

Technological changes in cancer prevention

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FISHBEIN L. Technological changes in cancer prevention. *Scand J Work Environ Health* 1992;18 Suppl 1:97–109. Exposures and technologies in the workplace are changing due to a variety of factors, including newly developed technologies, mechanization and automation, and improvements in industrial hygiene primarily effected in many developed countries. In addition substitution and removal of carcinogenic constituents in the workplace and general environment are increasing in a number of instances, particularly in North America, Western Europe, and Japan, and they are being accompanied as well by remediation either by source reduction, recycling, or compliance to more stringent national and international regulations and standards. This overview highlights some of the strategies employed in the technological changes in cancer prevention and cites examples in source reduction, changes in formulation, product or process changes, recycling, and hazardous materials management.

Key terms: automation, formulation, hazardous materials management, industrial hygiene, mechanization, process changes, product changes, recycling.

A broad spectrum of potentially toxic chemicals, including a number of carcinogenic and genotoxic chemicals and modulators of the process of carcinogenesis and spanning many organic and inorganic structural categories, is released, often in complex mixtures, into local, regional, and global environmental compartments from many industrial and disposal activities in both industrialized and developing countries. The number and extent of use of these agents are due to a large extent to the very large increases, particularly over the last four or five decades, in the production and use of synthetic organic chemicals, plastics, pesticides, and drugs and the production of energy. The release of many toxicants into the work and ambient atmosphere can be direct or indirect as a consequence of the initial discharge from a manufacturing process or disposal site. Hazardous pollutants can be accidentally released into ambient air or via the escape of raw materials or finished products at their manufacturing or processing site. Many toxicants are accidentally released from the thousands of chemical facilities and numerous small businesses, as well as from disposal sites (1–4).

The substitution and removal of carcinogenic constituents in the workplace and general environment are increasing in many facilities and environments, particularly in North America and in many countries in Europe, as well as in Japan, and they are being accompanied by remediation either by source reduction, recycling, or compliance to increasingly more stringent national and international regulations and standards.

This overview highlights some of the strategies employed for technological changes leading to cancer prevention and remediation through changes in formulation, product or process changes, recycling, and hazardous materials management.

Sources and scope of emissions and industrial waste

A recent study of 90 unregulated pollutants from 60 different sources of pollution indicated that estimated outdoor exposures can result in 1700–2000 excess cancer cases annually in the United States (US) (5). The national inventory required by the 1986 “Superfund” amendment on environmental releases of more than 320 toxic chemicals indicates that 2.7 billion pounds ($1.2 \cdot 10^9$ kg) of these chemicals were emitted into the air in the United States in 1988 (6). The figure was based on reports of 17 500 companies submitting more than 75 000 reports for the inventory. However it represents only 55 to 75% of the total number of companies responding to a questionnaire. Even the total emission figure may be a small percentage since it does not include the thousands of small companies that emit these chemicals but were not included in the inventory. The largest single source of chemical air emissions, by more than fourfold, was the chemical industry, which reported the release of some 886.5 million pounds ($402.1 \cdot 10^6$ kg). Other major sources of air emission were primary metals (approximately $90 \cdot 10^6$ kg), paper production ($94 \cdot 10^6$ kg), transport equipment ($87 \cdot 10^6$ kg), and rubber and plastics production ($60 \cdot 10^6$ kg).

Sixty of the substances in the aforementioned inventory are listed as carcinogens by the International Agency for Research on Cancer and the National Toxicology Program. Releases of listed carcinogens were

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estimated to be approximately 98 million kilograms and included dichloromethane (methylene chloride) ($46.5 \cdot 10^6$ kg), benzene ($10.3 \cdot 10^6$ kg), chloroform ($9.8 \cdot 10^6$ kg), formaldehyde ($6.3 \cdot 10^6$ kg), butadiene ($4.1 \cdot 10^6$ kg), and carbon tetrachloride ($1.8 \cdot 10^6$ kg). While comparable European estimates are not available, it is at least possible to compare production figures for certain compounds in different parts of the world. The yearly dichloromethane production in the United States was 226 000 tons (204 982 t, t = metric tons) in 1983 and 270 000 tons (244 890 t) in Europe in 1980. Since about 80% of all dichloroethane produced ends up in the atmosphere, Europe and the United States contribute equally to its dispersion in the environment. Worldwide production of benzene was estimated to be about 19 million tons ($17 \cdot 10^6$ t) annually, of which about half was produced in Europe.

It should also be noted that the United States national inventory in 1988 (6) indicated that the reporting facilities released a total of 4.5 billion pounds ($2 \cdot 10^9$ kg) of pollutants directly into the environment. Of this total 360 million pounds ($163 \cdot 10^6$ kg) of toxic chemicals was released into rivers, lakes, streams, and other bodies of water, 560 million pounds ($254 \cdot 10^6$ kg) was disposed of in landfills, 1.2 billion pounds ($0.54 \cdot 10^9$ kg) was injected into underground wells, 1.1 billion pounds ($0.5 \cdot 10^9$ kg) was transferred to commercial treatment and disposal facilities, 570 million pounds ($259 \cdot 10^6$ kg) was transferred to municipal waste water treatment plants, and, as noted earlier, 2.4 billion pounds ($1 \cdot 10^9$ kg) was emitted into the air.

The goal of the current strategy of the US Environmental Protection Agency (EPA) is to reduce 17 major pollutants that present significant risk to both human health and the environment by enlisting the voluntary help of industries in reducing aggregate environmental releases of these chemicals to all media by 33% by the end of 1992 and at least 50% by the end of 1995 (7).

It is important to note that the US Clean Air Act of 1990 mandates that industrial emitters of 1989 airborne toxicants (carcinogens, mutagens, or reproductive toxins) be required to install "maximum achievable control technology" (MACT) by the year 2003 (8). If there is still a cancer risk, the EPA is to impose standards by 2008 tough enough to protect public health with an "ample margin of safety," which, in the case of carcinogens, is defined as limiting lifetime risk of getting cancer to 1 in 10 000. Carbon tetrachloride and methyl chloroform essentially become forbidden solvents by the year 2000 and 2002, respectively, and the recycling of chlorofluorocarbons in air conditioners and refrigerators must begin in 1992. The Clean Air Act freezes production of substitutes for chlorofluorocarbons called hydrochlorofluorocarbons by 2015 and eliminates their use 15 years later. By November 1991 the EPA must publish a list of major sources emitting 10 tons (9.07 t) a year of any one, or 25 tons (22.68 t) a year of any combination, of the

1989 pollutants, as well as area sources, such as dry cleaners. The EPA must then issue maximum achievable control technologies for each listed source category so that all controls are achieved within 10 years. It will then examine residual risk after the introduction of maximum achievable control technologies and determine whether additional controls are needed. It will not only examine pollution control equipment but also pollution prevention methods such as the substitution of nontoxic chemicals for the toxic ones currently in use.

Hazardous waste management

Estimates vary widely regarding the amount of hazardous wastes produced in most industrialized countries. The United States is believed to generate more than 260 million metric tons (approximately 1 t per person per year) of hazardous and toxic wastes annually [a quantity equal to more than 70 billion gallons ($297 \cdot 10^9$ l)]. Most, about 90%, comes from large firms, the rest from small businesses and institutions. Approximately 70% of the amount of hazardous waste is generated by the chemical industry (9, 10). About 14 000 installations generate regulated quantities of hazardous wastes, while 4000 companies manage these wastes using treatment storage and disposal techniques.

