HYDROCHLORIC ACID

Hydrogen chloride is a gas; its solutions in water are commonly referred to as hydrochloric acid. This monograph covers both forms.

1. Exposure Data

1.1 Chemical and physical data

1.1.1 *Synonyms, structural and molecular data*

Chem. Abstr. Serv. Reg. No.: 7647-01-0
Replaced CAS Reg. Nos.: 51005-19-7; 61674-62-2; 113962-65-5
Chem. Abstr. Name: Hydrochloric acid
IUPAC Systematic Name: Hydrochloric acid
Synonyms: Anhydrous hydrochloric acid; chlorohydric acid; hydrochloric acid gas; hydrogen chloride; muriatic acid

HCl

HCl Mol. wt: 36.47

1.1.2 *Chemical and physical properties*

(*a*) *Description*: Colourless or slightly yellow, fuming pungent liquid or colourless gas with characteristic pungent odour (Sax & Lewis, 1987; Budavari, 1989; Weast, 1989)

(*b*) *Boiling-point*: Gas, –84.9 °C at 760 mm Hg (101 kPa); constant boiling azeotrope with water containing 20.24% HCl, 110 °C at 760 mm Hg (Weast, 1989)

(*c*) *Melting-point*: anhydrous (gas), –114.8 °C (Weast, 1989); aqueous solutions, –17.1 °C (10.8% solution); –62.25 °C (20.7% solution); –46.2 °C (31.2% solution); –25.4 °C (39.2% solution) (Budavari, 1989)

(*d*) *Density*: Aqueous solutions, 39.1% solution (15 °C/4 °C), 1.20 (Budavari, 1989); constant boiling HCl (20.24%), 1.097 (Weast, 1989)

(*e*) *Specific volume*: Gas, 1/47–1/52 g/l (Linde/Union Carbide Corp., 1985; Matheson Gas Products, 1990; Alphagas/Liquid Air Corp., 1991; Scott Specialty Gases, 1991)

(*f*) *Solubility*: Soluble in water (g/100 g water): 82.3 at 0 °C, 67.3 at 30 °C; methanol (g/100 g solution): 51.3 at 0 °C, 47.0 at 20° C; ethanol (g/100 g solution): 45.4 at 0 °C, 41.0 at 20 °C; diethyl ether (g/100 g solution): 35.6 at 0 °C, 24.9 at 20 °C (Budavari, 1989); and benzene (Weast, 1989)

(*g*) *Volatility*: Vapour pressure, 40 atm (4 MPa) at 17.8 °C (Weast, 1989)

(*h*) *Conversion factor*: $mg/m^3 = 1.49 \times ppm^a$

1.1.3 *Technical products and impurities*

Hydrochloric acid as an aqueous solution is available in several grades (technical, food processing, analytical, commercial, photographic, water white) as 20 °Bé (31.45% HCl), 22 °Bé (35.21% HCl) or 23 °Bé (37.1% HCl), with the following specifications (mg/kg): purity, (20 °Bé) 31.45–32.56%, (22 °Bé) 35.21–36.35%, (23 °Bé) 36.5–38.26; sulfites, 1–10 max; sulfates, 1–15 max; iron (as Fe), 0.2–5 max; free chlorine, 1–30 max; arsenic (see IARC, 1987), 0.01–1 max; heavy metals (as Pb), 0.5–5 max; fluoride, 2; benzene (see IARC, 1987), 0.01–0.05 max; vinyl chloride (see IARC, 1987), 0.01–0.05 max; total fluorinated organic compounds, 25.0 max; toluene (see IARC, 1989), 5.0 max; bromide, 50 max; ammonium, 3 (Dow Chemical USA, 1982, 1983; Atochem North America, 1986a,b; American National Standards Institute, 1987; Vista Chemical Co., 1987; BASF Corp., 1988; Du Pont Co., 1988; BASF Corp., 1989; Dow Chemical USA, 1989; BASF Corp., 1990; Occidental Chemical Corp., 1990).

Hydrogen chloride is also available as a liquefied gas in electronics grade with a purity of 99.99% and the following impurity limits (ppm): nitrogen, 75; oxygen, 10; carbon dioxide, 10; and hydrocarbons, 5 (Dow Chemical USA, 1990).

1.1.4 *Analysis*

Methods have been reported for the analysis of hydrochloric acid in air. One method involves drawing the sample through a silica gel tube, desorbing with sodium bicarbonate/-sodium carbonate solution and heat and analysing for chloride ion with ion chromatography. The lower detection limit for this method is 2 μg/sample (Eller, 1984). A similar method entails collecting a sample from the stack and passing it through dilute (0.1 N) sulfuric acid. The chloride ion concentration is analysed by ion chromatography, with a detection limit of 0.1 μg/ml (US Environmental Protection Agency, 1989).

Hydrogen chloride can be detected in exhaust gas (stack emissions) by: the ion-selective electrode method (absorb in dilute potassium nitrate solution and measure potential difference); silver nitrate titration (absorb in sodium hydroxide solution, add silver nitrate and titrate with ammonium thiocyanate); and a mercuric thiocyanate method (absorb in sodium hydroxide solution, add mercuric thiocyanate and ammonium iron[III] sulfate solutions and measure absorbance of ferric thiocyanate) (Japanese Standards Association, 1982).

1.2 Production and use

1.2.1 *Production*

In the fifteenth century, the German alchemist Valentin heated green vitriol (iron[II] sulfate, $FeSO_4 \cdot 7H_2O$) with common salt (sodium chloride) to obtain what was then called 'spirit of salt'. In the seventeenth century, Glauber prepared hydrochloric acid from sodium chloride and sulfuric acid. In 1790, Davy established the composition of hydrogen chloride by

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[a]Calculated from: mg/m^3 = (molecular weight/24.45) × ppm, assuming normal temperature (25 °C) and pressure (760 mm Hg [101.3 kPa])

synthesizing it from hydrogen and chlorine. In the same year, Leblanc discovered the process named after him for the production of soda (sodium carbonate), the first stage of which is to react sodium choride with sulfuric acid, liberating hydrogen chloride. This was first considered an undesirable by-product and simply released into the atmosphere in large amounts. In 1863, English soda producers were compelled by the Alkali Act to absorb the hydrogen chloride in water, which quickly led to large-scale industrial use of the acid produced. Excess hydrogen chloride that could not be used as hydrochloric acid was oxidized to chlorine (Austin & Glowacki, 1989).

