

DRAFT

ÉBAUCHE

CANADIAN ENVIRONMENTAL PROTECTION ACT

PRIORITY SUBSTANCES LIST

SUPPORTING DOCUMENTATION

STYRENE

**Government of Canada
Environment Canada**

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Disclaimer

Data relevant to the environmental assessment of styrene were presented in a review of the literature prepared for Environment Canada under contract by Ecological Services for Planning Ltd., Guelph, Ontario. This review covered the literature published up to June 1991. Additional information was subsequently identified by staff of Environment Canada during the preparation of this Supporting Documentation from more recent review articles and from searches of two commercial databases (Pollution Abstracts and Chemical Abstracts) conducted in February 1992. This is an unedited document made available for public information. A published Assessment Report is available under the title "*Canadian Environmental Protection Act, Priority Substances List, Assessment Report, Styrene*" from:

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Unedited Supporting Documentation pertaining to environmental health aspects of styrene is available from Health Canada at the address cited above.

TABLE OF CONTENTS

1.0	IDENTITY OF SUBSTANCE	1
2.0	PHYSICAL AND CHEMICAL PROPERTIES	1
3.0	SOURCES AND RELEASES TO THE ENVIRONMENT	4
3.1	Natural Sources	4
3.2	Production	4
3.3	Canadian Manufacture of Styrene	5
3.4	Canadian Imports of Styrene	5
3.5	Uses	5
3.6	Demand	6
3.7	Releases	6
3.8	Disposal	9
4.0	ENVIRONMENTAL TRANSPORT, TRANSFORMATION AND CONCENTRATIONS	9
4.1	Transport and Transformation Processes	9
4.1.1	Atmospheric Processes	9
4.1.2	Abiotic Hydrolysis, Photolysis and Oxidation	10
4.1.3	Volatilization	10
4.1.4	Sorption	10
4.1.5	Biotransformation	11
4.1.6	Bioaccumulation	13
4.2	Environmental Concentration and Trends	13
4.2.1	Air	13
4.2.2	Freshwater	18
4.2.2.1	Surface Water	18
4.2.2.2	Ground Water	19
4.2.2.3	Waste Water	20
4.2.2.4	Sediments	21
4.2.2.5	Biota	21
4.2.3	Marine Water	21
4.2.4	Soils	21
5.0	POPULATION EXPOSURES	22
5.1	Exposures of Wildlife Populations	22
6.0	TOXICOKINETICS AND METABOLISM	23
7.0	EFFECTS ON THE ECOSYSTEM	24
7.1	Aquatic Toxicity	24
7.1.1	Freshwater Organisms	25
7.1.1.1	Acute Toxicity	25
7.1.1.2	Chronic Toxicity	29
7.1.2	Marine Organisms	31
7.1.2.1	Acute Toxicity	31
7.1.2.2	Chronic Toxicity	34
7.2	Terrestrial Toxicity	34

8.0	CRITERIA, GUIDELINES AND STANDARDS	36
9.0	REFERENCES	38

LIST OF TABLES

Table 1:	Physical and Chemical Properties of Styrene	3
Table 2:	Annual Production Capacity of Styrene in Canada	5
Table 3:	Styrene Imports to Canada by Country	5
Table 4:	Canadian Demand Pattern for Styrene	6
Table 5:	Measured Concentrations of Styrene in Air	13
Table 6:	Measured Concentrations of Styrene in Water	18
Table 7:	Measured Concentrations of Styrene in Effluents	20
Table 8:	Estimated worst-case total daily intake of styrene for a 1 kg adult mink in the St. Clair River area	23
Table 9:	Acute Toxicity of Styrene to Freshwater Invertebrates	25
Table 10:	Acute Toxicity of Styrene to Freshwater Fish	26
Table 11:	Chronic Toxicity of Styrene to Freshwater Microorganisms	30
Table 12:	Chronic Toxicity of Styrene to Freshwater Plants	30
Table 13:	Acute Toxicity of Styrene to Marine Invertebrates	32
Table 14:	Acute Toxicity of Styrene to Marine Echinodermata	33
Table 15:	Acute Toxicity of Styrene to Marine Fish	34
Table 16:	Toxicity of Styrene to Birds	35

LIST OF FIGURES

Figure 1:	The Chemical Structure and Molecular Formula for Styrene.	2
Figure 2:	Styrene Production from Ethylbenzene	4
Figure 3:	Proposed Metabolic Pathway of Styrene in the Rat.	24

1.0 IDENTITY OF SUBSTANCE

Styrene is a monoaromatic hydrocarbon (CAS Registry Number 100-42-5). Synonyms for styrene include: ethenylbenzene; vinylbenzene; vinylbenzol; phenylethylene; styrolene; styrol; styrole; cinnamene; cinnamenol; and cinnamol (Sax and Lewis 1989; Bond 1989; CCOHS 1990).

Solid and liquid absorbants may be used to sample airborne styrene. A cryogenic preconcentration trap and a gas chromatograph with flame ionization detector and electron capture detector may be used for the analysis of styrene in air (detection limit = 0.05-0.1 $\mu\text{g}/\text{m}^3$) (T. Dann 1991, pers. com.). Analysis can also be achieved with visible, ultraviolet (detection limit 4.323 mg/m^3) or infrared spectrophotometry (detection limit 86.5 mg/m^3) (Verschuere 1983; WHO 1983). Analysis of styrene in water samples may be carried out by means of batch purge-and-trap/capillary column gas chromatography/mass spectrometry (GC-MS), with a detection limit of 1.0 $\mu\text{g}/\text{L}$ (Environment Canada 1988a). Environmental styrene concentrations may be slightly understated because styrene may polymerize during preconcentration and analysis (R. Otson 1992, pers. com.).

Styrene and its metabolites have been measured in other environmental media including plant and animal tissues, whole blood, urine, exhaled air, water and soil. Gas chromatography is generally used for most media, but a direct spectrofluorometric method is available for blood. The detection limit for GC-MS analysis of styrene in whole blood and tissue homogenates ranged from 2 to 200 ng/g (Colin et al. 1986).

2.0 PHYSICAL AND CHEMICAL PROPERTIES

The physical and chemical properties of styrene are summarized in Table 1. The molecular weight of styrene is 104.14 and the chemical structure and molecular formula are presented in Figure 1. Styrene is soluble in alcohol, ethanol, ether, methanol, acetone and benzene, but only slightly soluble in water. Unpure styrene usually contains aldehydes which have a penetrating, sharp and unpleasant smell. The human odour perception threshold is 0.036 mg/m^3 in air and the non-perception threshold is 0.02 mg/m^3 (Verschuere 1983).

Pure styrene will spontaneously polymerize slowly at room temperature to give a viscous solution and eventually a clear glassy solid. Polymerization occurs rapidly at high temperatures (200°C) to produce polystyrene (Chang and Tikkanen 1988). Styrene also undergoes oxidation on exposure to natural light and air (WHO 1983). Most commercially available styrene contains a polymerization inhibitor, such as 4-tertiary-butylcatechol.

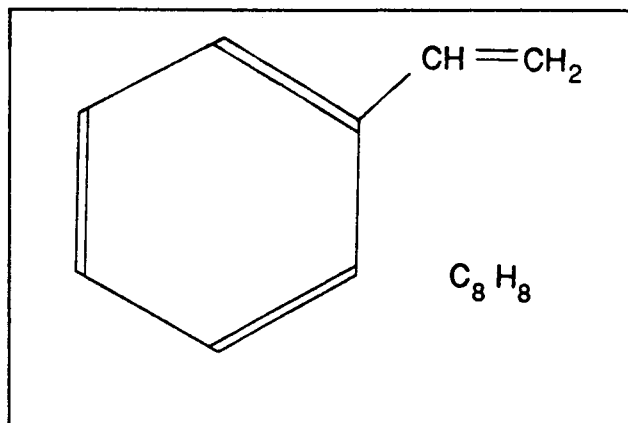


Figure 1: The chemical structure and molecular formula for styrene (Hoskins 1984)

The flash point of styrene is 31°C , consequently it is a flammable liquid with a hazchem code of 3Y and UN No. 2055. The autocatalytic polymerization of styrene which occurs in the presence of heat and light becomes self-sustaining above 65°C and thus makes it capable of exploding.

Table 1: Physical and Chemical Properties of Styrene	
Molecular formula	C ₈ H ₈ (1)
Molecular weight	104.14 (1,2)
Physical State	Liquid at 20°C (2)
Colour	Colourless (2)
Odour	If pure, sweet and pleasant; with aldehydes, sharp, unpleasant (2)
Melting point	-30.6°C (3,4), -31°C (5), -33°C (6)
Boiling Point	145.2°C (3,4), 146°C (4,5)
Specific gravity	0.9045 at 25/25°C (1,2), 0.9074 at 20/4°C (5)
Vapour Density	3.6 (air = 1) (6)
Vapour pressure	667 Pa at 20°C (2), 600 Pa at 20°C (1) 1267 Pa at 30°C (2)
Henry's Law Constant	285 Pa·m ³ ·mol ⁻¹ (7)
Air saturation concentration	31 g/m ³ at 20°C (2) 52 g/m ³ at 30°C (2)
Flash point	31.1°C (5); 30.6°C (4)
Autoignition temp.	490°C (5)
Explosive range	1.1 to 6.1% by volume in air (1)
Solubility in water	250 mg/L at 25°C to 400 mg/L at 40°C (8) 280 mg/L at 15°C (2) 300 mg/L at 20°C (2) 320 mg/L at 25°C (6) 400 mg/L at 40°C (2)
Partition coefficients	4.38 water/air (1) 32.0 blood/air (1) 130 oil/blood (1) 4160 oil/air (1)
log K _{ow}	2.75 (9) 2.95 (9) 2.76 to 3.39 (10)
log K _{oc}	2.95 (11) 3.16 (11)
K _{oc} = soil sorption coefficient standardized to organic carbon	900 estimated from K _{ow} (9) (ow = octanol/water partition coefficient) 567 estimated from aqueous solubility (9)
Legend: <div style="display: flex; justify-content: space-between; padding: 0;"> <div style="width: 45%;"> 1 Bond 1989 2 Verschueren 1983 3 Chang and Tikkanen 1988 4 The Merck Index 1989 5 Sax and Lewis 1989 6 Sax 1986 </div> <div style="width: 45%;"> 7 Howard 1989 8 Hefter 1985 9 Alexander 1990 10 Sangster 1989 11 U.S. EPA 1984 </div> </div>	

3.0 SOURCES AND RELEASES TO THE ENVIRONMENT

3.1 Natural Sources

Styrene occurs naturally in the sap of styraceous trees, in pyrolysis and cracking products of petroleum derivatives, and in bituminous-coal and shale-oil tars (Royal Society of Chemistry 1989).

Sato et al. (1988), investigating the source of a petroleum-like off-flavour in seasoned herring roe, found that styrene was produced by the yeast, *Torulopsis candida* (Saito) Lodder 1922. The precursor of the styrene was unknown. Styrene may also be produced naturally by the decarboxylation of certain organic acids by a variety of microorganisms (Shirai and Hisatsuka 1979a).

