



SCOEL/REC/386

Chromium VI compounds

Recommendation from the
Scientific Committee on Occupational Exposure Limits



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The present Recommendation was adopted by SCOEL on 22-05-2017



EUROPEAN COMMISSION

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SCOEL/REC/386

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**RECOMMENDATION FROM THE
SCIENTIFIC COMMITTEE ON OCCUPATIONAL
EXPOSURE LIMITS
FOR CHROMIUM VI COMPOUNDS**

8-hour TWA:	See Table on page 9 in Recommendations and Summary
STEL:	None recommended
BLV:	None
Additional categorisation:	Carcinogen group A (genotoxic carcinogen without a threshold)
Notation:	Sensitisation (respiratory and dermal) No skin notation

The present Recommendation was adopted by SCOEL on 22-05-2017.

RECOMMENDATION EXECUTIVE SUMMARY

Outcome Considerations

The critical effect of the occupational inhalation of hexavalent chromium (CrVI) -containing compounds is lung cancer. In addition, occupational exposure can lead to nephrotoxicity, hypersensitivity (sensitization), corrosion of the skin, irritation of the respiratory tract and gastrointestinal tract.

Cr VI compounds have been classified as a carcinogen, in Category 1 based on both humans and animal data by IARC. Most Cr VI compounds are classified by the European Union in Category 1B (*substance presumed to be carcinogenic to humans*). The exceptions are chromium trioxide, zinc chromate and zinc potassium chromate which are classified in Category 1A (*substance known to be carcinogenic to humans*).

Reevaluation of the information on the mode of action underlying carcinogenicity has resulted in the conclusion that in case of CrVI the formation of ternary DNA adducts are relevant. These DNA lesions are not easily repaired and eventually may lead to the outgrowth of repair-deficient cell clones exerting genomic instability. Thus, Cr VI acts as a directly genotoxic carcinogen for which no threshold can be assumed and for which, linear extrapolation is commonly applied by SCOEL in this situation if the available data permits.

Derived Limit Values

Several epidemiological studies, from a number of countries including Germany, the UK and the USA have shown that an excess lung cancer risk exists after occupational Cr VI exposure (Birk et al., 2006; Frentzel-Beyme, 1983; Gibb, et al., 2000; Luippold et al., 2003; Luippold et al., 2005; Mancuso, 1997; Park et al., 2004; Sorahan et al., 1998; Sorahan et al., 1987). Excess lung cancer risk is observed in populations with occupational exposure to both soluble and poorly soluble Cr VI compounds (Steenland et al., 1996). The available human evidence on risk differences between soluble and poorly soluble chromium compounds does not allow a distinction in risk which can be used in risk assessments. Since the late 1990-ies, no new animal experiments have been conducted and published and several reviews of these studies have been published (IARC, 1990, 2012; Levy et al., 1986; NTP, 2008). Animal experiments show that a number of Cr VI compounds are carcinogenic because they induce tumours in the lung after repeated inhalation (Adachi, 1987; Adachi et al., 1986; Glaser et al., 1985; Glaser et al., 1986; Nettesheim et al., 1971), and intracheal and intrabronchial administration (Steinhoff et al., 1986). Animal experiments indicate that differences exist in the carcinogenic potential of the different Cr VI compounds, which are probably related to solubility and the resulting bio-availability. However, variation in experimental designs of the animal studies and lack of complete and reliable data on poorly soluble Cr VI compounds do not allow a differentiation on the role of solubility in relation to carcinogenic potency on the basis of animal experiments (DECOS, 2016; IARC, 1990, 2012; SCOEL, 2004). Also, with regard to mechanistic studies, no distinction can be made between the genotoxicity of poorly soluble and soluble Cr VI compounds.

Therefore, no distinction can reliably be made in the risk assessment between soluble and poorly soluble Cr VI compounds.

A limited number of the epidemiological studies have described quantitative exposure response relations that can be utilised for risk assessment purposes. Recently, these studies have been evaluated by Seidler and others (Seidler et al., 2013). They performed a systematic review for studies with quantitative exposure response relations for Cr VI. Studies which had more than one chromium exposure category and were adjusted for smoking habits were selected. Studies were reviewed for quality using the SIGN (Scottish Intercollegiate Guidelines Network) approach. Only high quality studies (Sign scores ++) were considered to assess a meta- exposure response relation. Exposure response relations were obtained by fitting linear models to the data using least square statistics weighted by persons' years in each exposure category. Five studies, originating from two USA cohorts were selected. One study, which estimated Cr VI exposure on the basis of biomonitoring data, was not selected because of the uncertainties resulting from the exposure estimation process (Birk et al., 2006). Urinary chromium measurements cannot distinguish between chromium III and VI exposure because inhaled Cr VI is reduced to chromium III in the human body.

Excess risk was calculated using the exposure response relationships from the last updates of the two cohort studies. Excess risk was calculated for a 40 year exposure period from age 20-60 and a latency period of 10 years. Calculation were made using a lifetable analysis using European lung cancer and total mortality data obtained from all EU countries for males and females. For the calculations, a lifetable analysis was conducted as described by Goldbohm et al., (2006), till all members were deceased. Risk assessments using lifetable analysis take into account other causes of mortality in human populations. The following risk estimates were produced for the combined studies (with confidence interval based on the the s.e.'s of the exposure response slope), together with the points estimates for the individual studies used:

Exposure 8 hour time weighted average	Number of excess lung cancer cases / 1000			
	Point estimate combined exposure response slopes	Confidence interval	(Crump et al., 2003)	(Park et al., 2004)
0.1 µg/m ³	0.4	0.3-0.5	0.2	0.6
1 µg/m ³	4	3.2-4.8	2	6
5 µg/m ³	20	16-24	8	32
10 µg/m ³	39	31-47	15	62
25 µg/m ³	94	76-112	38	146

Exposure at which risk benchmarks of 4/1000 and 4/100 000 are realized, are similar to the exposure estimates which have recently been published by other organisations and researchers. These benchmarks are in some countries considered as 'acceptable' and 'negligible' risk levels respectively. Although the exposure which corresponds with these risks are similar, differences exist in the approaches taken to calculate these exposure estimates (AGS, 2014; DECOS, 2016; Seidler et al., 2013) The differences relate to a) methodology to estimate risk, b) age at which the risk is estimated, c) use of average male and female rates instead of male rates only. The different combinations of assumptions lead in the end to similar estimates as produced by the different sources. SCOEL believe it is essential that the exposure response relationship should be based on those studies that provide the most reliable exposure response and that the lifetime risk should be calculated on the basis of a lifetable analysis, which gives the most accurate and precise estimate of the risk.

Notations

Skin notation

Substantial dermal uptake of Cr VI is not anticipated and therefore a skin notation is not recommended.

Sensitisation notation, dermal and respiratory

Cr VI compounds show a strong potential for sensitisation following exposure both dermal and respiratory.

A notation should therefore be added: '**sensitisation dermal and respiratory**'

Skin sensitisation resulting from exposure to hexavalent compounds has been demonstrated in patch-testing studies of contact dermatitis patients and in various chromate-exposed occupational groups (Sun, 1984; Samoen et al, 1984; Fregert et al, 1970; Engel & Calnan, 1963). Cr VI-sensitised subjects may react to trivalent chromium compounds although the latter are less able to penetrate the skin and thus have a lower skin sensitising potential (Fregert & Rorsman, 1964; Samitz & Shrager, 1966). Available case reports, together with supporting evidence from bronchial challenge tests, show that inhaling Cr VI compounds can induce occupational asthma (Park et al, 1994). As with skin sensitisation, Cr VI-sensitised subjects may react following exposure by inhalation to trivalent chromium compounds.

Biological Monitoring

Methods are available for the biomonitoring of Cr VI. However, Cr VI will be reduced in the human body, to trivalent chromium in urine; thus when there is co-exposure to chromium III compounds it will be difficult to know what proportion came from the hexavalent and trivalent compounds. In such cases, speciation of the inhaled exposure is important in order to interpret biomonitoring data.

RECOMMENDATION FROM THE SCIENTIFIC COMMITTEE ON OCCUPATIONAL EXPOSURE LIMITS FOR CHROMIUM VI COMPOUNDS

RECOMMENDATION REPORT

1. CHEMICAL AGENT IDENTIFICATION AND PHYSICO-CHEMICAL PROPERTIES

Cr VI compounds are one of a number of oxidation states in which chromium occurs. Chromates and dichromates exist as a wide variety of compounds with 20 to 30 being of major industrial importance. These include, ammonium chromate and dichromate, barium chromate, calcium chromate and dihydrate, chromic chromate, chromium (IV) chloride, chromium trioxide (chromic acid), chromyl chloride, lead chromates, molybdenum orange ($\text{PbCrO}_4\text{PbMoO}_4\text{Pb}\cdot\text{SO}_4\text{Al}_2\text{O}_3$), potassium chromate and dichromate, sodium chromate and dichromate and zinc chromates. The solubility of chromates varies widely and ranges from virtually insoluble to highly soluble. The various uses of the term "solubility" have caused much confusion and to harmonize discussions and classification it has been proposed that the water solubility of Cr VI compounds can be defined as: poorly soluble (<1g/l), sparingly soluble (1-10g/l); highly soluble (>100g/l)(Cross et al., 1997). Thus, poorly soluble includes lead and barium chromate, sparingly soluble includes strontium, calcium and zinc chromate and highly soluble would include sodium and potassium chromates and dichromate.

