference of Governmental Industrial Hygienists (ACGIH)

Threshold limit value – time-weighted average (TLV-TWA) = 1 ppm.

National Institute for Occupational Safety and Health (NIOSH, CDC, HHS)

Recommended exposure limit (time-weighted-average workday) = < 0.1 ppm (0.18 mg/m^3).
Ceiling recommended exposure limit = 5 ppm (9 mg/m^3) (10 min/day).
Immediately dangerous to life and health (IDLH) limit = 800 ppm.
Listed as a potential occupational carcinogen.

References

ATSDR. 2018. *Letter Health Consultation: Evaluation of Potential Health Impacts from Ethylene Oxide Emissions.* Agency for Toxic Substances and Disease Registry. https://www.atsdr.cdc.gov/HAC/pha/sterigenic/Sterigenics_International_Inc-508.pdf.

ATSDR. 2020. *Toxicological Profile for Ethylene Oxide.* Draft for Public Comment. Agency for Toxic Substances and Disease Registry. http://www.atsdr.cdc.gov/toxprofiles/tp137.pdf.

CDC. 2020. Ethylene oxide hemoglobin adducts. In *National Report on Human Exposure to Environmental Chemicals*. Centers for Disease Control and Prevention. Last updated: 2/5/20. https://www.cdc.gov/exposurereport/ethylene_oxide_hemoglobin.html.

CDPHE. 2018. *Ethylene Oxide/Terumo BCT Air Sampling Study Pre- and Post-Control Air Monitoring Report*. Colorado Department of Public Health & Environment. https://environmentalrecords.colorado.gov/HPRMWebDrawer/RecordView/1272508.

ChemIDplus. 2020. *ChemIDplus Advanced*. National Library of Medicine. https://chem.nlm.nih.gov/chemidplus/name/ethylene%20oxide and select Physical Properties. Last accessed: 11/1/20.

Colledge M, Johnson M. 2019. *ATSDR's Assessments of Ethylene Oxide (EtO) in Ambient Air in Willowbrook, IL*. Agency for Toxic Substances and Disease Registry. https://www.epa.gov/sites/production/files/2019-05/documents/atsdr_slides_sterigenics_5-29-19_meeting.pdf.

Elias J, Wylie N, Yassi A, Tran N. 1993. Eliminating worker exposure to ethylene oxide from hospital sterilizers — An evaluation of cost and effectiveness of an isolation system. *Appl Occup Environ Hyg* 8(8): 687-692.

EPA. 2018a. *2014 NATA: Assessment Results*. U.S. Environmental Protection Agency. Last updated: 8/27/18. https://www.epa.gov/national-air-toxics-assessment/2014-nata-assessment-results and select Nationwide Results and select 2014 NATA natl cancer risk by pollutant.

EPA. 2018b. *2014 National Air Toxics Assessment: Fact Sheet*. U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2018-08/documents/2014_nata_overview_fact_sheet.pdf.

EPA. 2019. Ethylene Oxide Emissions: Frequent Questions. In *EPA in Illinois*. U.S. Environmental Protection Agency. Last updated: 12/17/19. https://www.epa.gov/il/ethylene-oxide-emissions-frequent-questions.

Fuchs J, Wullenweber U, Hengstler JG, Bienfait HG, Hiltl G, Oesch F. 1994. Genotoxic risk for humans due to work place exposure to ethylene oxide: remarkable individual differences in susceptibility. *Arch Toxicol* 68(6): 343-348.

GAEPD. 2020a. Cobb County Air Monitoring Results. *Ethylene Oxide Information*. Georgia Environmental Protection Division. https://epd.georgia.gov/cobb-county-air-quality-monitoring and select Posted June 25, 2020; Posted May 19, 2020; Posted May 14, 2020; Posted March 26, 2020.

GAEPD. 2020b. Covington Monitoring Results. *Ethylene Oxide Information*. Georgia Environmental Protection Division. https://epd.georgia.gov/covington-monitoring-results and select Posted June 23, 2020; Posted May 19, 2020; Posted May 18, 2020; Posted May 18, 2020; Posted March 26, 2020.

GAEPD. 2020c. Fulton County Monitoring Results. *Ethylene Oxide Information*. Georgia Environmental Protection Division. https://epd.georgia.gov/cobb-county-air-quality-monitoring and select Posted Posted June 25, 2020; Posted May 19, 2020; Posted May 18, 2020.

Goodman B, Miller A. 2019. Blood tests show exposure to ethylene oxide. *WebMD Health News*. https://www.webmd.com/cancer/news/20191209/blood-tests-show-exposure-to-ethylene-oxide.

HSDB. 2020. *Ethylene Oxide*. Hazardous Substances Data Bank, PubChem, National Library of Medicine. https://pubchem.ncbi.nlm.nih.gov/source/hsdb/170. Last accessed: 11/2/20.

IARC. 1994. Ethylene oxide. In *Some Industrial Chemicals*. IARC Monographs on the Evaluation of Carcinogenic Risk of Chemicals to Humans, vol. 60. Lyon, France: International Agency for Research on Cancer. pp. 73-159.

IARC. 2012. Ethylene oxide. In *Chemical Agents and Related Occupations*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 100F. Lyon, France: International Agency for Research on Cancer. pp. 379-400.

IPCS. 1985. *Environmental Health Criteria No. 55, Ethylene Oxide*. International Programme on Chemical Safety. http://www.inchem.org/documents/ehc/ehc/ehc55.htm.