3.2 Production

Styrene is produced commercially by the catalytic dehydrogenation of ethylbenzene (Figure 2). Pure ethylbenzene is heated to 520°C and mixed with superheated steam, resulting in a mixture temperature of 630°C. This mixture is fed into a reactor containing the catalyst, usually a metal oxide, on activated carbon or aluminum oxide. As the gas mixture flows through the reactor the ethylbenzene is converted to styrene at an efficiency of 35-40%. The styrene is then isolated by distillation, treated with a polymerization inhibitor (sulphur or tertiary-butyl catechol) and stored at temperatures below 20°C. By-products of production include benzene, toluene and tar (Chang and Tikkanen 1988).

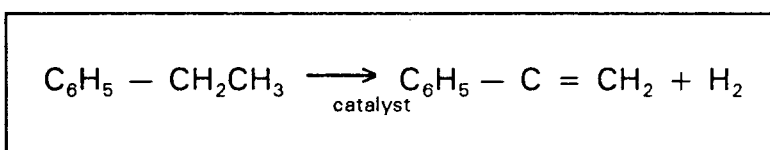


Figure 2: Styrene production from ethylbenzene

Styrene is also produced from the oxidation of ethylbenzene to ethylbenzene hydroperoxide that reacts with propylene to form α -phenylethanol and propylene oxide. The alcohol, α -phenylethanol, is then dehydrated to styrene (U.S. EPA 1984).

Styrene ranked 21st among the top 50 chemicals produced in the United States in 1991, with a total production of 4.1×10^6 tonnes, up from 3.6×10^6 tonnes produced in 1990 (Reisch 1992).

3.3 Canadian Manufacture of Styrene

In Canada, the total annual production capacity of styrene in 1988, 1989 and 1990 was 650, 740 and 812 kilotonnes, respectively (Camford Information Services 1991a). The principal Canadian manufacturers are Dow Chemical Canada, Novacor Chemicals (formerly Polysar) and Shell Canada Chemical. The Canadian production statistics for styrene are summarized in Table 2.

Table 2: Annual Production Capacity of Styrene in Canada (kilotonnes)										
Company	Plant Location	1976	1982	1984	1985	1986	1987	1988	1989	1990
Dow Chemical Canada	Samia, Ont.	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Novacor Chemicals (formerly Polysar)	Samia, Ont.	113.5	272.0	272.0	272.0	272.0	272.0	272.0	362.0	362.0
Shell Canada Chemical	Scotford, Alta.	-	-	150.0	300.0	300.0	308.0	308.0	308.0	380.0
TOTAL CAPACITY		183.5	342.0	492.0	642.0	642.0	650.0	650.0	740.0	812.0
Source: Camford Information Services 1991a Corpus Information Services 1989										

3.4 Canadian Imports of Styrene

In Canada, styrene is imported in relatively small quantities from the United States. Import statistics for styrene are outlined in Table 3.

Table 3: Styrene Imports to Canada by Country (kilotonnes)											
Country	1976	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
United States	0.31	2.97	0.60	0.01	0.16	0.36	0.15	0.00	0.16	0.39	0.32
Source: Camford Information Services 1991a Corpus Information Services 1989											

3.5 Uses

Styrene is used primarily in the production of plastics, styrene-butadiene rubber, and resins including polystyrene resins, acrylonitrile-butadiene-styrene (ABS) terpolymer resins, styrene-acrylonitrile (SAN) copolymer resins, styrene-butadiene copolymer resins and unsaturated polyester resins. The U.S. Food and Drug Administration permits the use of styrene as a synthetic flavouring substance and adjuvant (IARC 1979).

More than half of the styrene produced is used for the manufacturing of polystyrene products including styrofoam, a styrene polymer. The second single largest use of styrene is in synthetic rubbers including styrene-butadiene rubber (SBR). SBR is most commonly used in automobile tires.

Styrene is also a component in floor waxes and polishes, paints, adhesives, putty, metal cleaners, autobody fillers, fibreglass boats and varnishes (Howard 1989). TEC-styrene (α -2,2,2-trichloroethyl styrene), also known as Dowco 221, was a herbicide used for the selective control of annual grasses in transplanted rice (De Datta et al. 1969)

3.6 Demand

In Canada, domestic and foreign polystyrene demand is the main driving force behind monomer production. Since 1976, total domestic demand and export sales of styrene have increased 47% and 6000%, respectively. The fastest growing markets are housings for electric and computer equipment, packaging and the increased use of plastics in cars. Demand pattern statistics for polystyrene are outlined in Table 4.

Table 4: Canadian Demand Pattern for Styrene (kilotonnes)							
	1976	1981	1986	1987	1988	1989	1990
Polystyrene	86.0	125.5	143.0	155.0	162.0	157.0	148.0
ABS/SAN resins	20.85	26.0	24.0	25.0	26.0	26.0	28.6
Styrene-butadiene latices	21.0	22.0	27.0	33.0	35.0	35.0	34.0
Styrene-butadiene rubbers	21.0	25.0	18.0	0.0	5.0	5.0	5.0
Polyester resins	7.5	8.0	10.5	11.0	13.0	12.0	12.0
Miscellaneous	0.5	1.0	1.0	2.0	3.0	3.0	3.0
Total domestic demand	156.5	208.58	223.5	226.0	244.0	238.0	230.6
Export sales	8.0	154.0	326.5	404.0	476.0	473.7	487.7
Total disappearance	164.5	361.5	550.0	630.0	720.0	711.7	718.3
Source: Camford Information Services 1991a							

In 1990, Canadian production/importation of styrene amounted to 718.3 kilotonnes, of which 68% was exported. Of the remaining 230.6 kt, 64% was used in the manufacture of polystyrenes, 14.7% for styrene-butadiene latex preparations, 12.4% for acrylonitrile-butadiene-styrene resins, 5.2% for unsaturated polyester resins and 2% for styrene-butadiene rubber (Camford Information Services 1991a).

A survey of the Canadian market predicted that in 1993, the total production of styrene would exceed 756 kilotonnes, with export sales approximately twice that of domestic sales (Corpus Information Services 1989).

3.7 Releases

Styrene enters the environment primarily via anthropogenic emissions and effluents associated with its production and its use

in the manufacture of polymers, and also through accidental spills and leakage. It is a combustion product in exhausts from spark-ignition engines, oxy-acetylene flames and cigarette smoke, and is also a component of gases emitted by pyrolysis of brake linings (Santodonato et al. 1980) and emissions from waste incineration (Junk and Ford 1980).

There are three styrene production plants in Canada. Two are in Sarnia, Ontario, and one in Scotford, Alberta. In 1989/90 these three plants emitted a total of 64 tonnes per year (t/y) of styrene to the atmosphere (Environment Canada 1990a). Releases of styrene to water from these plants are small. One of the styrene production plants in Ontario discharged about 0.04 t/y of styrene to water through its effluent, while styrene was not detected in the effluents of the other Ontario styrene plant (OME 1992a).

There are seven polystyrene production plants in Canada, three in Ontario, three in Quebec and one in Alberta. Total production of polystyrene in 1990 was around 170 kt (Camford Information Services 1991b). Total styrene emissions from these plants are estimated at 272 t/y if the U.S. average emission factor of 1.6 kg per tonne of polystyrene resins production is used (U.S. EPA 1990).

There are two ABS resin production plants in Canada, one in Ontario and one in Quebec and one SB (Styrene-Butadiene) rubbers and latices production plant in Ontario. ABS resins, SB rubbers and SB latices production in Canada are estimated to be 58 kt/y, 12 kt/y and 51 kt/y, respectively (Camford Information Services 1991a). If an average emission factor of 1.8 kg per tonne of resin production (U.S. EPA 1990) is used, total styrene emissions from these plants would be 217 t/y. Releases of styrene to water from these plants are small. The SB rubbers and latices plant discharged 0.2 t/y of styrene to water through its effluents while styrene was not detected in the effluents of the Ontario ABS plant (OME 1992a).

Unsaturated polyester resins are copolymers of polyester and styrene (30-60%). They are usually reinforced with fibreglass and are used in boat building/repairing or in the manufacturing of vehicle parts/accessories. The Environment and Plastics Institute of Canada estimated that the reinforced plastics industry in Canada emits about 1 kt/y of styrene from the use of about 12.2 kt/y of resin. Plants using reinforced plastics are mainly located in Ontario, Quebec, British Columbia and Nova Scotia.

Styrene emissions may also occur from plastic processing (injection moulding and extrusion) plants. Emission factors for plastic processing plants are 5 to 50 g per tonne of resin used (U.S. EPA 1990). If an average value of 27 g is used, total styrene emissions from plastic processing plants would be around 8 t/y. Plastic processing plants are mainly located in Ontario and Quebec.

Total estimated styrene emissions from industrial plants in Canada are thus:

Styrene production plants	64 t/y
Polystyrene Production Plants	272 t/y
ABS Resins, SB Rubbers and SB Latices Plants	217 t/y
Unsaturated Polyester Plants (Boat Building/Repairing and Vehicle Parts/Accessories)	1,000 t/y
Plastic Processing Plants	8 t/y
Total	<hr/> 1,561 t/y

Almost all of these releases occur as air emissions. It should be noted that some of the above quantities of releases are estimated based on U.S. emission factors (EPA 1990). Actual emissions from the Canadian plants may be substantially different, depending upon the technology used to control their air emissions.

Data from the Municipal and Industrial Strategy for Abatement (MISA) program of the Ontario Ministry of the Environment showed 12-month average concentrations of styrene as high as 71.1 $\mu\text{g/L}$ in various effluents from organic chemical plants from October 1989 to September 1990 (OME 1992a). Average loadings from individual plants ranged as high as 0.511 kg styrene/day.

In an Ontario Ministry of the Environment (OME 1988) pilot monitoring study on "hazardous contaminants" from 37 municipal water pollution control plants, styrene was detected in 9 of 274 samples of raw waste water at a maximum concentration of 1,208 $\mu\text{g/L}$, 1 of 38 samples tested from primary effluents at a concentration of 15.0 $\mu\text{g/L}$, 1 of 224 samples of secondary effluent at a concentration of 13.0 $\mu\text{g/L}$, and 1 of 51 samples of raw sludge at a concentration of 6,011 $\mu\text{g/kg}$ wet weight. Styrene was not detected in the effluents of the two lagoons, in the one tertiary effluent, or in treated sludges from 34 plants included in the study. The detection limit for styrene in this study was 40 $\mu\text{g/L}$ in raw sewage and 3 $\mu\text{g/L}$ in effluents. The detection limit for styrene in sludge was not stated.

Forty-four spills of styrene monomer, releasing a total of approximately 186,000 kg of the substance, were reported from across the country in Environment Canada's NATES database between 1978 and 1990 (NATES 1992). Of these, by far the largest was a release of about 80,000 kg at Sarnia, Ontario, in 1978. A total of about 385 kg of styrene were reported spilled into the St. Clair River in 1989, according to the Ontario government's Spills Response Program. In 1990, approximately 45 kg of styrene were spilled into the river (OME 1991).

3.8 Disposal

In Canada, federal, provincial and local government requirements must be reviewed prior to styrene disposal (CCOHS 1990). The Ontario Ministry of the Environment requires that styrene-contaminated waste water be disposed of in a biological treatment facility. Pure styrene waste is seldom generated during production since most is collected and recycled in the production process; however, if applicable, it must be disposed of by means of a hazardous waste disposal facility (Burgess 1991).