Table 1: Basic descriptive information on some widely used Cr VI compounds (based on (AGS, 2014; DECOS, 2016; IARC, 1990 and various ECHA documents))

Substance	CAS No.	EC No.	Molecular Formula		Solubility in water (mg/l)
Lead sulfochromate yellow (C.I. Pigment Yellow 34)	1344-37-2	215-693-7	$\text{Pb}(\text{Cr,S})\text{O}_4$ Mixture containing (PbCrO_4) and (PbSO_4)		See data of lead chromate (major component)
Lead chromate	7758-97-6	231-846-0	PbCrO_4		0.058mg/L (25°C)
Lead chromate molybdate sulphate red (C.I. Pigment Red 104)	12656-85-8	235-759-9	$\text{Pb}(\text{Cr,S,Mo})\text{O}_4$ variable solid mixed phase crystal which contains lead chromate, lead sulfate and lead molybdate in varying proportions		See data of lead chromate (major component)
Acids generated from chromium trioxide and their oligomers. Names of the acids and their oligomers: Chromic acid, Dichromic acid, Oligomers of chromic acid and dichromic acid	7738-94-5 13530-68-2	231-801-5 236-881-5			
Ammonium chromate	7788-98-9	232-138-4	$(\text{NH}_4)_2\text{CrO}_4$		405g/L (30°C)

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Substance	CAS No.	EC No.	Molecular Formula		Solubility in water (mg/l)
Ammonium dichromate	7789-09-5	231-143-1	(NH ₄) ₂ Cr ₂ O ₇		308 g/L (15°C)
Barium chromate	10294-40-3	233-660-5	BaCrO ₄		4.4mg/L (28°C)
Chromium trioxide	1333-82-0	215-607-8	CrO ₃		625g/L (20°C)
Potassium chromate	7789-00-6	232-140-5	K ₂ CrO ₄		49g/L (0°C) 793g/L (100°C)
Potassium dichromate	7778-50-9	234-190-3	K ₂ Cr ₂ O ₇		49g/L (0°C) 1020g/L (100°C)
Sodium chromate	7775-11-3	231-889-5	Na ₂ CrO ₄		873g/L (30°C)
Sodium dichromate dihydrate	7789-12-0 10588-01-9	234-190-3	Na ₂ Cr ₂ O ₇ ·2H ₂ O		2300-2380g/L (0°C)
Pentazinc chromate octahydroxide	49663-84-5	256-418-0	Zn ₅ (CrO ₄)(OH) ₈		< 0.02 g/L at 20°C
Dichromium tris(chromate)	24613-89-6	246-356-2	Cr ₂ (CrO ₄) ₃		
Potassium hydroxyocataoxodizincatedichromate	11103-86-9	234-329-8			
Strontium chromate	7789-06-2	232-142-6	SrCrO ₄		1.2g/L(0) 30g/L(100)
Calcium Chromate	13765-19-0	237-366-8	CaCrO ₄		163g/L (20°C)

2. EU HARMONISED CLASSIFICATION AND LABELLING

Information about the EU harmonised classification and labelling for Cr VI compounds is provided by ECHA (2017) in their Classification and Labelling Inventory database. Whether compounds contain Cr VI is not always obvious purely from their name. Three strings indicating three 'groups' of chemicals containing Cr VI were found: "chromate", "chromium", "chromyl".

Using the search string "chromate", "chromium" and "chromyl", the number of entries found in the C&L Inventory was respectively 33, 5 and 1.

A tabulated overview of classification and skin sensitisation is provided in the table below.

Table 2: Classification of many Cr VI compounds according to CLP [Regulation \(EC\) No 1272/2008](#), Annex VI, Table 3.1 "List of harmonised classification and labelling of hazardous substances" with respect to carcinogenicity and skin sensitisation (ECHA, 2017)

Index no.	CAS no.	EC / List no.	EC / List name	IUPAC Name
various	various	various	various	various
Classification				
Hazard Class & Category Codes			Hazard Statement Codes	
Skin sens. 1			H317	
Muta. 1B			H340	
Carc. 1A or Carc. 1B			H350	

3. CHEMICAL AGENT AND SCOPE OF LEGISLATION

Cr VI compounds are hazardous chemical agents in accordance with Article 2 (b) of Directive 98/24/EC and fall within the scope of this legislation.

Cr VI compounds are also carcinogens or mutagens for humans in accordance with Article 2(a) and (b) of Directive 2004/37/EC and fall within the scope of this legislation.

Although many exposures have been ceased or keep decreasing, a subset of Cr VI compounds (out of over 100) are listed in Annex XIV of the REACH Regulation (authorisation list) and so are, or will be, subject to 'authorisation' for continued use in the EU for a certain period, most of them being chromates and dichromates (ECHA, 2016).

In addition, two other pieces of EU legislation apply to Cr VI with special reference to restricting its occurrence in cement and leather products:

- COMMISSION REGULATION (EU) No 301/2014 of 25 March 2014 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards Cr VI compounds (Text with EEA relevance).
- DIRECTIVE 2003/53/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 June 2003 amending for the 26th time Council Directive 76/769/EEC relating to restrictions on the marketing and use of certain dangerous substances and preparations (nonylphenol, nonylphenol ethoxylate and cement) (Text with EEA relevance).

Regarding the restriction in cement which took effect in 2005, there are already study results demonstrating significant reduction by almost half in the occurrence of occupational allergic contact dermatitis (OACD) attributed to Cr VI in cement observed in two distinct occupational surveillance schemes in France and the UK (Bensefa-Colas, et al. 2016).

4. EXISTING OCCUPATIONAL EXPOSURE LIMITS

Several Cr VI compounds have been classified as carcinogen by many regulatory authorities. In the EU CLP [Regulation \(EC\) No 1272/2008](#) they are classified as genotoxic (Muta. 1B) and as carcinogen (Carc. 1B or 1A); see chapter 2. Also, the German DFG categorized Cr VI compounds (respirable fraction) as carcinogenic substance in Category 1 (meaning a genotoxic mechanism of action is likely or cannot be excluded). Because of this, DFG does not recommend specific exposure limits. In contrast, in various EU Member States as well as outside the EU, OEL's are established. These OEL's are presented in Table 4 as examples and the list should not be considered as exhaustive.

For biomonitoring Cr VI using urine samples, it is important to recognise that all Cr VI ends up in urine as Cr III due to reduction whether workers inhale III, VI or a mixture of both. In other biological matrices however such as blood or exhaled breath condensate, both Cr VI and Cr III occur. They can be speciated using ion chromatography and subsequently quantified using ICP-MS (see chapter 6.2).

BLVs (Biological Limit Value) have not been adopted for Cr VI compounds at the EU level nor in the US (EU SCOEL, Germany DFG, USA OSHA and NIOSH). In the EU, only the Spanish authorities set a BLV for Cr VI (INSHT, 2016). The values were 'total chromium concentration increase in urine during one shift' 10 µg/L and 'total chromium at the end of the workweek' 25 µg/L. In addition, in the UK, a biological monitoring guidance value (BMGV) of 10 µmol/mol creatinine in post shift urine was established (HSE, 2011). In Germany, in line with the absence of an OEL (MAK), no BLV (German BGW) was established. Instead, in order to help interpretation of occupational biomonitoring results, DFG did set a BAR (Biologischer Arbeitsstoff-Referenzwert) for the general (not occupationally-exposed) population of working age of 0.6 µg/L urine for Cr VI compounds

(inhalable fraction) (DFG, 2012). DFG further established the DFG-EKA values (biological exposure equivalents for carcinogenic substances) for Cr VI (DFG, 2015). For an overview of these biological values see table 3a and 3b.

Table 3a: Biological exposure equivalents for Cr VI (DFG, 2015)

Air (CrO ₃ (mg/m ³))	Sampling time : long-term exposure : after several shifts Erythrocyte fraction of whole blood * Chromium (µg/l whole blood)	Sampling time : end of exposure or end of shift urine ** Chromium (µg/l)
0.03	9	12
0.05	17	20
0.08	25	30
0.10	35	40

*not applicable for exposure to welding fumes

**also applicable for exposure to welding fumes

Table 3b: Biomonitoring values for Cr VI*

Term	Biomonitoring values	Country	Reference
BLV	total chromium increase in urine <ul style="list-style-type: none"> during one shift 10 µg/L at the end of the workweek 25 µg/L 	Spain	(INSHT, 2016)
BLV	end of week 2.5 µg/L (1.8 µg/g of creatinine)	France	(ANSES, 2017)
VBR	0.65 µg/L or 0.54 µg/g of creatinine		
BAR	0.6 µg/L urine**	Germany	(DFG, 2012)
BMGV	10 µmol/mol creatinine in urine (post shift)	UK	(HSE, 2011)
BEI	total chromium in urine <ul style="list-style-type: none"> end of shift at end of workweek 25 µg/L increase during shift 10µg/L 	USA	(ACGIH, 2011)
BAT	11 µg/l (212 nmol/l) urine	Switzerland	(SUVA, 2016)

* BAR = (Biologischer-Arbeitsstoff Referenzwert) Biological Reference Value; i.e. the background level of a substance in biological material in a reference population of persons of working age not occupationally exposed to this substance; BARs are based on the 95th percentile without regarding effects on health; BAT = (Biologische Arbeitstoftoleranzwerte) biological occupational chemical tolerance level; BMGV = biological monitoring guidance value; BEI = Biological Exposure Index; VBR = 'Valeur Biologique de Reference'='Biological Reference Value'.

** Total chromium

Table 4: Overview of existing OELs for Cr VI compounds as Cr in EU Member States and elsewhere¹

	TWA (8 hrs)	STEL (15 min)	Remarks	Refs
	mg/m ³	mg/m ³		
EU-Countries				
Austria	0.1 (arc welding with coated rod electrodes, production of soluble Cr VI compounds) 0.05 (otherwise)	0.4 (arc welding with coated rod electrodes, production of soluble Cr VI compounds) 0.2 (otherwise)	TMW and KZW (both TRK); inhalable aerosol	(GKV, 2011)
Belgium	0.05 0.01	-	All soluble Cr VI compounds All insoluble Cr VI compounds	(KB, 2002)
Denmark	0.005 (7738-94-5 Chromsyre og chromater. beregnet som Cr 0.0005 (7789-06-2 Strontiumchromat. beregnet som Cr			(DWEA, 2011)
Finland	0.005	-		(MSAH, 2012)
France	0.001	0.005	VME; VLE	(INRS, 2012)
Germany	0.001	-	Tolerance value	(BAuA, 2014)
Hungary	-	0.05	Cr VI inorganic compounds	(MHSFA, 2000)
Ireland	0.05 (Water soluble); 0.01 (Insoluble); 0.001 (calcium chromate CAS nr 237-366-8)	-	Cr VI compounds (as Cr)	(HSA, 2016)
The Netherlands	0.01 0.05	0.05	Applies for soluble compounds Poorly soluble chromium compounds	(STSCR, 2014)
Spain	0.05 (Cr VI insoluble compounds) 0.01 (Cr VI soluble compounds) 0.001 (Calcium chromate) 0.0005 (Strontium chromate) 0.012 (Lead chromate)	-		(INSHT, 2016)
Sweden	0.005	0.015	LLV; STV Total aerosol	(SWEA, 2015)
United Kingdom	0.05	-	Cr VI compounds (as Cr)	(HSE, 2011)

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	TWA (8 hrs)	STEL (15 min)	Remarks	Refs
	mg/m ³	mg/m ³		
Non-EU Countries				
Australia	0.05	-	Certain water insoluble. water soluble	(SWA, 2013)
Canada (Ontario)	0.05 (Water soluble) 0.01 (Insoluble)	-	Cr VI compounds	(OML, 2015)
Canada (Québec)	0.05 (soluble) 0.01 (insoluble)	-	TWAEV Inorganic compounds	(IRSST, 2010)
Japan	0.05	-		(JSOH, 2015)
New Zealand	0.05 (soluble) 0.05 (insoluble)	-	as Cr (bio)	(WSNZ, 2016)
Norway	-	-		(NLIA, 2011)
Singapore	0.05 (water soluble) 0.01 (insoluble)	-		(IFA, 2016)
South Korea	0.05 (water soluble) 0.01 (insoluble)	-		(IFA, 2016)
Switzerland	0.05	-	MAK; inhalable aerosol	(SUVA, 2016)
USA (NIOSH)	0.0002	-	REL (8 hr TWA);	(OSHA, 2017)
USA (Cal OSHA)	0.005	0.1	PEL (TWA respective ceiling value)	(OSHA, 2017)

¹ Abbreviations are explained below

- LLV= Level Limit Value =TWA
- MAK [Maximale Arbeitsplatz Konzentration] = maximum workplace concentration.
- PEL = Permissible Exposure Level (OSHA).
- REL = Recommended Exposure Limit (NIOSH).
- STEL = Short Term Exposure Limit (usually 15 minutes average).
- TMW [Tagesmittelwert] = TWA; KZW [Kurzzeitwert] = STEL.
- TRK [Technische Richtkonzentration] = Technical Guidance Concentration. Used when no 'safe' exposure level can be derived. Value based on technical feasibility.
- TWA = Time-Weighted Average (usually 8 hours average).
- TWAEV = Time-Weighted Average Exposure Value = TWA.
- STV = Short-Term value =STEL
- VME [Valeur Moyenne d'Exposition] = TWA.

