



An overview of occupational benzene exposures and occupational exposure limits in Europe and North America

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Available online 18 April 2005

Abstract

Benzene has become one of the most intensely regulated substances in the world. Its ubiquitous use as a solvent has led to many working populations being exposed; in the early days often in uncontrolled conditions, leading to high exposures. Current occupational exposures are tightly controlled and are largely confined to workers in the petrochemical industry, vehicle mechanics, firefighters, workers exposed to automobile emissions, and some other occupational groups. Typically, occupational exposure levels are currently at or below 3.25 mg/m^3 (1 ppm), and environmental exposures are typically below $50 \text{ } \mu\text{g/m}^3$ (15 ppb). Smoking remains a significant source of exposure in both occupationally and non-occupationally exposed individuals.

The early experiences of high occupational exposures led to the identification of haematopoietic effects of benzene and the need for improved control and regulation. As with most occupational standards, there has been a reduction in exposure limits as effects have been identified at ever-lower levels, accompanied by a societal concern for improved standards of occupational health. In 1946, the United States occupational exposure limit for benzene, promulgated by the American Conference of Governmental Industrial Hygienists, was 325 mg/m^3 (100 ppm), but nowadays most European and North American countries have harmonised at $1.63\text{--}3.25 \text{ mg/m}^3$ (0.5–1 ppm). This latter figure was agreed within the European Union in 1997 and was adopted within national legislation by all Member States. The data on which this limit is set are essentially the same as those used by other standard-setting committees; this is an excellent example of how standards are set using science, pragmatism and societal values in the absence of complete information.

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Keywords: Benzene; Occupational exposure; Industrial hygiene; Environmental exposure

1. Introduction

Benzene was first isolated in 1825, by Michael Faraday, from oil gas. In 1845, Charles Mansfield and Au-

gust Wilhelm von Hoffmann isolated benzene from coal tar and, 4 years later, the first industrial-scale production of benzene began based on the coal tar method [1]. Benzene has been used widely as a solvent in the manufacture of industrial chemicals, in adhesives, shoe manufacturing and in the printing industry [2]. However, as its toxic effects became more apparent, it was

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ever more tightly regulated and, where possible, substituted by less hazardous compounds. Benzene is now principally a product of petroleum refining and is used as an intermediate in the production of a wide variety of chemical substances, and is a minor component of gasoline (petrol) [2]. Exposure to benzene in developed countries principally occurs in the petroleum and chemical industries and is also a result of exposure to gasoline engine emissions and combustion products. This paper aims to provide an overview of current occupational exposures to benzene in Europe and North America and illustrate how regulatory and advisory standards have changed over time. Throughout this paper benzene concentrations are expressed in mg/m^3 and a conversion factor of $1 \text{ ppm} = 3.25 \text{ mg}/\text{m}^3$ has been used when converting units. Personal air monitoring exposure equivalents of biomarker levels have been calculated using the regression equations of Boogaard and van Sittert [3,4].

2. Health effects and the setting of occupational exposure limits

Early uses of benzene as a solvent in occupational situations with uncontrolled high exposures led to the discovery that it could be a potent bone marrow toxicant. The first report of aplastic anemia occurred in women engaged in the production of bicycle tires in Sweden [5]. The rapid expansion of many industries at the turn of the last century and the use of benzene for the production of toluene during World War I led to many other cases of aplastic anemia being reported. For example, Greenburg [6], in a survey in the USA of plants using benzene, reported that around one third of workers had abnormally low white blood cell counts (less than 5500 per ml). It was noted that benzene exposure was $292.5 \text{ mg}/\text{m}^3$ (90 ppm) and greater. Dolore and Borgomano [7] reported the first case of benzene-induced leukemia (acute lymphatic leukemia) in a pharmaceutical worker exposed to high benzene levels. In the 1940s to 1960s, many countries reported blood diseases due to high exposure to benzene. Of particular note, Vigliani and Saita [8] reported acute leukemia in workers “heavily exposed to benzene” in Italy in the rotogravure and shoe industries. However, it was not until the 1970s that epidemiological studies conducted in the USA [9] discovered excesses of leukemia (acute

and chronic). This was essentially the starting point of many more detailed epidemiological investigations that examined leukemia in well-defined cohorts with estimated exposure profiles, which enabled quantitative risk assessments to be developed [10].