Following the development of the chlor-alkali electrolytic process early in the twentieth century, the industrial synthesis of hydrogen chloride by burning chlorine in hydrogen gas became an important route. This method generates a product of higher purity than that based on the reaction between chloride salts and sulfuric acid or sodium hydrogen sulfate. These processes are being superseded, however, with the availability of large amounts of hydrogen chloride that arise as by-products of chlorination processes, such as the production of vinyl chloride from ethylene (Leddy, 1983; Austin & Glowacki, 1989).

Hydrogen chloride can thus be formed according to the following reactions: (1) synthesis from the elements (hydrogen and chlorine); (2) reaction of chloride salts, particularly sodium chloride, with sulfuric acid or a hydrogen sulfate; (3) as a by-product of chlorination, e.g., in the production of dichloromethane, trichloroethylene, tetrachloroethylene or vinyl chloride; (4) from spent pickle liquor in metal treatment, by thermal decomposition of the hydrated heavy metal chlorides; and (5) from incineration of chlorinated organic waste. By far the greatest proportion of hydrogen chloride is now obtained as a by-product of chlorination. The degree of purification required depends on the end-use. Recovery from waste materials (Methods 4 and 5) is becoming increasingly important, whereas the amount generated by Method 2 is decreasing (Austin & Glowacki, 1989).

Many impurities in hydrogen chloride gas (e.g., sulfur dioxide, arsenic and chlorine) can be removed by adsorption on activated carbon. As use of the chlorination by-product process increases, removal of chlorinated hydrocarbons from hydrogen chloride gas or hydrochloric acid becomes of greater practical relevance. Gaseous hydrogen chloride can be purified by low-temperature scrubbing with a high-boiling solvent, which may be another chlorinated hydrocarbon (e.g., hexachlorobutadiene (see IARC, 1979) or tetrachloroethane), or with special oil fractions. Chlorine may be removed with carbon tetrachloride (see IARC, 1987), in which it is more soluble than is hydrogen chloride gas. Hydrochloric acid, used as such or for generation of hydrogen chloride, contains mainly volatile impurities, including chlorinated hydrocarbons, and these can be removed from the acid by stripping. An inert gas stream, which results in lower energy consumption, can be used for stripping, although heating the gas is preferable for environmental reasons. Inorganic impurities, in particular iron salts, are removed by ion exchange (Austin & Glowacki, 1989).

Worldwide production of hydrochloric acid in 1980–90 is shown in Table 1. The numbers of companies producing hydrochloric acid/hydrogen chloride are shown in Table 2.

Table 1. Trends in production of hydrochloric acid (thousand tonnes) with time, 1980–90

Country or region	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Australia	63	59	55	60	57	58	54	62	69	64	NA
Canada	177	186	135	170	161	158	153	164	180	180	187
China	1177	1292	1483	1583	NA	NA	NA	NA	NA	NA	NA
France	674	700	687	673	767	656	626	647	684	692	675
Germany[a]	889	886	846	898	954	943	929	988	980	956	909
Italy	NA	NA	NA	NA	NA	NA	NA	679	1006	635	742
Japan	570	565	551	511	521	549	549	543	565	571	637
Mexico	36	33	47	79	77	63	83	117	118	NA	NA
Taiwan	179	184	191	212	241	228	242	251	255	217	234
United Kingdom	137	117	118	130	156	153	157	174	176	166	162
USA	2620	2335	2223	2239	2478	2546	2189	2718	2928	2882	2124

From Anon. (1984a,b, 1986, 1987, 1988, 1989, 1990, 1991); NA, not available
[a]Figures prior to 1990 are for western Germany only.

Table 2. Numbers of companies in different countries or regions in which hydrochloric acid/hydrogen chloride were produced in 1988

Country or region	No. of companies	Country or region	No. of companies
Japan	32	Portugal	3
USA	27	Thailand	3
Germany (western)	15	Turkey	3
Italy	13	Austria	2
Spain	13	Greece	2
India	12	Pakistan	2
Brazil	11	Romania	2
United Kingdom	11	South Africa	2
Australia	10	Bulgaria	1
Mexico	8	Chile	1
Canada	7	Colombia	1
France	7	Egypt	1
Argentina	6	Indonesia	1
Sweden	5	Republic of Korea	1
Switzerland	5	Kuwait	1
Yugoslavia	5	New Zealand	1
Taiwan	4	Norway	1
Bangladesh	3	Philippines	1
Belgium	3	Saudi Arabia	1
China	3	Singapore	1
Finland	3	USSR	1
Israel	3	Venezuela	1
Peru	3		

From Chemical Information Services (1988)

1.2.2 *Use*

Hydrochloric acid is one of the most important basic industrial chemicals. A major use is in the continuous pickling of hot rolled sheet steel; it is also used widely in batch pickling to remove mill scale and fluxing, in cleaning the steel prior to galvanizing and other processes. It is widely used in the production of organic and inorganic chemical products: Inorganic chlorides are prepared by reacting hydrochloric acid with metals or their oxides, sulfides or hydroxides. Hydrochloric acid has long been used in the production of sugars and, more recently, of high fructose corn syrup. It is also involved in the production of monosodium glutamate, for acidizing crushed bone for gelatin and in the production of soya sauce, apple sweetener and vegetable juice. It is used to increase production of oil and gas wells by acidizing and formation fracturing and cleaning and by cleaning and descaling equipment. Acidizing reduces resistance to the flow of oil and gas through limestone or dolomite formations. Inhibited hydrochloric acid is used to remove sludge and hard-water scale from industrial equipment, ranging from boilers and heat exchangers to electrical insulators and glass. Hydrochloric acid has been used in the extraction of uranium, titanium, tungsten and other precious metals. It is used in the production of magnesium from seawater, in water chemistry (from pH control to the regeneration of ion-exchange resins in water purification), brine purification and in pulp and paper production (Sax & Lewis, 1987; Dow Chemical USA, 1988; Austin & Glowacki, 1989; Budavari, 1989).