5. OCCURRENCE, USE AND OCCUPATIONAL EXPOSURE

Information on sources of human and environmental exposure to chromium is often described in terms of total chromium, because information on speciation is frequently not available. So unless otherwise specified, chromium reflect total chromium.

5.1. Occurrence

Chromium is a relatively common element, occurring naturally in rocks, soil, plants, animals and volcanic dust and gases. The most stable valence states are chromium(0), trivalent chromium (Cr III) and hexavalent chromium (Cr VI). Chromium is chiefly found as the trivalent form in nature, with Cr VI generally produced by industrial processes.(WHO-IPCS-CICAD, 2013)

Hexavalent compounds, with the exception of some small amounts in minerals, do not occur naturally in the environment but are formed from trivalent chromium during chromate-production processes. The starting point for all hexavalent compounds is chromite ore, which contains trivalent chromic oxide and this is oxidised to sodium chromate during kiln roasting in the chromate-producing industry. This is the usual starting material for all other hexavalent compounds. Apart from in the chromate-producing industry, occupational exposure may occur in the production of ferrochromium alloys and chromium metal, production and welding of stainless steels, metal finishing processes (chromium plating) and the manufacture and use of chromium chemicals. These latter include corrosion inhibitors (strontium, calcium, zinc and barium chromates); pigments in paints and in metal primers (lead and zinc chromates and molybdenum orange); wood preservatives (sodium and potassium chromates and chromium trioxide); dye mordants, catalyst and leather tanning (ammonium, sodium and potassium chromate). It should be noted that within the European Community, leather tanneries are known to use basic trivalent chromium sulphate, which contains no measurable Cr VI. However, Cr VI release has been observed in survey which suggests the use of this form of chromium in leather tanneries (Bregnbak et al. 2015). According to the EU Regulation No 301/2014, such Cr VI compounds can be formed in leather through the oxidation of Cr III compounds, which are added in some tanning processes to cross- link the collagen subunits in order to increase leather's dimensional stability, as well as its resistance to mechanical action and heat. According to the ECHA Annex XV dossier, the mechanisms of and conditions under which Cr VI is formed are known and most tanneries in the EU have already developed and widely implemented measures in order to control and minimise its formation.

Some Cr VI is present in cement as a contaminant arising from its manufacture and possibly from the clinker or gypsum constituents, or from the kiln dust during the firing stage which comes from chromium-containing refractories. The hexavalent form is, however, reduced to the trivalent form by the addition of ferrous sulphate, or other agents, to the cement. Additionally, also according to EU Regulation 1907/2006, any cement-containing mixture would have added reducing agents in order to comply with the 2ppm soluble Cr VI limit. The mentioned cement-containing mixtures are usually construction products such as mortar or concrete which, besides cement, contain other constituents that can be natural or artificial. Natural aggregates are not expected to present contents of Cr VI but other kind of materials obtained from industries mentioned before, such as different types of slag, could present a

content of Cr VI that might affect the exposure of construction workers, unless they have been certified to fulfil the same restrictions than cement.

Chromium is released into the atmosphere mainly by anthropogenic stationary point sources, including industrial, commercial and residential fuel combustion via the combustion of natural gas, oil and coal. Another important anthropogenic stationary point source of chromium emissions to the atmosphere is the metal industry.

On a worldwide basis, disposal of chromium-containing commercial products may be the largest contributor to chromium in soil, accounting for approximately 51% of the total chromium released to soil, followed by the disposal of coal fly ash and bottom fly ash from electric utilities and other industries (33.1%), agricultural and food wastes (5.3%), animal wastes (3.9%) and atmospheric fallout (2.4%). Solid wastes from metal manufacturing contributed less than 0.2% to the overall chromium release to soil. Soil emission of Cr VI was reported in 2005 for all three European production sites. At the first site, landfill waste of Cr VI was equivalent to an annual load of 1.7 tonnes of chromium. At site 2, residual solid sodium hydrogen sulfate, which contains approximately 1% chromium(VI) oxide from the production of chromium trioxide, was disposed of via landfill (the content of Cr VI oxide in the waste is regulated). Site 3 had a solid waste treatment plant that received solid waste from the kiln and the sludge from the wastewater treatment plant. Cr VI impurities in the solid waste from this facility were present at a concentration of 8 mg/kg. The solid waste was eventually transported to a waste disposal site.

The general population is exposed to chromium by inhaling ambient air and ingesting food and drinking water containing chromium. Dermal exposure of the general public to chromium can occur from skin contact with certain consumer products that contain chromium, such as certain wood preservatives, cement, or cement-containing mixtures, cleaning materials, dyed textiles and leather tanned with chromium (WHO IPCS CICAD, 2013). In 1984, levels of chromium in ambient air of $<0.01\text{--}0.03\ \mu\text{g}/\text{m}^3$ were reported (Fishbein, 1984) in (WHO-IPCS-CICAD, 2013).

5.2. Production and use information

Sodium chromate and sodium dichromate (both Cr VI compounds) are produced by roasting chromite ore with soda ash. Most other chromium compounds are produced from sodium chromate and sodium dichromate. For example, basic chromic sulfate ($\text{Cr}(\text{OH})\text{SO}_4$), which is a Cr III compound commonly used in tanning, is commercially produced by the reduction of sodium dichromate with organic compounds (e.g. molasses) in the presence of sulfuric acid or by the reduction of dichromate with sulfur dioxide. Lead chromate, commonly used as a pigment, is produced by the reaction of sodium chromate with lead nitrate or by the reaction of lead monoxide with chromic acid solution.

According to the ICDA (International Chromium Development Association; <http://www.icdacr.com>) in 2009, only 2% of the world's production of chromite was used for chromium chemicals. Approximately 638,000 tonnes of sodium dichromate were produced in 2009. The sodium chromate is then converted into a variety of chemicals including sodium dichromate, ammonium and potassium dichromate, chromic acid, chromic oxide and basic chromium sulphate.

According to WHO (WHO IPCS CICAD, 2013) the world production capacity of chromium chemicals in 2008 was 272 000 tonnes as chromium. EU annual production figures in 1997 were 103 000 tonnes for sodium chromate, 110 000 tonnes for sodium dichromate, 32 000 tonnes for chromium trioxide, 1500 tonnes for potassium dichromate and 850 tonnes for ammonium dichromate. Since 2007, all the hexavalent chromates used in the EU are imported and the imports are being reduced.

Chromium compounds are widely used. Major applications reported in 1996 included wood preservation, leather tanning, metals finishing and pigments. Smaller uses are in drilling muds, chemical manufacturing and dye setting on textiles and as catalysts. Many uses are predominantly in the form of Cr III compounds (e.g. leather tanning). The primary uses of Cr VI compounds are in electroplating (chrome plating), the manufacture of dyes and pigments, wood preservatives, surface coatings and corrosion inhibitors. Cr VI has also been used in cooling towers as a rust and corrosion inhibitor (WHO-IPCS-CICAD, 2013).

Recently, the following uses of the main Cr VI compounds were published by the Health Council of the Netherlands (DECOS, 2016).

- *Chromium trioxide*: Metal finishing; for manufacturing of wood preservation products, catalysts, chromium dioxide and pigments
- *Sodium chromate*: Manufacturing of other chromium compounds
- *Sodium dichromate*: Manufacturing of other chromium compounds, wood preservative products, vitamin K and wax; mordant in dyeing; in metal finishing
- *Potassium dichromate*: Manufacturing of pigments, wood preservation products, dyes, catalysts and chromium metal; colouring agent in ceramics
- *Chromic acid*: Production of various chemicals (chromates, oxidizing agents, catalysts); as intermediate in chromium-plating, in ceramic glazes and colored glass.
- *Ammonium chromate*: Sensitizer for gelatine coatings used in photography; in textile printing pastes and fixing chromate dyes on wool; analytical reagent, catalyst, and corrosion inhibitor
- *Ammonium dichromate*: Intermediate and laboratory reagent
- *Calcium chromate*: Pigment, a corrosion inhibitor; in electroplating, photochemical processing, and industrial waste treatment
- *Potassium chromate*: Mordant in dyeing fabrics; tanning agent in the leather industry, in bleach oils and waxes; oxidizing agent in organic synthesis
- *Dichromium tris(chromate)*: Corrosion inhibitor; catalyst in the mordanting of yarns.

According to the Institute of Occupational Medicine (IOM, 2011) an important use of Cr VI is found in wood preservatives, metal coatings, chromium production and catalyst manufacture followed by Montan wax manufacture, vitamin K manufacture and use as a fixative in wool dyeing

5.3. Occupational exposure

Occupational exposure can be to a simultaneous number of different hexavalent compounds, depending on the industry, and in some industries can be further complicated by exposure to both trivalent and hexavalent compounds. The chromate-producing industry is an example of this. Such mixed exposures can make interpretation problematical for both hazard and risk assessment in human studies in relation to individual compounds, especially when exposures are expressed only as total chromium.

Measurement results of occupational exposures to Cr VI compounds have been published for a number of industrial activities and an overview of recent studies is presented in the following table.