With the rapidly increasing number of reports of the haematological effects of benzene in the 1930s and 1940s, along with estimates of the exposure levels causing such effects, came the introduction of modern occupational exposure limits (OELs). In the USA in 1946, the newly formed American Conference of Governmental Industrial Hygienists (ACGIH) recommended a benzene exposure limit of $325 \text{ mg}/\text{m}^3$ (100 ppm) as a Maximum Allowable Concentration, but the following year this was reduced to $162.5 \text{ mg}/\text{m}^3$ (50 ppm); the next year (1948) a Threshold Limit Value (TLV) of $81.25 \text{ mg}/\text{m}^3$ (25 ppm) was set, where it remained until 1977, when it was reduced again to $32.5 \text{ mg}/\text{m}^3$ (10 ppm). A number of other changes were proposed and withdrawn over the next 20 years until the current TLV of $1.63 \text{ mg}/\text{m}^3$ (0.5 ppm) was set in 1997 (Fig. 1), together with a $8.125 \text{ mg}/\text{m}^3$ (2.5 ppm) short-term exposure limit (STEL) [11]. It should be noted that, although the ACGIH have been very influential in standard setting, it is essentially an independent advisory body and, within the USA, regulatory OELs are set by the Occupational Safety and Health Administration (OSHA), acting for the US Department of Labor. OSHA has been actively involved in promulgating an OEL for benzene since issuing a permissible exposure limit of $32.5 \text{ mg}/\text{m}^3$ (10 ppm) in 1971, and was engaged in an extended debate and risk assessment procedure after issuing an emergency temporary standard of $3.25 \text{ mg}/\text{m}^3$ (1 ppm) for an 8-h time-weighted average (TWA) in 1977 [12]. In 1987, a new benzene standard, which included the $3.25 \text{ mg}/\text{m}^3$ (1 ppm) 8-h TWA exposure limit, was finally issued and remains extant today [13] (Fig. 1).

Many other countries either used or followed the ACGIH TLVs until the 1980–1990s and thus they have been influential in setting the standards for exposure controls worldwide. Even countries setting their own limits have been much influenced by the ACGIH TLVs. Within the European Union (EU), as part of the Single European Act, there was a need to set harmonised OELs and benzene was one of the first compounds to receive the scrutiny of the Scientific Expert Group (SEG), now the Scientific Committee on Occupational Exposure

