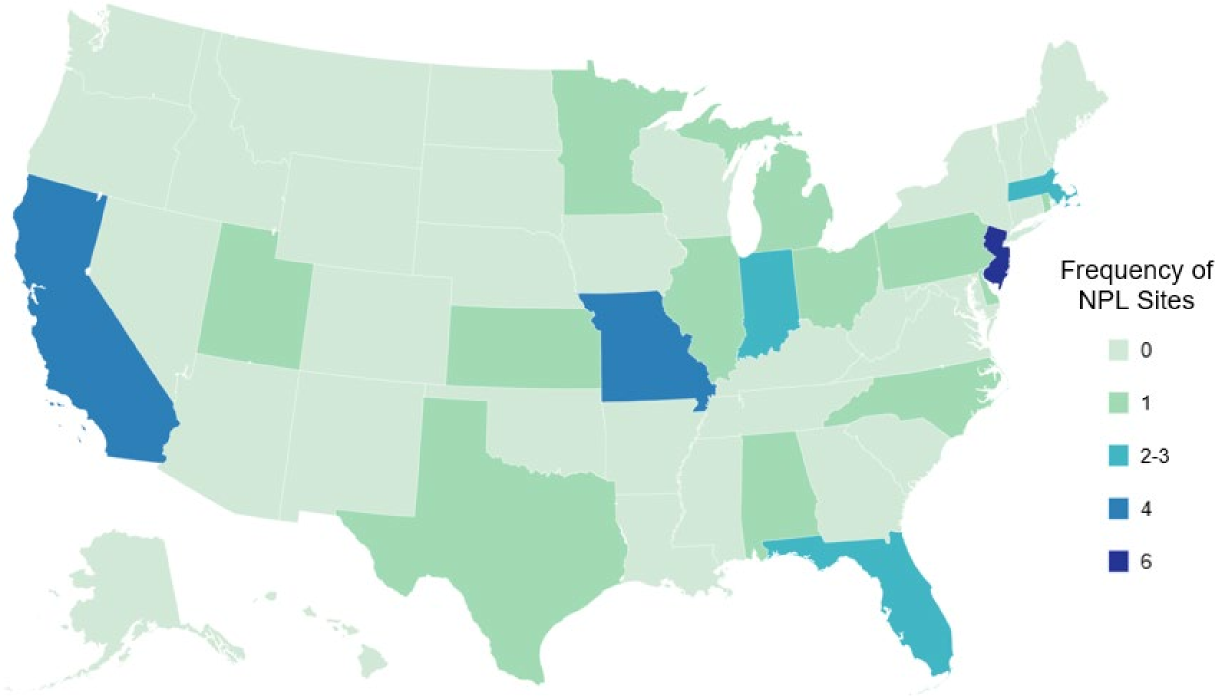
CHAPTER 5. POTENTIAL FOR HUMAN EXPOSURE

5.1 OVERVIEW

Acrolein has been identified in at least 33 of the 1,868 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (ATSDR 2022a). However, the number of sites in which acrolein 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 Acrolein Contamination



Source: ATSDR 2022a

- The main route of acrolein exposure for the general population stems from indoor air; smoking (cigarettes, e-cigarettes, marijuana), cooking with oils and fats, and building materials all contribute to acrolein levels in the air.

- Ingestion of some foods and beverages and consumption of contaminated drinking water can also be routes of exposure.

- Acrolein is released to the environment in emissions from manufacturing and use facilities, combustion processes (including automobile emissions and smoke from any type of fire), degradation of other pollutants, and direct release.

- Acrolein is a reactive compound and is unstable in the environment.

- Acrolein is not persistent in the atmosphere and reacts with hydroxyl radicals, with a half-life of 15–20 hours.
- Acrolein can be removed from water and soil by volatilization, abiotic, and biodegradation processes.

Acrolein may be released to the environment in emissions and effluents from its manufacturing and use facilities, in emissions from combustion processes (including cigarette smoking and combustion of petrochemical fuels), from direct application to water and wastewater as a slimicide and aquatic herbicide, as a photooxidation product of various hydrocarbon pollutants found in air (including propylene and 1,3-butadiene), and from land disposal of some organic waste materials. Acrolein is a reactive compound and is unstable in the environment.

In ambient air, the primary removal mechanism for acrolein is predicted to be reaction with photochemically generated hydroxyl radicals (half-life, 15–20 hours). Products of this reaction include carbon monoxide, formaldehyde, and glycolaldehyde. In the presence of nitrogen oxides, peroxynitrate and nitric acid are also formed. Small amounts of acrolein may also be removed from the atmosphere in precipitation. Insufficient data are available to predict the fate of acrolein in indoor air. In water, small amounts of acrolein may be removed by volatilization (half-life, 23 hours from a model river 1 m deep), aerobic biodegradation, or reversible hydration to β-hydroxypropionaldehyde, which subsequently biodegrades. Based on the reactivity of acrolein, it is expected that removal of acrolein from water through the binding of the chemical to dissolved and suspended organics will become increasingly important as the concentration of the organics in water increases. However, information on this removal process could not be located.

Half-lives of <1–3 days for small amounts of acrolein in surface water have been observed. When highly concentrated amounts of acrolein are released or spilled into water, this compound may polymerize by oxidation or hydration processes. In soil, acrolein is expected to be subject to removal through volatilization, abiotic and biotic degradation processes, and possibly irreversible binding to soil components. This compound can be highly mobile in soil; however, this movement is expected to be attenuated by the removal processes given above.

Data regarding the monitoring of acrolein are available for ambient and indoor air. Data from the EPA National Air Quality System (AQS) show the most recent mean acrolein concentrations in ambient air in the United States ranging between 0.062 and 0.591 ppbv (ppb based on volume) (EPA 2023a). For indoor air, acrolein concentrations range from <0.02 to 43 μg/m^3 (<0.02–18 ppbv), with the higher concentrations in this range typically being obtained from indoor environments where the combustion of tobacco products occurs (Chan et al. 2016; Seaman et al. 2007; Weber et al. 1979).

No current data indicate that acrolein is a contaminant of drinking water supplies in the United States. Acrolein was found in drinking water stored in polyethylene cisterns in Brazil (de Oliveira Moura et al. 2019). The Water Quality Portal (WQP) database data indicate that acrolein occurs at a low frequency in wastewater streams, ambient surface water, and groundwater in the United States (WQP 2023). Acrolein is intentionally introduced into irrigation canals and other waterways to control underwater plants and other aquatic life. No current information on the quantities of acrolein that are released into waterways as a pesticide are available.

Acrolein is a gaseous constituent of cigarette smoke and has been detected at levels equivalent to 3–220 μg per cigarette. Acrolein is formed when fats are heated to high temperatures. It has also been found in foods and food products such as raw cocoa beans, volatiles from cooked mackerel and white bread, and vegetable oils, wine, whiskey, and lager beer. Acrolein concentrations in food are typically under 40 μg/g, with most concentrations at ≤1 μg/g (WHO 2002). Acrolein can be produced endogenously as a product of lipid peroxidation (Uchida et al. 1998a, 1998b) and can form protein adducts that have been implicated in atherosclerosis and Alzheimer's disease.

Monitoring data indicate that the general population may be exposed to acrolein through inhalation of contaminated air and ingestion of certain foods. Because of the lack of recent, comprehensive monitoring data, the average daily intake of acrolein through the consumption of food and drinking water, and the relative importance of each of these sources of exposure, cannot be adequately determined. However, based on the assumption that all foods contain maximal reported levels of acrolein, an exposure of around 1 mg/person/day (17 g/kg body weight/day) may be estimated (Guth et al. 2013). Estimating the typical level of exposure to acrolein is complicated because acrolein is a common component of tobacco smoke, and there is wide variation among individuals regarding the frequency and level of exposure to tobacco smoke. Even so, estimates of acrolein exposure in both the general population and for nonsmokers living with a resident smoker are available. A study from Canada (Environment Canada 2000) suggests that the general population is exposed to an average acrolein concentration of 1.3 μg/m^3, with a median value of 0.6 μg/m^3 from outdoor and indoor air. Based on this average acrolein exposure and an inhalation volume of 20 m^3, it can be estimated that the average adult inhales 26 μg acrolein/day. Nazaroff and Singer (2004) estimated that the daily average inhalation intakes of acrolein through environmental tobacco smoke (ETS) over the lifetime of a nonsmoker are 22–50 μg/day for males and 16–36 μg/day for females.

These exposure levels for nonsmokers in a household with ETS are approximately 2.2–3.7 times higher than residents living within a household without ETS.

There is potential for exposure to acrolein in many occupational settings as the result of its varied uses and its formation during the combustion and pyrolysis of materials such as wood, petrochemical fuels, and plastics. As a result, it would be difficult to list all occupations in which work-related exposure to acrolein occurs. Occupational exposure can occur via inhalation and dermal contact.