1.3 Occurrence

1.3.1 *Natural occurrence*

Hydrochloric acid is produced by human gastric mucosa and is present in the digestive systems of most mammals. The adult human gastric mucosa produces about 1.5 l per day of gastric juices with a normal acid concentration of 0.05–0.10 N (Rosenberg, 1980).

Natural sources of hydrogen chloride may make an important contribution to atmospheric hydrogen chloride. Hydrogen chloride is emitted from volcanoes; total world emissions of hydrogen chloride from this source are very uncertain but have been estimated at 0.8–7.6 million tonnes per year. Methyl chloride, produced in the sea by marine plants or microorganisms and on land during the combustion of vegetation, reacts with OH radicals in the atmosphere to generate hydrogen chloride. Worldwide natural sources produce about 5.6 million tonnes of methyl chloride per year, equivalent to about 4 million tonnes hydrogen chloride. Hydrogen chloride is also produced from the reaction of sea-salt aerosols with atmospheric acids (Lightowlers & Cape, 1988).

1.3.2 *Occupational exposure*

Occupational exposure to hydrochloric acid is described in the monograph on occupational exposure to mists and vapours from sulfuric acid and other strong inorganic acids (pp. 44–47). Hydrochloric acid occurs in work-room air as a gas or mist. During pickling and other acid treatment of metals, the mean air concentration of hydrochloric acid has been reported to range from < 0.1 (Sheehy *et al.*, 1982) to 12 mg/m^3 (Remijn *et al.*, 1982). Mean levels > 1 mg/m^3 have been reported in the manufacture of sodium sulfate, calcium chloride and hydrochloric acid, in offset printing shops, in zirconium and hafnium extraction and during some textile processing and laboratory work (Bond *et al.*, 1991).

1.3.3 *Air*

In areas influenced by marine air masses, displacement reactions between either sulfuric acid or nitric acid and aerosol chlorides, such as sea salt, can be an appreciable source of hydrochloric acid (Harrison, 1990).

Atmospheric levels of hydrogen chloride in Europe and in Michigan, USA, are summarized in Table 3 (Kamrin, 1992). Ambient concentrations are generally in the range of 0.4–4 μg/m^3.

Table 3. Atmospheric levels of hydrogen chloride

Location	Season	Sampling duration	Concentration range (μg/m^3)
Maritime, background	All	Weekly	0.07–0.3
Europe			
United Kingdom, rural	Summer	2–4 h	1–3
United Kingdom, rural	All	Daily	0.3–2
United Kingdom, urban	All	Weekly	0.6–1.2
Switzerland	April 1982	1 h	0.2–3
Dübendorf, Switzerland, urban	Winter 1985	Daily	0.03–3
Dubendorf, Switzerland, rural	March 1986–87	–	0.3–1.3
	Winter 1986–87	–	0.2–3
Po River, Italy, rural	November 1984	Daily	0.1–0.5
Ljubljana, Yugoslavia, urban	February 1985	Daily	0.1–0.5
Linz, Austria, urban, industrial	Summer 1985	Daily	0.2–1.6
Vienna, Austria, urban	Winter 1983–84	Daily	0.1–1.5
Dortmund, Germany, urban	September–October 1980	Daily	0.3–11
Michigan, USA			
Northern, rural	Winter 1983–84	Weekly	0.1–0.5
South Haven, urban	July 1990	6 h	0.5–2
Ann Arbor, urban	August 1990	Daily	0.1–2

From Kamrin (1992)

The main anthropogenic sources of hydrogen chloride in the troposphere are the burning of coal and the incineration of chlorinated plastics, such as polyvinyl chloride. Under conditions typical of a modern coal-fired combustion plant, approximately 80 ppm (119 mg/m^3) of hydrogen chloride are contributed to the stack gas for each 0.1% chlorine in the coal. Hydrogen chloride may be an important determinant of precipitation acidity close to incinerators and coal-burning plants (Cocks & McElroy, 1984).

Estimated annual emissions of hydrogen chloride in the United Kingdom in 1983 (total, 260 000 tonnes/year) by source were: coal burning, 92%; waste incineration, 6%; and atmospheric degradation of chlorinated hydrocarbons, automobile exhausts, glass making, fuel oil combustion and steel pickling acid regeneration, 1%. Similarly, in western Germany, power stations and industrial furnaces produced 81.4% of hydrogen chloride emissions, waste incineration produced 17.5% and other sources only 1.1% (Lightowlers & Cape, 1988).

In comparison with the emissions of sulfur dioxide (3.7 million tonnes/year) and nitrogen oxides (1.9 million tonnes/year) in the United Kingdom, hydrogen chloride is a minor source of potential atmospheric acidity, contributing only 4% of the total potential acidity compared to 71% from sulfur dioxide and 25% from nitrogen oxides. In western Europe as a whole, hydrogen chloride contributes less than 2% of the total potential acidity, whereas sulfur dioxide contributes 68% and nitrogen oxides 30% (Lightowlers & Cape, 1988).

Estimated emissions of hydrochloric acid from coal burning, waste incineration and total emissions in 12 western European countries in the early 1980s are presented in Table 4 (Lightowlers & Cape, 1988).

Table 4. Estimated emissions of hydrogen chloride from two sources in 12 European countries (thousand tonnes/year)

Country	Source	
	Coal burning	Waste incineration
Austria	0.5	1.3
Belgium	14	5.9
Denmark	4.3	6.2
Ireland	2.1	0
France	50	64
Germany[a]	93	14
Italy	21	15
Netherlands	9.4	10
Norway	0.5	1.4
Spain	45	2.2
Sweden	2.6	4.7
Switzerland	0.7	12
Total	240 (63%)	140 (27%)

From Lightowlers & Cape (1988)
[a]Western part only

In 1989 in the USA, total air emissions of hydrochloric acid/hydrogen chloride were estimated to be approximately 27 552 tonnes from 3250 locations; total ambient water releases were estimated to be 1389 tonnes; total underground injection releases were estimated to be 136 440 tonnes; and total land releases were estimated to be 1926 tonnes (US National Library of Medicine, 1991).