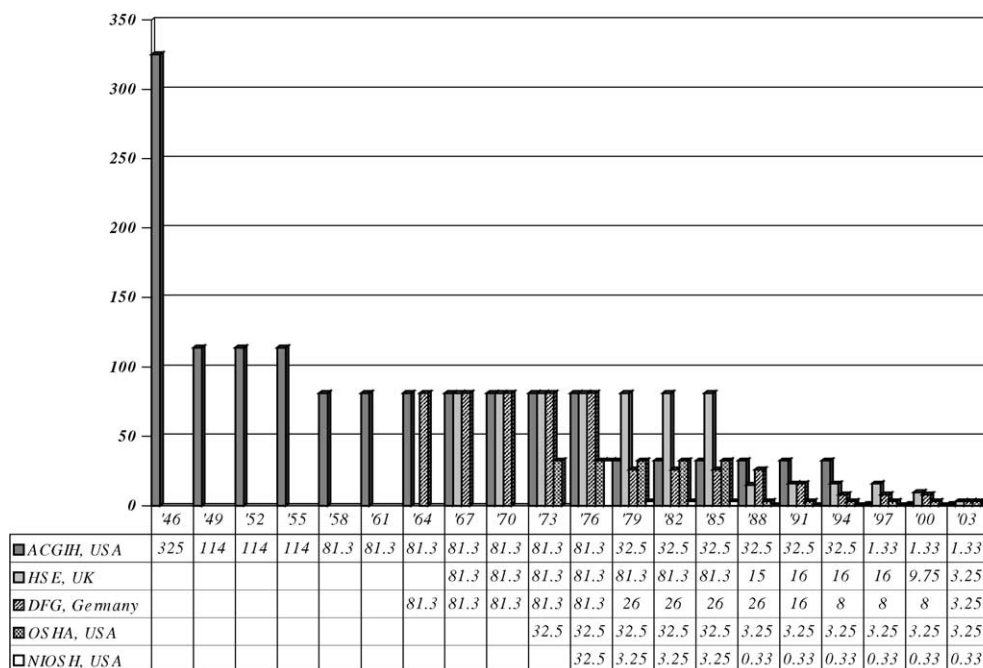


Fig. 1. Trends in advisory and regulatory benzene occupational exposure limits in Germany, the United Kingdom and the United States of America. ACGIH, American Conference of Governmental Industrial Hygienists; DFG, Deutsche Forschungsgemeinschaft; HSE, Health and Safety Executive; NIOSH, National Institute for Occupational Safety and Health; OSHA, Occupational Safety and Health Administration; UK, United Kingdom; USA, United States of America. Adapted from: [11,53–60].

Limits. SEG reported directly to the European Commission (EC; in this case, the Directorate General - Employment, Industrial Relations and Social Affairs). The SEG used a specially prepared Criteria Document for benzene [14] and developed an agreed summary position with a recommendation. The SEG took into account all the rodent studies as well as the mechanistic and epidemiological studies available at that time. In addition, they had their own quantitative risk assessment conducted [15], which gave a range of estimates of additional leukemias based on exposures of from 0.33 mg/m³ (0.1 ppm) to 9.75 mg/m³ (3 ppm). As an example, they estimated that there would be 0.5–6.6 additional cases of leukemia per 1000 workers exposed to 3.25 mg/m³ (1 ppm) benzene over a working lifetime of 40 years (40 ppm-years). Based on these estimates, and the other available data, SEG recommended to the EC that the limit value should be below 3.25 mg/m³ (1 ppm). As a result of this recommendation, the EC proposed an amendment to the Carcinogens Directive leading to the adoption of a new binding exposure limit

for benzene across all Member States of 1 ppm (8-h TWA). However, Council Directive 97/42/EC [16] allowed for transitional measures to achieve compliance. As an example, in the United Kingdom the Maximum Exposure Limit of 16.25 mg/m³ (5 ppm), set in 1988, was reduced to 9.75 mg/m³ (3 ppm) in 2000 and further reduced to 3.25 mg/m³ (1 ppm) in 2003 (Fig. 1). It is of interest to note that SEG, in their Summary Document, observed that occupational exposures and uses of benzene have been much reduced during recent decades and much of the published data seemed to support the view that most personal exposures (probably around 90%) were below 1 ppm (3.25 mg/m³).

3. Overview of benzene exposures in Europe and North America

Benzene exposure occurs in a number of industries, and has declined as regulations have tightened. The remainder of this paper describes typical exposures in

Europe and North America, and major changes and determinants of exposures. A summary of current exposures is presented in Table 1.

4. Upstream petrochemical industry

The upstream petrochemical industry encompasses operations to develop, produce, gather, treat/process and transport oil and gas to market; the industry can be broadly classified into exploration, drilling, conventional oil/gas, conventional gas, heavy oil processing, tar sands, and pipelines. Benzene is a natural component of the petroleum streams [17].

In the conventional oil/gas sector (where crude oil, and sometimes gas, are recovered from beneath the earth's crust by means of a well), mean benzene exposures have been found to be low ranging from 0.035 mg/m³ for technical staff to 0.608 mg/m³ for field operators [17]. Only 0.5% of samples exceeded the full-shift OEL of 3.2 mg/m³ for a 8-h TWA, extant in Alberta, Canada (where most of the published exposure data for the upstream petrochemical industry originate) at the time of sampling, and none exceed the STEL of 16 mg/m³ for a 15 min exposure [17].

In the conventional gas sector, natural gas is extracted by means of a well, from which impurities may need to be separated. Overall, full-shift benzene exposures were low (Table 1), with only 0.7% of full-shift samples greater than the OEL of 3.2 mg/m³ for Alberta, Canada. Exposures above the OEL were mainly associated with a dehydrator plant (where glycol is regenerated by heating, resulting in vaporization of water and organic compounds), and with a plant where a liquid with 20% benzene content was injected into the gas stream at the wells to prevent diamantane wax build-up [17]. Short-term exposures exceed the STEL 5% of the time, although the available data almost entirely related to general/maintenance workers [17]. Median benzene exposures of maintenance workers on North Sea gas production platforms ranged from <0.1 to 10.1 mg/m³ for a 12-h shift and during routine operations overall median 12-h exposures were 0.85 mg/m³ [3].