4.0 ENVIRONMENTAL TRANSPORT, TRANSFORMATION AND CONCENTRATIONS

4.1 Transport and Transformation Processes

4.1.1 Atmospheric Processes

The fate of styrene in the atmosphere is determined by its chemical and photochemical reactivity and the prevailing physical and chemical conditions in the atmosphere. Hydroxyl radicals are major reactants and the predicted half-life for reaction with styrene is about 3.6 hours (Atkinson et al. 1982). Although hydroxyl radicals are major reactants, the ozone concentrations in polluted air in cities may be sufficiently high for ozone to destroy styrene more readily than hydroxyl radicals (Alexander 1990). The half-life of styrene due to its reaction with ozone is about 9 hours (U.S. EPA 1984). In the atmosphere, the products of the styrene reaction with ozone are benzaldehyde, formaldehyde, benzoic acid, and trace amounts of formic acid (Grosjean 1985). Styrene will also react slowly with singlet oxygen (Datta and Rao 1979) with a predicted half-life of 48 years.

Because styrene absorbs little light at the wavelengths of sunlight reaching the earth's surface, it is not likely to be rapidly destroyed by direct photolysis. However, in the presence of NO_x and natural sunlight, styrene degrades rapidly. Yanagihara et al. (1977) observed that 90% of the styrene present at an initial concentration of 2 ppm (8.65 mg/m³) disappeared in 5 hours when irradiated with 700 $\mu\text{W}/\text{cm}^2$ of light at wavelengths between 245 and 355 nm and in the presence of 1 ppm NO_x . In the presence of sunlight and NO , styrene is rapidly oxidized, with a conversion of NO to NO_2 and the production of ozone and several oxidation products, including benzoic acid, formaldehyde, benzaldehyde and its reaction product, peroxybenzoyl nitrate (Grosjean 1985). Korth (1963) reported a disappearance of 55% of the styrene from auto exhaust in smog chambers in only 2 hours.

The physical removal of airborne styrene by processes such as dry and wet deposition has not been studied but it is thought to be relatively minor. Because of the rapid rate of degradation of

styrene in the atmosphere, long-range atmospheric transportation is unlikely and airborne styrene is not considered a significant source of styrene for waters or soils distant from point source emissions (Alexander 1990).

4.1.2 Abiotic Hydrolysis, Photolysis and Oxidation

Abiotic hydrolysis, photolysis and oxidation are not considered to be significant mechanisms of styrene degradation in the environment (Alexander 1990; Howard 1989; Santodonato et al. 1980; Toole and Crosby 1988; U.S. EPA 1987a).

4.1.3 Volatilization

Volatilization may be the dominant transport and transformation process for styrene in water (Howard 1989). Styrene volatilized rapidly from samples of distilled and lake water in open flasks, with 50% losses in 6 to 7 and 1 to 3 hours, respectively, at initial concentrations of 4 mg/L (Fu and Alexander 1992). Styrene is rapidly lost from surface waters by volatilization and the half-life typically varies with environmental conditions. The half-life reported for waters in a turbulent lake is from 1 to 6 hours (at a depth of 1 metre) to 60 hours (at a depth of 10 metres) (U.S. EPA 1987a, 1987b). The half-life of styrene from a river 1 metre deep with a current speed of 1 m/sec and wind velocity of 3 m/sec is about 3 hours (Howard 1989). Zoeteman et al. (1980) estimated the overall half-life of styrene in a river in the Netherlands to be about 14 hours. Based on an EXAMS modeling with input parameters as given by Lewis et al. (1983) in U.S. EPA (1984), the half-life was estimated to be 3 days in a pond and 13 days in an oligotrophic lake (U.S. EPA 1984). Half-life values are likely to be longer for groundwater and stagnant deep water where volatilization does not occur (Alexander 1990; Zoeteman et al. 1980).

The half-life for the volatilization of styrene at the soil surface has been estimated to be approximately 1 minute; however, the rate of volatilization becomes slower with increasing depth (U.S. EPA 1987a). Volatilization of styrene proceeded at about twice the rate of mineralization (by microbial action) in the upper 1.5 cm of soil (Fu and Alexander 1992).

4.1.4 Sorption

Although the major route of dissipation of styrene may be volatilization, adsorption to particulate matter and sediments does occur.

Although the styrene concentration in the suspended and exposed bottom sediment in natural waters is expected to be higher than in the water column, the amount of styrene in bottom and suspended sediments is not likely to exceed 10% of that in most

surface water (U.S. EPA 1987a). Because of the relatively small amount of styrene adsorbed to suspended or bottom sediment, removal of the chemical from surface water by adsorption is not considered significant (U.S. EPA 1987a).

Persistence and movement of styrene in soil is determined to a large extent by the organic content of the soil, the amount of soil moisture and the cation exchange capacity of the soils. Relative mobility of styrene in soil is estimated by the soil sorption constant which has been normalized for organic content. The K_{OC} for styrene is 900 when derived from the K_{OW} and 567 when derived from aqueous solubility (Table 1). These values place styrene in the class of chemicals having low mobility (Swann et al. 1983). Roberts et al. (1980) observed relatively strong adsorption of styrene in a sand aquifer, with a breakthrough time approximately 80 times longer for styrene than for a nonadsorbing tracer.

4.1.5 Biotransformation

The biodegradability of styrene has been demonstrated in experiments with biofilms on glass beads, which have shown that styrene concentrations can be reduced from 7.6 $\mu\text{g/L}$ to less than 0.05 $\mu\text{g/L}$ in 20 minutes, after acclimation (Bouwer and McCarty 1984). The microbial populations associated with the biofilms required O_2 and no appreciable degradation occurred under anaerobic conditions: only 8% degraded in an anaerobic biofilm column in 2 days. Churchman and Grbic-Galic (1987) observed that methane-producing bacteria were capable of anaerobically degrading styrene to CO_2 plus organic compounds. Styrene was completely biodegraded under anaerobic conditions within 8 months (Grbic-Galic et al. 1990).

Microbial degradation of styrene in natural surface waters has not been extensively investigated; however, Bridié et al. (1979) reported 42% degradation of styrene in 5 days, with BOD (biological oxygen demand) as the endpoint in water inoculated with unadapted sewage microbes. Eighty percent degradation of styrene occurred in 5 days when the microbial inoculum contained preconditioned organisms. Price et al. (1974) reported 65% degradation of styrene in domestic waste water with a microbial inoculum.

The slow vertical movement of styrene in soils favours biodegradation by microbial organisms. Neither biodegradation (Wilson et al. 1983) nor mineralization (Sielicki et al. 1978) of styrene occurred in sterilized soils. However, biodegradation was observed in non-sterile soils containing an abundance of microorganisms, suggesting biodegradation is of major importance (Alexander 1990). Styrene is converted to CO_2 (mineralized) in aerobic soils by organisms that use styrene as a carbon source for growth. Sielicki et al. (1978) reported that 95 and 87% of ^{14}C -

styrene in soil at a concentration of 2 g/kg was converted to CO₂ in 16 weeks in a landfill soil and a sandy loam soil, respectively. About 75% was converted to CO₂ in 16 weeks in these soils with initial levels of styrene at 5.0 g/kg. Styrene in a soil-groundwater system with an initial concentration of 70 mg/L was not detectable after 25 hours incubation at 20°C (Kuhlmeier 1988). A tanker spill of 4900 gallons of styrene monomer into permeable soils resulted in groundwater contamination. Site remediation of contaminated soil and groundwater using preconditioned microbial populations reduced the styrene concentration from as high as 500 mg/L to less than 0.05 mg/L in 14 weeks (Kuhlmeier 1988). However, styrene that leaked into soil surrounding buried drums persisted for up to 2 years (Howard 1989) and eventually contaminated groundwater (Roberts et al. 1980).

The rate of styrene degradation in groundwater is much slower than in surface water, with a half-life estimated at 6 weeks to 7.5 months (Wilson et al. 1983). Batterman and Werner (1984) demonstrated that styrene at 1.47 mg/L in a sandy aquifer declined to 0.019 mg/L as a result of microbial degradation in laboratory tests.

The concentration of styrene in soil and water appears to have a significant affect on its persistence. Fu and Alexander (1992) showed that mineralization of styrene in soil decreased with increasing concentrations. After 30 days, 62% was mineralized with an initial concentration of 20 µg/kg, while only 16% was mineralized with an initial concentration of 1000 mg/kg. The situation was reversed in lake water samples, with mineralization of about 22% after 28 days at 100 µg/L, but only about 10% in the same time period at a concentration of 2.5 µg/L. The authors suggested that a threshold may exist at still lower concentrations at which styrene may not support microbial growth and may therefore persist in lake water (Fu and Alexander 1992).

Hartmans et al. (1990) isolated 14 strains of aerobic bacteria and 2 strains of fungi from various soil and water samples by using styrene as the sole source of carbon and energy. Examination of styrene degradation in one of the bacteria strains showed that styrene was first converted to styrene oxide, which was subsequently isomerized to phenylacetaldehyde and then oxidized to phenylacetic acid. Further metabolism of phenylacetic acid was not studied. Other studies have shown that styrene is aerobically converted by microbes to 2-phenylethanol, phenylacetic acid (Sielicki et al. 1978; Shirai and Hisatsuka 1979b), 2-hydroxyphenylacetic acid (Baggi et al. 1983), 1,2-dihydroxy-3-ethenyl-3-cyclohexane (Bestetti et al. 1989), styrene oxide (Hou et al. 1983) and styrene oligomers (Sielicki et al. 1978). Most of these aerobic transformation products are non-persistent. Anaerobic transformation products of styrene include 2-phenylethanol, phenylacetaldehyde, phenylacetic acid, benzoate,

phenol, ethylbenzene, toluene, and ethyl- and methylcyclohexane (Churchman and Grbic-Galic 1987) and many of these transformation products are relatively persistent under anaerobic conditions (Alexander 1990).

4.1.6 Bioaccumulation

Aquatic organisms may take up a chemical in aquatic environments directly through gills and integument, or ingest it in water or in food. If the chemical is not degraded and/or excreted, it can accumulate in the organism. The extent of accumulation from water only is expressed as a bioconcentration factor (BCF), which is the concentration of a chemical in the whole body or one or more tissues of the organism divided by the average exposure concentration in the test at apparent equilibrium. Based on an octanol/water partition coefficient ($\log K_{ow} = 3.16$), the predicted bioconcentration factor (BCF) of styrene is less than 100 for aquatic biota (U.S. EPA 1984). Therefore, it is unlikely that styrene will bioconcentrate in freshwater biota (U.S. EPA 1984); however, there is little empirical data, and no data were found in the literature on the contribution of dietary sources of styrene to the bioaccumulation of styrene in aquatic organisms.

4.2 Environmental Concentration and Trends

4.2.1 Air

Styrene has been detected in ambient air in a wide variety of locations in North America, Europe and Asia (Table 5). The highest concentrations were reported in styrene manufacturing plants (WHO 1983).