Table 5: Overview of exposure levels measured in different industrial sectors

Sector activity	Exposure Information	Ref.
Welding	3659 personal measurements of inhalable Cr VI were collected between 1994 and 2009. Two-thirds of the measurements were below the limit of quantification (LOQ) The 75th percentile value was 5.2 $\mu\text{g}/\text{m}^3$ and the 95th percentile was 57.2 $\mu\text{g}/\text{m}^3$	Pesch, B. et al. 2015
Welding	Personal air sampling and biological monitoring carried out in 53 welders and 20 references. The median exposures to HCr compounds were 0.23, 0.20, and 0.08 $\mu\text{g}/\text{m}^3$, respectively. Median concentrations of TCr in urine, blood plasma and erythrocytes were elevated in all welders, compared with the references.	Scheepers P.T. et al. 2008
Welding	Data sets were analysed. As a main conclusion overexposure to CrVI in stainless steel welding is likely widespread, especially in certain operations such as shielded metal arc welding, which is commonly used in construction. However, exposure could be substantially reduced with proper use of LEV (local exhaust ventilation)..	Meeker J.D. et al. 2010
Electroplating	157 electroplating workers and 93 healthy unexposed controls were recruited. Chromium in erythrocytes was determined by graphite furnace atomic absorption spectrophotometer. The median of short-term exposure concentration of chromium in the air at electroplating workplace was 0.06 mg/m^3 (median) and ranging from 0.01 (detect limit) to 0.53 mg/m^3 . The median concentration of Cr VI in erythrocytes in electroplating workers was 4.41 (2.50 ~ 5.29) $\mu\text{g}/\text{L}$, which was significantly higher than that in control subjects	Zonghua Lao et al. 2012
Aircraft painting	Exposure control systems performance was investigated in an aircraft painting hangar in the UK. All 12 Cr[VI] 8-hr time-weighted averages exceeded the recommended exposure limit of 1 $\mu\text{g}/\text{m}^3$, 11 out of 12 exceeded the permissible exposure limit of 5 $\mu\text{g}/\text{m}^3$, and 7 out of 12 exceeded the threshold limit value of 10 $\mu\text{g}/\text{m}^3$, with means 38 $\mu\text{g}/\text{m}^3$ for sprayers and 8.3 $\mu\text{g}/\text{m}^3$ for hosemen	Bennett J.S. et al. 2016
Aircraft painting	To evaluate workers exposure levels in Italy the personal measurements results have been compared with the exposure limit values (TLV-TWA) and the urinary chromium contents with the biological exposure indices (IBE).	Gherardi M. et al. 2017
Aircraft painting	This study measured CrVI exposures during corrosion control procedures. Mean time-weighted average (TWA) exposure to chromic acid during conversion coat treatment was 0.48 $\mu\text{g}/\text{m}^3$, below the current American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV(R)) TWA of 50 $\mu\text{g}/\text{m}^3$ for water-soluble CrVI compounds. Mean TWA exposures to strontium chromate were 5.33 $\mu\text{g}/\text{m}^3$ during mechanical abrasion and 83.8 $\mu\text{g}/\text{m}^3$ during primer application. These levels are in excess of the current ACGIH TLV-TWA of 0.5 $\mu\text{g}/\text{m}^3$ for strontium chromate.	Carlton G. N. 2003
Aircraft painting	This study reported that 71.8% of Cr VI mass in paint spray aerosol potentially inhaled by a spray painter may deposit in the head airways region. Only 2.0 and 1.4% of Cr VI mass in the paint aerosol may potentially deposit in the alveolar and tracheobronchial region, respectively. The ratio of Cr VI mass to total Cr mass was determined in bulk paint and the data indicate that Cr was predominantly in the Cr VI valence state, before spraying.	Sabty-Daily R.A. et al 2005
Various sectors in Italy	Data were collected from exposure registries of companies compulsorily notified by the National Workers' Compensation Authority in Italy. Over 8400 measurements of Cr VI exposures were selected from the database of registries for 1996-2009. Most exposures occurred in the manufacture of fabricated metal products (>50%), and the occupational group most frequently measured was metal finishing-, plating- and coating-machine operators (>52%). The mean level of exposure to Cr VI was 30.41 $\mu\text{g}/\text{m}^3$, and 50,118 workers were estimated at exposure risk in the selected industrial sectors.	Scarselli A. et al. 2012

Sector activity	Exposure Information	Ref.
Various sectors in France	The survey included 99 companies involved in various activity sectors. The inhalable fraction of airborne particles was sampled, and exposure levels were determined using ion chromatography analysis combined with post-column derivatization and UV detection. The quality of the measurement results was guaranteed by an inter-laboratory comparison system involving all the laboratories participating in this study. Exposure levels frequently exceeded the French occupational exposure limit value (OELV) of 1 µg m ⁻³ in activities such as thermal metallization and manufacturing and application of paint in the aeronautics sector. The results also reveal a general trend for a greater proportion of soluble Cr VI compounds compared with insoluble compounds.	Vincent R. et al. 2015
Various sectors in the EU	A quantitative job-exposure matrix (JEM) was developed based on statistical modeling of large quantities of personal measurements. The study estimated time-, job-, and region-specific exposure levels for asbestos, chromium-VI, nickel, and RCS. Through statistical modeling of large amounts of personal occupational exposure measurement data the study derived a quantitative JEM to be used in community-based studies	Peters S. et al. 2016
Various sectors in the USA	NIOSH conducted 21 field surveys in selected industries to characterize workers' exposures to Cr VI-containing airborne particulate. NIOSH researchers concluded that, in many of the evaluated processes, Cr VI exposures at or below the current NIOSH REL are achievable. However, for some processes, it is unclear whether controlling exposures to this range is consistently achievable without respirator use. Some operations involving the application of coatings and finishes may be among those most difficult to control to this range.	Blade L. M. et al. 2007

In 2006 about 917,000 workers in the EU were exposed to chromium across a wide range of industries. There were estimated to be 552,000 workers with relatively high levels of exposure who were employed in chemicals manufacture, basic metals production, manufacture of machinery and equipment, manufacture of other transport equipment and the manufacture of furniture. Since 2006, the manufacture of Cr VI compounds and the use of copper chrome arsenate wood preservatives have ceased in the EU, Cr VI has been banned in new vehicles or electronic/electrical equipment and plating processes are increasingly replacing Cr VI with trivalent chromium or chrome-free substances. The number of workers in sectors relatively with relatively high levels of exposure is likely to have declined substantially since 2006 (IOM, 2011).

In the working environment of stainless steel welders in Germany, chromium oxide levels with median values ranging from 4 to 10 µg/m³ and a maximum value of 80 µg/m³, were reported in 1987. In Europe in 2005, geometric mean exposures in most chromium chemical industries were reported to be generally <20 µg/m³. In a modern ferrochromium and stainless steel mill in Finland, the median concentration of Cr VI in 1987 was ≤0.1 µg/m³ in all production areas except one, where it was 0.5 µg/m³. The highest measured airborne concentration of Cr VI was 6.6 µg/m³. In 1999, the median and maximum breathing zone Cr VI concentrations were 0.3 and 0.7 µg/m³, respectively (see several references in (WHO-IPCS-CICAD, 2013)).

It was estimated in the EU in 2005 that dermal exposure of workers engaged in packing chromium(VI) products was 0–0.1 mg/cm² per day, and dermal exposure of workers weighing and charging dry ingredients to mixers in the manufacture of Cr VI pigments was estimated to be 0.1–1 mg/cm² per day (WHO-IPCS-CICAD, 2013).

The average urinary excretion half-life of Cr VI following oral uptake of 0.05 mg/kg bw by volunteers was rather long, i.e. 39 h, indicating a risk for human biopersistence at those intake levels (WHO-IPCS-CICAD, 2013).

For the purpose of systematically comparing exposures in different industrial sectors in the EU, (IOM, 2011) estimated exposure levels by extrapolation from data found to be representative of 1995 to 2010 and assuming an annual decrease in air concentration of 7% (see Table 5 below).

Table 5.1: Estimated occupational exposure levels for Cr VI in 1995 and 2010 for key industrial sectors in the EU (IOM, 2011)

NACE Code	Industry	Estimated Geometric Mean 1995[1] mg/m ³	Estimated Geometric Mean 2010[2] mg/m ³	Estimated Geometric Standard Deviation
24	Manufacture of chemical and chemical products	0.0050	0.002	NK[3]
27	Manufacture of basic metals	0.0060	0.002	3.8
28	Manufacture of fabricated metal products, except machinery and equipment	0.0047	0.002	9.3
29[4]	Manufacture of machinery, except electrical	0.0047	0.002	9.3
35	Manufacture of other transport equipment	0.0160	0.005	14.0
36[4]	Other Manufacturing Industries	0.0047	0.002	9.3

[1] The majority of the data were from 1990 - 2000 therefore the data was assumed to be representative of 1995

[2] 1995 levels were extrapolated to 2010 assuming an annual decrease in concentration of 7%.

[3] NK = Not Known

[4] No data were available for NACE 29 and 35 however because the exposure scenarios in these groups resemble those in NACE 28 we have used the exposure levels for NACE 28 to represent estimated exposures levels in NACE 29 and 35.

5.4. Routes of exposure and uptake

Inhalation of dusts, mists or fumes and dermal contact with chromium containing products are the main routes of occupational exposure (IARC, 2012).

According to (NIOSH, 2013) workers are potentially exposed to airborne Cr VI compounds in three different workplace scenarios: (1) when Cr VI compounds are manufactured from other forms of Cr such as in the production of chromates from chromite ore; (2) when products or substances containing Cr VI are used to manufacture other products such as chromate-containing paints; or (3) when products containing other forms of Cr are used in processes and operations that result in the formation of Cr VI as a by-product, such as in welding. Dermal exposure to Cr VI may occur with any task or process in which there is the potential for splashing, spilling, or other skin contact with material that contains Cr VI. If not adequately protected, workers' skin may be directly exposed to liquid forms of Cr VI as in electroplating baths or solid forms, as in Portland cement. Dermal exposure may also occur because of the contamination of workplace surfaces or equipment.

6. MONITORING EXPOSURE

6.1. External exposure

There are several methods developed by various organizations to quantify Cr VI levels in workplace air. Recommended methods characterize time-weighted average (TWA), breathing zone exposure across full work shifts. Sampling considerations for determination of Cr VI levels in workplace air are well established in the literature (Ashley, Howe, Demange, & Nygren, 2003). An important consideration is the reduction of Cr VI to Cr III during sampling and sample preparation. Another concern is the possibility of oxidation of Cr III to Cr VI during sample preparation. Factors that affect the reduction of Cr VI or oxidation of Cr III include the presence of other compounds in the sampled workplace air, which may affect reduction or oxidation (notably iron, especially Fe[II]), the ratio of Cr VI to Cr III concentrations in the sample, and solution pH (Ashley et al., 2003). The pH of a solution is an important factor, because in acidic conditions the reduction of Cr VI is favourable, while in basic conditions Cr VI is stabilized. The use of NIOSH Method 7703 in the field minimizes reduction of Cr VI during transport and storage (NIOSH, 2013). The use of polyvinyl chloride (PVC) filters are recommended (NIOSH Method 7605; OSHA Method ID-215). Other suitable filter materials that are generally acceptable for airborne Cr VI sampling include polyvinyl fluoride (PVF), polytetrafluoroethylene (PTFE), PVC- and PVF-acrylic copolymers, and quartz fiber filters (Ashley et al., 2003). Other filter types to be used for sampling should be tested before use. Sampling should be based on inhalable dust sampling. Inhalable dust samplers capture dust particulates that can penetrate all parts of the respiratory organ.