Benzene exposures from heavy oil processing (the extraction of oil from tar sands that are too deep for open pit mining) are low. Mean long-term exposure for individual job categories ranged from 0.064 to 0.148 mg/m³, with the highest short-term exposures of

0.731 mg/m³ being experienced by truck drivers [17]. Very limited or no published exposure data were identified for exploration, drilling or tar sands, although, based on data in other areas of the industry, benzene exposures are expected to be low.

5. Downstream petrochemical industry

Benzene exposures in the downstream petrochemical industry have been studied extensively. Generally, benzene exposures occur in four main areas: refinery operations, road tanker distribution, marine and rail car distribution and at service stations.

5.1. Refinery on- and off-site operators, maintenance workers and laboratory technicians

Refinery on-site operators carry out various tasks involved in controlling the processing of hydrocarbon streams containing benzene to produce gasoline components (e.g. distillation units, crackers and reformers), whereas refinery off-site operators carry out ancillary tasks such as tank farm activities and water effluent treatment. In general, tasks involving potential exposure are infrequent and of short duration [18]. In the early 1980s, mean full-shift benzene exposures for on- and off-site operators were 0.78 mg/m³ (range: 0.03–39.77 mg/m³) and 1.68 mg/m³ (range: 0.03–42.38 mg/m³), respectively [19]. Since then a number of operating practices have changed, including moving from the use of open to closed bottle process sampling in reformer and isomerisation units, the addition of fixed tank roofs over internal floating roofs, automation of blending of refinery streams, and the introduction of automatic tank level gauging [20]. These changes have resulted in lower benzene exposures such that mean full-shift exposures for on- and off-site operators are 0.22 mg/m³ (range: 0.005–7.88 mg/m³) and 0.32 mg/m³ (range: 0.008–23.3 mg/m³), respectively [20].

Refinery maintenance workers tend to experience intermittent benzene exposures as a result of the variety of tasks carried out, which may include draining, opening up, cleaning and working on enclosed equipment [21]. Available exposure data suggests that mean full-shift exposures are low (Table 1),

Table 1
Typical benzene exposure levels in different occupational groups/areas in Europe and North America^a