Approximately 330 million metric tons of hazardous wastes are believed to be generated by countries in the Organization for Economic Cooperation and Development (OECD). Another estimate concerning 19 countries was more than 100 million metric tons higher (11). Germany was reported to have 35 000 abandoned waste sites which could require 20 years to completely deactivate at a cost of approximately 9 billion dollars. In The Netherlands about 5000 waste sites have been identified, with at least 350 requiring immediate clean-up. Poland generates roughly 30 million metric tons of hazardous wastes annually, two-thirds of it being dumped in unregulated sites. By 1989, it was estimated that nearly 2 million metric tons of hazardous industrial wastes were shipped from Western to Eastern Europe for disposal (11).

Since 1980 more than 31 000 abandoned or inactive waste sites have been identified in the United States. Of these 1224 have been placed on what is called the National Priority List (NPL) (also known as Superfund sites). As of early 1989 the EPA has initiated studies of approximately 70% of the NPL sites, actual remediation having been begun on about 250 of them and clean-ups having been completed on 43.

The time from site identification to the start of clean-up is approximately seven to nine years. Costs of clean-up range up to 1 million dollars per acre (1 acre = 0.41 ha) with some sites containing more than 100 acres (41 ha). One estimate by the Office of Technology Assessment suggests that as many as 10 000 sites in the United States will need detoxification (10).

Contamination of ground waters is common to the majority of waste sites in the United States. The principal organic compounds found in leachates are small-chain chlorinated hydrocarbons, benzene, toluene, and xylene.

Since World War II, more than 40 billion pounds ($18 \cdot 10^9$ kg) of small chain C_1 – C_4 chlorinated hydrocarbons have been distributed, of which 4 billion pounds ($1.8 \cdot 10^9$ kg) or more have been incorporated into waste sites in the United States. Large quantities of chemicals have been broadly distributed, and some fractions of these chemicals have entered US ground water as long as two to four decades ago. For example, between 1945 and 1984, more than 14 billion pounds ($6.4 \cdot 10^9$ kg) of perchloroethylene and about 12 billion pounds ($5.4 \cdot 10^9$ kg) of trichloroethylene were widely used and distributed, and, although some of these agents were lost by volatilization, a significant portion was believed to have been discarded in waste dumps or to have entered the ground elsewhere (12).

In the United States industrial organics constitute the highest class in hazardous waste volume, accounting for 60–80 million metric tons. Other major hazardous waste categories were general chemical manufacturing (40 – $50 \cdot 10^6$ t), petroleum refining (20 – $30 \cdot 10^6$ t), explosives (10 – $15 \cdot 10^6$ t), plastic materials/resins (6 – $10 \cdot 10^6$ t), refuse systems (5 – $8 \cdot 10^6$ t), agricultural chemicals (5 – $8 \cdot 10^6$ t), cyclic crudes/intermediates ($58 \cdot 10^6$ t), inorganic pigments (3.5 – $5 \cdot 10^6$ t), and alkalis/chlorine (2.5 – $4.5 \cdot 10^6$ t) (13).

Hazardous waste management involves several technologies and processes in addition to waste minimization and reduction. These technologies and processes include (i) recovery and reuse, (ii) destruction via incineration, (iii) biological degradation and treatment, (iv) thermal treatment and destruction; (v) chemical detoxification, (vi) stabilization and solidification, and (vii) above-ground, long-term storage (9, 13–15).

Table 1 illustrates the type of technology or process and the waste volume managed, as recently estimated by the treatments, storage, disposal, or recycling survey of the EPA (13). The US Congressional Budget Office (14) estimated the volumes of incinerable hazardous waste generated in the United States in 1983 (table 2) (16).

Although about one-fourth of all industrial hazardous wastes are incinerable, historically in the United States a relatively small portion of these have been burned. The rest have been recycled or sent to ultimate land disposal. While some flammable wastes have enough energy content to be useful as fuels to replace purchased fuels, others do not, but will burn in combination with regular fuels (17).

Incineration is generally considered to have a major role in the hierarchy of waste management methods, although it is currently uncertain as to whether or not incineration will be able to reach its full potential, at least in the United States (9, 15–23).

Thermal destruction of hazardous waste involves the controlled exposure of waste to high temperatures (usually 900°C or greater) in an oxidizing environment. Thermal destruction processes include thermal oxidation, starved-air, and pyrolytic incineration systems; high-temperature industrial processes such as boilers, cement kilns, and industrial furnaces in which hazardous waste is burned as a fuel; and a variety of high-temperature processes such as molten salt or plasma or electric furnaces (18). The elements that best assure the destruction of the hazardous wastes are incinerator temperature and turbulence and residence times (3).

During 1987, the use of incineration for hazardous wastes in the United States was reported to have increased 36% from the previous year, while resources recovery rose 25%, landfilling increased about 5%, and deep-well injection rose only 1% (19).

It has been estimated that there were approximately 280 hazardous-waste incineration facilities operating as of 1987. Most of these facilities are private, on-site

Table 1. Technologies used in hazardous waste management.

Type of technology or process	Waste volume managed (million metric tons)
Incineration	0.85–0.95
Reuse as fuel	1–1.2
Fuel blending	0.45–0.6
Solidification/stabilization	0.5–0.6
Solvent recovery	0.7–0.8
Metal recovery	0.4–0.5
Wastewater treatment	350–450
Other treatment processes	1.5–3
Waste pile	0.4–0.5
Surface impoundment	150–225
Landfill	1.7–2.0
Land treatment	0.3–0.4
Underground injection	11.5–13.5

Table 2. Estimated quantities of incinerable hazardous waste generated in the United States in 1983.

Type of waste	Quantity (million metric tons)
Liquids	
Waste oils	14.25
Halogenated solvents	3.48
Nonhalogenated solvents	12.13
Other organic liquids	3.44
Pesticides/herbicides	0.026
Polychlorinated biphenyls	0.001
Total liquids	33.33
Sludges and solids	
Halogenated sludges	0.72
Non-halogenated sludges	2.24
Dye and paint sludges	4.24
Oily sludges	3.73
Halogenated solids	4.58
Resins, latex, monomer	4.02
Total sludges and solids	29.31
Total incinerable wastes	62.64
Total hazardous wastes	265.60

Table 3. Chemical conversion processes for hazardous wastes.

Process	Waste type
Wet oxidation	Variety of organic compounds
Ozonation	Phenols, cyanides, and organic lead compounds in waste waters, compounds in air
Molten-salt combustion	Variety of organic compounds
Electrochemical oxidation	Cyanate, thiocyanate, acetate, phenols, cresols
Treatment with form-aldehyde	Chromium(VI), cyanide ion, metalcyanide complexes
Catalytic reduction with metal powder	Chlorinated organic compounds in waste waters
Catalytic hydrogenation	Polychlorinated hydrocarbons
Dechlorination	Polychlorinated organic compounds
Destruction by microwave plasma	Pesticides, polychlorinated biphenyls
Hydrolysis	Organophosphorus pesticides, carbamate pesticides
Neutralization	Strong acids, alkalies

Table 4. Potential applications of the UOP decontamination process. (UOP = Universal Oil Products, PCB = polychlorinated biphenyl, LPG = liquified petroleum gas)

Pollutant chemical	Transformed hydrocarbon
Trichloroethylene	Ethane
Tetraethyl lead	Ethane
Cresol	Toluene
PCB	Biphenyl
Polluted stream	Treated product(s)
Still bottoms from solvent recycle	Solvent fuel
Used motor oil	Lube base stock
Spent solvent	LPG fuel
Coal tar	Fuel oil
Transformer oil	PCB-free mineral oil

incinerators, while 40 commercial facilities were available that same year. Together the private and commercial incinerators were believed in 1987 to be treating less than 2% of the wastes designated as hazardous under the Resources Conservation and Recovery Act (24). A variety of chemical conversion processes for hazardous wastes has been recommended, and these processes have the potential of converting wastes to less hazardous products, primarily organic compounds. Table 3 presents 11 chemical conversion processes and the waste type treated (14). Wet oxidation is the process by which compounds in water are destroyed by oxidation at temperatures between 175 and 345°C and pressures between 20.4 and 204 atmospheres. Oxidation products include chlorides from chlorinated hydrocarbons, carbon dioxide, and biodegradable alcohols, ketones, aldehydes, and carboxylic acids (14).