Cr VI compounds can be monitored in workplace air using various analytical methods. Some methods are more or less specific for the occupational setting. Important aspects that determine which method is to be used preferably are the process that is monitored and which is linked to the matrix in which Cr VI occurs (e.g. chromium plating mists) and whether the actual Cr VI compound to be monitored is soluble or not. In all methods, sampling is by trapping onto a filter. The relevant and easily accessible regulatory methods are listed below with their main characteristics that discern them from the other methods. They are summarised more extensively in Table 6.

- NIOSH Method 7600 - DPC derivatization, UV-VIS. (NIOSH, 2015a)
- NIOSH Method 7604 - Ion chromatography with conductivity detection. (NIOSH, 1994)
- NIOSH Method 7605 - Ion chromatography and post-column DPC derivatization, UV-VIS. (NIOSH, 2003)
- NIOSH. Method 7703 – SPE enrichment, DPC derivatization, UV-VIS. (NIOSH, 2015b)
- DFG Method Chromium-2-PHOT - DPC derivatization, UV-VIS and Method Chromium-3-IC - Ion chromatography and post-column DPC derivatization, UV-VIS. (DFG, 1993a, 1993b)
- HSE MDHS Chromium plating mist. DPC-derivatization in combination with stationary measurements. (HSE, 2014)
- ISO 16740: ion chromatography and post-column derivatization. (ISO, 2005)
- OSHA Method ID-215 (version 2): ion chromatography and post-column derivatization. (OSHA, 2006)

This is followed by extraction with an inorganic buffer. Some are extracting with a buffer for the direct determination of soluble Cr VI (only) and some other with the more strong

digestion (wet ashing) for the determination of the soluble and insoluble chromium simultaneously. Once solubilised, further steps can be enrichment (decrease the volume to increase the concentration) and/or separation from chromium III. Subsequently, in several methods ion-chromatography and post-column derivatization by diphenylhydrazine (DPH) are used. Other methods use direct derivatization by DPH.

The analytical determination of the coloured Cr VI-DPH complex using the NIOSH Method 7600 is based on UV-VIS photometry or on colorimetric comparison (NIOSH, 2015a).

Less sensitive than the colorimetric method 7600, is the NIOSH Method 7604 (NIOSH, 1994b) but its advantage is that it contains fewer sample preparation steps (is faster) and was found free from interferences when used for samples of five chromate-containing paints. Both methods (7600 and 7604) may be used for the determination of insoluble or soluble Cr VI.

NIOSH Method 7605 was used to measure Cr VI from samples taken during spray-painting and electroplating operations. These samples were analysed in parallel by other methods (e.g. NIOSH Method 7703, 7300). The analytical outcomes show no statistical difference among the NIOSH Method 7605 and the other two (NIOSH Method 7703, 7300).

NIOSH Method 7703 (according to the method description) could be used in the field although elaborate laboratory treatment in separate instruments is needed for this method as well, i.e. the extraction process, the SPE clean-up and the derivatization.

Although the DFG IC-3 method is laborious, it has the advantage that it can simultaneously measure Cr (III) as well as Cr VI.

The detection limits of all the analytical methods (see Table 6) range from 0.0008 $\mu\text{g m}^{-3}$ to 25 $\mu\text{g m}^{-3}$

In addition, there are several methods focussing on settled dust samples or swipe samples. These are not discussed here as inhalation exposure is regarded as the most relevant route of exposure to Cr VI compounds.

Table 6: Overview of sampling and analytical methods for monitoring of Cr VI in workplace air

Method	Use purpose including	Sampling	Filters	Desorption solution	Analysis	LOD/LOQ	Concentration range	Evaluated #	Refs
NIOSH Method 7600	Soluble chromates and chromic acid. Insoluble chromates and chromates in the presence of iron or other reducing agents	Personal	PVC membrane	Soluble Cr ^{VI} : H ₂ SO ₄ Insoluble Cr ^{VI} : NaOH / Na ₂ CO ₃	DPC-derivatization UV-VIS detection	LOD: 0.05 µg	0.2 - 7 µg 0.001 - 5 mg/m ³ (200 L)	Yes	(NIOSH, 2015a)
NIOSH Method 7604	Soluble and insoluble Cr ^{VI}	Personal	PVC membrane	Extraction and elution: NaOH / Na ₂ CO ₃	IC Conductivity detection	LOD: 3.5 µg	10 - 250 µg 0.01 - 4 mg/m ³ (500 L)	Yes	(NIOSH, 1994)
NIOSH Method 7605	Soluble chromates Insoluble chromates	Personal	PVC membrane	Extraction - Solubles: (NH ₄) ₂ SO ₄ / NH ₄ OH Insolubles: NaOH / Na ₂ CO ₃ Elution: (NH ₄) ₂ SO ₄ / NH ₄ OH	IC with post-column DPC-derivatization UV-VIS detection	LOD: 0.02 µg LOQ: 0.07 µg	0.05 - 20 µg 0.00025 - 0.1 mg/m ³ (200 L)	Yes	(NIOSH, 2003)
NIOSH Method 7703	Soluble and insoluble Cr VI For insoluble ultrasonic extraction carbonate buffer required	Personal	PVC membrane or MCE or PTFE	Extraction and elution: (NH ₄) ₂ SO ₄ / NH ₄ OH Elution: Use SPE cartridges	DPC-derivatization UV-VIS detection	LOD: 0.08 µg	0.00005 - 1 mg/m ³ (200-500 L)	Yes	(NIOSH, 2015b)

Method	Use purpose including	Sampling	Filters	Desorption solution	Analysis	LOD/LOQ	Concentration range	Evaluated #	Refs
DFG Chromium-2-PHOT	Inhalable dust	Personal Stationary	Glass fibre filter, wet ashing	NaOH / Na ₂ CO ₃	DPC-derivatization UV-VIS detection	LOQ (calculated as CrO ₃) Personal sampling (0.42 m ³): 4.8 µg/m ³ Stationary sampling 45 m ³): 0.04 µg/m ³			(DFG, 1993a)
DFG Chromium-3-IC	Inhalable dust	Personal Stationary	Glass fibre filter, wet ashing	Aqueous solution of pyridine-2,2-dicarboxylic acid, disodium hydrogen phosphate dodecahydrate, NaI, ammonium acetate, lithium hydroxide monohydrate	IC with post-column derivatization (DPC) UV-VIS detection	LOQ CrO ₃ : Personal sampling: 0.2 ng and 0.24 µg/m ³ for 0.42 m ³ air. Stationary sampling: 0.2 ng and 0.01 µg/m ³ for 45 m ³ air.			(DFG, 1993b)
HSE MDHS 52-4	Chromium plating mists	Stationary	Membrane	Sulphuric acid	DPC derivatization. Photometric detection or colorimetric comparison	Theoretical: LOD: 0.04 µg, 1.5 µg/m ³ LOQ: 0.14 µg, 5 µg/m ³ Practice: LOD 25 µg/m ³			(HSE, 2014)

Method	Use purpose including	Sampling	Filters	Desorption solution	Analysis	LOD/LOQ	Concentration range	Evaluated #	Refs
ISO 16740	Personal air sampling				IC with post-column derivatization (DPC) UV-VIS detection	LoQ: 0.07 µg (total or insoluble Cr VI with hotplate extraction)	Working range 0.01 – 10 µg/m ³ for 1 m ³		(ISO, 2005)
ID-215 (version 2) OSHA	Chromium plating operations Soluble and insoluble chromium-containing chemicals	Personal	Plating operations: 37-mm PS cassettes containing NaOH coated binderless quartz fibre filters Other operations: PS cassettes containing PVC filters with cellulose back-up pads	Na ₂ CO ₃ / NaHCO ₃ KH ₂ PO ₄ / K ₂ HPO ₄	IC with post-column derivatization (DPC) UV-VIS detection	LOD and LOQ dependent on exact procedure: LOD: 0.80-1.0 ng, 0.83-1.0 ng/m ³ LOQ: 2.67 – 3.12 ng, 2.9 – 3.5 ng/m ³		Validated method	(OSHA, 1998)
Metropol M-43 Method	Cr VI	Active sampling	37 mm cassettes (quartz filter)	Na ₂ CO ₃ 1M MgSO ₄	Ion chromatography UV-Vis detection	LOD: 7.6 ng/filter (Cr VI soluble); 20.4 ng/filter (Cr VI insoluble); 22.5 ng/filter (Cr VI soluble + insoluble)	0.1 µg/m ³ - 2 µg/m ³ (960 L, 8 h at 2 L/min)	Validated method	(INRS, 2016)

Method	Use purpose including	Sampling	Filters	Desorption solution	Analysis	LOD/LOQ	Concentration range	Evaluated #	Refs
MTA/MA-063/A14	Inhalable Cr VI (soluble, insoluble and total Cr VI)	Air sampling	PVC, PVF PTFE and quartz filter	Extraction - Solubles: (NH ₄) ₂ SO ₄ / NH ₄ OH Insolubles: NaOH / Na ₂ CO ₃ Elution: (NH ₄) ₂ SO ₄ / NH ₄ OH	Ion chromatography UV-Vis detection	LOD: 0.112 µg LOQ: 0.375 µg	0.001 mg/m ³ to 0.2 mg/m ³ (500 L)		(INSHT, 2015)

DPC – diphenylcarbazine; IC – ion chromatography; ICP-OES - inductively coupled plasma optical emission spectrometry; LOD - limit of detection; LOQ - limit of quantification; MCE – mixed cellulose ester; SPE –solid phase extraction; VIS – visible absorption spectroscopy;

Any evaluation statement is as given in the original method description. Wording may have different meanings in different methods

** Information taken from summary on the internet*

& For the ISO method, only an internet summary was available

6.2. Internal exposure/Biomonitoring of exposure

Biomonitoring of Cr VI exposure in the workplace can readily be undertaken by measuring total chromium in urine and blood. The first method (urine) does not allow any distinction as to the oxidation state of the inhalation/absorbed chromium so can only be used as a proxy and first indication of occupational exposure to specifically Cr VI as all the urinary chromium in the urine will be measured as the trivalent form. The second method (blood) can be used to estimate the exposure to Cr VI because erythrocytes can be measured separately from plasma. Based on references 5-7 in DFG (1990) that only Cr VI and not Cr III can pass the erythrocyte membrane, the 'total chromium' as measured in erythrocytes is thus assumed to be Cr VI.