5.2 PRODUCTION, IMPORT/EXPORT, USE, AND DISPOSAL

5.2.1 Production

Acrolein was first produced commercially in the 1930s through the vapor-phase condensation of acetaldehyde and formaldehyde (Etzkorn et al. 2002). A second method was developed in the 1940s, which involved the vapor-phase oxidation of propylene; however, this method was not used at first due to the poor performance of cuprous oxide catalysts. During the 1960s, propylene oxidation was greatly enhanced by the introduction of bismuth molybdate-based catalysts and has since become the primary method used for the commercial production of acrolein. Acrylic acid and carbon oxides are the major byproducts produced during this reaction. Minor byproducts are acetaldehyde, acetic acid, formaldehyde, and polyacrolein.

The national aggregate production volume of acrolein was between 250 million and <500 million pounds annually in the years 2016–2019, for five reporting companies (Arkema Inc; Baker Hughes, Inc; Evonik Corp; Halliburton; The Dow Chemical Company); specific information is not available based on confidential business information (CBI) (EPA 2022a).

Table 5-1 summarizes information on companies that reported the production, import, or use of acrolein for the Toxics Release Inventory in 2021 (TRI21 2023). The TRI data should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list.

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

State[a]	Number of facilities	Minimum amount on site in pounds[b]	Maximum amount on site in pounds[b]	Activities and uses[c]
AL	2	0	999,999	1, 3, 5, 6
CA	1	100,000	999,999	9
GA	1	1,000	9,999	1, 5
IA	28	0	99,999	1, 5, 9, 12, 13, 14
IL	11	0	99,999	1, 5, 12, 13, 14
IN	8	100	999,999	1, 5, 9, 13, 14
KS	7	0	9,999	1, 4, 5, 12, 13, 14
LA	2	100	999,999	1, 3, 4, 5, 6, 13, 14
MI	4	100	9,999	1, 5, 9, 13, 14
MN	8	0	99,999	1, 5, 9, 13, 14
MO	1	100	999	1, 5, 13, 14
NC	2	100	9,999	1, 5
ND	3	100	9,999	1, 5, 9, 13, 14
NE	15	0	99,999	1, 5, 9, 13, 14
NY	1	1,000	9,999	1, 13
OH	5	100	9,999	1, 5, 12, 13, 14
OK	1	0	99	1, 5
OR	1	100	999	1, 5, 13, 14
PA	1	100	999	1, 4, 13, 14
SC	2	0	99	1, 5
SD	6	100	99,999	1, 5, 9, 13, 14
TN	1	1,000	9,999	1, 5, 13, 14
TX	18	0	999,999	1, 3, 5, 6, 7, 12, 13, 14
VA	1	0	99	1, 5
WI	2	0	999	1, 5, 13, 14

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

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

Source: TRI21 2023 (Data are from 2021)

Acrolein is also produced within the body by the metabolism of other substances, such as allyl acetate, allyl alcohol, cyclophosphamide, and ifosfamide (Auerbach et al. 2008; Sakata et al. 1989).

5.2.2 Import/Export

The Baker Hughes Corporation reported that 630,960 pounds of acrolein were exported in 2019; however, the four other manufacturers declared these data as CBI or no exports (EPA 2022a). All five domestic chemical companies reporting to the CDR declared zero imports or that information as CBI in 2019 (EPA 2022a).

5.2.3 Use

The largest single use for acrolein is as an intermediate in the manufacture of acrylic acid, most of which is converted to its lower alkyl esters (IARC 2021). Acrolein is also used as an herbicide (trade name Magnacide H) and biocide (trade name Magnacide B) (NPIRS 2023). It is used as an herbicide in irrigation waters and drainage ditches to control algae and aquatic weeds, and as a biocide to control mollusks in recirculating process water systems; as a slimicide in the paper industry; as a biocide in oil wells and liquid petrochemical fuels; in the cross-linking of protein collagen in leather tanning; as a tissue fixative in histological samples; in the manufacture of colloidal forms of metals; in the production of perfumes; as a warning agent in methyl chloride refrigerant; and as an intermediate in the manufacture of methionine and its hydroxyl analogue, glutaraldehyde, allyl alcohol, pyridines, and tetrahydrobenzaldehyde (Arntz et al. 2012; Etzkorn et al. 2002; Hess et al. 1978; IARC 2021; Lewis 1997; NPIRS 2023; O’Neil 2013; Windholz et al. 1983). Isolated, refined acrolein is used mainly as a biocide and as an intermediate in the production of methionine, which is a protein supplement used in animal feed (Arntz et al. 2012; IARC 2021). Due to its pungent odor, acrolein was once added as a warning agent to methyl chloride refrigerant, which is no longer manufactured or used (IARC 2021). Acrolein has been used to make synthetic glycerol, acrolein polymers, polyurethane, and polyester resins (Lewis 1997). It has also been used in military poison gas mixtures (IARC 2021).

5.2.4 Disposal

Prior to implementing land disposal of waste residues (including waste sludge), environmental regulatory agencies should be consulted for guidance on acceptable disposal practices. Acrolein may be subject to explosive self-polymerization: discharge carefully into water; add excess 10% sodium bisulfite solution; dilute product with excess water and discharge into an oxidation pond; or transport without dilution to an incineration plant (WHO 1991). Materials containing small amounts of acrolein may be disposed of by neutralization (if needed), followed by secondary biological treatment or by submerged combustion (to concentrate the waste) followed by incineration (Hess et al. 1978). On-site combustion is an option for disposal if the spill site is in a very remote, inaccessible area, and there is danger of subsequent discharge if other methods of disposal are attempted.

Acrolein has been identified as a hazardous waste by the EPA, and the disposal of this compound is regulated under RCRA. Specific information regarding federal regulations concerning disposal of hazardous wastes through land treatment, landfilling, incineration, thermal treatment, chemical/physical/biological treatment, underground injection, and deep-sea injection are provided in the Code of Federal Regulations (40 CFR 190–399). Release of acrolein in wastewater is regulated under the Clean Water Act by the National Pollutant Discharge Elimination System (NPDES).

Information regarding effluent guidelines and standards for acrolein may be found in 40 CFR 122, 40 CFR 125, 40 CFR 268, 40 CFR 413, 40 CFR 423, and 40 CFR 433 (EPA 2022b, 2022c, 2022d, 2022e, 2022f, 2022g).

Pursuant to RCRA Section 3004(g)(5), EPA has proposed to restrict the land disposal of acrolein (EPA 1989). Acrolein may be land disposed only if prior treatment standards have been met, or if disposal occurs in units that satisfy the statutory no migration standard (EPA 1989). Proper guidelines and standards are outlined in the Federal Register (EPA 1989).

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 2022i). 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's North American Industry Classification System (NAICS) codes is covered under EPCRA Section 313 or is a federal facility; and if their facility manufactures (defined to include importing) or processes any TRI chemical in excess of 25,000 pounds, or otherwise uses any TRI chemical in excess of 10,000 pounds, in a calendar year (EPA 2022i).

5.3.1 Air

Estimated releases of 330,370 pounds (~149.85 metric tons) of acrolein to the atmosphere from 135 domestic manufacturing and processing facilities in 2021, accounted for about 97% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2023). These releases are summarized in Table 5-2.

Table 5-2. Releases to the Environment from Facilities that Produce, Process, or Use Acrolein[a]

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
AL	2	1,250	0	0	0	0	1,250	0	1,250
CA	1	3	0	0	0	5	3	5	8
CO	2	0	0	0	0	0	0	0	0
GA	1	7,928	0	0	0	0	7,928	0	7,928
IL	9	14,098	87	0	0	0	14,098	87	14,185
IN	8	11,884	0	0	0	0	11,884	0	11,884
IA	27	128,322	634	0	1	0	128,900	57	128,957
KS	7	22,012	0	0	0	0	22,012	0	22,012
LA	2	1,549	1	0	0	0	1,550	0	1,550
MI	4	7,627	0	0	0	0	7,627	0	7,627
MN	8	12,172	0	0	0	0	12,172	0	12,172
MO	2	1,721	0	0	0	0	1,721	0	1,721
NE	15	51,921	0	0	5	0	51,926	0	51,926
NY	1	3,543	0	0	0	0	3,543	0	3,543
NC	2	14,826	4	0	0	80	14,830	80	14,910
ND	3	5,844	0	0	0	0	5,844	0	5,844
OH	5	6,948	0	7,028	0	0	13,976	0	13,976
OK	1	1,373	0	0	0	0	1,373	0	1,373
OR	1	281	0	0	0	0	281	0	281
PA	1	2,011	0	0	0	0	2,011	0	2,011
SC	2	2,020	0	0	0	0	2,020	0	2,020
SD	6	11,852	0	0	0	0	11,852	0	11,852
TN	1	3,601	0	0	0	0	3,601	0	3,601
TX	20	2,936	582	3,022	0	0	5,958	582	6,540
VA	1	12,987	0	0	0	0	12,987	0	12,987