The largest proportion of organic waste liquids originate in petroleum or coal-based hydrocarbon matrices. Some typical waste liquids derived from these base stocks include dielectric fluids, heat transfer fluids,

used lubricating, cutting and hydraulic oils, used solvents, still bottoms from solvent recycle operations, coal tars, and oils contaminated with polychlorinated biphenyl (25). The Universal Oil Products, Inc (Illinois) Corporation recently developed a catalytic hydrogenation process (hydroprocessing) which can convert or segregate major components of contaminated waste liquids into clean fuel products at moderate temperature pressures. Table 4 lists the potential applications of the UOP decontamination hydroprocess (25).

Municipal solid wastes

By any reckoning, the scope of both the volume and disposal of municipal solid wastes (trash, garbage, refuse), particularly in the United States, is of monumental proportions (26–32). Americans generate 2.9 to 8.6 pounds (1.9–3.9 kg) of waste per person daily. In the span of one year US homes and businesses generate at least 180 million tons ($163 \cdot 10^6$ t) of municipal solid wastes, and therefore the United States ranks among the highest waste producers in the world (30). Between 1960 and 1988, municipal solid wastes more than doubled, while the US population grew by only 36%. Waste output is expected to grow by as much as 20% by the year 2000 to approximately 216 million tons ($195.9 \cdot 10^6$ t) (30).

Other industrialized countries appear to produce much fewer pounds or kilograms of waste per day (30).

Although solid waste from each municipality can vary significantly due to differences in climate, season, and social and economic factors, the typical composition of municipal solid wastes by weight has been stated to be 36–40% paper and paper board; 18–20% yard waste; 8–9% food waste; 8–9% rubber, leather, textiles and wood; 8% glass; 6–7% plastics; and about 2% miscellaneous (27, 31). Toxicity in the waste stream is derived from pigments and stabilizers in plastics, dyes and ink in paper, and a variety of toxic household products, including oil-based paints, motor oil, pesticides, batteries, paint thinners, general solvents, and many common household cleaners. It is generally acknowledged that an integrated approach to the management of municipal solid wastes involves source reduction, reuse where possible, recycling, waste-to-energy incineration, and landfilling. The reduction of toxins is needed to minimize exposure to workers involved in these steps and to increase the potential use of the final product.

Recycling

As noted earlier, solid waste has continued to increase in the United States [ie, the amount of municipal solid wastes grew from 112.8 million tons ($102.3 \cdot 10^6$ t) in 1975 to 126.5 million tons ($114.7 \cdot 10^6$ t) in 1984], but the percentage of the waste made up by plastics almost

doubled, growing from 3.9 to 7.2% during the same period (33).

In 1987 the plastics industry produced a total of 55 billion pounds ($25 \cdot 10^9$ kg) of plastics, and the public discarded about 22 billion pounds ($10 \cdot 10^9$ kg) of that amount. It is projected that by the year 2000, plastics production may reach 75 billion pounds ($34 \cdot 10^9$ kg) with the public expected to discard about 38 billion pounds ($17 \cdot 10^9$ kg) of that amount, a figure accounting for 10% of the municipal solid waste of that year (34). More than half of the discarded plastics are found in the form of packaging.

The EPA has set a national goal of 25% for source reductions and recycling in aggregate by 1992. Currently about 13% of the total US municipal solid waste (more than 300 billion pounds or 136 billion kilograms) is recycled. It is estimated that approximately 2% of plastics was recycled in 1990 compared with 23% of paper, 15% of steel, 25% of aluminum, and 8.5% of glass.

Recycling, which is relatively cheap, revenue-generating and a low-technology solution, is slowly gaining favor in most industrialized countries, but it still faces heavy competition from incineration. In poor countries recycling has always ranked high in waste reduction, and in many Third World cities whole communities of people support themselves as dump scavengers and recyclers (35).

Landfilling

From antiquity to modern times, the primary strategy for disposing of solid wastes has been to dump them on land. In 1986, the EPA estimated that more than three-fourths of all municipal solid waste was deposited in the nation's 6000 municipal landfills. Currently about 75% of US garbage is deposited in landfills, while 11% is recycled and 13% is burned in waste-to-energy plants (29). While in 1987 approximately 14 000 solid waste landfills operated in the United States, today 70% of these have closed in the face of intensified public pressure and concern about ground water contamination, and local officials have rarely approved construction of new or expanded facilities. By the year 2000, the EPA has estimated that landfills will receive nearly 96.3 million tons ($87.3 \cdot 10^6$ t) of garbage [approximately 50% of the 192.7 million tons ($174.8 \cdot 10^6$ t) projected], while recycling and waste-to-energy will account for 48.2 million tons ($43.7 \cdot 10^6$ t) (50%) each (29, 31).

It should be noted that landfilling can represent an essential component to many community plans when landfills are equipped with proper liners and leachate collection systems (27, 29).

Incineration

Owing to unsightliness and the threat of ground water pollution, landfilling with municipal solid waste is giving way in the United States to incineration. Wastes

have been commercially disposed of by burning in Western Europe for over 100 years.

A wide range of materials comprise the combustible fraction of municipal solid waste. These materials include (weight %) paper (50.2%), yard wastes (17.8%), food wastes (16.8%), plastics (5.2%), wood (4.6%), leather and rubber (3.4%), and textiles (2.0%) (34).

The newest means of incineration, called mass burn, is a European technique whereby garbage, for example, is fed into a furnace, where it falls onto moving grates that tumble it to temperatures of up to 2400°F (1314°C). The burning mass heats water, and the steam drives a turbine to generate electricity, which is sold to a utility. To curb pollution, the waste gases are blown into electrostatic precipitators or acid scrubbers and then passed through fabric filters. The ash residue is extracted, cooled, and generally dumped into municipal landfills, where it takes up approximately 10% of the room it would have taken as raw garbage. It is estimated that there are 100 mass burn incinerators in the United States, and there may be about 300 by 1995 (32). In the United States approximately 80% of the municipal solid waste is disposed of in landfills, 10% is recycled, and the remainder is incinerated with or without energy recovery. In comparison, in Japan, approximately 16% of municipal solid waste is disposed of in landfills, and 34% is incinerated. Sweden incinerates 50% of its municipal solid waste, Switzerland 75%, and Germany 34% (36).

The EPA estimates that the 161 US incinerators and waste-to-energy facilities emit 12 000 tons (10 884 t) of particulate matter, 210 000 tons (190 470 t) of acid gases, and 60 000 tons (54 420 t) of nitrogen oxides. A large waste-to-energy facility (2200 tons/d, ie, 1995 t/d) can be expected to generate 150 tons (136 t) of particulate matter. Metals such as cadmium, chromium, lead, and arsenic can condense into particulate matter during and after combustion (30, 37). In addition large waste-to-energy facilities, depending on design and operating conditions, can emit polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF).

In the European Community (EC), 540 municipal incinerators dispose of about a quarter of the waste of member countries each year (38). Plans are being prepared in the EC to set limits on the quantities of chemicals that can be released into the atmosphere from the incineration of municipal solid waste. Those being considered include PCDD, PCDF, and heavy metals (38). It should also be noted that several countries, including Belgium, France, Germany and the United Kingdom, burn some of their wastes at sea on incinerator ships. However, this practice is being curtailed and may soon be banned (35).