Hydrochloric acid differs from sulfuric acid and nitric acid in that it is emitted into the atmosphere as a primary pollutant and is not formed by atmospheric chemistry. Oxidation of sulfur dioxide and nitrogen oxides typically proceeds at approximately 1 and 10% per hour or less, respectively. Over appreciable distances from a major source of all three pollutants (e.g., a power plant), hydrochloric acid may therefore predominate, even though it comprises only a small percentage of the total potential acidity (Harrison, 1990).

A municipal incinerator in Newport News, VA, was studied over a four-day period in 1976 to evaluate gaseous emissions when wet chemical and electro-optical methods were

used. Hydrogen chloride concentrations in the stack gas averaged 25.1 ppm (37.4 mg/m^3; range, 12.5–56.7 ppm [18.6–84.5 mg/m^3]). The authors compared their results with those from studies of similar facilities (ppm [mg/m^3]): New York City, NY, 41–81 [61–121]; Brooklyn, NY, 64.3 [95.8]; Babylon, NY, 217–248 [323–370]; Hamilton Avenue, NY, 45–89 [67–133]; Oceanside, NY, 96–113 [143–168]; Flushing, NY, 38–40 [57–60]; Yokohama, Japan, 280 [417] (large amounts of industrial plastic wastes incinerated at this source) and Salford, United Kingdom, 227 [338]. The authors noted that use of a water scrubber appeared to provide an effective means of removing hydrochloric acid (Jahnke *et al.*, 1977).

Emissions from a municipal waste incinerator fired by water wall mass and by fuel derived from refuse contained hydrochloric acid at concentrations of 22–336 ppm (33–501 mg/m^3); emission rates were 0.8–27.0 kg/h (0.2–3.3 g hydrochloric acid/kg of refuse burned) (Nunn, 1986).

The exhaust from a space shuttle launch in which a solid rocket fuel was used contained approximately 60 tonnes of hydrochloric acid (Pellett *et al.*, 1983). Partitioning of hydrochloric acid between hydrochloric acid aerosol and gaseous hydrogen chloride in the lower atmosphere was investigated in the exhaust cloud from a solid fuel rocket in humid ambient air. Hydrochloric acid was present at 0.6–16 ppm (0.9–24 mg/m^3); the partitioning studies indicated that unpolluted tropospheric concentrations of hydrochloric acid (< 1 ppb [< 1.5 μg/m^3]) would be in the gaseous phase except under conditions of very high humidity (Sebacher *et al.*, 1980).

Thermal degradation products of polyvinyl chloride food-wrap film were studied under simulated supermarket conditions, using a commercial wrapping machine with either a hot-wire or a cool-rod cutting device. At 240–310 °C, hydrogen chloride is the major volatile thermal degradation production: mean emissions were 3–59 μg/cut (total range, 1–81 μg/cut) when the hot-wire cutting device was used; hydrogen chloride was not detected when the cool-rod cutting device was used. Other compounds found were the plasticizer [di(2-ethylhexyl)adipate, di(2-ethylhexyl)phthalate, acetyl tributyl citrate], benzene, toluene, acrolein and carbon monoxide (Boettner & Ball, 1980).

1.4 Regulations and guidelines

Occupational exposure limits for hydrochloric acid or hydrogen chloride in some countries and regions are presented in Table 5.

Table 5. Occupational exposure limits and guidelines for hydrochloric acid/hydrogen chloride

Country or region	Year	Concentration (mg/m^3)	Interpretation[a]
Australia	1990	7	TWA
Austria	1982	7	TWA
Belgium	1990	7.5	Ceiling
Brazil	1978	5.5	Ceiling
Bulgaria	1977	5	TWA
Chile	1983	5.6	Ceiling
China	1979	15	TWA

Table 5 (contd)

Country or region	Year	Concentration (mg/m^3)	Interpretation[a]
Czechoslovakia	1990	5	TWA
		10	STEL
Denmark	1990	7	Ceiling
Egypt	1967	15	TWA
Germany	1990	7[b]	TWA
Finland	1990	7[b]	STEL (15 min)
France	1990	7.5	STEL
Hungary	1990	5[b]	Ceiling
India	1983	7	Ceiling
Indonesia	1978	7	Ceiling
Italy	1978	4	TWA
Japan	1990	7.5	Ceiling
Mexico	1983	7	TWA
Netherlands	1986	7	Ceiling
Norway	1990	7	Ceiling
Poland	1990	5	TWA
Romania	1975	10	STEL
Sweden	1990	8	Ceiling
Switzerland	1990	7.5	Ceiling
		15	STEL
Taiwan	1981	7[b]	Ceiling
United Kingdom	1990	7	TWA
		7	STEL (10 min)
USA			
ACGIH	1990	7.5	Ceiling
NIOSH	1990	7	Ceiling
OSHA	1989	7	Ceiling
USSR	1990	5	STEL
Venezuela	1978	7	TWA
Yugoslavia	1971	7	Ceiling
		7	TWA

From Cook (1987); US Occupational Safety and Health Administration (OSHA) (1989); American Conference of Governmental Industrial Hygienists (ACGIH) (1990); Direktoratet for Arbeidstilsynet (1990); US National Institute for Occupational Safety and Health (NIOSH) (1990); International Labour Office (1991)

[a]TWA, 8-h time-weighted average; STEL, short-term exposure limit

[b]Skin irritant notation

In 1961, the US Food and Drug Administration listed hydrogen chloride as Generally Recognized as Safe when used as a miscellaneous or a general-purpose food ingredient, with the limitation that it be used as a buffer and neutralizing agent. In 1977, it was reclassified as a multiple-purpose food substance with the same limitation. In 1984, it was also regulated as a food additive to be used to modify food starch and in the manufacture of modified hop

extract. It was listed as an optional ingredient in the following food standards: acidified milk, acidified low-fat milk, acidified skim milk, dry curd cottage cheese, tomato paste, tomato purée and catsup (US Food and Drug Administration, 1984). Hydrochloric acid is currently approved by the US Food and Drug Administration (1984, 1989, 1990) for the same uses, except for tomato concentrates (paste, pulp, purée).