Table 5-2. Releases to the Environment from Facilities that Produce, Process, or Use Acrolein[a]

		Reported amounts released in pounds per year[b]							
							Total release		
State[c]	RF[d]	Air[e]	Water[f]	UI[g]	Land[h]	Other[i]	On-site[j]	Off-site[k]	On- and off-site
WI	3	1,661	0	0	0	0	1,661	0	1,661
Total	135	330,370	1,307	10,050	6	85	341,008	811	341,819

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

RF = reporting facilities; UI = underground injection

Source: TRI21 2023 (Data are from 2021)

Potential sources of atmospheric release of acrolein include emissions from facilities involved in the manufacture or use of products containing acrolein; volatilization from treated waters and contaminated waste streams; formation as a photooxidation product of various hydrocarbon pollutants such as propylene, 1,3-butadiene, and other dienes; emissions from combustion processes; and use in petroleum operations (DOI 1994; Ghilarducci and Tjeerdema 1995; Graedel et al. 1978; Maldotti et al. 1980; WHO 1991, 2002).

Specific combustion sources include exhaust gas from engines powered by gasoline, diesel or other petrochemical fuels, power plants, burning vegetation (i.e., forest fires), combustion of cellulose materials such as wood, cotton, tobacco, and marijuana, and combustion of polyethylene plastics (EPA 1998a; 1998b; Hodgkin et al. 1982; Jonsson et al. 1985; Lipari et al. 1984; Spada et al. 2008; WHO 1991, 2002). Acrolein is also a pyrolysis product of polyethylene, animal fats and vegetable oils, cellophane, plastics, and paraffin wax (Boettner and Ball 1980; Chiang et al. 2022; EPA 1980; Potts et al. 1978; Tanne 1983; Wharton 1978). The concentrations of acrolein in emissions from various combustion and pyrolysis processes are listed in Table 5-3.

Table 5-3. Acrolein in Emissions from Combustion

Source	Concentration	References
Auto exhaust gas		
Gasoline engine	Not detected to 27.7 ppm (detection limit 0.01 ppm); 0–7.79% of total aldehydes, excluding acetone	IARC 2021; Lipari and Swarin 1982; Nishikawa et al. 1987a; Seizinger and Dimitriades 1972; Sigsby et al. 1987; Zweidinger et al. 1988
Gasoline engine	0.16 mg/L gasoline	Grosjean et al. 2001
	0.01–0.26 mg/mile	Baldauf et al. 2005
Diesel engine	2.26 mg/L diesel fuel	Grosjean et al. 2001
Diesel engine	0.05–0.3 ppm	IARC 2021; Seizinger and Dimitriades 1972
Ethanol engine	Not detected (detection limit 0.01 ppm)	Lipari and Swarin 1982
Cigarette smoke	3–220 µg/cigarette	Dong et al. 2000; Guerin et al. 1987; Hoffmann et al. 1975; Horton and Guerin 1974; Lau et al. 1997; Magin 1980; Manning et al. 1983
	1.6–22 µg/cigarette with carbon filter	Thweatt et al. 2007
Marijuana smoke	92–145 µg/cigarette	Hoffmann et al. 1975; Horton and Guerin 1974
e-cigarette vapor	<9.28–9,180 ng/puff	Belushkin et al. 2020; Gillman et al. 2020
Smoke		
Wood	50 ppm	Einhorn 1975
Cotton	60 ppm	
Kerosene	<1 ppm	
Emissions from woodburning fireplaces	21–132 mg/kg wood 20–103 mg/kg wood	Lipari et al. 1984 EPA 1993
Softwood	46.90 mg/kg wood	McDonald et al. 2000
Hardwood	91.23 mg/kg wood	
Hardwood, wood stove	45.54 mg/kg wood	
Emissions from power plants		
Coal-fueled	0.002 pounds of aldehydes/ 1,000 pounds of fuel	Natusch 1978
Gas-fueled	0.2 pounds of aldehydes/1,000 pounds of fuel	
Oil-fueled	0.1 pounds of aldehydes/1,000 pounds of fuel	
Pyrolysis of polyvinyl chloride food-wrap film during hot wire cutting	27–151 ng/cut	Boettner and Ball 1980

Table 5-3. Acrolein in Emissions from Combustion

Source	Concentration	References
Emissions from the combustion of polyethylene foam	2–23 ppm	Potts et al. 1978
Pyrolysis of polyethylene foam	76–180 ppm	Potts et al. 1978
15 cm above heated cooking oil	2.5–30 mg/m^3	EPA 1980
Emissions from burning candle	0.18 μg/kg	Lau et al. 1997

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. Emissions are estimated 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. Acrolein emissions estimated from the 2017 inventory are summarized in Table 5-4.

Table 5-4. Acrolein Emissions to the Air Based on 2017 National Emissions Inventory (NEI)

Emission sector	Pounds emitted
Bulk gasoline terminals	201
Fires, prescribed fires	47,288,355
Fires, wildfires	90,147,017
Fuel combustion, commercial/institutional, biomass	40,794
Fuel combustion, commercial/institutional, coal	378
Fuel combustion, commercial/institutional, natural gas	41,834
Fuel combustion, commercial/institutional, oil	1,114
Fuel combustion, commercial/institutional, other	1,613
Fuel combustion, electric generation, biomass	207,929
Fuel combustion, electric generation, coal	103,362
Fuel combustion, electric generation, natural gas	61,135
Fuel combustion, electric generation, oil	861
Fuel combustion, electric generation, other	23,726
Fuel combustion, industrial boilers, ICEs, biomass	691,309
Fuel combustion, industrial boilers, ICEs, coal	5,419
Fuel combustion, industrial boilers, ICEs, natural gas	3,699,365

Table 5-4. Acrolein Emissions to the Air Based on 2017 National Emissions Inventory (NEI)

Emission sector	Pounds emitted
Fuel combustion, industrial boilers, ICEs, oil	6,154
Fuel combustion, industrial boilers, ICEs, other	9,827
Fuel combustion, residential, other	0
Fuel combustion, residential, wood	1,841,371
Gas stations	0
Industrial processes, cement manufacturing	32
Industrial processes, chemical manufacturing	195,644
Industrial processes, ferrous metals	6,939
Industrial processes, mining	8
Industrial processes, not elsewhere classified	212,798
Industrial processes, non-ferrous metals	5,707
Industrial processes, oil and gas production	3,238,585
Industrial processes, petroleum refineries	9,935
Industrial processes, pulp and paper	412,298
Industrial processes, storage and transfer	5,904
Miscellaneous non-industrial, not elsewhere classified	147,237
Mobile, aircraft	2,470,330
Mobile, commercial marine vessels	159,792
Mobile, locomotives	837,941
Mobile, non-road equipment, diesel	3,194,566
Mobile, non-road equipment, gasoline	655,099
Mobile, non-road equipment, other	76,384
Mobile, on-road diesel heavy duty vehicles	1,463,230
Mobile, on-road diesel light duty vehicles	532,979
Mobile, on-road gasoline heavy duty vehicles	29,545
Mobile, on-road gasoline light duty vehicles	1,684,985
Solvent, degreasing	270
Solvent, graphic arts	15
Solvent, industrial surface coating and solvent use	8,015
Waste disposal	257,242

ICE = internal combustion engine

Source: EPA 2022h

Formation of acrolein in air is known to occur through photochemical reactions of VOCs that are released from a number of differing source types, including solvent and fuel vapors and automobile exhaust (Ghilarducci and Tjeerdema 1995; Liu et al. 1999a; 1999b). Acrolein has been produced by the photodegradation of plastic debris (Lomonaco et al. 2020). Seaman et al. (2007) measured the emission of acrolein from building materials used in homes; results are summarized in Table 5-5.

Table 5-5. Acrolein Emissions from Building Material

Source	Concentration
Latex paint	0.35 ng/g of material
Particle board	1.0 ng/g of material
Lumber	
Pine	5.9 ng/g of material
Douglas fir	8.1 ng/g of material
Yellow poplar and red oak	1.0 ng/g of material
Redwood lumber	1.3 ng/g of material

Source: Seaman et al. 2007

The intentional release of acrolein into irrigation channels as an herbicide and molluscicide also results in the volatilization of acrolein into air (DOI 1994; EPA 2003; Ghilarducci and Tjeerdema 1995). In the San Joaquin Valley of California, it was reported that 194,668 pounds (97.3 tons) of acrolein were emitted into the air from agricultural uses of the pesticide in 2001, which amounted to 1.4% of the total pesticide emissions from this region (CEPA 2002).