Occupational group/area	Year	Long-term exposure levels (mg/m ³)					Short-term exposure levels (mg/m ³)					Reference
		N	AM	GM	Min	Max	N	AM	GM	Min	Max	
Upstream petrochemical industry												
Conventional oil/gas	1985–96	198	0.206	0.036	0.003	7.78	23	0.662	0.021	<0.004	7.954	[17]
Conventional gas	1985–96	608 ^b	0.089	0.024	0.006	6.868	40	2.328	0.144	<0.02	35.2	[17]
Heavy oil processing	1985–96	236	0.112	0.051	<0.003	1.60	24	0.056	0.027	<0.017	0.731	[17]
Pipeline	1985–96	8	0.392	0.350	0.160	1.540	–	–	–	–	–	[17]
Downstream petrochemical industry												
Refinery												
On-site operators	1993–98	97	0.22	–	0.008	7.88	–	–	–	–	–	[20]
	1999–01	–	–	–	–	–	6	1.0	0.9	0.8 ^c	1.4 ^c	[22]
Off-site operators	1993–98	321	0.32	–	0.008	23.3	49	2.19	–	0.08	11.8	[20]
	1999–01	–	–	–	–	–	7	0.7	0.7	0.6 ^c	0.8 ^c	[22]
Maintenance workers	1993–98	373	0.41	–	0.008	18.1	7	2.62	–	0.23	8.6	[20]
Laboratory technicians	1993–98	628	0.30	–	0.0015	5.0	5	1.93	–	0.28	4.6	[20]
Marine and rail car loading												
Deck crew, open loading	1993–98	41	0.56	–	0.08	5.4	4	0.23	–	0.23	0.3	[20]
Deck crew, closed loading	1993–98	2	0.56	–	0.51	0.6	–	–	–	–	–	[20]
Marine unloading	1993–98	32	0.51	–	0.023	3.7	2	0.7	–	0.23	1.2	[20]
Jetty staff	1993–98	46	0.37	–	0.023	1.7	24	0.79	–	0.23	5.8	[20]
Rail car terminal operators (top loading with VR)	1999–01	21	0.5	0.4	0.2 ^c	0.7 ^c	3	0.5	–	0.5	0.5	[22]
Road tanker distribution												
Terminal supervisors	1993–98	151	0.36	–	0.001	3.1	8	2.20	–	0.23	11.2	[20]
Drivers, bottom loading & VR	1999–01	33	0.6	0.4	0.2 ^c	1.2 ^c	15	1.8	1.4	0.5 ^c	3.8 ^c	[22]
Drivers, delivery	1999–01	–	–	–	–	–	7	0.7	0.4	0.2 ^c	1.6 ^c	[22]
Service station												
Attendants	1999–00	78	0.102	–	0.0115	0.478	–	–	–	–	–	[28]
Cashiers	1993–98	268	0.05	–	0.001	1.92	–	–	–	–	–	[20]
Miscellaneous workers	1999–01	6	0.2	0.1	0.1 ^c	0.2 ^c	–	–	–	–	–	[22]
Gasoline pump maintenance	1993–98	2	0.55	–	0.16	0.93	6	3.8	–	0.19	11.8 ^d	[20]
Coke oven industry												
Coke plant	1994–95	19	0.13 ^e	–	ND ^f	1.76 ^f	–	–	–	–	–	[31]
Coke plant	1994–95	17	1.79 ^e	–	0.52 ^f	23.82 ^f	–	–	–	–	–	[31]
By-product plant	1994–95	21	1.17 ^e	–	0.20 ^f	5.30 ^f	–	–	–	–	–	[31]
Motor mechanics												
	1994–98	243	0.362		<0.005	13.0	8	10.15 ^g	–	1.2	46	[31,34–36]
	1981	–	–	–	–	–	–	0.52	–	0.33	1.50	[19]

Table 1 (Continued)

Occupational group/area	Year	Long-term exposure levels (mg/m ³)					Short-term exposure levels (mg/m ³)					Reference
		N	AM	GM	Min	Max	N	AM	GM	Min	Max	
Aviation												
Civilian airport operators	1993–98	10	0.10	–	0.008	0.60	–	–	–	–	–	[20]
Military fuel maintenance workers	2003	114	0.252 ^e	–	0.006	6.63	–	–	–	–	–	[37]
Military fuel handling, distribution, recovery & testing workers	2003	38	0.007 ^e	–	0.001	1.85	–	–	–	–	–	[37]
Firefighters	1991–02	43	–	–	<0.37 ^h	6.14 ^h	22 ⁱ 96 ^j	– 1.24	–	<LOD 0.228	68.25 6.468	[40,42] [41]
Urban workers												
Traffic police/wardens	1994–00	236	0.020	–	0.009	0.316	–	–	–	–	–	[28,44,45]
Bus drivers	1998–00	152	0.0238	–	0.003	0.092	–	–	–	–	–	[28]
Office workers	1994–00	289	0.016	–	0.002	0.115	–	–	–	–	–	[28,43–45]

AM, arithmetic mean; GM, geometric mean; Max, maximum; Min, minimum; N, number of samples; VR, vapour recovery.

^a When selecting typical benzene exposure values, preference has been given to studies published within the previous 10 years and for which greater than 10 subjects were sampled. Where appropriate, datasets have been combined to give an overall mean exposure.

^b Data for which an arithmetic mean was available.

^c 10th and 90th percentile values.

^d The mean was strongly influenced by one high exposure level of 46 mg/m³, if this is excluded the mean exposure is 5.03 mg/m³ (range:1.2–14.0 mg/m³).

^e Median value.

^f 5th and 95th percentile values.

^g Small spillage associated with the highest result.

^h Exposure estimated from biological monitoring.

ⁱ Exposure during the knockdown phase of fire fighting.

^j Exposure during the overhaul phase of fire fighting.

although the variable nature of the job means that higher exposures may occasionally be experienced when containment is broken, e.g. during shutdown and cleaning procedures. For example, exposure data for the period 1986–1992 suggested that such short-term exposures were high, with mean exposures of 153.5 mg/m^3 (range: $22.43\text{--}656.5 \text{ mg/m}^3$) for periods of 67–265 min. However, more recent data, although limited, suggests such exposures are now lower (Table 1).