In Table 8, two regulatory methods are briefly summarised; the first for total chromium in urine, the second for total chromium in whole blood as well as in plasma and in erythrocytes. The analytical determination is done using a standard graphite or a pyrolytically-coated graphite tube in combination with electrothermal atomic absorption spectroscopy (EAAS).

It should be noted that the blood method reports a correlation between concentrations found in blood and urine and air concentrations (DFG, 1990).

It is noted that several methods aiming at direct or indirect measurement of Cr VI are being published in the scientific literature. The biological sample used is urine or exhaled breath. They are usually based on some kind of separation of Cr III and Cr VI followed by ICP-MS quantification (Beattie, et al. 2017). As far as we understand, none of these new methods have obtained the status of 'governmental method' yet nor have they undergone an inter-laboratory validation.

Table 7: Overview of the available methods for bio-monitoring of occupational exposures to total chromium*

Method	Matrix	Analysis		LOD	Linear range	References
DFG	Urine	Graphite tube / Pyrolytically coated graphite tube EAAS	Standard tube Pyrolytically coated tube	0.5 µg /L 0.1 µg /L	0.5 – 70 µg /L 0.1 – 30 µg /L	(DFG, 1985)
DFG	Blood	Pyrolytically coated graphite tube EAAS	Whole blood Plasma Erythrocytes	0.5 µg / L WB 0.5 µg / L WB 0.5 µg / L WB	1.94 – 50 µg / L WB 12.5 – 50 µg / L WB 12.5 – 50 µg / L WB	(DFG, 1990)

* EAAS – electro-thermal atomic absorption spectroscopy; LOD – limit of detection; WB – whole blood

7. HEALTH EFFECTS

7.1. Toxicokinetics (absorption, distribution, metabolism, excretion)

7.1.1. Human and animal data

The limited number of volunteer and worker studies would suggest much of the animal toxicokinetic data is relevant to humans. Biological monitoring of occupational exposure is routinely carried out using blood or urine, but as noted above, the analytical techniques employed for the latter tend to express the amounts as total chromium.

7.1.2. Animal data

Absorption of inhaled Cr VI from the respiratory tract varies according to the solubility of the compound with high or sparingly soluble compounds absorbed more rapidly than poorly soluble or insoluble compounds (Adachi *et al.*, 1981). Repeated inhalation results in the accumulation of chromium in lung tissue. This is more marked for poorly soluble compounds. Absorption of orally-administered Cr VI, which has only been studied with soluble compounds, is poor presumably due to its rapid reduction to the trivalent species in the acidic conditions of the stomach (Mackenzie *et al.*, 1959; Donaldson & Barreras, 1966; Ogawa *et al.*, 1976). Reduction from hexavalent to trivalent chromium will also take place in the lung (De Flora, 2000). Dermal absorption occurs following direct skin contact with soluble hexavalent compounds in aqueous solutions and this can amount to up to 4% of the applied dose (Wahlberg & Skog, 1963).

Cr VI absorbed into the blood stream is taken up by blood cells, Red Blood Cell (RBC) uptake is rapid and involves a specific anion transport carrier in the cell membrane. Following uptake, the Cr VI is reduced and irreversibly bound to haemoglobin. Chromium can only be transported into cells when in the hexavalent oxidation state and extracellular reduction serves to prevent its uptake. Non-enzymatic reducing agents include glutathione, ascorbic acid and cysteine; enzymatic agents include microsomal P450 enzymes. Inhaled intratracheally-instilled Cr VI has been shown to be distributed to the lungs, liver, kidneys, testes, spleen and GI tract. Parenteral administration studies in pregnant animals have shown that Cr VI compounds can cross the placenta and be distributed within the embryo. These findings however, are of questionable relevance to occupational exposure. Inhaled or intratracheally-instilled Cr VI is excreted in the urine or faeces with the relative contribution varying with compound solubility. Orally administered compounds are mainly excreted in the faeces.

7.1.3. In vitro data

7.1.4. Toxicokinetic modelling

7.1.5. Biological monitoring

Urinary chromium levels and blood or whole blood chromium levels are a measure of total chromium exposure as Cr VI is reduced within the body to Cr III. As already stated in Chapter 6.2 it is important to note that only Cr VI and not Cr III can pass the erythrocyte membrane. In the light of this, the 'total chromium' as measured in erythrocytes can be assumed to be Cr VI. Several studies have explored associations between environmental chromium exposure and urinary levels (Angerer *et al.*, 1987).

7.2. Acute toxicity

7.2.1. Human data

Data on the effects of single exposures in human is mainly from case-reports involving accidental exposures and only relates to highly soluble compounds. An incompletely and poorly reported volunteer study of 10 subjects exposed to chromic (IV) oxide reported that "brief exposures" to 10-24 $\mu\text{g}/\text{m}^3$ (apparently CrO_3 , thus 5-12 $\mu\text{g Cr}/\text{m}^3$) caused nasal irritation (Kuperman, 1964). The threshold for irritation was reported to be 2.5 $\mu\text{g}/\text{m}^3$ (apparently as CrO_3 ; thus 1.3 $\mu\text{g Cr}/\text{m}^3$). Severe skin damage and renal toxicity have been reported in two fatal cases involving accidental exposure involving direct skin contact with hot (>90°C) acidified solutions of highly soluble chromates (Fritz et al, 1960). Corrosive damage to the GI tract mucosa and renal toxicity has been reported in cases of accidental or intentional ingestion of soluble hexavalent compounds. In many of the case reports, death (Cross et al) was often the outcome with ingestion of approximately 350mg Cr and above.

Information relating to the irritant effects of Cr VI compounds in human is primarily available for soluble compounds. Evidence, mainly from case reports, clearly shows that highly soluble compounds cause irritant and corrosive effects to the eyes. There are numerous reports of skin ulcers in workers exposed to soluble chromium compounds; in particular chrome plating workers or chromate-production workers (Cross et al., 1997). These "chrome ulcers" are mostly located on the hands and forearms.

7.2.2. Animal data

Single exposures to hexavalent compounds by inhalation cause inflammation and necrotic changes to the upper respiratory tract with effects in rats reported at 7.4mg Cr/m^3 and above (Suzuki et al, 1984; Last et al, 1979). LC50 values of between 33 and 83mg Cr/m^3 have been reported for rats (Gad et al, 1986). An oral LD50 With male rats using sodium chromate, sodium dichromate potassium dichromate and ammonium chromate has given values of 87, 59, 74, and 55mg Cr/kg respectively. Equivalent values for female rats were 13, 16, 17 and 20mg Cr/kg (Gad, 1986). Not surprisingly, higher LD50 are seen with sparingly or poorly soluble chromate.

7.3. Specific Target Organ Toxicity/Repeated Exposure

7.3.1. Human data

Kidney function has been investigated in chrome platers, chromate production workers, ferrochromium workers and stainless steel welders. Some but not all studies have reported renal dysfunction indicated by altered urinary levels of specific enzymes or proteins (Lindberg & Vesterberg, 1983; Nagaya et al, 1994; Verschoor et al, 1988; Wang et al, 1994; Mutti et al, 1985; Littorin et al, 1984). Effects were observed partly at comparatively low concentrations between 4 and 20 $\mu\text{g}/\text{m}^3$ (Lindberg & Vesterberg, 1983). Irritant and corrosive effects on the GI tract and hepatotoxicity have been reported but these effects cannot be related to exposure data.

7.3.2. Animal data

7.3.2.1. Inhalation

The effect of repeat exposure in animals to hexavalent compounds has been studied in animals using inhalation exposure, intratracheal instillation, oral dosing and parenteral administration. In inhalation studies, near continuous exposure to aerosols of sodium dichromate at concentrations up to 0.1mg Cr/m^3 for 18 months, or 0.2mg Cr/m^3 for 90 days, had no effects on body weight gain, haematology or histopathology (Glaser et al, 1985). However, with exposure to 0.5mg Cr/m^3 and above for 28 days or more, there

was increased organ weights (lung, liver, spleen and kidney). Similar results were seen in another study (Miyai, 1980) in which sodium chromate or barium chromate dusts at concentrations between 0.01 and 0.13mg Cr/m³ for up to 8 months. Exposure to sodium chromate aerosol (0.9mg Cr/m³ for up to 6 weeks) caused no damage to the respiratory tract epithelium in rabbits, but had a stimulating effect on pulmonary macrophages (Johansson et al, 1986 a & b). From these repeat inhalation studies, it is not possible to identify with any confidence a NOAEL for Cr VI compounds.

7.3.2.2. Oral exposure

In a number of oral-dosing studies, administration of highly soluble hexavalent compounds at concentrations up to 100ppm caused no sign of toxicity. One study at 70ppm in drinking water caused reduced body weight gain in rats. In a dietary study, high doses of lead chromate caused reduced weight gain, haematological effects and renal toxicity in rats and dogs although it is possible that both chromium and lead might have contributed to these effects. (Kennedy et al, 1976; Christofano et al, 1976)

7.4. Irritancy and corrosivity

7.4.1. Human data

In humans occupationally exposed by inhalation to Cr VI compounds, the main health effects are irritant and corrosive effects on the skin and respiratory tract. Effects on the respiratory tract include inflammation of the nasal septum. Lower respiratory effects include inflammation and obstructive disorders; transient impairment on lung function has been reported. It is uncertain to what extent short-term exposure to high Cr VI levels or direct contamination of the nasal mucosa with chromium may be involved in the development of the nasal lesions and this complicates a clear interpretation of the significance of the reported average exposure levels in relation to these health outcomes. Renal dysfunction has been reported in some studies, indicated by altered urinary protein or enzyme levels. In contrast, some studies have reported no effects on kidney function. Irritant and corrosive effects on the GI tract and effects in the liver have been reported following repeated exposure, but these cannot be related to exposure data. Cr VI compounds are potent skin sensitisers in humans and can cause respiratory sensitisation. Sensitised individuals may also react to trivalent chromium compounds. In general, the animal investigations from both single and repeated exposures are supportive of the effects seen in humans although the data do not cover the wide range of Cr VI compounds in common use, most focussed on the highly soluble compounds, and do not allow clear NOAELs to be established for the health endpoints investigated.

A large number of studies are available, which have investigated the health of workers with repeated long-term exposure to Cr VI compounds. The two most studied groups are chrome platers and chromate-production workers (Cross et al., 1997). Many of these studies have reported effects on the upper respiratory tract but few have presented exposure details for chromium exposure. Effects on the upper respiratory tract include inflammation, atrophy of the nasal mucosa and ulceration or perforation of the nasal septum (Colvin *et al*, 1993; Royle, 1975; Lin *et al*, 1994). In the lower respiratory tract, the reported effects include inflammation and various obstructive disorders (Ameille *et al*, 1983; Wieser *et al*, 1982). Transient impairment of lung function has also been reported (Lindberg & Hedenstierna, 1983). In this latter study on chrome platers, effects on the nasal passages were reported with exposures to average concentrations of 0.002mg Cr/m³ and above although some effects were even reported at lower average concentrations. However, it should be noted that short-term exposure to higher concentrations or, direct contamination of the nasal mucosa with chromic acid might have been involved in the development of these lesions.