The US Environmental Protection Agency has established a limit for emissions of hydrogen chloride from hazardous waste incinerators at a mass rate of 4 pounds (1.8 kg) per hour or 1% of the hydrogen chloride entering the pollution control equipment (Shanklin *et al.*, 1990).

2. Studies of Cancer in Humans

2.1 Cohort studies

In a follow-up study of workers with potential exposure to acrylamide in four US chemical plants, Collins *et al.* (1989) reported an excess of lung cancer at one of the facilities studied. The excess was due partly to an increased number of lung cancer deaths (11) observed among men who had worked in a muriatic acid (hydrochloric acid) department. [The Working Group noted that the expected numbers were not reported.]

In the study of Beaumont *et al.* (1987) of 1165 male workers employed in 1940–64 in three US steel-pickling operations for at least six months (described in detail on p. 83), a subset of 189 workers had been exposed to mists of acids other than sulfuric, which were primarily of hydrochloric acid. An excess risk for lung cancer was seen (standardized mortality ratio [SMR], 2.24 [95% confidence interval (CI), 1.02–4.25]; 9 deaths). The excess persisted for workers who had been employed in 1950–54 when other steelworkers were used as a control for socioeconomic and life-style factors such as smoking (SMR, 2.00; 95% CI, 1.06–3.78).

In the study by Steenland *et al.* (1988) of the same cohort (described on pp. 83–84), an excess of incident cases of laryngeal cancer was observed in steel picklers ([relative risk, 2.6; 95% CI, 1.2–5.0]; 9 cases). Two of the cases had been exposed only to acids other than sulfuric, and three had been exposed to a mixture of acids. [The Working Group noted that confounding by exposure to sulfuric acid could not be ruled out.]

2.2 Case–control studies

A case–control study of primary intracranial neoplasms conducted at a US chemical plant (Bond *et al.*, 1983), described in detail on p. 161, found no association with any exposure to hydrogen chloride (odds ratio, 1.40; 90% CI, 0.70–2.80, using the first control group; odds ratio, 1.02; 90% CI, 0.81–1.29, using the second control group). The odds ratio for exposure to hydrogen chloride for people who had been employed for 1–4 years was 2.02 (90% CI, 0.5–8.1); no association was seen for individuals who had been employed for > 20 years.

In a case–control study of renal cancer (Bond *et al.*, 1985, see pp. 161–162), the odds ratios for exposure to hydrogen chloride were 0.90 (90% CI, 0.44–1.83) in comparison with the first control group and 0.86 (90% CI, 0.40–1.86) in comparison with the second (12 cases).

A case–control study of lung cancer, nested in a cohort of 19 608 men employed at a Dow chemical plant (Bond *et al.*, 1986), is described in detail in the monograph on sulfur dioxide (p. 162). The risk associated with exposure to hydrogen chloride was 1.02 (95% CI, 0.77–1.35; 129 cases); the risk was essentially the same when exposures that had occurred within 15 years of the date of death of the cases were ignored (0.92; 95% CI, 0.68–1.24; 108 cases). The work histories of the 308 cases of lung cancer and 616 controls in this study were augmented with 8-h time-weighted average exposures to hydrochloric acid for each job (0, 0.2–0.3 ppm [0.3–0.5 mg/m^3], 0.9–2.0 ppm [1.3–3.0 mg/m^3] and 2.2–5.1 ppm [3.3–7.6 mg/m^3]) (Bond *et al.*, 1991), and several exposure measures were developed: duration of exposure, a cumulative exposure score, highest average exposure category achieved during a career. In addition, a latency analysis was done excluding all exposures that had occurred within 15 years of the death of the worker. Smoking histories were available for about 71% of the cases and 76% of the controls, based on telephone interviews conducted with the subjects themselves or with a proxy. Calculation of Mantel–Haenszel adjusted relative risks revealed no association between any of the measures of exposure used and lung cancer. [The Working Group noted that the methods used may not have been optimal.]

In the population-based case–control study of Siemiatycki (1991), described in detail on p. 95, no association was found between all cancers of the lung and exposure to hydrogen chloride (7% life-time prevalence of exposure for the population). The odds ratio for oat-cell carcinoma of the lung in exposed workers was 1.6 (19 cases; 90% CI, 1.0–2.6); for workers exposed at the substantial level, the odds ratio was 2.1 (8 cases; 90% CI, 1.0–4.5). In an analysis restricted to the French-Canadian subset of the study population and population controls, the odds ratio for non-Hodgkin's lymphoma was 1.6 (90% CI, 1.0–2.5; 18 cases), and that for rectal cancer was 1.9 (90% CI, 1.1–3.4; 18 cases).

3. Studies of Cancer in Experimental Animals

3.1 Inhalation exposure

Rat: Three groups of 100 male Sprague–Dawley rats, nine weeks old, were unexposed (colony controls), exposed by inhalation to air (air controls) or exposed to 10.0 ± 1.7 (standard deviation) ppm [14.9 ± 2.5 mg/m^3] hydrogen chloride (purity, 99.0%) for 6 h per day on five days per week for life (maximum, 128 weeks). Mortality did not differ significantly between the treated and the air control groups (*t* test). No preneoplastic or neoplastic nasal lesion was observed in any group, but hyperplasia of the larynx and trachea was observed in treated animals (22/99 and 26/99, respectively). Tumour responses were similar in the treated and control groups, the total incidences of tumours at various sites being 19/99, 25/99 and 24/99 in treated, air control and colony control animals, respectively (Sellakumar *et al.*, 1985). [The Working Group noted that the experiment was not designed to test the carcinogenicity of hydrogen chloride and that higher doses might have been tolerated.]