Another source of acrolein is through the emissions from dairy silages and other feedstuffs (Malkina et al. 2011). Acrolein was released into the air from a cowshed, oxidation pond, and solid-liquid separation tank on a large dairy farm (Guo et al. 2019). When deep-frying using palm, soybean, or olive oil, acrolein was released at rates of 73.4–674 μg/m^3 (Chiang et al. 2022).

5.3.2 Water

Estimated releases of 1,307 pounds (~0.59 metric tons) of acrolein to surface water from 135 domestic manufacturing and processing facilities in 2021, accounted for < 1% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2023). This estimate includes releases to wastewater treatment and publicly owned treatment works (POTWs) (TRI21 2023). These releases are summarized in Table 5-2.

Acrolein may be released to water in effluents from its manufacturing plants and use facilities (see Section 5.2.3 for specific information regarding uses) and from its direct application to water as a broadrange biocide in irrigation canals, cooling towers, water treatment basins, and process water circuits (DOI 1994; EPA 2003; Ghilarducci and Tjeerdema 1995; IARC 2021; Lue-Hing et al. 1981; Nordone et al. 1996a, 1996b; WHO 1991; WSSA 1983).

Acrolein in effluent concentrations from seven types of potable water reuse systems were reported as <0.010–0.333 μg/L (Marron et al. 2020).

The amount of acrolein released from industrial operations to publicly owned treatment works (POTWs) in U.S. waters in 1986 was estimated to be 1,645,600 pounds/year (823 tons/year) (EPA 1991). However, it was reported that a large portion of the acrolein received by POTWs is removed before discharge in effluent streams, with 5% released to surface waters, 0–5% to air, and 10% to sludge (EPA 1991).

Data on the release of acrolein into water as a consequence of its use as a pesticide are available only for the state of California. It is reported that usage of acrolein in California declined from 328,238 pounds (164 tons) in 1999 to 290,180 pounds (145 tons) and 233,928 pounds (117 tons) in 2000 and 2001, respectively (EPA 2003). The predominant use of acrolein is as an aquatic herbicide with releases into rights-of-way (i.e., irrigation canals) and other water areas amounting to 326,767 pounds (163 tons), 297,320 pounds (149 tons), and 239,362 pounds (120 tons) in 1999, 2000, and 2001, respectively. The decrease in acrolein usage is due to changes in the permitting process required prior to acrolein treatment of irrigation canals instituted in 2001. No current information is available on the usage of acrolein after the permitting process changed.

5.3.3 Soil

Estimated releases of 6 pounds (~0.0027 metric tons) of acrolein to soil from 135 domestic manufacturing and processing facilities in 2021, accounted for < 1% of the estimated total environmental releases from facilities required to report to the TRI (TRI21 2023). An additional 10,050 pounds (~4.56 metric tons), constituting about 3% of the total environmental emissions, were released via underground injection (TRI21 2023). These releases are summarized in Table 5-2.

The occurrence of acrolein in soil at one hazardous waste site in the United States and leachate from several municipal landfills provides evidence that this compound has been released to soil as the result of land disposal of some organic wastes (ATSDR 2022a; TRI21 2023). No data were located regarding the amount of acrolein released to soil.

5.4 ENVIRONMENTAL FATE

5.4.1 Transport and Partitioning

Air. Acrolein is relatively unstable in the atmosphere; therefore, transport within the atmosphere is expected to be limited. The relatively high vapor pressure of acrolein (274 mm Hg at 25°C [Daubert and Danner 1987]) suggests that this compound will not partition from the vapor phase to particulates in the atmosphere. Occurrence of acrolein in rainwater (Grosjean and Wright 1983; Nishikawa et al. 1987b) indicates that this compound may be removed from the atmosphere by washout.

Water. Volatilization is expected to be a significant removal process for any acrolein released to surface waters (Nordone et al. 1996a, 1996b). Based on a measured Henry's law constant of 1.22×10^{-4} atm-m^3/mol at 25 °C (Gaffney et al. 1987), the volatilization half-life from a model river 1 m deep, flowing 1 m/second with a wind speed of 3 m/second, was estimated to be 23 hours using the method of Thomas (1982).

Sediment and Soil. Using a linear regression equation based on log octanol/water partition coefficient (K_{ow}) data (Lyman 1982), an adsorption coefficient (K_{oc}) of 24 was estimated, which suggests that adsorption of acrolein to suspended solids and sediments in water would not be significant. This does not take into account the reactivity of acrolein, which could lead to the removal of acrolein from water through chemical binding of the compound to dissolved or suspended organics in water and sediments. The relatively low estimated K_{oc} value suggests that acrolein will be highly mobile in soil and that this compound has the potential to leach (Swann et al. 1983). The relatively high vapor pressure of acrolein and its volatility from water suggest that this compound will evaporate rapidly from soil surfaces and that volatilization is probably a major removal process from soil. Degradation processes and volatilization, however, are expected to significantly retard movement of acrolein through soil.

Other Media. Veith et al. (1980) measured a bioconcentration factor (BCF) of 344 for acrolein in bluegill sunfish; however, this may be an overestimate, since total ^{14}C was measured in the fish, which may have resulted in the measurement of acrolein metabolites. A BCF of 0.6 was estimated for acrolein using a linear regression equation based on a log K_{ow} of -0.01 (Bysshe 1982; Hansch and Leo 1995). These BCFs, as well as the relatively high water solubility of this compound, suggest that acrolein does not bioconcentrate significantly in aquatic organisms. Acrolein did not accumulate in leaf lettuce after both single and multiple applications in irrigation water at a concentration of 75 ppm (Nordone et al. 1997). Acrolein residues in the lettuce fell to 0% within 53 days following the initial application.

5.4.2 Transformation and Degradation

Air. The dominant removal process for acrolein in ambient air is predicted to be a reaction with photochemically generated hydroxyl radicals in the troposphere. The atmospheric half-life for acrolein is estimated to be 15–20 hours, based on experimentally determined hydroxyl radical reaction rate constants ranging between 1.90×10^{-11} and 2.53×10^{-11} cm^3/molecules-second at 25–26°C and an average ambient hydroxyl radical concentration of 5.0×10^5 molecules/cm^3 (Atkinson 1985). Acrolein reacts with hydroxyl radicals as both an olefin and an aldehyde (Grosjean 1990). Products of this reaction include carbon monoxide, formaldehyde, glyoxal, and glycolaldehyde. In the presence of nitrogen oxides, products include peroxynitrate, acryloylperoxy nitrate, nitric acid, glycidaldehyde, malonaldehyde, and β-hydroxypropionaldehyde (Edney et al. 1986; Grosjean 1990; Liu et al. 1999b; Salgado et al. 2008).

Direct photolysis in the ambient atmosphere occurs but is expected to be of minor importance. Gardner et al. (1987) reported that the quantum yields for irradiation of acrolein at low air pressures were 0.0066 at 313 nm and 0.0044 at 334 nm. The study authors used a computer analysis of their photodissociation data to estimate the half-life of acrolein to be 10 days in the lower troposphere and <5 days in the upper troposphere.

Experimental data indicate that reaction of acrolein with ozone ($k=2.8 \times 10^{-19} cm^3$/molecules-second at 25°C; half-life, 59 days) or nitrate radicals ($k=5.9 \pm 2.8 \times 10^{-16}$ cm^3/molecules-second at 25°C; half-life, 16 days) in the troposphere would be too slow to be environmentally significant (Atkinson 1985; Atkinson et al. 1987). However, Salgado et al. (2008) measured a faster reaction rate with the nitrate radical of 3.30×10^{-15} cm^3/molecules-second at 25°C; this rate results in a lifetime of 168 hours (7 days), which corresponds to a half-life of 116 hours. The fate of acrolein in indoor air is expected to be different from its fate in outdoor air because of differences in the concentrations of oxidants in indoor air compared to outdoor air and the possibility of other mechanisms of removal.

Water. Low concentrations of acrolein may degrade in natural water by either aerobic biodegradation or reversible hydration to β-hydroxypropionaldehyde, which subsequently undergoes aerobic biodegradation (Bowmer and Higgins 1976; EPA 1979; Ghilarducci and Tjeerdema 1995; Tabak et al. 1981). Acrolein at a concentration of 5–10 mg/L was completely degraded in 7–10 days in a static culture flask screening procedure (Tabak et al. 1981). Acrolein applied to surface waters at application rates suggested for herbicidal use can persist up to 6 days (WSSA 1983). Bowmer and Higgins (1976) measured acrolein removal in both laboratory water and in field experiments using irrigation channels. Their studies suggested that the degradation of the hydration product of acrolein, β-hydroxypropionaldehyde, occurs after the concentration of acrolein falls below 2–3 ppm. The degradation of β-hydroxypropionaldehyde was also preceded by a 100-hour lag period, suggesting that biodegradation was occurring through the action of acclimated cultures.