7.4.2. Animal data

Repeat exposure to chromic acid (1.81mg Cr/m³ and above) caused irritant and corrosive effects in the respiratory tract of mice (Adachi *et al*, 1986).

7.5. Sensitisation

7.5.1. Human data

Skin sensitisation resulting from exposure to hexavalent compounds has been demonstrated in patch-testing studies of contact dermatitis patients and in various chromate-exposed occupational groups (Sun, 1984; Samoen *et al*, 1984; Fregert *et al*, 1970; Engel & Calnan, 1963). Cr VI-sensitised subjects may react to trivalent chromium compounds although the latter are less able to penetrate the skin and thus have a lower skin sensitising potential (Fregert & Rorsman, 1964; Samitz & Shrager, 1966). Available case reports, together with supporting evidence from bronchial challenge tests, show that inhaling Cr VI compounds can induce occupational asthma (Park *et al*, 1994). As with skin sensitisation, Cr VI-sensitised subjects may react following exposure by inhalation to trivalent chromium compounds.

7.6. Genotoxicity

7.6.1. Human data

In several studies increased frequencies of DNA strand breaks, sister chromatid exchanges and micronuclei were shown in lymphocytes of workers exposed to chromium(VI) compounds.(IARC, 2012) Chrome-plating workers (n=19), exposed at the workplace to chromium(VI) concentrations of 0.4 to 5.6 µg/m³, showed a higher level of chromium concentrations in urine, erythrocytes and lymphocytes as well as an increase of DNA strand breaks in the lymphocytes in comparison with two control groups (18 hospital workers and 20 university personnel). DNA strand breaks in lymphocytes were determined by comet assay (Gambelunghe *et al.*, 2003).

The increase of the frequency of sister chromatid exchange in blood cells of workers employed in electroplating plants correlated with the duration of exposure to Cr VI and also with smoking habits. The duration of exposure was between 2 and 14 years. The results of biomonitoring showed a significant increase in the chromium concentration in urine (3.67 ± 3.89 µg/g creatinine compared with 1.21 ± 1.16 µg/g creatinine in control persons) and a significant decrease in superoxide dismutase activity in blood, 86.86 ± 0.80 U/mg hemoglobin compared with 7.16 ± 0.53 U/mg hemoglobin in control persons (Wu *et al.*, 2001).

A significant increase in micronuclei in the peripheral lymphocytes and in buccal mucosa cells was found in chromium platers exposed to chromium concentrations at the workplace of 0.0249 to 0.0075 mg/m³. It was shown that half of the micronuclei contained fragments and the other half whole chromosomes, indicating clastogenic as well as aneugenic effects. However the incidence of sister chromatid exchanges and chromosomal aberrations was not increased in the exposed workers (Benova *et al.*, 2002).

In another study with 40 workers from chrome plants, the number of micronuclei in the peripheral lymphocytes increased significantly in a dose-dependent manner. The mean chromium exposure was 0.083 ± 0.01 mg/m³ in the high exposure group (n=24) and 0.0043 ± 0.01 mg/m³ in the low exposure group (n=16) (Vaglenov *et al.*, 1999).

At a steel production plant with very low exposure concentrations of 0.0004 to 0.0005 mg chromium/m³, no changes in the frequency of micronuclei in the cells of the nasal epithelium were found in 29 workers compared with in 39 controls (Huvinen et al., 2002).

7.6.2. Animal data

Animal studies have revealed that soluble Cr VI compounds induce genotoxic effects such as increased DNA repair, sister chromatid exchanges, micronuclei in somatic cells of rats and mice. In a few studies in which moderately to poorly soluble chromium(VI) compounds were administered, an increased incidence of sister chromatid exchanges, micronuclei and chromosomal aberrations were found in somatic cells of rats and mice. Also poorly soluble chromium(VI) compounds such as zinc potassium chromate and lead potassium chromate were shown to induce micronuclei in erythrocytes of mice after intraperitoneal injection. Dominant lethal mutations were induced in germ cells of mice after intraperitoneal injection of potassium dichromate but not, however, in rats after administration of the substance with the drinking water for 12 weeks. There are several studies in which chromium(VI) compounds were administered with the drinking water; their results are equivocal. In some studies a significant and concentration-dependent increase in micronuclei of bone marrow cells was found, but not in others (De Flora, Bagnasco, Serra, & Znacchi, 1990; DFG, 2016; IARC, 2012; Proctor et al., 2014).

7.6.3. In vitro

The formation of DNA adducts appears to play an important role in Cr VI-induced genotoxicity (Hartwig, 2013; Wise & Wise, 2012). Soluble Cr VI compounds are genotoxic in bacteria, yeasts and mammalian cells. Also, strontium chromate and zinc chromate, poorly soluble compounds, induce genotoxic effects in bacteria and mammalian cells. The same accounts for lead chromate and barium chromate (IARC, 2012). Barium chromate in concentrations of 0.1 to 5 µg/m² was clastogenic and induced chromatid and chromosome-type lesions in the human lung cell culture model WTHBF-6 (Wise, Schuler, Katsifis, & Wise, 2003) (Wise et al., 2003). Lead chromate particles from 0.45 to 0.58 µm and barium chromate particles from 0.4 to 32 µm were clastogenic in the near-normal human lung cell line WTHBF-6. In this assay barium chromate appears to be a stronger genotoxin than lead chromate (Wise et al., 2004). In bronchial epithelial cells (BEP2D), a significant concentration-dependent increase in chromosomal aberrations was observed for lead chromate concentrations of 0.5µg/m² (Wise, Holmes, & Wise, 2006). Lead chromate in concentrations of 0.5 and 1µg/m² induces centromere abnormalities, aneuploidy and DNA double-strand breaks in human lung cells WTHBF-6 (Holmes et al., 2006; Xie et al., 2005). Barium chromate at a concentration of 0.1µg/m² caused an increase in deletions in the gpt gene in a cell line derived from V79 cells (Klein et al., 2002).

7.7. Carcinogenicity

The basis for the carcinogenic classification of Cr VI compounds has been established by the International Agency for research on Cancer (IARC) in 1990 (IARC, 1990). IARC concluded then that there was '*sufficient evidence*' to consider Cr VI to be carcinogenic in both humans and experimental animals and that classification in Category 1 was justified ('*carcinogenic to humans*'). This IARC classification was again confirmed in 2009 and 2012 (IARC, 2012; Straif et al., 2009).

Most Cr VI compounds are classified by the European Union for carcinogenicity in Category 1B ('*substance presumed to be carcinogenic to humans*'). Exceptions are

chromium trioxide, zinc chromate and zincpotassium chromate classified in category 1A (*'substance known to be carcinogenic to humans'*)(European Parliament and Council, 2008).

7.7.1. Human data

The first case of cancer associated with chromium compounds was reported by Newman (Newman, 1890) and described an adenocarcinoma in the nasal passages of a chromate pigment production worker. Since then, there have been several case reports of lung cancer among chromate pigment production workers, chromate-production workers and chrome platers and some case reports of cancer of the GI tract in chromate production workers (IARC, 1990, 2012). A large number of epidemiological studies are available for the evaluation of carcinogenicity and there have been a number of reviews published in recent years (AGS, 2014; ATSDR, 2000; BAuA, 2016; DECOS, 2016; ECHA, 2013; Goldbohm et al., 2006; IARC, 2012). IARC reviewed individual cohort studies available upto approximately 1990 and those that became available before approximately 2012 in detail (IARC, 1990, 2012). SCOEL based this evaluation on the aforementioned reviews but checked whether new human epidemiological studies have been published. This was last evaluated December 2016.

Epidemiological studies have been performed in different groups of workers:

Chromate production workers:

The most extensive studies are those in the chromate production industry and can be grouped into those from the US, the UK, Germany, Italy and Japan (Cross et al., 1997; IARC, 2012). These studies provide clear evidence of consistently increased mortality among chromate workers with various proxies of exposure. Values of standardised mortality ratios (SMRs) from 200 to over 2000 have been reported. In many cases, the study populations involved workers employed in the first half of the 20th century. Steenland and others estimated a mean standardized SMR for lung cancer of 278 (Steenland et al., 1996).

Pigments-production workers:

A number of studies have reported excess risk of cancer for workers employed in the chromate pigment production industry. Most of the plants studied produced both lead and zinc chromate and in some, exposure to other chromates including strontium, may have occurred. Therefore, the independent effects of lead chromate and zinc chromate with respect to lung cancer are difficult to identify. However, a series based in three UK factories provided strong suggestive evidence that zinc chromate, and not lead chromate is associated with lung cancer risks in this industry (Davies, 1984a, 1984b). No detailed exposure data are available to enable the relationship between chromium exposure and increased lung cancer mortality in the chromate pigment production industry to be investigated.

Chrome plating workers:

Several studies of chrome plating workers are available for evaluation. One study provides clear evidence of increased lung cancer mortality (Sorahan et al., 1987). Exposure data provided in this study suggests that exposure to CrO₃ was generally below 0.05mg/m³ (0.026Cr/m³) but this figure should be treated with caution. Other, less well-conducted studies also report an elevated risk of mortality from lung cancer in chrome platers.

Ferrochromium workers:

Two studies are informative in the possible carcinogenicity of Cr VI to ferrochromium workers. One study reported a non-significant excess of lung cancer (Langård, 1988; Langård & Vigander, 1983) and one study reported a non-significant deficit in lung cancer (Axelsson & Rylander, 1980). Both studies noted possible co-exposure to other known carcinogens. Cancer risk among workers employed in the Finnish ferrochromium and stainless steel industry since the beginning of production in 1967 was evaluated by Huvinen & Pukkala (2013, 2015). Lung cancer risk was decreased in the whole cohort (SIR 0.79; 95% CI 0.65 to 1.08). The incidence of prostate cancer was significantly increased (1.31; 1.05 to 1.61) and that for kidney cancer was significantly decreased (0.38; 0.14 to 0.82). None of the department-specific SIRs for lung cancer were significantly different from 1.0. In the 2015 analysis overall mortality was significantly decreased (SMR 0.77; 95% confidence interval [CI] 0.70–0.84), largely due to low mortality from diseases of the circulatory system (SMR 0.71; 95% CI 0.61–0.81). In chromite mine, stainless steel melting shop and metallurgical laboratory workers, the SMR for circulatory disease was below 0.4 (SMR 0.33; 95% CI 0.07–0.95, SMR 0.22; 95% CI 0.05–0.65 and SMR 0.16; 95% CI 0.00–0.90, respectively). Mortality from accidents (SMR 0.84; 95% CI 0.67–1.04) and suicides (SMR 0.72; 95% CI 0.56–0.91) was also lower than in the reference population. Only relatively crude exposure data were available for this cohort. Exposure response analyses were not presented. These studies are not informative for risk assessment purposes. **Stainless steel production workers:** Studies in separate groups of French stainless steel production workers have been performed (Deschamps et al., 1995; Moulin et al., 1990; Moulin et al., 1993). A suggestive increase in lung cancer was considered to be more related to PAH exposure rather than chromium, but this form of potential confounding could not be dealt with quantitatively.