Table 5: Measured Concentrations of Styrene in Air			
Matrix	Location/Yr	Concentration	Reference
Air	Canadian urban centres	Ave. $0.6 \mu\text{m}^3$	Environment Canada 1991a
Air	Canadian urban centres, 1990	Max. $29.68 \mu\text{g}/\text{m}^3$	Dann 1992
Air	Vancouver, B.C.	mean values range from 0.17 - $6.47 \mu\text{g}/\text{m}^3$ (n=98)	Dann 1991
Air	Edmonton, Alberta	Non-detectable - $13.0 \mu\text{g}/\text{m}^3$	Alberta Environment Ministry cited in SENES 1989

Table 5: Measured Concentrations of Styrene in Air			
Matrix	Location/Yr	Concentration	Reference
Air	Workplace air, Saskatchewan	43,000 - 2,800,000 $\mu\text{g}/\text{m}^3$	Saskatchewan HRLE 1989, cited in SENES 1989
Air	Ontario communities	< 0.1 - 13.0 $\mu\text{g}/\text{m}^3$	OME 1992b
Air	Thunder Bay, Ont., Oct. - Dec. 1990	< 0.1 - 0.8 $\mu\text{g}/\text{m}^3$	OME 1992b
Air	Sault Ste. Marie, Ont., Oct. - Dec. 1990	0.2 - 0.4 $\mu\text{g}/\text{m}^3$	OME 1992b
Air	Dorset, Ont.	< 0.1 - 0.5 $\mu\text{g}/\text{m}^3$	OME 1992b
Air	Walpole Island, Ont.	mean values range from 0.09-0.5 $\mu\text{g}/\text{m}^3$ (n=55)	Dann 1991
Air	Walpole Island, Ont., Jan. - Sept. 1988	Non-detectable - 0.7 $\mu\text{g}/\text{m}^3$, Ave. 0.09 $\mu\text{g}/\text{m}^3$	Environment Canada 1989
Air	Walpole Island, Ont., Sept. 1988 - Oct. 1989	Non-detectable - 3.2 $\mu\text{g}/\text{m}^3$, ave. 1.5 $\mu\text{g}/\text{m}^3$	Environment Canada 1990b
Air	Windsor, Ont., July - Nov. 1987	0.87 - 13.0 $\mu\text{g}/\text{m}^3$, ave. 3.9 $\mu\text{g}/\text{m}^3$	Environment Canada 1988b
Air	Windsor, Ont., July 1987 - Sept. 1988	0.09 - 12.8 $\mu\text{g}/\text{m}^3$, ave. 2.3 $\mu\text{g}/\text{m}^3$	Environment Canada 1989
Air	Windsor, Ont., Sept. 1988 - Oct. 1989	0.13 - 1.8 $\mu\text{g}/\text{m}^3$, ave. 0.5 $\mu\text{g}/\text{m}^3$	Environment Canada 1990b
Air	Windsor, Ont., Apr. - Nov. 1989	< 0.1 - 2.0 $\mu\text{g}/\text{m}^3$	OME 1992c
Air	Windsor, Ont., Feb. - Dec. 1990	< 0.1 - 1.6 $\mu\text{g}/\text{m}^3$	OME 1992d
Air	Hamilton, Ont., May - Nov. 1989	< 0.1 - 0.4 $\mu\text{g}/\text{m}^3$	OME 1992c
Air	Hamilton, Ont., Jan. - Dec. 1990	< 0.1 - 0.7 $\mu\text{g}/\text{m}^3$	OME 1992d
Air	Toronto, Ont.	< 0.19 - 14.0 $\mu\text{g}/\text{m}^3$, ave. 2.31 $\mu\text{g}/\text{m}^3$	SENES 1985, cited in SENES 1989

Table 5: Measured Concentrations of Styrene in Air			
Matrix	Location/Yr	Concentration	Reference
Air	Toronto, Ont.	mean values range from 0.09-1.06 $\mu\text{g}/\text{m}^3$ (n = 146)	Dann 1991
Air	Toronto, Ont., Apr. - Oct. 1989	< 0.1 - 2.3 $\mu\text{g}/\text{m}^3$	OME 1992c
Air	Toronto, Ont., Feb. - Dec. 1990	< 0.1 - 0.7 $\mu\text{g}/\text{m}^3$	OME 1992d
Air	Ottawa, Ont.	mean = 0.03 $\mu\text{g}/\text{m}^3$ (n = 35)	Dann 1991
Air	Workplace air, Ontario	Non-detectable - 433,000 $\mu\text{g}/\text{m}^3$	Acres Consulting Services Ltd. 1981, cited in SENES 1989
Air	Montreal, P.Q.	mean values range from 0.35-0.59 $\mu\text{g}/\text{m}^3$ (n = 79)	Dann 1991
Air	Halifax, N.S.	mean = 0.20 $\mu\text{g}/\text{m}^3$ (n = 27)	Dann 1991
Air	Urban centres	6 ppb (0.026 mg/m^3)	Alexander 1990
Air	USA	Ave. 0.9 $\mu\text{g}/\text{m}^3$	Brodzinski and Singh, cited in SENES 1989
Air	Rural/suburban areas, USA	Medians 0.28 - 0.34 $\mu\text{g}/\text{m}^3$	2 References cited in ATSDR 1990
Air	Urban areas, USA	0.63 - 21.0 $\mu\text{g}/\text{m}^3$	6 References cited in ATSDR 1990
Air	Industrial areas, USA	Max. 25 $\mu\text{g}/\text{m}^3$	3 References cited in ATSDR 1990
Air	Hazardous waste sites, USA	Max. 65 $\mu\text{g}/\text{m}^3$	2 References cited in ATSDR 1990
Air	Tunnel, USA	Max. 6.6 $\mu\text{g}/\text{m}^3$	Hampton <i>et al.</i> 1983, cited in ATSDR 1990

Table 5: Measured Concentrations of Styrene in Air			
Matrix	Location/Yr	Concentration	Reference
Air	California cities	4.3 - 65 $\mu\text{g}/\text{m}^3$	Neligan <i>et al.</i> 1965, cited in SENES 1989
Air	Southern California, 1965	0.021 mg/m^3	WHO 1983
Air	Los Angeles, California	0.1-5.5 ppb (4.32-238 $\times 10^{-4} \text{ mg}/\text{m}^3$)	Grosjean and Fung 1984
Air	3 New Jersey cities 1981-1982	0.7-0.24 ppb (30-10 $\times 10^{-4} \text{ mg}/\text{m}^3$)	Harkov <i>et al.</i> 1984
Air	New Jersey cities	Medians 0.38 - 0.66 $\mu\text{g}/\text{m}^3$	Wallace <i>et al.</i> 1987b
Air	Outdoors, Kanawha Valley, West Virginia	Ave. 0.9 $\mu\text{g}/\text{m}^3$	Cohen <i>et al.</i> 1989, cited in SENES 1989
Air	Greensboro, North Carolina	Median 0.1 $\mu\text{g}/\text{m}^3$	Wallace <i>et al.</i> 1987b
Air	Delft, The Netherlands	Ave. <0.433 $\mu\text{g}/\text{m}^3$, Max. 3.031 $\mu\text{g}/\text{m}^3$	Bos <i>et al.</i> 1977
Air	Delft, The Netherlands	0.4 $\mu\text{g}/\text{m}^3$, 2.9 $\mu\text{g}/\text{m}^3$ maximum	IARC 1979
Air	Streets of Leningrad, USSR	NR	IARC 1979
Air	Japanese urban area	0.0008 $\mu\text{g}/\text{m}^3$	WHO 1983
Air	Nagoya, Japan	0.84 $\mu\text{g}/\text{m}^3$	IARC 1979
Air	homes (2125)	mean 1.41 ppb (0.0061 mg/m^3) median 0.31 ppb (0.00134 mg/m^3)	Shah and Singh 1988
Air	Indoor air, USA	Max. 6,500 $\mu\text{g}/\text{m}^3$	3 References cited in ATSDR 1990
Air	Homes, Kanawha Valley, West Virginia	1.28 - 3.34 $\mu\text{g}/\text{m}^3$	Cohen <i>et al.</i> 1989, cited in SENES 1989
Air	Non-smokers' homes, USA	Geometric means 0.5 - 1.7 $\mu\text{g}/\text{m}^3$	Wallace <i>et al.</i> 1987a
Air	Smokers' homes, USA	Geometric means 0.4 - 3.4 $\mu\text{g}/\text{m}^3$	Wallace <i>et al.</i> 1987a

Table 5: Measured Concentrations of Styrene in Air			
Matrix	Location/Yr	Concentration	Reference
Air	Workplace air, USA	Max. $4.5 \times 10^6 \mu\text{g}/\text{m}^3$	3 References cited in ATSDR 1990
Air	Manufacturing area for polystyrene	21-210 mg/m^3	WHO 1983
Air	Manufacturing area for styrene-butadiene rubber	42-840 mg/m^3	WHO 1983
Air	Near reinforced plastic processors, USA	0.29 - 2,934 $\mu\text{g}/\text{m}^3$	McKay <i>et al.</i> 1982
Vehicle emissions	NR	0.76% of total hydrocarbons of conventional engines	WHO 1983
Vehicle emissions	NR	2.67% of total hydrocarbons of rotary engines	WHO 1983
Cigarette smoke	NR	18-48 $\mu\text{g}/\text{cigarette}$	WHO 1983

Levels of styrene in air are elevated during pollution episodes and are generally higher in winter than in summer (Alexander 1990). The air in highway tunnels may be rich in styrene from gas combustion and styrene levels may also be elevated around hazardous waste sites, with average levels reported between 0.11 and 1.53 ppb ($0.476\text{--}6.61 \mu\text{g}/\text{m}^3$) and as high as 15.5 ppb ($67.0 \mu\text{g}/\text{m}^3$) (Alexander 1990). Sanitary landfills receiving municipal and nonhazardous industrial wastes had mean styrene concentrations in air of 0.23 to 0.41 ppb ($1\text{--}1.77 \mu\text{g}/\text{m}^3$) and maximum values of 1.52 ppb ($6.57 \mu\text{g}/\text{m}^3$) (Alexander 1990). A survey of air in residences showed average and median concentrations of 1.41 and 0.31 ppb ($6.10\text{--}1.34 \mu\text{g}/\text{m}^3$), respectively (Shah and Singh 1988).

Styrene concentrations in the atmosphere at Canadian air monitoring stations in 18 mostly urban centres from 1988 to 1990 averaged $0.59 \mu\text{g}/\text{m}^3$ ($n=586$), with styrene concentrations in individual samples ranging from non-detectable (detection limit= $0.05\text{--}0.1 \mu\text{g}/\text{m}^3$) to $34.2 \mu\text{g}/\text{m}^3$ (at Vancouver, B.C.) (Dann 1990, pers. com.). The only non-urban site monitored was Walpole Island, Ontario, which had a mean concentration of airborne styrene of $0.09 \mu\text{g}/\text{m}^3$ from January to October 1988 and $0.5 \mu\text{g}/\text{m}^3$ from February 1989 to January 1990, with concentrations in individual samples up to $3.2 \mu\text{g}/\text{m}^3$. Atmospheric styrene concentrations reported by the

Ontario government Volatile Organic Compound Sampling Network ranged from <0.1 to 13.0 $\mu\text{g}/\text{m}^3$ in 1991, with the highest concentration reported from Mississauga. Styrene concentrations from a non-urban site near Dorset ranged from <0.1 to 0.5 $\mu\text{g}/\text{m}^3$ (OME 1992b). Other studies of the air quality of major Canadian urban studies (Environment Canada 1988b, 1989, 1990b; SENES 1985) cite styrene concentrations ranging from 0.09 $\mu\text{g}/\text{m}^3$ (Windsor, Ontario) to 14.0 $\mu\text{g}/\text{m}^3$ (Toronto, Ontario).