In buffered laboratory water, acrolein reached equilibrium with its degradation products (predominantly β-hydroxypropionaldehyde) in approximately 300 hours; in irrigation channels, acrolein removal was complete. Half-lives were reportedly <1–3 days in surface water, but values were for the combined effect of degradation and volatilization (Bowmer and Higgins 1976; Bowmer et al. 1974). Kissel et al. (1978) measured acrolein removal in buffered laboratory water and natural river water using both chemical analysis methods and bioassays. Complete hydrolysis (which, according to the study authors, includes hydration to β-hydroxypropionaldehyde) occurred within 150, 120–180, and 5–40 hours in buffered solutions at 22°C and pH 5, 7, and 9, respectively. Based on fish kill bioassays in natural river water at pH 8.1, >93% degradation of acrolein occurred within 6 days. The half-lives of acrolein in aerobic test systems that were treated at an application rate of 15 mg/L were 9.5 hours in water and 7.6 hours in sediment (Smith et al. 1995). The half-lives of acrolein in anaerobic test systems treated at the same rate were 10.3 hours in water and approximately 10 days in sediment. Degradation products included β-hydroxypropionaldehyde, acrylic acid, allyl alcohol, propanol, 3-hydroxypropionic acid, propionic acid, glyceric acid, and oxalic acid, which indicate that hydrolysis, oxidation, and reduction contributed to the degradation of acrolein during this study.

Marron et al. (2020) studied acrolein in potable water reuse systems. The second-order rate constant of acrolein with aquatic hydroxyl radical was 7.0×10^9/moles-second; this indicates that it would not be a significate route of removal.

The decay rate constants for acrolein applied to irrigation canals have been reported to be similar (0.14–0.21) regardless of the difference in time-concentration regimens (100 μg/L for 48 hours to 15,000 μg/L for several hours) (DOI 1994). The half-life of acrolein, applied at a flow rate of 3,964 L/second to achieve 15 ppm for 1 hour, was 10.2 hours in a weedy canal and 7.3 hours in a non-weedy canal (Nordone et al. 1996b; USGS 1998). The concentration of acrolein was 25 μg/L in samples from the Columbia River collected 65 km from where it was applied at a concentration of 125 μg/L (DOI 1994).

Nordone et al. (1996a) studied the dissipation of acrolein applied to agriculture canals with flow rates of 142, 283, and 453 L/second to achieve target concentrations of 7.5, 11.6, and 10.4 ppm, respectively. The study authors concluded that typical application of acrolein as an aquatic herbicide in agricultural canals does not result in the introduction of acrolein into natural receiving waters 2.7 km downstream.

The ultraviolet (UV) spectrum of acrolein in hexane shows moderate absorption of UV light in the environmentally significant range (wavelengths >290), suggesting that acrolein might undergo photolysis in natural waters; however, hydration of acrolein destroys the chromophores that absorb UV light (EPA 1979), and the equilibrium appears to be far on the side of the hydration product. Thus, the potential for direct photolysis of acrolein in natural waters is probably slight. Oxidation of small amounts of acrolein in natural waters would not be environmentally significant; however, highly concentrated acrolein solutions (i.e., spills) may be polymerized by oxidation or hydration processes (EPA 1979). Insufficient data are available regarding anaerobic biodegradation to establish the significance of this process as a removal mechanism or to determine the rate at which such a process would proceed. This information would be particularly useful in determining the fate of acrolein under conditions frequently encountered in groundwater and in landfills.

Based on the reactivity and nucleophilicity of acrolein, it is expected that acrolein has the potential to react with dissolved and suspended organics in water. This removal process would become increasingly important for determining the fate of acrolein in water as the concentration of organics in water increased. However, no studies have been conducted to describe this possible route for removal of acrolein from water.

Sediment and Soil. Experimental data specifically pertaining to the degradation or transformation of acrolein in soil were not located. Results of studies in aquatic systems suggest that acrolein, at low concentrations, may be subject to aerobic biodegradation in soil or transformation via hydration followed by aerobic biodegradation of the hydrated product.

Since acrolein is a very reactive compound, abiotic processes, such as oxidation or conjugation with organic matter in soils, may be the most important degradation processes. However, no information could be located for these possible acrolein reaction pathways in soil.

5.5 LEVELS IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to acrolein depends, in part, on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of acrolein 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 acrolein 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.

Table 5-6 shows the lowest limits of detections achieved by analytical analysis in various environmental media. An overview summary of the range of concentrations detected in environmental media is presented in Table 5-7.

Table 5-6. Lowest Limit of Detection Based on Standards[a]

Media	Detection limit	Reference
Air	0.012 μg/m^3	Cahill (2010)
Drinking water	0.7 μg/L	EPA (1984)
Surface water and groundwater	0.7 μg/L	EPA (1984)
Soil	43 μg/kg	WQP (2023)
Sediment	2.1 μg/kg	WQP (2023)
Urine[b]	13 μg/L	CDC (2021)

[a]Detection limits based on using appropriate preparation and analytics. These limits may not be possible in all situations.
[b]Metabolite: 3-hydroxypropyl mercapturic acid.

Table 5-7. Summary of Environmental Levels of Acrolein

Media	Low	High	For more information
Outdoor air (μg/m^3)	<0.02	0.985	Section 5.5.1
Indoor air (μg/m^3)	<LOD	57.63	Section 5.5.1
Surface water (μg/L)	<LOD	7.5	Section 5.5.2
Groundwater (μg/L)	<LOD	12,000	Section 5.5.2
Food (μg/kg or L)	0.25	198,100	Section 5.5.4

LOD = limit of detection

Detections of acrolein in air, water, and soil at NPL sites are summarized in Table 5-8.

Table 5-8. Acrolein Levels in Water, Soil, and Air of National Priorities List (NPL) Sites

Medium	Median[a]	Geometric mean[a]	Geometric standard deviation[a]	Number of quantitative measurements	NPL sites
Water (ppb)[b]	NA	NA	NA	2	2
Soil (ppb)[b]	NA	NA	NA	2	1
Air (ppbv)	3.1	2.76	5.32	7	5

[a] Concentrations found in ATSDR site documents from 1981 to 2022 for 1,868 NPL sites (ATSDR 2022a). Maximum concentrations were abstracted for types of environmental media for which exposure is likely. Pathways do not necessarily involve exposure or levels of concern.

[b] There were not enough data found to calculate the median, mean, and standard deviations for these values.

5.5.1 Air

The atmospheric concentrations of acrolein have been measured in several locations, and the most comprehensive monitoring studies are discussed below. Data for 2015–2022 obtained from EPA's Air Quality System (AQS) database are presented in Table 5-9 (EPA 2023a). Data for 2022 show average concentrations of acrolein at various monitoring stations ranging from 0.062 to 0.591 ppbv (0.14–1.36 μg/m^3), with maximum values of 1.27 ppbv (2.91 μg/m^3). Data obtained for 2019 show similar average concentrations for acrolein, ranging from 0.060 to 0.482 ppbv (0.14–1.11 μg/m^3) with a maximum value of 1.21 ppbv (2.77 μg/m^3). Higher average concentrations of 0.071–1.028 ppbv (0.16–2.36 μg/m^3) for acrolein, with a maximum value of 11.1 ppbv (25.45 μg/m^3), were found for 2016. The National Air Toxics Monitoring Program (EPA) reported peak concentrations for acrolein of <1 ppbv (2.3 μg/m^3) at 12 monitoring sites, with 1 site reporting a peak concentration of 1–5 ppbv (2.3–11.46 μg/m^3) (Mohamed et al. 2002). These data were obtained in 1996 at 13 monitoring sites in New Jersey, Louisiana, Texas, and Vermont. Following the Norfolk Southern train derailment in East Palestine, Ohio on February 3, 2023, atmospheric samples obtained on February 20–21, 2023 showed acrolein levels in East Palestine up to 6 times higher than rural background concentrations near Pittsburgh, Pennsylvania (Oladeji et al. 2023). EPA sampling data from February to March 2023 showed a maximum concentration of approximately 0.35 ppbv (0.81 μg/m^3) obtained on February 9, 2023 (EPA 2023b).