Lake County. 2019. *Lake County Ethylene Oxide (EtO) Air Monitoring Results — October 2019–January 2020*. Lake County, IL, Health Department & Community Health Center. Last updated: 6/16/20. https://docs.google.com/spreadsheets/d/1mrY1MbFWUT5-ysl7SpD74CKMKOMo4x9i5wZAArdYJ2k/edit#gid=1269948513.

LaMontagne, AD, Kelsey KT. 1997. Evaluating OSHA's ethylene oxide standard: employer exposure-monitoring activities in Massachusetts hospitals from 1985 through 1993. *Am J Public Health* 87(7): 1119-1125.

Major J, Jakab MG, Tompa A. 1996. Genotoxicological investigation of hospital nurses occupationally exposed to ethylene-oxide: I. Chromosome aberrations, sister-chromatid exchanges, cell cycle kinetics, and UV-induced DNA synthesis in peripheral blood lymphocytes. *Environ Mol Mutagen* 27(2): 84-92.

MDEGLE. 2020. *Viant Medical, Inc*. Michigan Department of Environment, Great Lakes, and Energy. https://www.michigan.gov/egle/0,9429,7-135-3310_70314_89277---,00.html and select July 2019, August 2019, September & October 2019, November & December 2019, January 2020, and February 2020 Sampling Results.

Montrose. 2019. *City of Covington Ethylene Oxide Ambient Monitoring Data*. Montrose Air Quality Services report submitted to the City of Covington, GA. https://cityofcovington.org/ckeditorfiles/files/2019_MontroseCovingtonAirTestResults.pdf.

Mortimer VD, Kercher SL. 1989. *Control Technology for Ethylene Oxide Sterilization in Hospitals*. NIOSH Publication No. 89-120. Cincinnati, OH: National Institute for Occupational Safety and Health. 167 pp.

NCI. 1985. *Monograph on Human Exposure to Chemicals in the Workplace: Ethylene Oxide*. Technical Report No. 84-668. Bethesda, MD: National Cancer Institute.

NIOSH. 1981. *Ethylene Oxide (EtO): Evidence of Carcinogenicity*. NIOSH Current Intelligence Bulletin 35. NIOSH Publication No. 81-130. National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/docs/81-130.

Norman SA, Berlin JA, Soper KA, Middendorf BF, Stolley PD. 1995. Cancer incidence in a group of workers potentially exposed to ethylene oxide. *Int J Epidemiol* 24(2): 276-284.

NTP. 1987. *Toxicology and Carcinogenesis Studies of Ethylene Oxide (CAS No. 75-21-8) in B6C3F1 Mice (Inhalation Studies)*. NTP Technical Report Series no. 326. NIH Publication No. 88-2582. Research Triangle Park, NC: National Toxicology Program. 114 pp.

Oesch F, Hengstler JG, Arand M, Fuchs J. 1995. Detection of primary DNA damage: applicability to biomonitoring of genotoxic occupational exposure and in clinical therapy. *Pharmacogenetics* 5 Spec No: S118-S122.

OSHA. 2005. *Regulatory Review of the Occupational Safety and Health Administration's Ethylene Oxide Standard*. Occupational Safety and Health Administration. https://www.osha.gov/dea/lookback/ethylene_oxide_lookback.pdf.

Schulte PA, Walker JT, Boeniger MF, Tsuchiya Y, Halperin WE. 1995. Molecular, cytogenetic, and hematologic effects of ethylene oxide on female hospital workers. *J Occup Environ Med* 37(3): 313-320.

Shore RE, Gardner MJ, Pannett B. 1993. Ethylene oxide: an assessment of the epidemiological evidence on carcinogenicity. *Br J Ind Med* 50(11): 971-997.

Stayner L, Steenland K, Greife A, Hornung R, Hayes RB, Nowlin S, Morawetz J, Ringenburg V, Elliot L, Halperin W. 1993. Exposure-response analysis of cancer mortality in a cohort of workers exposed to ethylene oxide. *Am J Epidemiol* 138(10): 787-798.

Steenland K, Stayner L, Greife A, Halperin W, Hayes R, Hornung R, Nowlin S. 1991. Mortality among workers exposed to ethylene oxide. *N Engl J Med* 324(20): 1402-1407.

Sun M. 1986. Study estimates higher risk from ethylene oxide exposure. *Science* 231: 448.

Teta MJ, Benson LO, Vitale JN. 1993. Mortality study of ethylene oxide workers in chemical manufacturing: a 10 year update. *Br J Ind Med* 50(8): 704-709.

Tornqvist M. 1996. Ethylene oxide as a biological reactive intermediate of endogenous origin. *Adv Exp Med Biol* 387: 275-283.

TRI. 2020. *TRI Explorer Chemical Report*. U.S. Environmental Protection Agency. https://enviro.epa.gov/triexplorer/tri_release.chemical and select Ethylene oxide. Last accessed: 3/18/20.

USITC. 2020. *USITC DataWeb*. United States International Trade Commission. https://dataweb.usitc.gov and search on HTS no. 291010. (Requires free account.) Last accessed: 10/6/20.

Willowbrook. 2019a. *Closing of Sterigenics in the Village of Willowbrook*. Village of Willowbrook, IL. https://www.willowbrookil.org/DocumentCenter/View/1860/Press-Release-Re-Closing-of-Sterigenics-in-Willowbrook?bidId=.

Willowbrook. 2019b. *Posting of All Additional Air Sampling Results: October 31, 2019*. Village of Willowbrook, IL. https://www.willowbrookil.org/DocumentCenter/View/1897/ETO-V-2