4.2.2 Freshwater

4.2.2.1 Surface Water

Styrene is infrequently detected in surface waters, with contamination usually being traced to a direct input (eg. industrial effluent) (Table 6). Only a few samples from 23 Great Lakes sites had very low levels of styrene, e.g. close to detection (CPHA 1986).

Table 6: Measured Concentrations of Styrene in Water			
Matrix	Location/Yr	Concentration	Reference
Raw water	Alberta	<1.0 $\mu\text{g}/\text{L}$	Halina 1992
Water	Niagara R. at Fort Erie	Max. 0.2 $\mu\text{g}/\text{L}$	OME 1982, cited in SENES 1989
Raw water	Niagara area water treatment plants	Non-detectable - 0.3 $\mu\text{g}/\text{L}$	OME 1983, cited in SENES 1989
Raw water	Various Ontario municipalities	Ave. <0.1 - 0.5 $\mu\text{g}/\text{L}$, Max. > 1.0, <10.0 $\mu\text{g}/\text{L}$	Otson 1987
Raw water	Various Ontario municipalities, Winter	<0.1 - 1.3 $\mu\text{g}/\text{L}$	Otson 1992
Raw water	Various Ontario municipalities, Spring	0.1 - 1.7 $\mu\text{g}/\text{L}$	Otson 1992
Raw water	Various Ontario municipalities, Summer	<0.1 - 0.3 $\mu\text{g}/\text{L}$	Otson 1992
Water	St. Clair R., Ont.	<0.1 - 1.1 $\mu\text{g}/\text{L}$	Environment Canada/OME 1986
Intake water	Ontario organic chemical manufacturing plants	Max. 12-mo. ave. 1.1 $\mu\text{g}/\text{L}$	OME 1992a
Treated water	Niagara area water treatment plants	Non-detectable - 0.2 $\mu\text{g}/\text{L}$	OME 1983, cited in SENES 1989
Treated water	Various Ontario municipalities	Ave. 0.1 - 0.5 $\mu\text{g}/\text{L}$	Otson 1987
Treated water	Various Ontario municipalities, Winter	<0.1 - 1.3 $\mu\text{g}/\text{L}$	Otson 1992
Treated water	Various Ontario municipalities, Spring	<0.1 - 1.1 $\mu\text{g}/\text{L}$	Otson 1992
Treated water	Various Ontario municipalities, Summer	<0.1 - 0.5 $\mu\text{g}/\text{L}$	Otson 1992

Table 6: Measured Concentrations of Styrene in Water			
Matrix	Location/Yr	Concentration	Reference
Soil leachate	Industrial site, Laval, Quebec	<3.35 µg/L	MENVIQ, cited in SENES 1989
Surface water	Industrial site, Laval, Quebec	<10.0 µg/L	MENVIQ, cited in SENES 1989
Water	Cincinnati water supply	0.024 µg/L	Coleman <i>et al.</i> 1984
Water	British estuaries	Max. 1.7 µg/L	Law <i>et al.</i> 1991
Water	Rhine River	0.01-0.1 µg/L	Pagga 1987 Zoeteman <i>et al.</i> 1980
Water	Scheldt River, Netherlands	1 µg/L	NAP 1980, cited in U.S EPA 1985
Ground water	Netherlands	Max. 10.0 µg/L	Zoeteman <i>et al.</i> 1981
Water	Delaware River	Detected but not quantifiable	Sheldon and Hites 1978
Water	Iowa well water	1.0 µg/L	Kelley 1985
Water	Tennessee River	4.2 µg/L	Goodley and Gordon 1976
Water	Kanawha River, West Virginia	1 µg/L	IARC 1979

A survey of surface waters in Canada in 1988 had no reported concentrations of styrene above 1 µg/L, which was the detection limit for the method of analysis (NAQUADAT 1991). The surface water samples were collected from the Athabasca, McLeod, Peace, Smokey, Notikewin, Wabasca and Boyer rivers. A survey of 76 municipal and drinking water supplies in Atlantic Canada in 1988 revealed no styrene concentrations above 0.2 µg/L (NAQUADAT 1991). Various other studies of Canadian and Great Lakes water quality (Environment Canada/OME 1986; OME 1982, 1983, 1992a; Otson 1987, 1992) have cited styrene concentrations, ranging up to 1.7 µg/L (in raw water at Cornwall, Ontario) (Otson 1992). Surface water from an industrial site at Laval, Quebec, had a concentration of <10.0 µg styrene/L, while soil leachate from the site contained <3.35 µg/L (MENVIQ).

4.2.2.2 Ground Water

One study (Lesage *et al.* 1990) was identified in the available literature documenting the concentrations of styrene in Canadian groundwater. Three groundwater monitoring wells were sampled at the Uniroyal Chemical Company in Elmira, Ontario. Styrene was detected at a concentration of 0.07 mg/L in one of two wells situated beside existing and former waste holding lagoons, but was not detected (detection limit not reported) in the second well or in the third well located inside a former disposal lagoon (Lesage *et al.* 1990).

Styrene concentrations in groundwater from the Netherlands ranged up to 10.0 µg/L (Zoeteman et al. 1981).

4.2.2.3 Waste Water

Table 7: Measured Concentrations of Styrene in Effluents			
Matrix	Location/Yr	Concentration	Reference
Industrial Effluent	Alberta	< 1.0 µg/L	Halina 1992
Industrial Effluent	Sarnia, Ontario	< 1.0 - 970 µg/L	Environment Canada/OME 1986
Industrial Effluent	Synthetic rubber company	2.6 µg/L	Keith 1974
Industrial Effluent	Petrochemical company	0.031 µg/L	Keith 1974
Industrial Effluent	Latex plant Chemical plant Textile plant/Kentucky	NR NR NR	Shackelford and Keith 1976
Industrial Effluent	Chemical plant	Max. 970 µg/L	King and Sherbin 1986, cited in ATSDR 1990
Industrial Effluent	Coal gasification plant	Max. 83 µg/L	Pellizzari et al. 1979, cited in ATSDR 1990
Effluent	NR (Not Reported)	< 10 µg/L	Perry et al. 1979
Raw Sewage	Southern Ontario cities wastewater pollution control plants	43.0 - 6,010 µg/kg ww	OME 1988, cited in SENES 1989
Final Effluent	Southern Ontario cities wastewater pollution control plants	13.0 - 15.0 µg/L	OME 1988, cited in SENES 1989

A study of the St. Clair River in 1981 involved a survey of industrial effluents for organic compounds. Styrene was measured in the effluents of several petrochemical plants at concentrations ranging on average from 0.05-2100 µg/L with most of the values reported between 0.05 and 0.1 µg/L (Bonner and Meresz 1981). However, styrene concentrations were measured as high as 200 mg/L in a single grab sample from one plant effluent. The frequency of occurrence of styrene in effluents of the St. Clair River system was 14 out of 88 samples and 8 out of 31 sites (Bonner and Meresz 1981). More recent data from the Ontario organic chemistry manufacturing industry revealed that twelve-month mean styrene concentrations in effluents, from October 1989 to September 1990, ranged from 0.3 µg/L to 71.1 µg/L with average loading values of 0.022 to 0.511 kg/d. The styrene concentration in the intake water did not exceed 1.1 µg/L (OME 1992a).

Styrene has been detected, but not quantified, in various American chemical, textile and latex effluents in various locations in Kentucky, Tennessee and other U.S. states (Shackelford and Keith 1976) (Table 7). Keith (1974) reported styrene concentrations of 0.031 mg/L in a Los Angeles oil refinery waste water effluent discharging approximately 0.5 kilograms of styrene daily. Concentrations of 2.6 $\mu\text{g/L}$ were detected in the effluent from a synthetic rubber company. Perry et al. (1979) reported styrene concentrations of <10 $\mu\text{g/L}$ in an unidentified effluent.

4.2.2.4 Sediments

Little information was found concerning styrene concentrations in sediments. Samoiloff et al. (1983) detected styrene in sediments retrieved from Tobin Lake, Saskatchewan; however, concentrations were not quantified. Styrene concentrations of 4.2 $\mu\text{g/kg}$ were also reported in sediment samples from the lower Tennessee River in the United States (Goodley and Gordon 1976).

4.2.2.5 Biota

Styrene was detected but not quantified in the tissues of several species of fish (Emerald Shiner, *Notropis atherinoides*; Black Crappie, *Pomoxis nigromaculatus*; Bluegill, *Lepomis macrochirus*; Pumpkinseed, *Lepomis gibbosus*; and Walleye, *Stizostedion vitreum*) from the St. Clair River. Whole body styrene concentrations between 15 and 100 $\mu\text{g/kg}$ were measured in tissues of "Splake", *Salvelinus fontinalis* X *S. namaycush*, and Walleye caught in the St. Clair River near Stag Island (Bonner and Meresz 1981). Edible shellfish from Atlantic Canada contained <10.0 μg styrene/kg (Zenon 1989).

No data on levels of styrene in plants, birds or wild mammals were identified in the literature from Canada or elsewhere.

4.2.3 Marine Water

No information concerning styrene concentrations in marine surface waters, sediments or biota were identified.

4.2.4 Soils

Styrene may enter soil environments as accidental spills, leakage from buried drums, or as a component in leachate from industrial landfill sites.

OME (1980) reported concentrations of styrene as high as 29 $\mu\text{g/kg}$ at a depth of 45 cm in soil adjacent to the tracks at the site of a train derailment in Mississauga, Ontario. The concentration in the upper 15 cm of the soil was <0.05 to 9 $\mu\text{g/kg}$. A soil sample 100 m north of the tracks contained <0.05 to 17 $\mu\text{g/kg}$. In a study to determine background levels of organic chemicals in soil in the region, styrene concentrations were found to range from <0.05 to 0.2 $\mu\text{g/kg}$ at Port Credit, Ontario, and to be <0.05 $\mu\text{g/kg}$ in the Oakville/Burlington, Ontario, area (Golder Associates 1987). Soil from an industrial site at Laval, Quebec, contained <91 $\mu\text{g/kg}$ (MENVIQ).

5.0 POPULATION EXPOSURES

5.1 Exposures of Wildlife Populations

Based on the concentrations of styrene reported for fish in the St. Clair River, a potential exposure scenario for a fish-eating mammal such as the mink (*Mustela vison*) was estimated. Data for this scenario however are sparse and were measured over a decade ago. Mink are opportunistic carnivores with aquatic organisms comprising up to 100% of the diet. Based on the exposure scenario presented in Table 8, total daily intake of styrene by mink in the St. Clair River area is estimated to be 18 $\mu\text{g/kg-bw/day}$. This scenario represents a worst-case exposure since concentrations in air and water are the highest values recorded and the levels for fish were for trophic level 4 fish (thus overestimating oral exposure as mink typically ingest trophic level 3 fish). It is also assumed that current levels in fish and water are equivalent or less than those measured in the early 1980s. No data are available to confirm this latter assumption.

Table 8. Estimated worst-case total daily intake of styrene for a 1 kg adult mink in the St. Clair River area.