Table 5-9. Summary of Annual Concentration of Acrolein (ppbv) Measured in Ambient Air at Locations Across the United States[a,b]

Year	Number of monitoring locations	Number of samples	Lowest arithmetic mean at all locations	Average arithmetic mean at all locations	Highest arithmetic mean at all locations	Maximum concentration
2015	29	1,703	0.049	0.255	0.657	8.9
2016	49	2,650	0.071	0.321	1.028	11.1
2017	66	3,418	0.053	0.276	0.653	4.6
2018	61	3,336	0.037	0.228	0.498	1.7
2019	56	2,907	0.060	0.206	0.482	1.21
2020	60	3,478	0.081	0.192	0.469	4.83
2021	77	5,755	0.053	0.213	0.545	2.56
2022	61	1,702	0.062	0.224	0.591	1.27

[a]Values were originally reported in parts per billion carbon (ppbC) and converted to ppbv.
[b]24-hour sampling period.

Source: EPA 2023a

Background acrolein concentrations were estimated at <0.02 μg/m^3 based on data from the National Air Toxics Trends Sites network for 2001–2002 (McCarthy et al. 2006). Acrolein levels in congested areas of Camden, New Jersey were 0.1–5.5 μg/m^3 in a study conducted in 2004–2006 (Lioy et al. 2011). Logue et al. (2010) studied air pollutant concentrations at four sites in Pennsylvania from 2006 to 2008 and found acrolein arithmetic mean concentrations of 0.07–0.23 μg/m^3.

A concentration of acrolein in ambient air in California has been estimated to average 0.36 μg/m^3 (0.16 ppb) and is based on emissions and census tract data obtained in 1999 (Morello-Frosch et al. 2000). The concentration of acrolein was determined at 39 sites representing coastal, remote, intermediate, and urban areas of California in 2013 (Cahill 2014). Corresponding concentrations were <0.041–0.130 μg/m^3 (10 coastal sites), <0.041–0.160 μg/m^3 (10 remote sites), <0.041–0.110 μg/m^3 (8 intermediate sites), and 0.046–0.410 μg/m^3 (11 urban sites) (Cahill 2014). In the 2007 Harbor Community Monitoring Study (HCMS), a saturation monitoring campaign in the communities adjacent to the Ports of Los Angeles and Long Beach, California, mean acrolein concentrations of 0.01 and 0.03 ppbv (0.023 and 0.069 μg/m^3) were detected during the summer and winter, respectively (Mason et al. 2011). Acrolein ambient air concentrations in Roseville, California near several high-traffic roads showed fluctuations throughout the day peaking between 6 pm and midnight (Spada et al. 2008). The mean summer and winter time concentrations were 0.158 and 0.012–0.028 μg/m^3, respectively. The California Air Resources Board's Monitoring and Laboratory Division routinely determined acrolein concentrations at the same site and recorded mean concentrations of 0.985 μg/m^3 in 2005 and 1.240 μg/m^3 in 2006 (Spada et al. 2008). Ambient air concentrations of acrolein at the Oakland-San Francisco Bay Bridge Toll Plaza obtained in April 2001 showed differing concentrations between morning and evening measurements. Acrolein concentrations ranged from 0.096 to 0.140 μg/m^3 (0.041–0.060 ppb) during the morning commute, which were lower than the concentrations of 0.031–0.047 and 0.058–0.079 μg/m^3 (0.013–0.020 and 0.025–0.034 ppb) during two evening monitoring periods taken on consecutive days (Destaillats et al. 2002).

Acrolein levels in a tire smoke plume were 17.8 times higher than background levels when measured 300 m from an uncontrolled burn at a landfill in Iowa City, Iowa (Singh et al. 2015). Acrolein concentrations in the air near industrial fires are summarized in Table 5-10 (Griffiths et al. 2022).

Table 5-10. Acrolein Concentrations (ppm) at Ground Level During Industrial Fires

Primary burning material	Number of observations	Minimum to maximum	Median	Mean (SD)
Tires and tire crumble	3,706	0.00–1.46	0.56	0.53 (0.34)
Dry mixed recyclables	5,274	0.00–66.60	0.29	0.85 (1.55)
Timber and wood products	2,443	0.00–51.20	0.52	0.61 (1.93)
WEEE	100	0.00–0.94	0.35	0.36 (0.25)
Residual mixed wastes	2,178	0.00–9.04	0.46	0.66 (0.70)
Chemical manufacture	282	0.00–0.77	0.10	0.17 (0.19)

SD = standard deviation; WEEE = waste electrical and electronic equipment

Source: Griffiths et al. 2022

Acrolein concentrations in wildfire smoke are summarized in Table 5-11; the highest concentrations are found in actively forming smoke and dissipate as the smoke ages (O'Dell et al. 2020).

Table 5-11. Concentration of Acrolein (μg/m^3) Measured in Fresh and Aged Western U.S. Wildfire Smoke

Smoke type[a]	Number of observations	Percent detected (%)	Median	25th percentile	75th percentile
Young	344	100	0.0124	0.0092	0.0166
Medium	462	100	0.0051	0.003	0.0071

Table 5-11. Concentration of Acrolein (μg/m^3) Measured in Fresh and Aged Western U.S. Wildfire Smoke

Smoke type[a]	Number of observations	Percent detected (%)	Median	25th percentile	75th percentile
Old	83	55.4	0.0001	0	0.0004
Extra old	11	45.5	0	0	0.0003

[a]Designated young if 2-methylfuran >0.7 ppt; medium if 2-methylfuran was not elevated but acrolein was >7.4 ppt; and old if 2-methylfuran and acrolein were not elevated, but acrylonitrile was >2.9 ppt.

Source: O'Dell et al. 2020

Acrolein has been detected in indoor air and its concentrations are summarized in Table 5-12. The concentrations of acrolein range from 0.85 to 12.2 μg/m^3 in residential homes (Highsmith and Zweidinger 1988; Seaman et al. 2007). Acrolein concentrations are found to be typically higher in indoor air when comparing paired indoor/outdoor samples taken at a site (Seaman et al. 2007; Scheepers et al. 2017). Yin et al. (2021) studied carbonyl compounds concentrations in airliner cabins and found acrolein in conjunction with acetone at average concentrations of 20.7 μg/m^3. A review of ATSDR public health assessments for sites that evaluated soil vapor intrusion identified three sites with indoor air acrolein concentrations ranging from 6.4 to 30 μg/m^3 (ATSDR 2004a, 2004b, 2005; Burk and Zarus 2013).

Table 5-12. Acrolein Concentrations in Indoor Air

Type of building	Concentration	Location	References
Residential	0.36–1.95 ppbv (0.85–4.62 μg/m^3)[a]	Raleigh, North Carolina	Highsmith and Zweidinger 1988
Residential Semi-rural	3.5-12.2 μg/m^3 7.35 μg/m^3 (average)	Yolo County, California	Seaman et al. 2007
Residential Suburban	2.1–6.1 μg/m^3 3.5 μg/m^3 (average)	Placer County, California	
Residential Urban	2.5–6.5 μg/m^3 4.2 μg/m^3 (average)	Los Angeles County, California	
Restaurants	8–18 ppb (19–43 μg/m^3)[a]	Zürich, Switzerland	Weber et al. 1979
Hospital		Radboudumc, The Netherlands	Scheepers et al. 2017
Helicopter platform[b]	0.15–0.17 μg/m^3		
Dentistry building[b]	0.24–0.32 μg/m^3		
Kindergarten[b]	0.17–0.19 μg/m^3		
Hospital	0.1–18.1 μg/m^3	Rennes, France	Bessonneau et al. 2013

Table 5-12. Acrolein Concentrations in Indoor Air

Type of building	Concentration	Location	References
Grocery stores	1.7–26 μg/m^3	North Coast, Central Valley, South Coast, California	Chan et al. 2016
Hardware/furniture stores	0.02–3.9 μg/m^3		
Apparel stores	3.0 μg/m^3		
Student lounge			
Nonsmoking	0.8–1.6 μg/m^3	Bounds Green, United Kingdom	Williams et al. 1996
Smoking	6.4 μg/m^3		
Tavern	21–24 μg/m^3	Research Triangle Park, North Carolina	Löfroth et al. 1989
Airline cabin	<LOD–57.63 μg/m^3	28 at 1–4-hour flights; 5 at 4–10-hour flights; 23 at 10–14-hour flights	Yin et al. 2021

[a] Converted measurement in ppbv to μg/m^3, assuming an ambient temperature of 20°C and an atmospheric pressure of 1,013 mbars.

[b] 7th floor at helicopter pad; front desk in dentistry building; first floor office in kindergarten.

LOD = limit of detection; ppbv = parts per billion by volume

5.5.2 Water

According to the WQP database, from 2005 to 2019, acrolein has been detected in 20% of 69 surface water samples at average concentrations of 0.97–4.44 μg/L (WQP 2023). For groundwater sample data, acrolein was found in ~76% of 2,052 samples for the years 2005–2009; the average concentration was reported as 135.79 μg/L. Acrolein was not detected in 178 groundwater samples reported for 2010–2023 (WQP 2023).