Lead and cadmium

Refuse incineration is a major source of atmospheric cadmium and lead in the United States and the United

Kingdom (1, 28, 39). The risks from the incineration of municipal solid waste with focus on total and leachable metals (including lead and cadmium) in incinerator fly ashes has been reviewed by Denison & Silbergeld (40).

The major contributors of lead to discards in municipal solid waste in the United States in 1986 were lead-acid batteries, plastics, glass and ceramic products, solder, and pigments which accounted for 211 833 tons (192 133 t) (99.2 %). Lead-acid batteries (type used in automobiles) accounted for 65% (138 043 tons or 125 205 t) of lead in the municipal solid waste of 1986. Over two billion household batteries are sold annually in the United States. On the average, 1.7 pounds (0.8 kg) of these batteries are disposed of by each US family annually (41).

The major contributors to discards of cadmium into municipal solid wastes are plastics, nickel-cadmium batteries, plated products, glass and ceramic products, and pigments. These five areas accounted for 1775 tons (1610 t) of cadmium discharged into municipal solid waste in 1986. Rechargeable nickel-cadmium batteries which are incorporated into small appliances account for 52% (930 tons or 844 t) of cadmium discharges. Approximately 10 million nickel-cadmium batteries were sold in the United States in 1985. Other products that contain lead or cadmium that are frequently found in municipal solid wastes include brass and bronze products (lead), rubber products (lead and cadmium), used oil (lead and cadmium), printing inks (lead), and electric blankets and heating pads (cadmium) (41).

Lead-based pigments used in plastics and rubber include chromates and molybdate oranges. The plastics industry is one of the largest consumers of lead chromate pigments (41). Many inks used in commercial bread wrappers in the United States have been reported to contain relatively high concentrations of lead chromate (42). On the basis of the assumption that soft plastic bread packages have an average lead content of 26 mg, and $3.0 \cdot 10^7$ bread bags are disposed of daily in the United States, 0.8 t of lead would be added to municipal solid waste daily or 292.0 t a year (42). This lead could enter the environment as a result of incineration or leakage into ground water from a landfill or could be recycled with co-mingled waste. [In addition colored inks used in magazines and glossy newspaper inserts often contain lead-based pigments (43).]

Cadmium-based pigments employed in plastics are principally sulfides, sulfoselenides, or mercury complexes.

Several lead- and cadmium-based heat stabilizers are used in polyvinyl chloride (PVC) and other resins. The lead stabilizers with PVC have included dibasic lead sulfate, dibasic phosphate, phthalate, stearate, and carbonate. The cadmium-based stabilizers with PVC include (liquids and solids) barium-cadmium decanoate, barium-cadmium alkyl phenols and barium-cadmium benzoates.

Efforts are increasingly being made to reduce the levels of lead and cadmium (and also chromium and mercury) in municipal solid waste. In the United States some states and city or regional programs have collected or replaced household batteries on a pilot project basis. Germany collects nickel-cadmium batteries as a precaution against possible environmental pollution. Japan and many European countries have placed regulations, in effect during the last decade, regarding battery formulation and presorting prior to incineration or recycling.

In recognition of the human and environmental toxicity of lead and cadmium, the plastics industry is increasingly attempting to reduce the levels of cadmium, or totally replacing both cadmium and lead, in thermal stabilizers, pigments, and colorants. For example, monoazo, monoazonaphthol, quinacridone, perylene, and pyrazolone derivatives have been suggested as organo derivative replacements for lead chromate and cadmium sulfide and selenide pigments, and nickel titanium and iron oxide are possible substitutes for lead chromate and cadmium sulfide pigments (39).

The majority of lead- and cadmium-based heat stabilizers has been replaced in applications in which substitution is technically or economically feasible. For example, organotin stabilizers (ie, alkyltin mercaptides, alkyl tin carboxylates and barium-zinc stabilizers have been suggested) (41).

An additional area in which there is an increasing effort to replace lead involves the use of a new alloy of copper and bismuth (with small amounts of tin and phosphorus) for making faucets and other plumbing fixtures. Lead-containing solders for plumbing are also being eliminated. The use of cadmium for plating steel for consumer electronics and appliances is being greatly reduced by the increased use of circuit boards and plastics.

Polychlorinated dibenzodioxins and polychlorinated dibenzofurans

PCDD and PCDF are formed in trace amounts by a variety of industrial, combustion, and diffuse sources, including the pulp and paper industry, metal refining and smelting, manufacture of flame-retarded plastics, and dry cleaning (1, 2, 44–47). Theoretically, the production of all polychlorinated aromatic compounds (particularly chlorophenols and their derivatives, chlorobenzene and substituted chlorobenzenes) utilizing temperatures above 150°C, alkaline conditions, ultraviolet radiation, or the presence of free halogens or radical initiators can give rise to the formation of PCDD or PCDF (44).

The major pathway for PCDD and PCDF to enter the environment is via combustion processes (ie, hazardous, municipal, and hospital waste incinerators) (the presence of PCDD or PCDF in flue gas and fly ash of municipal incinerators appears to be universal);

the combustion of sewage sludge and scrap metal; recycling; production accidents (like the one that occurred in Seveso, Italy); and accidental fires and explosions (polychlorinated biphenyl contained in transformers, etc). Other sources of PCDD and PCDF emissions into the environment include dumps, residues (ie, hazardous waste disposal sites, contaminated areas, waste oil, pentachlorophenol-treated wood production, and the application of pesticides), and PCDD in automobile exhaust (44, 47, 48).

2,3,7,8-Tetrachlorodibenzo-p dioxin (TCDD) (dioxin) is the major PCDD of occupational, general public, environmental, and legislative concern.

A variety of efforts has been widely undertaken, principally in many industrialized countries, to reduce the formation and emissions of PCDD and PCDF. Their management and disposal options fall broadly into the following three categories: waste reduction and recovery (process modification and retro fitting), waste treatment, and waste management. These categories have principally involved the optimization of combustion processes for hazardous waste and municipal solid waste incineration, process changes in the pulp and paper industry, and the ban on polychlorinated biphenyls and pentachlorophenol in many places (44, 47–49).

Waste reduction and recovery options

Modifying manufacturing processes and adding waste reduction and recovery technologies forms a major strategy in reducing the release of PCDD and PCDF into the environment (44, 48). For example, one process modification developed by Velsicol for the preparation of hexachlorophene involves utilizing the feed stock 2,4,5-trichlorophenol from the chlorination of 2,5-dichlorophenol and thus avoiding the PCDD-forming step inherent in the alkaline hydrolysis of 1,2,4,5-tetrachlorobenzene to form 2,4,5-trichlorophenol (48).

The reduction of halogenated-hydrocarbon still bottoms by pyrolysis for the recovery of hydrochloric acid is another important risk reduction approach (44, 48).

Modification of pulp and paper mill bleaching processes

Bleached chemical pulp and paper production are of major importance in regard to their scale in many countries and as a possible source of PCDD and PCDF (44, 47, 50). The world production of bleached chemical pulp is 50 million tons ($45.3 \cdot 10^6$ t) per year. There are currently 21 pulp mills in Sweden producing 4 million tons ($3.6 \cdot 10^6$ t) of bleached pulp in addition to 104 mills in the United States and 47 mills in Canada that produce chlorine-bleached pulp (44).

Chlorinated hydrocarbons, PCDD, and PCDF are formed when chlorine reacts with organic matter in wood (ie, lignins, which contain complex polyphenolic

polymers). (For example TCDD and 2,3,7,8-tetrachlorodibenzofuran have been reported as a result of bleaching kraft pulp with chlorine or chlorine dioxide (44, 47, 48). Another source of PCDD and PCDF during the bleaching process is believed to involve the use of products which contain recycled oil to prevent or minimize foam prevention.