MEDIUM	CONCENTRATION	RATE OF CONSUMPTION ^d	DAILY INTAKE
Air	3.2 $\mu\text{g}/\text{m}^3$ ^a	0.55 m^3/day	1.8 $\mu\text{g}/\text{kg-bw}/\text{day}$
Water	1.6 $\mu\text{g}/\text{L}$ ^b	0.1 L/day	~0.2 $\mu\text{g}/\text{kg-bw}/\text{day}$
Fish	100 $\mu\text{g}/\text{kg}$ ^c	0.16 kg/day	16 $\mu\text{g}/\text{kg-bw}/\text{day}$
TOTAL	---	---	18 $\mu\text{g}/\text{kg-bw}/\text{day}$

^a The highest non-urban concentrations of styrene in air were detected at Walpole Island, Ontario (in the Lake St. Clair area) from January 1988 to October 1989 (Environment Canada 1991a).

^b Based on a concentration in fish of 100 $\mu\text{g}/\text{kg}$, and a maximum bioconcentration factor of 64 (using the equation of Veith et al. (1979) and a $\log K_{ow}$ of 2.95), the concentration in water would be 1.6 $\mu\text{g}/\text{L}$, which is similar to the maximum concentration of styrene found in surface water measured in the St. Lawrence River near Cornwall in 1983 (Otson 1987; 1992).

^c Styrene was found in trophic level 4 fish from the St. Clair River (near Stag Island) at a maximum whole body concentration of 100 $\mu\text{g}/\text{kg-ww}$ (Bonner and Meresz 1981).

^d Rate of consumption data for air from Stahl (1967), for water from Calder and Braun (1983), and for fish from Nagy (1987), with the additional assumption that fish comprise 75% of the mink diet.

6.0 TOXICOKINETICS AND METABOLISM

Pharmacokinetic studies have shown that absorption, distribution, metabolism and excretion of styrene is similar for all mammals examined with some species-specific differences. Styrene is metabolized rapidly following all standard routes of administration. Most of the styrene is excreted via urinary metabolites (85-90%), a small percent is excreted in the faeces (2-3%) and some is exhaled (12%) as CO_2 (Danishefsky and Willhite 1954;

Withey and Collins 1979). The major metabolites are mandelic acid and phenylglyoxylic acid (Figure 3) (Bond 1989; Ohtsuji and Ikeda 1971). Residues of styrene can be found in most soft tissues immediately following exposure (Shugaev and Yaroslavl 1969; Withey and Collins 1979; Carlsson 1981), but distribution studies indicate that adipose tissue can have the highest concentrations (Lof et al. 1983, 1984). However, no information was found regarding the mobilization of styrene from adipose tissue. The half-life of styrene is generally less than 4 hours and elimination kinetics are dose-dependent and biphasic (Withey and Collins 1979).

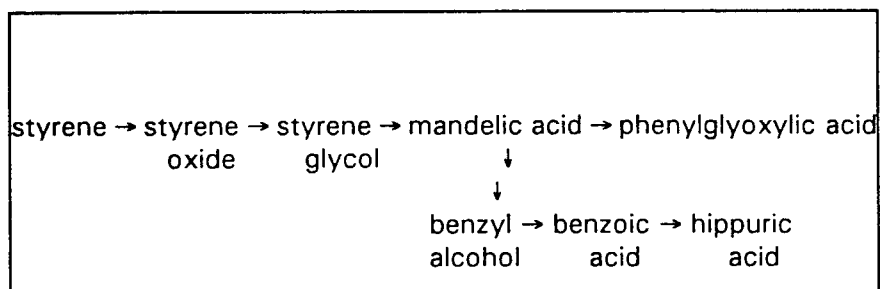


Figure 3: Proposed metabolic pathway of styrene in the rat (Ohtsuji and Ikeda 1971)

Styrene in mammalian systems may also be metabolized to styrene-7,8-oxide (phenyl-oxirane) which is then hydrated to styrene glycol (1-phenol-1,2-ethanediol) or conjugated with glutathione (Nordqvist et al. 1985).

7.0 EFFECTS ON THE ECOSYSTEM

7.1 Aquatic Toxicity

A number of studies have been conducted on the toxicity of styrene to aquatic organisms (Tables 9 to 15). However, the value of most of these studies is greatly diminished because they used static, open systems with results based on nominal, unmeasured exposure concentrations. These conditions are conducive to rapid volatilization of styrene from water, therefore initial styrene concentrations would not be maintained over the exposure period. For example, Fu and Alexander (1992) showed that the concentration of styrene in distilled and lake water declined through volatilization by about 95%, from 4 mg/L to about 0.2 mg/L, after 24 hours in flasks open to the air. Lindström and Lindström (1980) demonstrated that styrene declined from initial measured concentrations of 46 mg/L to 12.5 mg/L, and from 23 mg/L to 3.3 mg/L, in 2 hours. In view of these data, it is imperative that toxicity tests with styrene be performed in such a manner that volatilization of styrene is minimized and exposure concentrations are maintained.

7.1.1 Freshwater Organisms

7.1.1.1 Acute Toxicity

The lowest concentration of styrene reported to cause an adverse effect in microorganisms was 5.4 mg/L (a 5-minute EC₅₀ for reduction of light emitted) for the luminescent marine bacterium, *Photobacterium phosphoreum*, in the Microtox Test (Qureshi et al. 1982).

Acute toxicity data were identified for one crustacean species, *Daphnia magna* (Table 9). The lowest reported 48-h LC₅₀ for this species was 23 mg/L, based on nominal (unmeasured) styrene concentrations (LeBlanc 1980).

Species	Life Stage	Chemical Form	Test Conditions					Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Hardness (mg/L)	Code				
<i>Daphnia magna</i> (water flea)	≤ 24 h	styrene	7.4-9.4 mean = 8.0	22 ± 1	> 60% satur.	173 ± 13 (as CaCO ₃)	ASU	24	27	LC50	LeBlanc 1980
<i>D. magna</i>	≤ 24 h	styrene	7.4-9.4 mean = 8.0	22 ± 1	6.5-9.1	173 ± 13 (as CaCO ₃)	ASU	48	23	LC50	LeBlanc 1980
<i>D. magna</i>	≤ 24 h	styrene	7.4-9.4 mean = 8.0	22 ± 1	6.5-9.1	173 ± 13 (as CaCO ₃)	ASU	48	< 6.8	NOEC	LeBlanc 1980
<i>D. magna</i>	24 h	styrene (dechlorinated tap water as dilution water)	7.6-7.7	20-22	O ₂ saturated	70	ASU	24	255	LC50	Bringmann and Kühn 1977
<i>D. magna</i>	24 h	styrene (dechlorinated tap water as dilution water)	7.6-7.7	20-22	O ₂ saturated	70	ASU	24	300	LC100	Bringmann and Kühn 1977
<i>D. magna</i>	24 h	styrene (dechlorinated tap water as dilution water)	7.6-7.7	20-22	O ₂ saturated	70	ASU	24	130	LC0	Bringmann and Kühn 1977
<i>D. magna</i>	≤ 24 h	styrene (dechlorinated Toronto tap water as dilution water)	7.8-8.1	15 ± 1.0	NR (but non-aerated)	NR	ASU	48 (2-16h light, 8h dark cycles)	59	LC50	Qureshi et al. 1982
<i>D. magna</i>	NR	styrene	8.0	20	NA	NA	ASU	24	105	EC0	Bringmann and Kühn 1982
<i>D. magna</i>	NR	styrene	8.0	20	NA	NA	ASU	24	182	EC50	Bringmann and Kühn 1982
<i>D. magna</i>	NR	styrene	8.0	20	NA	NA	ASU	24	300	EC100	Bringmann and Kühn 1982

Table 9: Acute Toxicity of Styrene to Freshwater Invertebrates											
Species	Life Stage	Chemical Form	Test Conditions					Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Hardness (mg/L)	Code				
Legend:	A	acute			NOEC	no observed effect concentration					
	S	static			ECO	Effect Concentration 0%					
	M	measured			EC50	Effect Concentration 50%					
	U	unmeasured			EC100	Effect Concentration 100%					
	NA	not available			LCO	Lethal Concentration 0%					
	NR	not recorded			LC50	Lethal Concentration 50%					
					LC100	Lethal Concentration 100%					

Acute toxicity data were identified for seven species of freshwater fish: fathead minnows (*Pimephales promelas*), bluegills (*Lepomis macrochirus*), goldfish (*Carassius auratus*), guppies (*Poecilia reticulata*), rainbow trout (*Oncorhynchus mykiss*), Lake Emerald shiner (*Notropis atherinoides acutus*), and the European species, golden orfe (*Leuciscus idus*) (Table 10).

The lowest reported acute toxicity value identified for styrene in freshwater fish was a 24-h LC₅₀ value of 2.5 mg/L for rainbow trout (Qureshi et al. 1982). Acute toxicity values for the other fish species ranged from 25 mg styrene/L (24-h LC₅₀) for goldfish (Jensen 1978) to 74.83 mg styrene/L (24-, 48- and 96-h LC₅₀) for the guppy (Pickering and Henderson 1966). Once again, these values were based upon initial, nominal styrene concentrations.

Table 10: Acute Toxicity of Styrene to Freshwater Fish											
Species	Life Stage	Chemical Form	Test Conditions					Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Hardness (mg/L)	Code				
<i>Pimephales promelas</i> (fathead minnow)	3.8-6.4 cm 1 - 2 g	styrene (soft dilution water)	7.5	25	7.8	20	ASU	24	56.73	LC50	Pickering and Henderson 1966
<i>P. promelas</i>	3.8-6.4 cm 1 - 2 g	styrene (soft dilution water)	7.5	25	7.8	20	ASU	48	53.58	LC50	Pickering and Henderson 1966
<i>P. promelas</i>	3.8-6.4 cm 1 - 2 g	styrene (soft dilution water)	7.5	25	7.8	20	ASU	96	46.41	LC50	Pickering and Henderson 1966
<i>P. promelas</i>	3.8-6.4 cm 1 - 2 g	styrene (hard dilution water)	8.2	25	7.8	360	ASU	24	62.81	LC50	Pickering and Henderson 1966
<i>P. promelas</i>	3.8-6.4 cm 1 - 2 g	styrene (hard dilution water)	8.2	25	7.8	360	ASU	48	62.81	LC50	Pickering and Henderson 1966