Acrolein is a chemical that is on the EPA contaminant candidate list for study in the Unregulated Contaminant Monitoring Rule (UCMR), which collects drinking water data on substances that are suspected to be present in drinking water but do not have health-based standards set under the Safe Drinking Water Act (SDWA) (EPA 2019). The latest round of monitoring did not include acrolein as one of the chemicals chosen for study. Acrolein was found in drinking water stored in polyethylene cisterns in Brazil at concentrations of <3–115 μg/L; 75% were above the potability limit (de Oliveira Moura et al. 2019). Other data regarding drinking water were not located.

5.5.3 Sediment and Soil

Acrolein was not detected in five soil samples reported in the WQP database from 2005 to 2009; no soil samples for acrolein were reported for the years 2010–2023 (WQP 2023). In sediment samples, acrolein was found at a maximum of 1.9 µg/kg in 8 of 105 sediment samples reported for 2005–2014. No sediment sample data was reported for 2015–2023 (WQP 2023). Acrolein was identified in sediment/soil/water samples collected from Love Canal in Niagara Falls, New York (Hauser and Bromberg 1982); however, no quantitative data were available.

5.5.4 Other Media

Acrolein can be produced in endogenously as a product of lipid peroxidation (Uchida et al. 1998a, 1998b) and can form protein adducts that have been implicated in atherosclerosis (Uchida et al. 1998b) and Alzheimer's disease (Calingasan et al. 1999). As shown in Table 5-13, acrolein has been found in a variety of foods, including fruits, vegetables, baked or fried foods and alcoholic beverages (Jiang et al. 2022). In wine making, acrolein concentrations in initial grapes were reported at 45.8–49.8 µg/L and resulting musk levels were 41.1–46.8 µg/L. At the end of fermentation and in the final wine, acrolein levels were below the detection limit of 0.6 µg/L (Ferreira et al. 2018). Feron et al. (1991) reported concentrations of acrolein of <0.01–0.05 ppm in various fruits and up to 0.59 ppm in cabbage, carrots, potatoes, and tomatoes. The acrolein concentrations in heated fats and oils and in the headspace above these materials increase with increasing cooking temperature (Casella and Contursi 2004). For example, peanut oil heated for 2 hours at 110, 145, and 200°C resulted in the production of acrolein at concentrations of 0.2, 2.7, and 24 µM, respectively. In comparison to other oils, peanut oil was found to have the lowest production of acrolein after 2 hours of heating at 145°C, with higher concentrations found in sunflower (2.9 µM), corn oil (4.3 µM), and olive oil (9.3 µM) when heated under the same conditions (Casella and Contursi 2004). Sufficient data are not available to establish the level of acrolein typically encountered in these foods.

Table 5-13. Acrolein Content in Foods and Beverages

Food	Content (µg/kg or L)	Food	Content (µg/kg or L)
Fruits	10–50	Roasted cocoa beans	0.25–0.45
Vegetables	590	Fish oil	200–1,600
Cheese	1,000	Frying oils	7,400–198,100
Doughnuts	14.1–16.9	Frying fats	56,500

Table 5-13. Acrolein Content in Foods and Beverages

Food	Content (μg/kg or L)	Food	Content (μg/kg or L)
Codfish fillet	100	Cognacs	1,420–1,500
Sour dough	1,472	Scotch whiskey	670–11,100
Bread	161	Sparkling wine	20.3–33.4
French fries	14.8–19.9	Red wine	1.0–1.5
Potato chips	16.3–23.3	Cider	2,600–31,800
Frying cassava	1.7–10.2	Beer	<2.5–5.4
Frying pork sausage	~2–6		

Source: Jiang et al. 2022

Acrolein is a gaseous constituent of tobacco and marijuana smoke, occurring in both mainstream and side-stream smoke (Ayer and Yeager 1982; Hoffmann et al. 1975; Holzer et al. 1976; Rylander 1974; Weber-Tschopp et al. 1977). The level of acrolein in side-stream smoke has been found to be notably higher (12 times higher) than in mainstream smoke (Triebig and Zober 1984). The amount of acrolein emitted in tobacco smoke varies depending upon the kind of cigarette, smoking conditions, puff volume, puff rate, nature, and type of tobacco, as well as a number of other extraneous factors (Holzer et al. 1976). Smoke from various cigarettes has been found to contain 3–220 μg acrolein per cigarette (Dodson 1994; Hoffmann et al. 1975; Horton and Guerin 1974; Magin 1980; Manning et al. 1983). Smoke from a marijuana cigarette was also found to contain 92–145 μg/cigarette (Hoffmann et al. 1975; Horton and Guerin 1974). Studies performed to determine the concentration of acrolein in smoke-filled rooms (Rylander 1974; Triebig and Zober 1984; Weber-Tschopp et al. 1977) indicate that the concentration of acrolein in indoor air is highly dependent upon such factors as the number of cigarettes smoked, rate at which the cigarettes are smoked, size of the room, number of people in the room, and type of ventilation. Acrolein levels measured in various settings where people were smoking are: cafe, 30–100 ppb; train, 10–120 ppb; car with three smokers (windows open), 30 ppb (average); car with three smokers (windows closed), 300 ppb (average); restaurant, 3–13 ppb; tavern, 5–18 ppb; and cafeteria, l–10 ppb (Triebig and Zober 1984). Thirdhand smoke, defined as tobacco smoke residues lingering in the indoor environment, levels of acrolein were 127.9, 7.0, and 2.4 $\mu g/m^3$ in the room 20 minutes, 2 hours, and 8 hours after smoking was discontinued, respectively (Sleiman et al. 2014).

Electronic cigarettes (e-cig) have been determined to be a source of acrolein exposure (Belushkin et al. 2020; Chen et al. 2023; Dawkins et al. 2018; Gillman et al. 2020). Belushkin et al. (2020) studied 34 devices using 57 e-liquids manufactured in 2012, 2017, and 2018 from the United Kingdom, Poland, France, South Africa, and Canada. Emitted acrolein levels were <9.28–2,160 ng/puff in closed systems and 31.6–9,180 ng/puff in open systems. In another study, it was found that acrolein levels did not differ based on power levels of the e-cig device or nicotine content of the liquid (Dawkins et al. 2018). The formation of acrolein in e-cig aerosols in enhanced by the presence of triacetin (Vreeke et al. 2018).

5.6 GENERAL POPULATION EXPOSURE

The general population may be exposed to acrolein through inhalation of contaminated air, inhalation of cigarette smoke, and through ingestion of certain foods. Widespread exposure occurs due to the formation of acrolein during the cooking of fats. Primary factors influencing the level of exposure to acrolein via inhalation are location (urban versus rural), duration and frequency of exposure to tobacco smoke, concentration of tobacco smoke, duration and frequency of exposure to high concentrations of vehicle exhaust (e.g., in parking garages, in heavy traffic), occupational exposure, and downwind distance of residence or work site relative to stationary point sources. Primary factors influencing the level of exposure to acrolein via ingestion are diet and volume of intake, which is typically related to age and sex.

Acrolein may volatilize from water; thus, there is potential for inhalation exposure during showering and bathing. ATSDR's three-compartment Shower and Household-Use Exposure (SHOWER) model predicts air concentrations in the shower stall, bathroom, and main house throughout the day by estimating the contribution from showering or bathing and the contribution from other water sources in the house, such as the dishwasher, clothes washer, and faucets. This information, along with human activity patterns, is used to calculate a daily time weighted average exposure concentrations via inhalation exposure and from dermal uptake from skin contact. ATSDR's SHOWER model is available by sending a request to showermodel@cdc.gov. Using air and water levels discussed in Sections 5.5.1 and 5.5.2, reasonable maximum exposure (RME) levels for acrolein were calculated for different exposure groups (Table 5-14).