3.2 Administration with a known carcinogen

Rat: Five groups of 100 male Sprague-Dawley rats, nine weeks old, were exposed by inhalation for 6 h per day on five days per week for life (128 weeks) to: (i) a mixture of 15.2

ppm [18.7 mg/m^3] formaldehyde [purity unspecified] and 9.9 ppm [14.8 mg/m^3] hydrogen chloride (purity, 99.0%), premixed before entry into the inhalation chamber (average concentration of bis(chloromethyl)ether, which can form from hydrogen chloride and formaldehyde in moist air (see IARC, 1987), < 1 ppb [4.7 μg/m^3]) (Group 1); (ii) a combination of 14.9 ppm [18.3 mg/m^3] formaldehyde and 9.7 ppm [14.5 mg/m^3] hydrogen chloride, mixed after entry into the inlet of the inhalation chamber (Group 2); (iii) 14.8 ppm [18.2 mg/m^3] formaldehyde (Group 3); (iv) 10.0 ppm [14.9 mg/m^3] hydrogen chloride (Group 4); or (v) air (sham-exposed controls; Group 5). A comparable group of rats (Group 6) served as unexposed colony controls. From week 32, mortality in Group 1 was significantly higher ($p < 0.05$; t test) than that in groups 2–4. Tumours of the nasal mucosa occurred only in groups exposed to formaldehyde (groups 1–3), the numbers of tumour-bearing rats being 56/100 (13 papillomas/polyps, 45 squamous-cell carcinomas, one adenocarcinoma and one fibrosarcoma) in Group 1, 39/100 (11 papillomas or polyps, 27 squamous-cell carcinomas and two adenocarcinomas) in Group 2 and 48/100 (10 papillomas or polyps, 38 squamous-cell carcinomas, one fibrosarcoma and one mixed carcinoma) in Group 3. The average latency to tumour appearance was 603–645 days, and there was no remarkable difference among the groups. Statistical analysis of the tumour response (Peto's log rank test) revealed a significantly increased response in Group 1 as compared to Group 2 ($p < 0.001$) and as compared to Group 3 ($p < 0.025$). The authors suggested that formation of alkylating agents by the reaction between hydrogen chloride and formaldehyde was a possible explanation for the higher incidence in Group 1. Tumour response in organs other than the nose did not differ significantly between treated and control groups: the total incidences of tumours at other sites in groups 1–6 were 22/100, 12/100, 10/100, 19/99, 25/99 and 24/99, respectively [statistical method unspecified] (Sellakumar *et al.*, 1985).

4. Other Relevant Data

4.1 Absorption, distribution, metabolism and excretion

4.1.1 *Humans*

Because it is highly soluble in water, hydrogen chloride is normally deposited in the nose and other regions of the upper respiratory tract. By analogy to sulfur dioxide (see p. 96), deeper penetration into the respiratory tract can be expected at high ventilation rates. As with aerosols in general, air flow velocity and the aerodynamic diameter of the particles are important determinants of the deposition of hydrogen chloride aerosols. The acidity within the mucous lining of the respiratory tract may be neutralized, as with sulfuric acid.

Hydrochloric acid is a normal constituent of human gastric juice, in which it plays an important physiological role. The healthy stomach is adapted to deal with the potentially damaging effects of exposure to the acid. The toxicity of hydrochloric acid after inhalation or ingestion is due to local effects on the mucous membranes at the site of absorption. Absorption, distribution, metabolism and excretion of acids and chloride ions have not been studied in relation to toxicology, but these processes are well known from human physiology.

Ingestion by healthy volunteers of hydrochloric acid at 50 mM/day for four days resulted in a fall in blood and urinary urea, with a concomitant rise in urinary excretion of ammonia (Fine *et al.*, 1977).

4.1.2 *Experimental systems*

The absorption, distribution and excretion of hydrochloric acid are similar in humans and other mammals. Following intravenous infusion of 0.15 M hydrochloric acid into rats [50 ml/kg bw per hour] and dogs (20 ml/kg bw per hour), urinary excretion of the chloride ion was increased in both species (Kotchen *et al.*, 1980).

4.2 Toxic effects

4.2.1 *Humans*

Effects of industrial exposures were summarized by Fernandez-Conradi (1983). Exposure to hydrochloric acid can produce burns on the skin and mucous membranes, the severity of which is related to the concentration of the solution. Subsequently, ulceration may occur, followed by keloid and retractile scarring. Contact with the eyes may produce reduced vision or blindness. Frequent contact with aqueous solutions of hydrochloric acid may lead to dermatitis. Vapours of hydrogen chloride are irritating to the respiratory tract, causing laryngitis, glottic oedema, bronchitis, pulmonary oedema and death. Dental decay, with changes in tooth structure, yellowing, softening and breaking of teeth, and related digestive diseases are frequent after exposures to hydrochloric acid.

Kamrin (1991) estimated that the no-effect level for respiratory effects in humans would be 0.2–10 ppm [0.3–14.9 mg/m^3]. Respiratory symptoms were reported in 170 fire fighters who were exposed to hydrogen chloride produced during thermal degradation of polyvinyl chloride. [The Working Group noted that other chemicals were present.] The symptoms included chest discomfort and dyspnoea. One fatal case was reported, and post-mortem examination demonstrated severe pulmonary haemorrhage, oedema and pneumonitis (Dyer & Esch, 1976).

In one of eight asthmatic volunteers exposed to an aerosol of unbuffered hydrochloric acid at pH 2 for 3 min during tidal breathing, airway resistance was increased by 50%. Bronchoconstriction was increased in all eight subjects after inhalation of a mixture of hydrochloric acid and glycine at pH 2 (Fine *et al.*, 1987).

Dental erosion of the incisors was observed in 90% of picklers in a zinc galvanizing plant in the Netherlands, who spent 27% of their time in air containing concentrations of hydrogen chloride above the exposure limit (7 mg/m^3) (Remijn *et al.*, 1982).