Table 10: Acute Toxicity of Styrene to Freshwater Fish											
Species	Life Stage	Chemical Form	Test Conditions					Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Hardness (mg/L)	Code				
<i>P. promelas</i>	3.8-6.4 cm 1 - 2 g	styrene (hard dilution water)	8.2	25	7.8	360	ASU	96	59.30	LC50	Pickering and Henderson 1966
<i>P. promelas</i>	juvenile 4 - 8 wk. 1.1-3.1 cm	styrene (Lake Superior dilution water)	>5.9	18-22	> 4.0	NR	ASU	1	100	LC50	Matteson et al. 1976
<i>P. promelas</i>	4 - 8 wk. 1.1-3.1 cm	styrene (Lake Superior dilution water)	>5.9	18-22	> 4.0	NR	ASU	24	32	LC50	Matteson et al. 1976
<i>P. promelas</i>	4 - 8 wk. 1.1-3.1 cm	styrene (Lake Superior dilution water)	>5.9	18-22	> 4.0	NR	ASU	48	32	LC50	Matteson et al. 1976
<i>P. promelas</i>	4 - 8 wk. 1.1-3.1 cm	styrene (Lake Superior dilution water)	>5.9	18-22	> 4.0	NR	ASU	72	32	LC50	Matteson et al. 1976
<i>P. promelas</i>	4 - 8 wk. 1.1-3.1 cm	styrene (Lake Superior dilution water)	>5.9	18-22	> 4.0	NR	ASU	96	32	LC50	Matteson et al. 1976
<i>P. promelas</i>	4 - 8 wk. 1.1-3.1 cm	styrene (Acetone added to dilution water)	>5.9	18-22	> 4.0	NR	ASU	1	40	LC50	Matteson et al. 1976
<i>P. promelas</i>	4 - 8 wk. 1.1-3.1 cm	styrene (Acetone added to dilution water)	>5.9	18-22	> 4.0	NR	ASU	24	30	LC50	Matteson et al. 1976
<i>P. promelas</i>	4 - 8 wk. 1.1-3.1 cm	styrene (Acetone added to dilution water)	>5.9	18-22	> 4.0	NR	ASU	48	29	LC50	Matteson et al. 1976
<i>P. promelas</i>	4 - 8 wk. 1.1-3.1 cm	styrene (Acetone added to dilution water)	>5.9	18-22	> 4.0	NR	ASU	72	29	LC50	Matteson et al. 1976
<i>P. promelas</i>	4 - 8 wk. 1.1-3.1 cm	styrene (Acetone added to dilution water)	>5.9	18-22	> 4.0	NR	ASU	96	29	LC50	Matteson et al. 1976
<i>Notropis atherinoides acutus</i> (Lake Emerald Shiner)	NA	styrene	NA	NA	NA	NA		NA	31	LC50	Dow Chemical 1989, as cited in Alexander 1990
<i>Notropis atherinoides acutus</i> (Lake Emerald Shiner)	NA	styrene	NA	NA	NA	NA		NA	8	"safe" concentration	Dow Chemical 1989, as cited in Alexander 1990

Table 10: Acute Toxicity of Styrene to Freshwater Fish

Species	Life Stage	Chemical Form	Test Conditions					Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Hardness (mg/L)	Code				
<i>Lepomis macrochirus</i> (bluegill)	3.8-6.4 cm 1 - 2 g	styrene (soft dilution water)	7.5	25	7.8	20	ASU	24	25.05	LC50	Pickering and Henderson 1966
<i>L. macrochirus</i>	3.8-6.4 cm 1 - 2 g	styrene (soft dilution water)	7.5	25	7.8	20	ASU	48	25.05	LC50	Pickering and Henderson 1966
<i>L. macrochirus</i>	3.8-6.4 cm 1 - 2 g	styrene (soft dilution water)	7.5	25	7.8	20	ASU	96	25.05	LC50	Pickering and Henderson 1966
<i>Carassius auratus</i> (goldfish)	3.8-6.4 cm 1 - 2 g	styrene (soft dilution water)	7.5	25	7.8	20	ASU	24	64.74	LC50	Pickering and Henderson 1966
<i>C. auratus</i>	3.8-6.4 cm 1 - 2 g	styrene (soft dilution water)	7.5	25	7.8	20	ASU	48	64.74	LC50	Pickering and Henderson 1966
<i>C. auratus</i>	3.8-6.4 cm 1 - 2 g	styrene (soft dilution water)	7.5	25	7.8	20	ASU	96	64.74	LC50	Pickering and Henderson 1966
<i>C. auratus</i>	6.2 ± 0.7 cm 3.3 ± 1.0 g	styrene Amsterdam (tap water dilution water)	7.0	20 ± 1.0	> 4.0 with continuous aeration	NR	ASM	24	26	LC50	Bridié et al. 1979
<i>C. auratus</i>	NR	styrene	NR	NR	NR	NR	ASU	24	25	LC50	Jensen 1978
<i>Poecilia reticulata</i> (guppy)	1.9-2.5 cm 0.1-0.2 g 6 Months	styrene (soft dilution water)	7.5	25	7.8	20	ASU	24	74.83	LC50	Pickering and Henderson 1966
<i>P. reticulata</i>	1.9-2.5 cm 0.1-0.2 g 6 Months	styrene (soft dilution water)	7.5	25	7.8	20	ASU	48	74.83	LC50	Pickering and Henderson 1966
<i>P. reticulata</i>	1.9-2.5 cm 0.1-0.2 g 6 Months	styrene (soft dilution water)	7.5	25	7.8	20	ASU	96	74.83	LC50	Pickering and Henderson 1966
<i>Oncorhynchus mykiss</i> (rainbow trout)	0.5-3.0 g (yoy)	styrene (dechlorinated Toronto tap water as dilution water)	7.8-8.1	15 ± 1.0	NR	135	ASU	24	2.5	LC50	Qureshi et al. 1982
<i>Leuciscus idus</i> (golden orfe)	NR	styrene	NR	NR	NR	NR	SU	NR	9	LC0	Juhnke and Lüdemann 1978
<i>L. idus</i>	NR	styrene	NR	NR	NR	NR	SU	NR	17	LC50	Juhnke and Lüdemann 1978

Table 10: Acute Toxicity of Styrene to Freshwater Fish											
Species	Life Stage	Chemical Form	Test Conditions					Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Hardness (mg/L)	Code				
<i>L. idus</i>	NR	styrene	NR	NR	NR	NR	SU	NR	18	LC100	Juhnke and Lüdemann 1978
<i>L. idus</i>	NR	styrene	NR	NR	NR	NR	SU	NR	45	LC0	Juhnke and Lüdemann 1978
<i>L. idus</i>	NR	styrene	NR	NR	NR	NR	SU	NR	66	LC50	Juhnke and Lüdemann 1978
<i>L. idus</i>	NR	styrene	NR	NR	NR	NR	SU	NR	90	LC100	Juhnke and Lüdemann 1978
Legend: A acute LC100 Lethal Concentration 100% S static LC50 Lethal Concentration 50% M measured LC0 Lethal Concentration 0% U unmeasured yoy young of the year NA not available NR not recorded											

No data were found in the literature regarding the toxicity of styrene to amphibians or to freshwater plantlife.

7.1.1.2 Chronic Toxicity

Chronic toxicity data were available for one species of bacteria, *Pseudomonas putida*, and one species of protozoan, *Entosiphon sulcatum* (Bringmann and Kühn 1980). The toxicity threshold (TT) values were 72 mg styrene/L for *P. putida* (effects based on turbidity of the bacterial solution at the end of the 16-hour exposure period) and >256 mg styrene/L for *E. sulcatum* (effects based on the number of organisms measured by an electronic particle counter at the end of the 72-hour exposure period). Styrene concentrations were not measured.

Table 11: Chronic Toxicity of Styrene to Freshwater Microorganisms

Species	Life Stage	Chemical Form	Test Conditions				Code	Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Hardness (mg/L)					
<i>Entosiphon sulcatum</i> (flagellate euglenoid)	initial culture turbidity reported	styrene	NR	25	NR	NR	CSU	72	> 256	inhibition of growth	Bringmann and Kühn 1980
Legend: C chronic NR not recorded S static U unmeasured											

Chronic toxicity data were available for one species of green algae (Chlorophyceae), *Scenedesmus quadricauda*, one species of blue-green algae (Cyanophyceae), *Microcystis aeruginosa*, and for one cryptomonad species (Cryptophyceae), *Chilomonas paramecium* (Table 11). The lowest toxicity threshold was 67 mg styrene/L for *M. aeruginosa* (Bringmann and Kühn 1978, as cited in AQUIRE 1991). Eight-day cell multiplication inhibition tests were used to determine the toxicity threshold, defined as the concentration of styrene which results in the onset of inhibition of growth. Algal cell multiplication was determined turbidimetrically and exposure concentrations were nominal.

Table 12: Chronic Toxicity of Styrene to Freshwater Plants

Species	Life Stage	Chemical Form	Test Conditions				Code	Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Hardness (mg/L)					
<i>S. quadricauda</i>	initial culture turbidity reported	styrene	NR	27	NR	NR	CSU	7d	> 200	inhibition of growth	Bringmann and Kühn 1980
<i>S. quadricauda</i>	NR	styrene	NR	27	NR	NR	CSU	8d	> 200	inhibition of growth	Bringmann and Kühn 1978, as cited in AQUIRE 1991
<i>Microcystis aeruginosa</i>	NR	styrene	NR	27	NR	NR	CSU	8d	67	inhibition of growth	Bringmann and Kühn 1978, as cited in AQUIRE 1991
<i>Chilomonas paramecium</i>	NR	styrene	6.9	20	NR	NR	CSU	48	>100	inhibition of growth	Bringmann et al. 1980
Legend: C chronic NR not recorded S static U unmeasured											

No chronic toxicity data were identified for freshwater macroinvertebrates or vertebrates.

7.1.2 Marine Organisms

7.1.2.1 Acute Toxicity

Acute toxicity data were identified for four species of marine invertebrates, *Artemia salina* (brine shrimp) and *Pontoporeia affinis* (marine amphipod) (Table 13) and *Paracentrotus lividus* and *Psammechinus microtuberculatus* (Table 14).

Lindström and Lindström (1980) exposed *Pontoporeia affinis* (marine amphipod), for 10 d of a 40-d experimental period, to nominal sublethal concentrations of styrene ranging from 2.3 to 69 mg/L, to determine effects on nocturnal swimming behaviour. Exposure concentrations of styrene were difficult to determine because of the rapid diminution of the concentrations due to volatilization. In one test, the initial nominal concentration was 23 mg/L and the measured concentration 2 hours later was 3.3 mg/L. A second test with an initial concentration of 46 mg/L had only 12.5 mg/L of styrene in solution after 2 hours. The following results are expressed as nominal concentrations; however, the actual exposure concentrations declined rapidly over the 10-d exposure period. Styrene, at initial concentrations of 2.3 to 23 mg/L, immediately stimulated swimming activity, however, 35 and 46 mg/L resulted in an immediate cessation of swimming activity that lasted for 2 to 3 days after which activity increased to 2 to 3 times the normal level for several days and eventually returned to normal within the experimental period. Styrene concentrations at the time normal activity was achieved for 23, 35 and 46 mg/L initial concentrations were 0.4, 0.6 and 1.0 mg/L respectively. Mortality was measured at the end of the recovery period (40-45 d) and the LC_{50} estimate was between 46 and 69 mg/L. There was no mortality at 2.3 mg/L, 31% mortality at 46.0 mg/L and 100% mortality at 69.0 mg/L. Those organisms exposed to 69 mg/L of styrene died within a few hours. The exposure concentrations declined about one order of magnitude within 24 hours and were substantially less for the duration of the exposure period.

In a series of tests with two species of sea urchin, *Psammechinus microtuberculatus* and *Paracentrotus lividus*, embryos, eggs or sperm were exposed to varying concentrations of styrene (Pagano et al. 1978). To enhance solubility, styrene and control solutions were prepared with absolute ethanol. When embryos were exposed to 55.1 mg/L, subsequent differentiation of the embryos were entirely abnormal. Embryos of eggs or sperm pretreated for 5 minutes with 10.4 mg/L styrene were 100% and 30% abnormal respectively by the time they reached the pluteus stage of development (approximately 45 hours after fertilization). Protocol and results in this paper are vague, particularly for embryo exposure. Test conditions, control mortality, and exposure duration were not reported and the effect criteria were not clearly defined but appeared to be fertilization and embryonic development.