Several steps have and are being taken by major paper makers in North America and Europe to reduce the formation and emissions of PCDD and PCDF. These steps involve principally decreasing the amounts of chlorine used in the bleaching process or adding chlorine in slow stages or utilizing chlorine dioxide (44). Other steps in remediation that have been utilized involve the enzymatic removal of the lignin-hemicellulose coating with cellulase or hemicellulase, a process which significantly decreases the amount of chlorine needed for bleaching (51). Some companies are planning to install an oxygen delignification stage ahead of the bleach plant that would further diminish chlorine usage during bleaching. In addition some paper companies are developing "high-yield" technology that produces pulp that can be bleached with hydrogen peroxide and sodium hydrosulfite rather than chlorine compounds.

Waste treatment and waste management options

Some waste treatment and waste management options have been proposed for the reduction of PCDD and PCDF (44, 48). For example a variety of thermal methods which encompass a number of technologies (eg, rotary kiln incineration, fluidized bed incineration, electric pyrolysis, and plasma arc) have been employed. The rotary kiln incinerator is the basic unit in several thermal technologies that have been tested or proposed for dioxin disposal. One example is the EPA mobile incineration system that has treated over 900 000 kg of dioxin-containing soils and other solids and over 80 000 kg of liquid waste, with a destructive efficiency exceeding 99.9999% (48). This system first utilizes a trailer that is 4.9 m long and 1.2 m in diameter which operates at up to 1000°C with a nominal solid retention time of 60 min. The second combustion chamber operates to 1300°C with a retention time of 2–3 s. A final unit contains a water quench, a wet electrostatic precipitator, and an alkaline scrubber for off-gas treatment (48).

Other proposed thermal methods include an electric pyrolyzer system designed to operate at 1800°C and a thermal plasma system designed to produce temperatures greater than 5000°C (48).

Chemical and photolysis methods have included (i) the use of potassium polyethylene glycolate (prepared from potassium hydroxide and polyethylene glycol), which removes chlorine atoms as potassium chloride from PCDD and PCDF; (ii) thermal desorption or ultraviolet photolysis; and (iii) ultraviolet oxidation combined with oxidizing agents such as ozone or hydrogen peroxide. Other methods being investigated

include a super critical water oxidation system operated above 374°C and pressure over 3200 pounds per square inch (3207 kPa) and modified clays [ie, cetyl pyridinium montmorillonite, cetyl pyridinium hydroxy aluminum montmorillonite, and hydroxy aluminum montmorillonite (a zeolite-type clay)] (48).

Waste management options that are under development by the EPA to manage PCDD and PCDF wastes in order to reduce human and environmental exposure include (i) in situ stabilization and solidification, (ii) in situ vitrification (utilizing temperatures reaching 20 000°C that melt contaminated soil and decompose the organic materials), (iii) storage of wastes in abandoned mines, and (iv) biological methods (ie, employing white rot fungus (*phanerochaetechrysosporium*) to degrade toxic haloorganic constituents (48).

Volatile organic chemicals

The release of many volatile organic chemicals into the ambient environment (as well as into water and soil) is an issue of increasing concern to industry, the general public, and regulatory agencies in many societies with local, regional, national, and international impact. Emissions of many hundreds of such chemicals, including some carcinogenic agents, arise from the following three principal categories: point sources, area sources, and mobile sources (8, 52–56). Point sources, or industries, emit volatile organic chemicals (as a consequence of their use) from various processes that are used to make a product(s) and may utilize solvents, paints, oils, or they may emit volatile organic chemicals as a result of fugitive emissions. Emissions from point sources in the United States are believed to account for 30% of the country's smog-forming volatile organic chemicals (8).

Area sources are generally comprised of comparatively small-size emitters such as dry cleaners, printing shops, repair shops, in addition to a variety of consumer products (ie, hairsprays, deodorants). Because of their widespread use, area sources account for approximately 20% of volatile organic chemicals in the United States. Mobile sources, principally motor vehicles, because of their huge numbers and extensive use, constitute the largest source of volatile organic chemicals, accounting for perhaps 50% of emissions. Mobile sources, through fuel combustion (gasoline and diesel), contribute polycyclic aromatic hydrocarbons, benzene, 1,3-butadiene, formaldehyde, and fine particles, all of which are of particular concern.

According to a recent EPA source inventory, 85% of emissions in the United States comes from mobile sources, of which 70% is from exhaust, 14% from evaporative emissions, and 1% from vehicle refueling (57). Benzene emissions from 36 coke by-product recovery plants in the iron and steel industry were estimated at 18 700 tons (16 960 t) per year in 1989. In 1989, the EPA ordered a 90% reduction in the industrial emissions of benzene over the next five years (58).

A major review by the EPA in 1989 examined the sources and risks of air toxins and concluded that, of the approximately 90 pollutants evaluated, 12 accounted for over 90% of the total estimated annual cancer incidence for the chemical group. Products of incomplete combustion were responsible for about 35% of the calculated total, and other major contributors included 1,3-butadiene, benzene, hexavalent chromium, formaldehyde, and chloroform (53).

As noted earlier, the current strategy of the EPA is to reduce total releases and transfers of 17 targeted chemicals by one-third by 1992 and by one-half by 1995 (7, 8, 59). The 1988 Toxic Release Inventory is used as the base line for the reductions. [It should be noted that industry estimates of total emissions of more than 300 chemicals into the environment was down 11% in 1989 from 1988 (58)]. The 17 targeted chemicals have been taken from the Toxic Release Inventory. Each year the inventory reports on more than 300 toxic chemicals routinely released into the environment by some 20 000 industrial facilities. The 17 chemicals include several important volatile organic chemicals (ie, benzene, carbon tetrachloride, chloroform, dichloromethane, 1,1,1-trichloroethane, trichloroethylene, xylenes, methyl ethyl ketone, methyl isobutyl ketone). The additional chemicals on the EPA list of 17 toxic chemicals are cyanide compounds and chromium, cadmium, lead, mercury, and nickel and their compounds. These 17 chemicals are used in metal working or painting, machinery degreasing, petroleum refining, electrical and transportation equipment, pulp and paper products, furniture and instruments, and the making of chemicals. These chemicals were selected for a number of reasons, including their human health and environmental effects, high potential for exposure, production volume, high volume of releases, and recognized potential for cutting emissions (59).

Reduction of volatile organic chemicals

Major efforts are being made (and will increase by legislative mandates) by diverse industries in many countries to reduce the emissions of volatile organic chemicals. These efforts include the use of (i) carbon absorption systems, (ii) scrubbers, (iii) thermal regeneration with hot gases, (iv) thermal incineration with regenerative heat recovery, (v) combination of separate technologies, (vi) reformulation of paints, coatings and resins, and (vii) high solids emulsion technology.

For example, the EPA will increasingly force dry cleaners to use carbon absorbers or refrigerated condensers for controlling vent emissions of perchloroethylene from existing machines and will mandate the use of dry-to-dry machines which combine wash and dry cycles in the same unit (60). EPA is also expected to force commercial sterilizers using more than 600 pounds (272 kg) of ethylene oxide annually to use acid-water scrubbers and catalytic oxidizers for cutting

chamber and exhaust vent emissions of the sterilant gas (60).

To produce lower levels of volatile organic chemicals, paint formulators are increasingly turning to either water-based emulsions or to solvent coatings with higher solids and have adopted higher solvency power products (ie, higher alkyl chain ketones and di-basic ester solvents) (61). In addition, a new coating technology substitutes carbon dioxide for solvents in the manufacturing process. Carbon dioxide is introduced into a coating formulation immediately before application, and this process results in a reduction of volatile organic compounds from coating emissions by 30–70%, depending on the process.