Dysphagia and transient ulceration of the oesophagus with luminal narrowing are usually observed following ingestion of hydrochloric acid (Marion *et al.*, 1978; Zamir *et al.*, 1985; Subbarao *et al.*, 1988).

4.2.2 *Experimental systems*

Application of 10 µl hydrochloric acid to the cornea of rabbits caused desquamation of the surface epithelial cells at concentrations of $\geq$ 0.001 N (Brewitt & Honegger, 1979).

A decreased respiratory rate was observed in Swiss Webster mice exposed to hydrogen chloride at concentrations above 99 ppm [148 mg/m^3] in a study of exposure to 40–943 ppm (60–1405 mg/m^3). The return to control values was slow after exposure to 245 ppm [365 mg/m^3] and above (Barrow *et al.*, 1977).

The 30-min LC_{50}s for gaseous hydrogen chloride were estimated to be about 4700 ppm [7000 mg/m^3] for rats and 2600 ppm [3870 mg/m^3] for mice and those for aerosols of

hydrogen chloride to be about 5700 ppm [8500 mg/m^3] for rats and 2100 ppm [3130 mg/m^3] for mice. Moderate to severe alveolar emphysema, atelectasia and oedema of the lung were observed (Darmer *et al.*, 1974). All of a group of Swiss Webster mice died or were found moribund after exposure to hydrogen chloride at 304 ppm [453 mg/m^3], which is near the concentration that reduces the respiratory rate by 50% (309 ppm [460 mg/m^3]), for 6 h per day for three days. Respiratory epithelial exfoliation, erosion, ulceration, necrosis and less pronounced lesions in the olfactory epithelium were observed (Buckley *et al.*, 1984).

No pathological change or change in respiratory parameters was seen in guinea-pigs exposed to hydrogen chloride at 15 mg/m^3 for 2 h per day on five days per week for seven weeks, compared to control animals (Oddoy *et al.*, 1982). In guinea-pigs exposed by inhalation to hydrogen chloride at 1309–5708 ppm [1950–8505 mg/m^3], the LC_{50} for a 30-min exposure was about 2500 ppm [3800 mg/m^3] (Kirsch & Drabke, 1982).

In rabbits and guinea-pigs exposed to 0.05–20.5 mg/l [50–20 500 mg/m^3] hydrogen chloride for periods of 5 min to 120 h, the lethal dose after 30 min of exposure was 6.5 mg/l [6500 mg/m^3]; that after 2–6 h of exposure was 1 mg/l [1000 mg/m^3]. The highest non-lethal dose for 5 min was 5.5 mg/l [5500 mg/m^3], and that for five daily 6-h exposures was 0.1 mg/l [100 mg/m^3] (Machle *et al.*, 1942).

Three weeks after intratracheal instillation of 0.5 ml of 0.08 N hydrochloric acid into hamsters, a significant increase in secretory-cell metaplasia was observed in the bronchi, evaluated by estimating the amount of secretory product in the airway epithelium on histological slides (Christensen *et al.*, 1988).

Intratracheal instillation of a single dose of 0.1 N hydrochloric acid (1–3 ml/kg bw) into dogs increased mortality, lung weight and related histological changes; instillation of 2–3 ml/kg bw usually caused a fall in arterial pO_2 and lethality (Greenfield *et al.*, 1969). Similar histological findings were reported in rabbits 4 h after instillation of hydrochloric acid (pH 1.5, 2 ml/kg bw) (Dodd *et al.*, 1976). Instillation of hydrochloric acid (pH 1.6) at 25 meq/l into the oesophagus of sodium phenobarbital-anaesthetized dogs induced tritiated thymidine uptake and mitosis in the oesophageal mucosa within 24 h. This concentration was not sufficient to provoke erosion, ulceration or leukocytic infiltration (De Backer *et al.*, 1985).

In male adult baboons exposed for 15 min to 0, 500, 5000 or 10 000 ppm [745, 7450 or 14 900 mg/m^3] hydrogen chloride, no persistent alteration was observed in pulmonary function three days or three months after exposure (Kaplan *et al.*, 1988).

Studies in experimental animals *in vivo* and *in vitro* have been performed to elucidate the role of hydrochloric acid in the mammalian stomach in inducing peptic ulcers and oesophagitis. Severe damage and increased permeability to H^+ ions were observed in the oesophagus of rabbits after perfusion *in vivo* with solutions of hydrochloric acid (40–80 mM/l) (Chung *et al.*, 1975; Orlando *et al.*, 1981; Kiroff *et al.*, 1987). Oesophagitis was also observed in cats treated with hydrochloric acid (pH 1–1.3) for 1 h (Goldberg *et al.*, 1969). Isolated rat stomach and duodenum treated with 20–50 mM hydrochloric acid for 10 min showed extensive damage of the basal lamina (Black *et al.*, 1985). Oral administration of 0.35 N hydrochloric acid protected the gastric mucosa of rats against 0.6 N HCl-induced gastric lesions for 2 h. The pretreatment significantly increased prostaglandin concentrations in the gastric fundic mucosa (Orihata *et al.*, 1989).

4.3 Reproductive and developmental effects

4.3.1 *Humans*

No data were available to the Working Group.

4.3.2 *Experimental systems*

Groups of 8–15 female Wistar rats were exposed to hydrogen chloride at 450 mg/m^3 for 1 h either 12 days prior to mating or on day 9 of gestation (Pavlova, 1976). Offspring were examined for growth and viability after birth and also underwent pulmonary, hepatic and renal tests at two to three months of age. The authors reported that the exposure was lethal to one-third of the females, and disturbed pulmonary function (decreased oxygen saturation and increased vital dye absorption), renal function (increased chloride and protein excretion) were seen in the survivors. Hepatic function was affected only in exposed animals. Postnatal mortality was increased in the litters of dams exposed during pregnancy (31.9% *versus* 5.6%), and the weight of offspring of dams treated before pregnancy was reduced at four weeks after birth. Renal function was disturbed (increased diuresis and decreased proteinuria in males) in the group exposed during gestation at two but not at three months of age. Increased pulmonary sensitivity was reported in male offspring of females exposed either prior to or during gestation.