Laboratory workers are also exposed to benzene in refineries while carrying out quality control and research tests. Exposures over a full-shift are generally low, typically around 0.30 mg/m^3 [20], although recent data suggest that for specific tasks, such as the blending of test gasoline, higher full-shift mean exposures in the region of 3.7 mg/m^3 (10th and 90th percentiles: $0.2\text{--}8.3 \text{ mg/m}^3$) may be experienced [22].

5.2. Marine and rail car loading

Loading of ships and barges can result in exposure to benzene of jetty staff involved in the supervision of ship-loading operations, deck crew, and bridge crew located on the ship/barge during loading. Intermittent high exposures have been measured for jetty staff and deck crew during open loading, which allows displaced vapors to be vented close to deck level. Open loading has now been discontinued in favour of closed loading, during which displaced vapors are vented remotely. This has resulted in much lower exposures to jetty staff and deck crew. During unloading, deck crew exposures are low with reported mean full-shift exposures of 0.51 mg/m^3 (range: $0.023\text{--}3.7 \text{ mg/m}^3$) [23].

Rail car loading is another activity with a high potential for exposure to elevated levels of benzene as a result of the displacement of vapours from the rail car. An early survey identified 8-h TWA exposures as high as 45 mg/m^3 for a rail car weigher and $3.58\text{--}4.23 \text{ mg/m}^3$ for rail car loaders [24]. By the early 1980s mean 8-h TWA exposures had declined to $1.63\text{--}4.55 \text{ mg/m}^3$, although the range ($0.33\text{--}40.43 \text{ mg/m}^3$) indicates some high exposures still occurred [19]. The introduction of vapor recovery has further reduced exposures; a recent survey of rail car loaders indicated mean full-shift exposures were 0.5 mg/m^3 (10th and 90th percentiles: $0.2\text{--}0.7 \text{ mg/m}^3$) [22]. Bottom loading with vapor recovery is reported to be replacing top loading, and is

expected to result in still lower exposures [18], although no published data for bottom loading were identified.

5.3. Road tanker distribution

Road tanker distribution terminals are a source of benzene exposure for several job groups. Rack operators used to be responsible for loading road tankers and were exposed to moderate levels of benzene (e.g. mean 8-h TWA: 1.93 mg/m^3 , range: $<0.16\text{--}61.43 \text{ mg/m}^3$), but this job has been discontinued and drivers now load their own tankers [20,23]. Supervisors may be intermittently exposed while dealing with any problems, and by being in the vicinity of loading. However, mean full-shift exposures are low, averaging 0.36 mg/m^3 (range: $0.001\text{--}3.1 \text{ mg/m}^3$) [20].

Road tanker drivers are exposed to benzene during the loading and unloading of gasoline from tankers. In the past 10–15 years a number of changes to working practices have been implemented, partly as a result of EU Directive 94/63/EC, which was required to be implemented by 2004 [25]. These changes included a move from top loading, where the vehicle is filled through open hatches on top of the vehicle, to bottom loading, where tanker compartments are filled through hose connections to manifolds on the vehicle near the ground, and the introduction of Stage I vapor recovery systems at terminals and service stations. The corresponding reductions in exposure as a result of these changes are illustrated in Table 2.

Saarinén et al. [26] also examined the influence of installing vapor recovery systems in reducing benzene exposures and observed that mean short-term exposures were reduced from 0.41 mg/m^3 (range: $<0.1\text{--}2.1 \text{ mg/m}^3$) to 0.13 mg/m^3 (range: $<0.1\text{--}0.3 \text{ mg/m}^3$). Other important determinants of truck driver exposure include wind speed and air temperature. In one study, wind speed and air temperature were shown to account for 94% of the day-to-day fluctuations in benzene exposures of road tanker drivers. The authors suggested that the results indicated that exposure during bottom loading occurred mainly through evaporation of gasoline from the ground [27].