Reformulation of fuels

Enhanced vehicle controls such as canisters to contain vapors generated by diurnal heating of other fuel and improvements of fuel-dispensing hoses and nozzles on service station pumps are the simplest measures taken for the reduction of emissions from motor vehicles (55).

Since gasoline and diesel combustion are major sources of airborne toxicants, interest in the reformulation of fuels and, to a much less extent, to alternate fuels has led to changes in fuel combustion in mobile sources (53).

The principle goal of the reformulation of fuels, which in a sense can be considered a form of alternate fuel, is to lower smog formation constituents. Gasoline is a complex combination of as many as 100 hydrocarbons plus extenders and additives. Aromatic hydrocarbons are increased to compensate for the continued reduction of the lead content of leaded gasoline. On the average, benzene constitutes 1.5% of gasoline, and all forms of evaporative emissions of gasoline contain benzene. Approximately 85% of human exposure to benzene in the United States is believed to originate from gasoline (57). In reformulative gasoline, the average aromatics in unleaded fuel is about 20–30% to maintain a high octane rating. A variety of extenders and additives has been employed, including methyl butyl tertiary ether (MBTE), ethyl butyl tertiary ether, methanol, ethanol, and manganese catalyst to reduce benzene and nitrogen oxide emissions. Methyl butyl tertiary ether, when used as an octane enhancer and as an oxygenate for motor gasolines, allows more complete combustion in car engines and thereby reduces emissions as required by federal clean air regulations.

Alternate fuels — methanol

Methanol fuels have been gaining favor in the United States in recent years as an alternative to petroleum fuels for a number of reasons, including its excellent combustion characteristics, its possible contributions

to improved air quality and US energy security, and the possibility of lowering benzene and butadiene emissions from the combustion of petroleum fuels (62, 63). The use of methanol is advocated as a straight replacement for gasoline (M—100 = 100% methanol) or as a blend of 85% methanol and 15% gasoline (M—85). In addition flexible fueled vehicles are advocated in which vehicles can operate on conventional gasoline or with M—85.

Chronic exposure to transportation fuels and their exhaust emissions is a greater concern than acute exposure to the fuels themselves. Table 5 lists the 1986 US annual risk estimates for cancer death in relation to five emissions (fuel vapor; particulates, including particulate incomplete combustibles and particulate organic matter; benzene; formaldehyde; and butadiene) in contrast to gasoline, optimized M—100 and flexible fueled vehicles on M—85 (62, 63). M—100 (100% methanol) produces no particulates or benzene (except for a very small amount due no lubrication oil or other effects) and only a minute amount of butadiene.

Methanol exhaust contains at least 35% less smog-producing hydrocarbons (ie, less “indirect” formaldehyde formed in the atmosphere from the transformation of reactive hydrocarbon emissions), and 30–40% less airborne toxicants than gasoline. Methanol exhaust, however, can contain three to five times more formaldehyde than that of gasoline engines of equivalent technology. However, possible improvements in the technology of methanol engines and emission control are expected to effect a significant reduction in formaldehyde emissions from pure methanol (M—100) and M—85 fuels (62).

Chlorofluorocarbons

Several chlorine-containing compounds such as the chlorofluorocarbons (ie, trichlorofluoromethane and dichlorodifluoromethane), halons (ie, trifluorobromo-

Table 5. Air toxic emissions. (US = United States, M100 = 100% methanol, FFV = flexible fueled vehicles, M85 = 85% methanol and 15% gasoline)

	1986 US cancer risk estimates		
	Gasoline	Optimized M100 ^a	FFV on M85 ^a
Fuel vapor	17–68	0	9–34
Particulate ^b	1–176	0–2	0–50
Benzene	97–150	2–4	29–45
Formaldehyde ^c	43–81	30–58	90–171
1,3-Butadiene	221–252	2	80–91

^a Estimate assuming complete replacement of gasoline.

^b Including particulate incomplete combustibles and particulate organic matter.

^c Includes both direct formaldehyde emissions and indirect, photochemically generated formaldehyde.

methane and chlorodifluorobromomethane) and, to a less extent, methylchloroform and carbon tetrachloride have been implicated in the continued depletion of the stratospheric ozone layer which shields the earth's atmosphere from ultraviolet-B radiation. As the ozone is depleted, increased ultraviolet-B radiation results in more skin cancers, cataracts, and suppression of immune systems, and there is also the possibility of its damaging crops and aquatic organisms (1, 3, 53, 64, 65).

Averaged over the entire globe, ozone decreased about 2.5% between 1969 and 1986. New EPA estimates show that, as a result of the accelerating destruction of the ozone layer, there could be 200 000 more deaths from skin cancer in the United States over the next 10 years, roughly double the estimated current rate (66).

Because about 10% of the chlorofluorocarbons is employed in usages that involve slow emission to the atmosphere because of the delay from release at the earth's surface to decomposition in the upper atmosphere, coupled with the very long observed atmospheric lifetimes for these compounds, it is assumed that stratospheric ozone depletion and the effects of this ozone loss will be experienced on a global scale throughout the 21st century (64).

Chlorofluorocarbons have a broad spectrum of uses, including refrigerants, blowing agents, and cleaning agents, and global production expanded rapidly from 1960 through 1988 (66).

The use pattern of chlorofluorocarbons increased to about 1400 million pounds ($635 \cdot 10^6$ kg) a year until 1974, when the ozone depletion theory was first proposed. The use pattern changed significantly between 1974 and 1978. In 1974, 2050 million pounds ($930 \cdot 10^6$ kg) of chlorofluorocarbons were globally consumed, primarily as aerosol propellants and to a less extent as refrigerants and blowing agents. However, as aerosol uses of chlorofluorocarbons have been almost totally eliminated in the United States and decreases have been made elsewhere, chlorofluorocarbons are now the most used as refrigerants and blowing agents. For example, the estimated global consumption of chlorofluorocarbons in 1988 was 2510 million pounds ($1139 \cdot 10^6$ kg), of which 30% was used as refrigerants (in home appliances, automobile air conditioners, commercial cooling systems), 28% as blowing agents, 19% as cleaning agents, 19% as aerosols, and 4% in miscellaneous uses (65).

The United States is the largest producer and user of chlorofluorocarbons. Although the use of chlorofluorocarbons in aerosols was banned in the United States in 1978, the per capita consumption of chlorofluorocarbons continues to exceed that of Western Europe, Japan, the Soviet Union, Australia, China, and India by substantial margins. Although developed countries currently account for 85–90% of global use, consumption rates are increasing in developing coun-

tries in attempts to provide better essential services such as refrigeration and insulation (65).

Reduction of chlorofluorocarbons

In September 1987, the Montreal Protocol on Substances That Deplete the Ozone Layer was negotiated and signed by more than two dozen nations. The protocol entered into force in January 1989 and by January 1991, 68 nations had become a party of it. Under its terms, the total global emissions of chlorofluorocarbons are to be reduced 20% by 1994 (below 1986 emission levels), and an additional 30% by 1999 (64, 65). At the June 1990 meeting in London, amendments to the Protocol were adopted that call for the complete phasing out of chlorofluorocarbon and halon production and release by the year 2000 and for the phasing out of other significant ozone-depleting chemicals as well.

Title IV of the recently passed Clean-Air Act in the United States sets out scheduled reductions leading to the phase-out of production of chlorofluorocarbons, halons, and carbon tetrachloride by 2000 and methyl chloroform by 2002. It also freezes the production of hydrochlorofluorocarbons in 2015 and phases them out by 2030. Since these restrictions focus on production limitations to the extent that these chemicals can be recovered, recycled and reused, they may continue in commerce past the applicable phase-outdate (8).