4.4 Genetic and related effects (see also Table 6 and Appendices 1 and 2)

4.4.1 *Humans*

No data were available to the Working Group.

4.4.2 *Experimental systems*

Hydrochloric acid did not induce reverse mutations in *Escherichia coli* but caused mutations in L5178Y mouse lymphoma cells at the *tk* locus.

Hydrochloric acid induced chromosomal aberrations in *Vicia faba*, in grasshopper (*Spathosternum prasiniferum*) spermatocytes (by injection), in sea urchin spermatozoa and in cultured Chinese hamster ovary (CHO) cells. There was a threshold in the aberration response to increasing hydrochloric acid concentration. The effect in CHO cells was observed in the absence of rat liver S9 preparations at a nominal hydrochloric acid concentration of 14 mM (pH 5.5) but was greater in the presence of S9, when a nominal hydrochloric acid concentration of 10 mM (pH 5.8) was required (Morita *et al.*, 1989). The greater effect of pH in the presence of S9 was due to generation of substances from S9 at low pH, as demonstrated in experiments in which the pH of medium containing S9 was lowered to 0.9 and readjusted to 7.2 before the cells were exposed. A similar effect was observed in the absence of S9 in medium submitted to this cycle of pH changes with hydrochloric acid [suggesting that clastogens may be generated in serum-containing culture medium at low pH] (A.K. Thilager, reported by Brusick, 1986).

Although only results with hydrochloric acid are reported here, similar results were obtained with other inorganic acids and with acetic acid (A.K. Thilager, personal communication reported by Brusick, 1986) and lactic acid (Ingalls & Shimada, 1974), indicating that the hydrogen ion concentration is the most important factor in experiments with acids, although specific effects of cations cannot be ruled out.

Table 6. Genetic and related effects of hydrochloric acid

Test system	Result[a]		Dose[b] or pH	Reference
	Without exogenous metabolic system	With exogenous metabolic system		
ECR, *Escherichia coli*, (B/Sd–4/1,3,4,5) reverse mutation streptomycin^R	–	0	15.0000	Demerec *et al.* (1951)
ECR, *Escherichia coli*, (B/Sd–4/3,4) reverse mutation streptomycin^R	–	0	15.0000	Demerec *et al.* (1951)
VFC, Chromosomal aberrations, *Vicia faba* root tips	+	0	pH 4.3	Bradley *et al.* (1968)
*Chromosomal aberrations, *Sphaerechinus granularis* spermatozoa	+	0	pH 6.0	Cipollaro *et al.* (1986)
*Chromosomal aberrations, *Spathosternum prasiniferum* spermatocytes *in vivo*	+	0	pH 4	Manna & Mukherjee (1966)
CIC, Chromosomal aberrations, Chinese hamster CHO cells *in vitro*	+	+	380.0000	Morita *et al.* (1989)
G5T, Gene mutations, mouse lymphoma L5178Y cells, *tk* locus	(+)	+	0.0000	Cifone *et al.* (1987)

[a] +, positive; (+), weakly positive; –, negative; 0, not tested; ?, inconclusive (variable response in several experiments within an adequate study)
[b] In-vitro tests, μg/ml; in-vivo tests, mg/kg bw
*Not displayed on profile

5. Summary of Data Reported and Evaluation

5.1 Exposure data

Hydrochloric acid is one of the most widely used industrial chemicals. It is used in pickling and cleaning steel and other metals, in the production of many inorganic and organic chemicals, in food processing, in cleaning industrial equipment, in extraction of metals and for numerous other purposes.

Hydrochloric acid may occur in workroom air as a gas or mist. The mean concentration of hydrochloric acid during pickling, electroplating and other acid treatment of metals has been reported to range from < 0.1 to 12 mg/m^3. Mean levels exceeding 1 mg/m^3 may also occur in the manufacture of sodium sulfite, calcium chloride and hydrochloric acid, in offset printing shops, in zirconium and hafnium extraction, and during some textile processing and laboratory work.

Hydrochloric acid levels in ambient air usually do not exceed 0.01 mg/m^3.

5.2 Human carcinogenicity data

One US study of steel-pickling workers showed an excess risk for cancer of the lung in workers exposed primarily to hydrochloric acid. An increased risk for laryngeal cancer was observed in the same cohort; however, no analysis was performed of workers exposed to hydrochloric acid. None of three US industry-based case–control studies suggested an association between exposure to hydrogen chloride and cancers of the lung, brain or kidney. In one Canadian population-based case–control study, an increased risk for oat-cell carcinoma was suggested in workers exposed to hydrochloric acid; however, no excess risk was observed for other histological types of lung cancer.

5.3 Animal carcinogenicity data

In one lifetime study in male rats exposed by inhalation at one dose level, hydrogen chloride did not produce a treatment-related increase in the incidence of tumours. Hydrogen chloride was tested at one dose level in combination with formaldehyde by inhalation exposure in the same long-term experiment in male rats. Hydrogen chloride did not influence the nasal carcinogenicity of formaldehyde when mixed with it upon entry into the inhalation chamber. When the two compounds were premixed before entry into the inhalation chamber, an increased incidence of nasal tumours was observed over that seen in animals treated with the combination mixed on entry or with formaldehyde alone.

5.4 Other relevant data

In single studies, hydrochloric acid induced mutation and chromosomal aberrations in mammalian cells; it also induced chromosomal aberrations in insects and in plants. Hydrochloric acid did not induce mutation in bacteria.

5.5 Evaluation[1]

There is *inadequate evidence* for the carcinogenicity in humans of hydrochloric acid.

There is *inadequate evidence* for the carcinogenicity in experimental animals of hydrochloric acid.

Overall evaluation

Hydrochloric acid *is not classifiable as to its carcinogenicity to humans (Group 3).*

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[1]For definition of the italicized terms, see Preamble, pp. 26–29.

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