5.4. Service station attendants, cashiers and workers

Service station attendants can be exposed to low-levels of benzene during the filling of customers'

Table 2

The reduction in benzene exposure of road tanker drivers

	Benzene exposure (mg/m ³)	
	Full-shift exposures	Short-term exposures
Top loading, without VR	1.25 (range: 0.04–48.2)	8.26 (range: 0.03–186.6)
Bottom loading, without VR	0.82 (range: 0.01–15.0)	2.55 (range: 0.02–30.6)
Bottom loading, with VR	0.37 (range: 0.03–1.99)	1.40 (range: 0.08–17.5)

VR, vapour recovery. Adapted from [19,20,23].

vehicles and from ambient air concentrations of benzene. Extensive sampling has shown that exposures are low, with a recent survey in Italy reporting mean full-shift exposures of 0.102 mg/m³ (range: 0.012–0.478 mg/m³) [28]. Ambient temperature has been shown to significantly influence exposures of attendants, with higher exposures experienced at higher ambient temperatures [29]. The use of Stage II vapour recovery on gasoline pumps may reduce exposures of benzene; available data have shown a reduction in exposure from 0.3 mg/m³ (10th and 90th percentiles: 0.2–0.5 mg/m³) to 0.1 mg/m³ (10th and 90th percentiles: 0.1 mg/m³) [22], although it has been noted that minor spills occur more frequently with the use of Stage II recovery pumps [30]. Like service station attendants, service station cashiers and miscellaneous workers are similarly exposed to low-levels of benzene (Table 1).

6. Coke oven industry

The carbonisation of coal to form coke (which is used to make pig iron for steel manufacture) can result in benzene exposure from the crude coke fractions and their refining to produce benzene and other chemicals (a process which is similar to petroleum refining), all of which are known as by-products [1]. Median full-shift exposures to benzene in several European coke plants have been reported as 0.13 mg/m³ (5th and 95th percentiles <LOD–0.46 mg/m³) and 1.79 mg/m³ (5th and 95th percentiles 0.52–23.82 mg/m³), and in a by-product plant as 1.17 mg/m³ (5th and 95th percentiles 0.20–5.30 mg/m³) [31]. These exposure levels contrast with those from coke ovens in the early 1980s, reported by Runion and Scott [32]; all the TWAs of over 2000 employees were below 1.63 mg/m³.

7. Vehicle mechanics

Vehicle mechanics are exposed to low levels of benzene as a result of working with gasoline engines and from exposure to vehicle exhaust. Mean full-shift exposure levels range from 0.03 to 2.6 mg/m³ and short-term task specific exposure levels range from 0.33 to 15.28 mg/m³ [19,31,33–36]. Specific tasks associated with elevated short-term and full-shift benzene exposure levels include: working on fuel injection systems, draining and cleaning gasoline tanks, dismantling/renewing cylinder blocks/heads, carburetor adjustment and renewal, and replacing fuel pipes, filters, pumps and valves [34,35]. Benzene exposures have also been found to be higher in smaller garages and during winter (when garage doors are kept closed), as a result of reduced ventilation [34].

8. Aviation industry

Civilian airport operators may encounter exposure to benzene while carrying out over-wing refuelling of light aircraft with aviation gasoline (Table 1). However, relatively little aviation gasoline is used in large European airports (where the kerosene based Jet A1 is the main fuel) [20], thus the number of personnel exposed is likely to be small.

Among military personnel, exposure to benzene from JP-8 jet fuel has been studied extensively. The highest exposures occur amongst fuel maintenance (median full-shift exposures: 0.252 mg/m³) [37] and aircraft maintenance workers (mean TWA: 0.022 mg/m³) [38]. Over the past 20 years JP-8 has largely replaced JP-4 (a gasoline based jet fuel) and this has led to significantly lower benzene exposures (e.g. aircraft maintenance worker mean TWA exposure has decreased from 0.57 mg/m³) [38]. Peak exposures

generally occur during fuel tank repair, which requires worker entry into the fuel tank; mean short-term exposures of 9.71 mg/m^3 have been recorded [39]. The contribution of benzene exposure from smoking has been shown to outweigh that from fuel maintenance activities [39].