However, this paper does give an indication of the vulnerability of developing aquatic creatures to the mutagenic effects of styrene. These results are comparable with observations of several known mutagens/carcinogens in the same test system.

Table 13: Acute Toxicity of Styrene to Marine Invertebrates											
Species	Life Stage	Chemical Form	Test Conditions					Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Salinity (‰)	Code				
<i>Artemia salina</i> (brine shrimp)	nauplii	styrene	NR	24	NR	NR	ASU	48	52	LC50	Price <i>et al.</i> 1974
<i>A. salina</i>	nauplii	styrene	NR	24	NR	NR	ASU	24	68	LC50	Price <i>et al.</i> 1974
<i>Pontoporeia affinis</i> (amphipod)	6-10 mm	styrene	NR	4	>8	5-6	SM	NR	2.3	0 mortality	Lindström and Lindström 1980
<i>Pontoporeia affinis</i> (amphipod)	6-10 mm	styrene	NR	4	>8	5-6	SM	NR	46	31% mortality	Lindström and Lindström 1980
<i>Pontoporeia affinis</i> (amphipod)	6-10 mm	styrene	NR	4	>8	5-6	SM	NR	69	100% mortality	Lindström and Lindström 1980
Legend: A Acute LC50 Lethal Concentration 50% M measured S Static NR not recorded in study U Unmeasured											

Table 14: Acute Toxicity of Styrene to Marine Echinodermata											
Species	Life Stage	Chemical Form	Test Conditions					Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Hardness (mg/L)	Code				
<i>Psammechinus microtuberculatus</i> (sea urchin)	embryo	styrene	NR	NR	NR	NR	SU	NR	55.1	toxicant effect on sperm and egg before fertilization	Pagano et al. 1978
<i>Paracentrotus lividus</i> (sea urchin)	embryo	styrene	NR	NR	NR	NR	SU	NR	55.1	toxicant effect on sperm and egg before fertilization	Pagano et al. 1978
Legend: S Static NR not recorded in study U Unmeasured											

Acute toxicity data were available for one species of marine fish, *Cyprinodon variegatus* (Table 15). Heitmuller et al. (1981) exposed sheepshead minnows (*Cyprinodon variegatus*) to varying concentrations of analytical-grade styrene with a minimum purity of 80%. The 24-, 48-, 72- and 96-h LC₅₀ values were all 9.1 mg/L. A NOEC value of 5.1 mg/L was also reported. Nominal test concentrations were used.

Table 15: Acute Toxicity of Styrene to Marine Fish

Species	Life Stage	Chemical Form	Test Conditions					Exposure Duration (h)	Response (mg/L)	Effect Criterion	Reference
			pH	Temp (°C)	O ₂ (mg/L)	Salinity (‰)	Code				
<i>Cyprinodon variegatus</i> (sheepshead minnow)	8-15 mm 14-28 d	styrene (filtered natural seawater as dilution H ₂ O)	NR	25-31	NR (but no aeration)	1.0-3.1	ASU	24	9.1	LC50	Heitmüller <i>et al.</i> 1981
<i>C. variegatus</i>	8-15 mm 14-28 d	styrene (filtered natural seawater as dilution H ₂ O)	NR	25-31	NR (but no aeration)	1.0-3.1	ASU	48	9.1	LC50	Heitmüller <i>et al.</i> 1981
<i>C. variegatus</i>	8-15 mm 14-28 d	styrene (filtered natural seawater as dilution H ₂ O)	NR	25-31	NR (but no aeration)	1.0-3.1	ASU	72	9.1	LC50	Heitmüller <i>et al.</i> 1981
<i>C. variegatus</i>	8-15 mm 14-28 d	styrene (filtered natural seawater as dilution H ₂ O)	NR	25-31	NR (but no aeration)	1.0-3.1	ASU	96	9.1	LC50	Heitmüller <i>et al.</i> 1981
<i>C. variegatus</i>	8-15 mm 14-28 d	styrene (filtered natural seawater as dilution H ₂ O)	NR	25-31	NR (but no aeration)	1.0-3.1	SU	NR	5.1	NOEC	Heitmüller <i>et al.</i> 1981

Legend: A Acute
U Unmeasured
NR not recorded in study

LC50 Lethal Concentration 50%
S Static
NOEC no observed effect concentration

7.1.2.2 Chronic Toxicity

No data were found in the literature regarding the chronic toxicity of styrene to any marine organisms.

7.2 Terrestrial Toxicity

The toxicity of styrene to mammals and birds has been assessed in a number of reviews (U.S. EPA 1984, 1985; Santodonato *et al.* 1980; NIOSH 1981; Barlow and Sullivan 1982) and more recently by Bond (1989); however, there is a paucity of data regarding the toxicity of styrene to terrestrial invertebrates and microorganisms. The toxicity of styrene to laboratory mammals is presented in Supporting Documentation prepared by Health Canada, and is available from Health Canada at the address cited at the beginning of this document. The toxicity of styrene to birds has been summarized in Table 16.

Table 16: Toxicity of Styrene to Birds					
Species	Type of Test	Dose	Toxicity Criteria	Effect Concentration	Reference
Chicken embryos	teratogenic	0.5-5.0 $\mu\text{mol/egg}$ styrene injection into air space of fertilized eggs on d 4 of incubation	14-d LD50 with 15% malformations	40 $\mu\text{mol/egg}$	Vainio <i>et al.</i> 1977
		0.5-2.5 $\mu\text{mol/egg}$ styrene oxide into air space of fertilized eggs	14-d LD50 with 7% malformations	1.5 $\mu\text{mol/egg}$	Vainio <i>et al.</i> 1977
Legend: LD50 = lethal dose 50%					

No data regarding the acute toxicity of styrene to terrestrial plants, terrestrial invertebrate organisms, amphibians (frogs, newts and salamanders), reptiles (snakes and turtles), birds or mammalian wildlife were identified in the literature.

No chronic toxicity data for birds exposed to styrene were found, however, one chronic developmental study was reviewed. Styrene and styrene oxide were injected into the airspace of fertilized chicken eggs at various times during a 14-day incubation period (Vainio *et al.* 1977). Early stages of embryonic development were most susceptible and the 14-d LD₅₀s for injection on day 4 were 40 $\mu\text{mol/egg}$ (4 mg/egg) and 1.5 $\mu\text{mol/egg}$ (0.18 mg/egg) for styrene and styrene oxide, respectively (Table 16). Malformations occurred in 0-20% of the exposed embryos exposed to both compounds and included no eyes, shortened upper bill, one eye and stunted growth.

No data concerning the chronic toxicity of styrene to terrestrial invertebrate organisms, amphibians, reptiles or mammalian wildlife were found in the literature.

The only phytotoxicity data found in the literature involved the *in vivo* exposure of growing root tip cells of *Allium cepa* (onion) to styrene or styrene oxide to examine the cytogenic effects. Growing root tip cells of *Allium cepa* were exposed to styrene or tritiated styrene oxide at concentrations as low as 0.01% v/v (450,000 $\mu\text{g/L}$). The observed aberrations included chromosomal breakages, a strong c-mitotic effect and an inhibition of the mitotic spindle (prolonged and/or disordered anaphase) (Linnainmaa *et al.* 1978). In addition to these aberrations, styrene oxide caused a significant increase in the number of micronuclei and nuclear bridges. Autoradiography suggests that styrene oxide binds irreversibly to cytoplasmic and nuclear macromolecules (Linnainmaa *et al.* 1978). No NOEC value for plants exposed to styrene was found in the literature.

8.0 CRITERIA, GUIDELINES AND STANDARDS

Styrene is included in the group of substances termed "Volatile Organic Compounds" (VOCs). Currently, there are initiatives by the federal and provincial governments directed at limiting the release of VOCs from industrial and other sources as the means of controlling ground-level ozone (CCME 1990).

In Canada, federal, provincial and local government requirements must be reviewed prior to styrene disposal (CCOHS 1990). The Ontario Ministry of the Environment requires that styrene-contaminated waste water be disposed of via biological treatment facility. Pure styrene waste must be disposed of by means of a hazardous waste facility, but it is seldom generated during production since most is collected and recycled in the production process (Burgess 1991).

The Canadian Council of Ministers of the Environment (Environment Canada 1991b) has set interim assessment criteria of 0.1 μg styrene/g dry weight and 0.5 μg styrene/L, representing the concentrations in soil and water above which investigative action should be considered. Environment Canada (1991b) has also established a use-dependent set of Federal interim remediation criteria for soil. Criteria for agricultural, residential/parkland and commercial/industrial soils are 0.1, 5.0 and 50 μg styrene/g dry weight, respectively. The agricultural criterion is specifically intended to protect crops and livestock; the other two are directed at preserving human health. Styrene water quality guidelines for five use classes of water are currently being developed by Environment Canada (S. Walker 1991, pers. com.).

British Columbia has proposed clean-up criteria of 0.1, 5.0 and 50 μg styrene/g soil (Environment Canada 1991b). A soil concentration of 50 $\mu\text{g/g}$ represents significant soil contamination, while the other two levels represent concentrations that require investigation or possible remediation, depending upon the land use. A groundwater criteria of 0.5 $\mu\text{g/L}$ has been proposed by British Columbia as a concentration below which the water is considered uncontaminated (Environment Canada 1991b), while higher concentrations would warrant investigation. British Columbia has no provincial guidelines or interim guidelines for styrene in surface water; however there is a site specific styrene water quality objective of 0.05 mg/L (maximum) for the protection of aquatic life in the Port Moody Arm of Burrard Inlet, B.C. (L. Pommen 1991, pers. com.).

Alberta Environment has proposed a soil criteria of 0.1 μg styrene/g (Environment Canada 1991b).

Manitoba has no styrene guidelines or tentative guidelines for surface waters (D. Brown 1991, pers. com.).

The province of Ontario has completed a preliminary hazard assessment of styrene but this document is not yet available (R. MacFarlane 1991, pers. com.). Ontario Provincial Water Quality Guideline development documents for styrene and octachlorostyrene are currently in draft form. The interim water quality guideline recommended for the protection of freshwater life is 0.004 mg/L for styrene; however data were insufficient to derive a value for octachlorostyrene (Bazinet and McGillivray 1990; G. Rutherford 1991, pers. com.).

The Quebec environment ministry has recommended soil guidelines similar to those proposed by British Columbia, e.g. 0.1, 5.0 and 50 μg styrene/g, and has also recommended groundwater guidelines of 0.5, 40.0 and 120.0 μg styrene/L (Environment Canada 1991b). These three figures represent the approximate detection limit, site investigation level, and remedial action level, respectively. Quebec has two provisional guidelines for the short and long-term protection of freshwater aquatic life (I. Guay 1991, pers. com.). The acute and chronic toxicity criteria are 1.2 mg/L and 0.05 mg/L, respectively. These provisional criteria were derived from the acute (48-h) LC_{50} value of 23 mg/L for *Daphnia magna* (LeBlanc 1980).

Effluent guidelines are currently being developed by the U.S. EPA for 129 organic pollutants but styrene is not on this list (W. Forsht 1991, pers. com.). Styrene has been placed on a list of chemicals requiring ambient water quality criteria development by the U.S. EPA, however, no review has commenced at this time (K. Potts 1991, pers. com.).

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