Table 5-14. Reasonable Maximum Exposure of Acrolein for Daily Inhalation Dose and Administered Dermal Dose in μg/kg/day for the Target Person

Exposure group	Inhalation (μg/m^3)	Dermal (μg/kg/day)
Birth–<1 year	1.2	0.0048
1–<2 years	1.2	0.0044
2–<6 years	1.2	0.0038
6–<11 years	1.2	0.0031
11–<16 years	1.2	0.0025
16–<21 years	1.2	0.0023

Table 5-14. Reasonable Maximum Exposure of Acrolein for Daily Inhalation Dose and Administered Dermal Dose in μg/kg/day for the Target Person

Exposure group	Inhalation (μg/m^3)	Dermal (μg/kg/day)
Adult	1.2	0.0023
Pregnant and breastfeeding women	1.2	0.0023

Source: ATSDR 2022b

Probabilistic estimates of 24-hour time-weighted concentrations of acrolein in air have been used to assess human exposures to acrolein in the Canadian population (Environment Canada 2000; WHO 2002). Mean and median estimates of acrolein concentration of 1.3 and 0.6 μg/m^3 (0.56 and 0.26 ppb), respectively, were derived, with a 95% percentile value of 5.0 μg/m^3 (2.1 ppb). The estimate used measured data on acrolein concentrations obtained between 1989 and 1996 for outdoor air in rural, suburban, and urban sites and indoor air measurements taken in 40 homes between 1991 and 1993. The exposure estimate assumed both a mean time of 3 hours spent outdoors and that the general population was exposed to concentrations of acrolein similar to those in indoor air of their homes. Based on the mean estimate for acrolein concentration and an inhalation volume of 20 m^3 of air per day, it was estimated that an average adult will inhale 26 μg acrolein/day (Environment Canada 2000). Because of the limited data regarding acrolein levels in foods, a reliable assessment of the acrolein exposure through foods is not possible at present. However, based on the assumption that all foods contain maximal reported levels of acrolein, an exposure of around 1 mg/person/day (17 g/kg body weight/day) may be estimated (Guth et al. 2013).

Levels of the acrolein metabolite, 3-hydroxypropyl mercapturic acid (3-HPMA), were measured in individuals before and after consumption of self-prepared and commercially available potato crisps (Watzek et al. 2012). Levels of 3-HPMA increased reaching a maximum at 4–6 hours, with a half-life of 9-12 hours. Wang et al. (2019) examined the levels of 3-HPMA in urinary samples and serum acrolein-protein conjugates (Acr-FDP) before and after the consumption of fried foods. Urinary 3-HPMA levels increased 2 hours after consumption of fried food, with an elimination half-life of 10 hours. Concentrations decreased, approaching baseline level after 24 hours. Acr-FDP levels in plasma were slightly, but not significantly, increased 2, 6, or 24 hours after consuming fried food (Wang et al. 2019).

ETS, including primary, secondhand, and thirdhand smoke, is a major source of acrolein exposure for many individuals in the general population. Nazaroff and Singer (2004) estimated that in 2000, between 31 and 53 million nonsmokers in the United States were exposed to acrolein concentrations in indoor air, ranging from 1.6 to 3.6 μg/m^3 in households where ETS is generated by one or more individuals residing in the same household. Between 15 and 25 million of the affected number of nonsmokers are adults. Based on the lifetime average for the volume of inspired air of 14 m^3/day for males and 10 m^3/day for females, it is estimated that the inhalation intake of acrolein through inspiration of ETS over a lifetime is 22–50 μg/day for males and 16–36 μg/day for females. Assuming that the exposure data obtained from the Canadian study (Environment Canada 2000) discussed above are representative of exposures of residents in the United States to acrolein in households without ETS, then it is estimated that the inhalation intake of acrolein for nonsmokers exposed to ETS in the residence is 2.2–3.8 times greater for both males and females than in households without ETS. This comparison is based on inhalation intakes of acrolein for males and females in non-ETS households of 18 and 13 μg/day, respectively, that are based on an estimated mean acrolein concentration in air of 1.6 μg/L taken from the Canadian study (Environment Canada 2000) and on the average daily inhalation volumes of air for males and females given by Nazaroff and Singer (2004). National Health and Nutrition Examination Survey (NHANES) data from 2005 to 2006 reported that urinary levels of 3-HPMA and CEMA were higher among tobacco smokers (cigarette, cigar, and pipe users) compared to non-tobacco users (Alwis et al. 2015).

There is potential for exposure to acrolein in many occupational settings as the result of its varied uses and its formation during the combustion and pyrolysis of materials such as wood, petrochemical fuels, and plastics. As a result, it would be difficult to list all occupations in which work-related exposure to acrolein occurs. Some of these occupations include those involved in the production of acrylates, methionine, perfumes, plastics, refrigerants, rubber, or textile resins (Ghilarducci and Tjeerdema 1995).

Acrolein has been detected in workplace air at a number of locations (Feng et al. 2022b; NIOSH 1982, 1983, 1986). Acrolein concentrations of 0.057–0.085 ppm were detected during system testing conducted as part of a submarine overhaul in Portsmouth Naval Shipyard in Portsmouth, New Hampshire (NIOSH 1986). NIOSH (1983) reported >0.0044–0.18 ppm acrolein in the wire line department of Rubbermaid Inc. in Wooster, Ohio, and NIOSH (1982) reported >0.06 ppm in molding areas of Gerlinger Casting Corporation in Salem, Oregon. A year-long air monitoring program in a petroleum refinery named acrolein as the largest contributor to the hazard index (Feng et al. 2022b).

The concentrations of acrolein were 0.01 mg/m^3 (0.004 ppm) in the air of a food factory, 0.59, 0.31, 0.15, 0.16, and 0.06 mg/m^3 (0.25, 0.13, 0.064, 0.069, and 0.026 ppm) in the air of five restaurant kitchens, and 0.02 mg/m^3 (0.009 ppm) in the air of two bakeries (Vainiotalo and Matveinen 1993). Henriks-Eckerman et al. (1990) reported that acrolein was emitted from coated steel plates heated to 350°C. This indicates that workers involved in welding or heating painted metal may be exposed to acrolein

5.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Those segments of the general population with potentially high exposure to acrolein from exogenic sources include people who come in frequent or prolonged contact with tobacco or marijuana smoke, people who are occupationally exposed, and people who live or work near dense traffic areas, in smoggy areas (e.g., Los Angeles), or downwind from stationary point sources or may have been exposed to high levels from accidental releases. Acrolein uptake from cigarette smoke for individuals working in bars and taverns that allow indoor smoking can range from 15 to 1,830 μg/day, based on an 8-hour shift, a respiration volume of 20 m^3 air/day, and a concentration range of acrolein in air of 2.3–275 μg/m^3 (IARC 1995). With the passage of legislation prohibiting smoking indoors, it is expected that these exposure levels would now be much lower. Individuals who work or reside near irrigation canals and other bodies of water that are undergoing treatment with acrolein to eliminate unwanted plants or aquatic life are at risk for exposure to acrolein. Individuals living near some landfills and other waste sites may be exposed to acrolein in ambient air or drinking water.

Firefighters are at high risk of exposure to acrolein when battling house fires, wildfires, and industrial fires (Fent et al. 2022; Griffiths et al. 2022; O'Dell et al. 2020). Navarro et al. (2021) monitored 81 firefighters in different job tasks while fighting wildfires; the minimum and maximum acrolein exposure levels were 0.6 and 13.8 ppb (1.38 and 31.64 μg/m^3), respectively. The highest levels were for direct suppression workers (Navarro et al. 2021). The concentrations of the acrolein metabolite, 3-HPMA, measured in urine samples pre- and post-firefighting are presented in Table 5-15 (Fent et al. 2022). Attack firefighters have the position of advancing hose lines and suppressing all active fires, while search and rescue conduct forcible entry and enter burning buildings. Student and instructors were exposed to burning pallets of straw, oriented strand board fires, and simulated smoke and electronic flames; all of these exercises were performed in enclosed areas. For the general population, the median concentrations of 3-HPMA are 175 μg/g creatinine for nonsmokers and 508 μg/g creatine for smokers (Fent et al. 2022).

Table 5-15. 3-HPMA Concentration (µg/g creatinine) in Urine of Firefighters Pre- and Post-Fire Response

	Collection period	Number of samples	Mean	Median	Minimum–maximum
Attack and search firefighters	Pre-fire	48	207	182	68.1–739
	3 hours	48	209	196	92.2–665
Firefighter student	Pre-fire	36	172	146	92.7–403
	3 hours	36	342	211	96.3–1,660
Instructor	Pre-fire	12	231	168	97.7–764
	3 hours	12	439	322	179–1,230

Source: Fent et al. 2022

Patients receiving oxazaphosphorine drugs, such as cyclophosphamide and ifosfamide, for their cancer treatment are at risk for exposure to acrolein, a metabolite of these drugs (Furlanut and Franceschi 2003; Kaijser et al. 1993). For example, patients receiving cyclophosphamide at a dose of 60 mg/kg body weight/day by 1-hour infusion for 2 consecutive days had peak blood acrolein concentrations ranging between 6.2 and 10.2 µM (Ren et al. 1999). The urinary clearance of acrolein from blood during therapy results in concentrations of acrolein in urine ranging from 0.3 to 406.8 nM, depending on urine volume (Takamoto et al. 2004). This range of urinary acrolein concentrations is sufficient to result in acrolein-induced renal toxicities that must be reduced through increasing urine volume during treatment with diuretics or receiving uroprotective drugs during treatment (Kaijser et al. 1993).