The European Commission is considering stricter protocols than those in the Montreal Protocol, including a 50% cut of 1986 levels by 31 December 1991. Average consumption of chlorofluorocarbons in the European Community is down 50% from the 1986 levels, although production has not been cut as much because of exports. Traditionally, Europe has exported 25–30% of its production and that is down to 15%–20% (67).

Chlorofluorocarbons released from automobile air conditioners represent the single largest source of emissions (8), which account for about 16% of all releases of chlorofluorocarbons. These emissions can be reduced considerably if the coolant is recovered and recycled during servicing, repair, or disposal.

To a great extent, the recycling of chlorofluorocarbons will be necessary in the United States, if this country hopes to cut the use of chlorofluorocarbons and still maintain its standard of living (53). However it should also be noted that, in some industries, steps are being taken to eliminate the use of chlorofluorocarbons. For example, in the electronics industry, ultrasonic cleaning is being employed for electronic components (cleaning soldering debris and rosins from circuit boards) instead of relying on chlorofluorocarbons. Several alternative fluorocarbon-based substitutes are being developed to replace chlorofluorocarbon-113 ($C_2Cl_3F_3$), which has been widely used to clean computer components and circuit boards. These are based on chlorofluorocarbon-141b ($C_2H_3Cl_2F$) and a blend

of chlorofluorocarbon-141b, chlorofluorocarbon-123 ($C_2HCl_2F_3$), and methanol, as well as on a mixture of solvents and surface active agents (68). The Nordic Council of Ministers has reported on a joint project on a technical economic assessment of the possibilities for reducing the consumption and emissions of chlorofluorocarbons in Denmark, Finland, Norway, and Sweden for all the principal areas of applications of chlorofluorocarbons excluding aerosols (69). The occupational implications of the ban on chlorofluorocarbons were recently described by Orlander et al (70). In 1988, the amounts used in Sweden were approximately as follows: a total of about 3600 tons (3265 t), of which 5% was used as a propellant, 50% in foams, 9% in degreasing operations and cleaning, 9% in dry cleaning, 21% in refrigeration and heat pumps, and 6% for miscellaneous operations.

Miscellaneous chemicals and technologies

Water treatment chemicals

In the United States about 325 billion gallons ($1374 \cdot 10^9$ l) of water are used daily, primarily by industry and municipalities (excluding residential and commercial and power generating utilities). Almost all of this water must be treated by physical, chemical, or biological methods to remove pollutants or contaminants that may interfere with its use or its discharge into surface water (71). Most of the attention in the industry has focused on chromates (hexavalent chromium), once used extensively for corrosion inhibition in recirculating cooling water systems. Concern about the presence of chromium is principally directed at airborne heavy metals from the misting of open cooling towers and in waste water discharges.

Replacement products, which are being increasingly employed, are based in part on inorganic phosphates and pyrophosphates or all-organic treatments, used in various mixtures with zinc, phosphonates, and dispersants. Only about 10% of all US plant locations still use chromates, although the refinery industry still relies on their use to some extent (71, 72).

Hydrazine has been used as an oxygen scavenger and metal passivator to prevent corrosion in boiler and water systems. Cyclohexylamines and sulfites, as well as diethylhydroxylamine, have been used or suggested for use to replace hydrazine (71). Sodium and potassium salts of pyrophosphate, tripolyphosphate, polyacrylates, polyacrylamides, and polymethacrylates are increasingly being employed for scale control (71).

Rubber chemicals

Approximately 200 organic substances are used in rubber processing (ie, activators, accelerators, retarders, curing agents, antioxidants, antiozonants) (73–75). An average of 4.5 pounds (2 kg) of rubber chemicals is used per 100 pounds (45 kg) of rubber. There is an increasing attempt to replace carcinogenic rubber

chemicals predominantly in the area of accelerators and curing agents. Thus greater use is being made of accelerators such as *N*-tert-butyl, *N*-cyclohexyl, or *N,N*-dicyclohexyl-2-benzothiazole sulfenamides to replace accelerators that can form carcinogenic nitrosamines (ie, tetramethyl thiuram disulfide and *N*-oxydiethylene-2-benzothiazole sulfenamide). In addition thiazole or piperidinium dithiocarbamates are being utilized as replacements for lead and cadmium dithiocarbamates as rubber curing agents (75).

References

1. Fishbein L. Sources, nature and levels of air pollutants. In: Tomatis L. ed. Air pollution and human cancer. Berlin: Springer-Verlag, 1990:9–34. (European School of Oncology monographs.)
2. Fishbein L. Exposure in occupational versus other sources. *Scand J Work Environ Health*. 1991;18 Suppl 1:5–16.
3. World Health Organization (WHO). Air quality guidelines for Europe. Copenhagen: WHO, Regional Office for Europe, 1987. (European series; no 23.)
4. Vainio H, Sorsa M, McMichael AJ, ed. Complex mixtures and cancer risk. Lyon: International Agency for Research on Cancer, 1990. (IARC scientific publications; no 104.)
5. US Environmental Protection Agency. Cancer risk from outdoor exposure to air toxins. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1989:peS–2.
6. US Environmental Protection Agency (EPA). The toxics-release inventory: a national perspective. Washington, DC: EPA, 1986. (EPA report 560-4-89-005.)
7. Anonymous. EPA commits to plan to halt pollution at source. *Chem Eng News* 1991;March 18:48.
8. US Environmental Protection Agency. The new clean air act: what it means to you. *EPA J* 1991;17:2–64.
9. Murphy K. Hazardous waste incineration overview. In: Theodore L, Reynolds J, ed. Introduction to hazardous waste incineration. New York, NY: Wiley-Interscience, 1987:3–17.
10. fund solutions. *Chem Week* 1988;February 24:28–31.
11. Lean G, Hinrichsen D, Markham A. Atlas of the environment. New York, NY: Prentice-Hall, 1990:101–4.
12. Abelson PH. Inefficient remediation of ground-water pollution. *Science* 1990;250:733.
13. Krieger J. Hazardous waste management data base starts to take shape. *Chem Eng News* 1989;February 6:19–22.
14. Tucker SP, Carson GA. Deactivation of hazardous chemical wastes. *Environ Sci Technol* 1985;19:215–20.
15. Metry AA. Elements of a balanced approach towards hazardous waste management In: Mactezou SP, Biswas AK, Sutter H, ed. Hazardous waste management. London: Tycooly Publishers, 1989:117–9.
16. US Congressional Budget Office. Hazardous wastes management: recent changes and policy alternatives. Washington, DC: US Government Printing Office, 1985.
17. Black BB, Gushee DE. After regulation of industrial hazardous waste: what rule for incineration. Washington, DC: Library of Congress, 1989:1–18. (Congressional Research Service, CRS report for Congress.)
18. Oppelt ET. Hazardous waste destruction. *Environ Sci Technol* 1986;20:312–8.
19. Winton JM, Rich LA, Kiasche ES, Mackerron CL. Hazardous wastes: minimization eases the clean-up. *Chem Week* 1987;August 19:22–6,30.
20. Minkhabwala M, Mehta R. Case study; transportable incineration technologies for permanent Superfund