9. Firefighters

Firefighters can encounter benzene exposure both during the knockdown phase (where the main body of the fire is brought under control) and during overhaul (which involves searching for and extinguishing hidden fires). During the knockdown phase benzene exposure levels have been measured in the range of $<\text{LOD}$ – 68.25 mg/m^3 and it has been suggested that benzene is predominantly present in the later stages of knockdown, when firefighters are more likely to remove self-contained breathing apparatus [40]. During overhaul (which typically lasts 30 min) benzene exposure levels are lower; one recent study found short-term mean exposures to be 1.25 mg/m^3 (range: 0.23 – 6.46 mg/m^3) [41]. Biological monitoring of *t,t*-muconic acid has been used to assess total exposure. Biomarker levels were found to be low, with $<50\%$ of the study population of 43 firefighters having detectable biomarker levels, and only six samples exceeding 1.1 mmol/mol creatinine (equivalent to an 8-h TWA of about 3.25 mg/m^3); the highest was 2.8 mmol/mol creatinine (equivalent to an 8-h TWA of about 6.1 mg/m^3) [42]. Firefighters can also be exposed to benzene whilst tackling wildland fires, although 12-h TWAs are low, ranging from $<\text{LOD}$ to 1.625 mg/m^3 [1].

10. Workers in urban environments

Workers in urban environments are exposed to benzene from automobile exhaust emissions and evaporative gasoline emissions. Measured mean exposure levels are low, ranging from 0.004 to 0.029 mg/m^3 for office workers [43,44] to 0.024 mg/m^3 for bus drivers [28] and 0.009 to 0.053 mg/m^3 for traffic police [44,45]. Shift exposure to benzene has been shown to account for only a small fraction of the total variance in benzene biomarker levels, whereas tobacco smoke con-

tributes significantly to benzene biomarker levels [44]. For example, it has been estimated that a worst case scenario of an urban smoker working adjacent to a busy road for 8 h per day (e.g. a maintenance worker) would receive an average daily exposure of approximately 814 – $819 \text{ } \mu\text{g/day}$ (equivalent to an estimated exposure of 0.04 mg/m^3) of which 49% would be derived from smoking [46].

11. Other occupationally exposed groups

Very few published data are available regarding recent benzene exposures in the chemical industry, despite it being a principal user of benzene. Production processes are generally closed [1], and so the potential for benzene exposure is thought to be limited. Median exposures in surveys in three European chemical manufacturing plants in the early 1990s were 0.65 , 1.26 and 17 mg/m^3 , but it was not reported whether these measurements were representative of routine operations [3].

Benzene exposure has been studied in several other occupational groups. Officials involved in the checking of gasoline pump dispensing volume can be exposed to low levels of benzene; 8-h TWA exposures of 0.4 – 0.65 mg/m^3 have been reported [34,47]. Short-term exposures of coast guard personnel inspecting commercial barges carrying gasoline were in the range of <0.33 – 1.63 mg/m^3 [48]. Limited data has been reported for workers involved in an oil refinery land reclamation operation; full-shift mean exposures were 0.033 – 0.195 mg/m^3 , and short-term exposures ranged from 0.52 to 2.63 mg/m^3 [30]. Mean full-shift benzene exposures of forestry workers from the refuelling and exhaust of gasoline driven chain saws has been found to be between 0.52 and 2.1 mg/m^3 [20]. Benzene exposure can also occur during hot wiring in the meat packaging industry; typical full-shift exposures of 0.07 – 0.13 mg/m^3 have been reported and these have been confirmed through biological monitoring [49]. Other exposed groups may include workers in the hospitality industry exposed via environmental tobacco smoke, although exposure is expected to be low.

Historically, benzene exposure in Europe and North America has also been a concern in industries such as printing, shoe manufacture, and in rubber and tyre manufacture where it was used as a solvent for rubber, inks,

glues and paint removers. However, changes in work practices, such as switching to non-benzene containing substitutes (e.g. to toluene based inks in printing in the 1950s–1960s [50]), has led to these uses becoming minimal in most of the developed world [11], although such exposures are still a concern in developing countries [51,52].

12. Conclusions

Over the past 25 years benzene exposure limits have been extensively revised and reduced to the point that currently most developed countries have full-shift exposure limits in the range of 1.625–3.25 mg/m³ (0.5–1.0 ppm). Similarly, benzene exposures have declined to the point that most occupational groups experience exposures of less than 3.25 mg/m³ (1 ppm), although occasional higher exposures occur in some occupational groups, warranting sustained efforts to continue to reduce exposures.

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