- remediations. *Hazard Waste Manage* 1988;6:19—21.
21. Josephson J. Hazardous waste research. *Environ Sci Technol* 1984;18:222A—3A.
22. Thibodeaux LJ. Hazardous material management in the future. *Environ Sci Technol* 1990;24:456—9.
23. Trentholm A, Lapp T, Scheil G, et al. Total mass emissions from a hazardous waste incinerator. *J Hazard Mater* 1988;18:99—106.
24. Environ Corporation. Incineration as a treatment option. Washington, DC: Environ Corporation, Environmental Department, 1987:3—4.
25. Youtsey KJ, Kalnes TN, Johnson RW, Hedden DR. Treatment and recycling of waste oils and solvents. In: Maltezos SP, Biswas AK, Sutter H, ed. *Hazardous waste management*. London: Tycooly Publishers, 1989: 104—13.
26. Fishbein L. Potential metal toxicity from hazardous waste incineration. *Toxicol Environ Health* 1989;18: 287—309.
27. O'Leary PR, Walsh PW, Ham RK. Managing solid waste. *Sci Am* 1988;259:36—42.
28. Lisk DJ. Environmental implications of incineration of municipal solid waste and ash disposal. *Sci Total Environ* 1988;74:39—66.
29. National Solid Waste Management Association. Public attitudes toward garbage disposal special report. Washington, DC: National Solid Waste Management Association, 1989;1—10.
30. National Governors' Association. Curbing waste in a throwaway world: a report of the task force on solid waste management. Washington, DC: National Governors' Association, 1990.
31. US Environmental Protection Agency. Solid waste disposal in the United States. Washington, DC: US Environmental Protection Agency, 1989. (Report to Congress.)
32. Ratjke WL. Rubbish! *The Atlantic* 1989;December: 1—10.
33. Graff G. The looming crisis in plastics waste disposal. *Issues Sci Technol* 1988;4:105—110.
34. Thayer A. Solid waste concerns spur plastic recycling efforts. *Chem Eng News* 1989;January 30:7—15.
35. Seager J, ed. *The state of the earth atlas*. London: Simon & Schuster Inc, 1990:109.
36. Council on Solid Wastes. *The solid waste management problem*. 2nd ed. Washington, DC: Council on Solid Wastes, 1990:9.
37. Haynes BW, Law SL, Campbell WJ. Metals in the combustible fraction of municipal solid waste. Washington, DC: US Department of Interior, 1977:16. (Rept Invest 8244.)
38. O'Sullivan DA. Environmental concerns gain prominence in Europe. *Chem Eng News* 1989;March 27:7—14.
39. Hutton M, Wadge A, Mulligan PH. Environmental levels of cadmium and lead in the vicinity of a major refuse incinerator. *Atmos Environ* 1988;22:411—6.
40. Dension RA, Silbergeld EK. Risk of municipal solid waste incineration: an environmental perspective. *Risk Anal* 1988;8:343—55.
41. Franklin Associates. Characteristics of products containing lead and cadmium in municipal solid waste facilities 1970 to 2000. Prairie Village, KS: Franklin Associates, 1989:1—40.
42. Weisel, C, Demack M, Marcus S, Goldstein BD. Soft bread packaging: lead content and reuse by families. *Am J Public Health* 1991;81:756—8.
43. Taylor, R. A loaf of bread, a jug of wine and lead. *J Natl Inst Health Res* 1991;3:36,39.
44. Fiedler H, Hutzinger O, Timms CW. Dioxins: sources of environmental load and human exposure. *Toxicol Environ Health* 1990;29:157—234.
45. Rappe C. Environmental stable chlorinated contaminants from the paper and pulp industry. In: Vainio H, Sorsa M, McMichael AJ, ed. *Complex mixtures and cancer risk*. Lyon: International Agency for Research on Cancer, 1990:341—53. (IARC scientific publications; no 104.)
46. Rappe C, Andersson R, Bergquist PA, Brohede C, Hansson M, Kjeller LO, et al. Overview on environmental fate of chlorinated dioxins and dibenzofurans: sources, levels and isomeric patterns in various materials. *Chemosphere* 1987;16:1603—18.
47. Hutzinger O, Fiedler H. Sources and emissions of PCDD/PCDF. *Chemosphere* 1989;18:23—32.
48. des Rosiers PE, Skinner JH. Advances in dioxin risk management control technologies. *Chemosphere* 1989; 18:41—55.
49. Naikwadi KP, Karasek FW. Prevention of PCDD formation in MSW incinerators by inhibition of catalytic activity of fly ash produced. *Chemosphere* 1989;19: 299—304.
50. US Environmental Protection Agency. The national dioxin study; tiers 3, 5, 6 and 7. Washington, DC: Office of Water Regulations and Standards, 1987. (EPA Report 440/4-003 1987.)
51. Anonymous. Promising new markets emerging for commercial enzymes. *Chem Eng News* 1990;September 24:17.
52. Zanetti R. No paper tiger. *Chem Eng* 1989;96(3):5.
53. US Environmental Protection Agency (EPA). The report of the Strategic Options Subcommittee: relative risk reduction project. Washington, DC: EPA, 1990:70—3. (EPA SAB-90-021C.)
54. Shah JJ, Singh HB. Distribution of volatile organic chemicals in outdoor and indoor air. *Environ Sci Technol* 1988;22:1381—8.
55. Lave LB, Wecker WE, Reis WS, Ross DA. Controlling emissions from motor vehicles. *Environ Sci Technol* 1990;24:1128—35.
56. Hanson DJ. Toxic release inventory growing more contentious. *Chem Eng News* 1991;June 3:20—1.
57. Dasch JM, Williams RL. Benzene exhaust emissions from in-use General Motors vehicles. *Environ Sci Technol* 1991;25:853—5.
58. Hanson D. Benzene emissions ordered cut by 90%. *Chem Eng News* 1989;September 4:5—6.
59. Ember LR. Rising pollution control costs may alter EPA's regulatory direction. *Chem Eng News* 1991;February 18:25—6.
60. Anonymous. Reduction of emissions. *Environ Policy Alert* 1991;February:6.
61. Reisch MS. Demand puts paint sales at record levels. *Chem Eng News* 1989;October 30:47—8.
62. Machiele PA. A health and safety assessment of methanol as an alternative fuel. In: Kohl WL, ed. *Methanol as an alternative fuel choice: an assessment*. Washington, DC: The Johns Hopkins Foreign Policy Institute, Paul H Nitze School of Advanced International Studies, 1990:217—39.
63. US Environmental Protection Agency. Analysis of the economic and environmental effects of methanol as an alternative fuel. Washington DC: Office of Mobile Sources, 1989. (Special report.)
64. Rowland FS. Stratospheric ozone in the 21st century: the chlorofluorocarbon problem. *Environ Sci Technol* 1991; 25:622—8.
65. McFarland M. Chlorofluorocarbons and ozone. *Environ Sci Technol* 1989;23:1203—7.
66. Zurer P. Destruction of ozone layer is accelerating. *Chem Eng News* 1991;April 15:6.
67. Chynoweth E. European CFC makers set to rationalize as ban is lifted. *Chem Week* 1990;July 18:10.
68. Anonymous. Substitute solvents to replace CFC-113. *Chem Eng News* 1989;March 13:19.
69. Nordic Council of Ministers and Federation of Nordic Industries. Reduction of CFC-consumption. Copenhagen: Nordic Council of Ministers and Federation of Nordic Industries, 1988. (Main report 12 E.)

70. Olander L, Colmsjö A, Holmberg B, Krantz S, Landström U. Occupational implications of the chlorofluorocarbon ban in Sweden. *Am J Ind Med* 1991;19: 818—26.
71. Thayer AN. Water treatments chemicals: tighter rules drives demand. *Chem Eng News* 1990;March 26:17—34.
72. Karras G. Pollution prevention story. *Environment* 1990;31:4—5.
73. International Agency for Research on Cancer (IARC). The rubber industry. Lyon: IARC, 1989. (IARC monographs on the evaluation of carcinogenic risk of chemicals to humans; vol 28).
74. Fishbein L. Chemicals used in the rubber industry. In: Hutzinger O, ed. *The handbook of environmental chemistry*. Berlin: Springer-Verlag, 1990:45—95.
75. Stinson S. Rubber chemical industry strong, slowly growing despite changes. *Chem Eng News* 1990;May 21:45—66.