Stainless steel welders:

There are several studies that have investigated cancer mortality in stainless steel welders, but few have specifically investigated chromium (Cross et al., 1997). Of the available studies, some have reported increased risk of lung cancer mortality in stainless steel welders whilst others have not. By far the most comprehensive is a large study (Simonato et al., 1991) which reported increased lung cancer mortality in stainless steel welders, although a greater excess was reported for mild steel welders. In most of the studies reported, exposure to asbestos and other confounders were noted. Thus, any association between Cr VI exposure and increased risk of lung cancer in stainless steel welders remains to be elucidated.

Quantitative exposure data are available for two cohorts – which have regularly been updated. The available exposure data enable the relationship between airborne chromium, in particular Cr VI and increased lung cancer mortality in the chromate production industry to be investigated. Most importantly, no exposure data are provided regarding types of chromium compounds including specific hexavalent compounds.

Previous quantitative risk assessments

The above described available epidemiological evidence has been used by several organisations in quantitative risk assessments:

SCOEL 2004

SCOEL earlier reviewed the toxicological and epidemiological evidence available for Cr VI in 2004 (SCOEL, 2004). SCOEL made use of a number of reviews (ATSDR, 2000; Cross et al., 1997; Cross et al., 1997; EPA, 1984; IARC, 2012) and additional literature up to 2004. The SCOEL reported that exposure to Cr VI compounds may lead to lung cancer. The SCOEL concluded that carcinogenicity was the critical effect of Cr VI compounds in agreement with the classification of Cr VI compounds by the EU. SCOEL based a quantitative risk assessment on the combined epidemiological data from ten cohort studies concerning employees occupationally exposed to chromate. These epidemiological studies were previously selected (mainly because of their size) by Steenland et al. in

1996 for a meta-analysis ((Alderson et al, 1981; Davies, 1984a, 1984b; Enterline, 1974; Frentzel-Beyme, 1983; Hayes et al., 1979; Korallus et al., 1982, 1993; Sorahan et al., 1987; Sotah et al., 1981; Takahashi & Okubo, 1990). In addition to the analysis by Steenland et al. the SCOEL calculated cancer risk values for three different scenarios of exposure (500, 1,000 and 2,000 $\mu\text{g}/\text{m}^3$ for 15 years; cumulative 7,500, 15,000 en 30,000 $\mu\text{g} \times \text{m}^{-3} \times \text{year}$) by assuming average exposure levels and an average duration of exposure for some of the cohorts for which quantitative exposure information was lacking. In its final recommendation the SCOEL decided to follow the first scenario and estimated that approximately 5-28 extra cases of cancer mortality would occur in a cohort of 1,000 employees, followed from age 20 to 85 and exposed to retirement at age 65, by using lifetable analyses which made use of mortality data for England and Wales. Lifetable analysis take into account competing causes of death, and are therefore referred to as an unconditional analysis of risk, and are most accurate:

- at an exposure level of 25 $\mu\text{g}/\text{m}^3$ this was estimated to be 2-14 extra mortality cases,
- at an exposure level of 10 $\mu\text{g}/\text{m}^3$ this estimate was 1-6 extra mortality cases,
- at 5 $\mu\text{g}/\text{m}^3$ this estimate was 0.5-3 extra mortality cases,
- at 1 $\mu\text{g}/\text{m}^3$ this estimate was 0.1-0.6.

ANSES 2009

The Occupational Exposure Limit Committee (OELC) of the French Agency for Environmental and Occupational Health Safety (AFSSET, ANSES in French) reported on a risk assessment on a request from the French Directorate General of Labour. Analysis of the literature led to the conclusion that Cr VI and its compounds are genotoxic and mutagenic, and lead to carcinogenic effects. The selected critical effect by inhalation is lung cancer. It was also concluded that derivatives of Cr VI are substances for which there is no threshold of toxicity. As a result, for risk calculations, a no-threshold effect approach was used. The OELC selected the Painesville (Gibb et al., 2000) and Baltimore (Luippold et al., 2003) cohorts, because it considered them to be the ones with the best exposure data, and most specific for exposure to Cr VI.

The OELC recommended one occupational exposure value valid for all Cr VI derivatives. The health risk assessment as proposed below thus applies to all types of Cr VI. It does not seem possible to identify any health effect thresholds (particularly with regard to the proven carcinogenicity in humans of Cr VI derivatives), the OELC considered that the toxicity of Cr VI derivatives occurs through a non-threshold mechanism of action, with lung cancer being selected as the critical effect.

The OELC chose to assess the excess risk of death by lung cancer. The excess risk calculation was taken from the upper interval from the OSHA estimate, obtained from the Gibb occupational cohort because estimates made from these calculations were considered solid, were verified by the NIOSH and the chromium industry, gave substantially the same results, had minimal confounding bias due to smoking because smoking was adjusted for. The reference population chosen to apply this model was the Baltimore cohort, using the best and most specific exposure data in relation to exposure to Cr VI and its derivatives. It was also stated that the study of the Gibb cohort was originally financed through public funds (US EPA), and the many measurements allowed the establishment of a job-exposure matrix.

The exposure scenario involves an occupational population which is exposed 8 hours a day, 5 days a week, 240 days a year, for 45 years, from the age of 20 to 65, and results are expressed as "whole life" excess risks. The linear model (excess relative risk) was chosen because of the best fits. The following results were obtained:

- 0.1 $\mu\text{g CrVI}/\text{m}^3$ is associated with an excess risk of dying from lung cancer of 10^{-3}
- 0.01 $\mu\text{g CrVI}/\text{m}^3$ is associated with an excess risk of dying from lung cancer of 10^{-4} .

ECHA-RAC 2013

The Committee for Risk Assessment (RAC) agreed on a proposal prepared by the ECHA Secretariat for a risk assessment (ECHA, 2013). A review was performed for 14 Cr VI compounds. The committee acknowledged that extrapolating outside the range of observations inevitably introduces uncertainties in the risk assessment. As the mechanistic evidence is suggestive of non-linearity it is acknowledged that the excess risk in the low exposure range might be an overestimate of the true risk. Nevertheless, ECHA concludes that there is insufficient evidence to exclude a genotoxic mode of action and that therefore a threshold cannot be assumed (ECHA, 2013). RAC used the analysis published by Seidler in 2012 as a starting point for their risk calculations. (Seidler et al., 2013) Seidler evaluated the epidemiological literature, selected studies which had incorporated quantitative exposure estimates and conducted a quality review of the available papers. Only two studies were considered to be of sufficient quality, also because of the adjustment for the potential confounding effects of smoking. These were the Baltimore cohort and the Painesville cohort studies. Calculations were made assuming:

- a lifetime background cancer risk of 48 per 1000 for the EU male population;
- an 89 year life-expectancy;
- and according to the RAC-ECHA document (Annex 1), an excess risk linear function was derived from a RR (relative risk) of about 2, which seems obtained by rounding off the average exposure response slope as calculated by Seidler ($\beta = 1.75$) on the basis of the two cohort studies, at the cumulative exposure of $0.5 \text{ mg Cr VI/m}^3/\text{year}$, which is equivalent to a RR of 2 for exposure to $12.5 \text{ } \mu\text{g Cr VI/m}^3$ for 40 years.

The associated excess lifetime risk (ELR) at this cumulative exposure for a RR of 2 was determined by multiplying the excess RR ($RR - 1$) by the background lung cancer risk in the EU population (P_0) according to the equation for calculation of a conditional excess lifetime risk (ELR), which is an excess lifetime risk not taking into account other competing causes of death $ELR = P_0(RR-1)$, where P_0 was rounded off to a value of 0.05 ($48/1000=0.048$). This resulted in a ELR of 50×10^{-3} at $12.5 \text{ } \mu\text{g Cr VI/m}^3$ for 40 years (equivalent to a ELR of 4×10^{-3} at $1 \text{ } \mu\text{g Cr VI/m}^3$ for 40 years). It should be made explicit that these calculations made did not allow for competing risks as is usually considered in a life-table analysis to derive risk estimates.

AGS (2014)

In 2014 the "Ausschuss für Gefahrstoffe (AGS)" published a report based on the evaluation of existing human and experimental toxicological literature. The AGS confirmed the EU classification of Cr VI compounds. According to the AGS both 'direct genotoxic' mechanisms and mechanisms affecting 'tumor initiation and promotion' underly the carcinogenicity of all Cr VI compounds. For the quantitative risk assessment the AGS selected the study by Birk and others (Birk et al., 2006), which reported the German part of the multi-plant study by Mundt et al. (Mundt et al., 2002). This study involved 739 employees in the chromate production in Leverkusen and Uerdingen. Exposure data was established by biomonitoring chromium in urine and urine chromium levels were converted to concentrations in air. An increase in lung cancer mortality was observed in 22 cases. The AGS concluded that occupational exposure to $12.5 \text{ } \mu\text{g/m}^3$ would potentially lead to a doubling of the lung cancer risk (5/100). The AGS derived a cancer risk value of 4 per 1,000 (4×10^{-3}) at 40 year occupational exposure to $1 \text{ } \mu\text{g/m}^3$ by using a conditional analysis of lifetime risk, and thus ignoring competing causes of death. The AGS did not extrapolate to lower exposure levels because of the uncertainty related to the shape of the dose-effect relationship and the uncertainty in the outcome of the risk calculation. See the AGS advice and the study by Birk et al. for details of the calculation (AGS, 2014; Birk et al., 2006). It should be made explicit that these calculations made did not allow for competing risks as is usually considered in a life-table analysis to derive risk estimates.

NIOSH (2013)

The US National Institute for Occupational Safety and Health (NIOSH) of the Centers of Disease Control (CDC) published a criteria document containing a quantitative risk assessment for Cr VI compounds in 2013 (NIOSH, 2013). NIOSH summarized in its report existing human and experimental animal studies. NIOSH used human data for the quantitative risk assessment. Data were considered from two American cohorts of employees in the chromate industry (in Baltimore, Maryland and in Painesville, Ohio respectively). NIOSH used the data of Gibb et al. (Gibb et al., 2000)(Baltimore cohort) to conduct its risk assessment (Park et al., 2004). This involved a cohort of 2,357 employees in the chromate production industry with 122 mortality cases from lung cancer. NIOSH selected Gibb et al. (Gibb et al., 2000) because of the quality of the exposure data, the large number of mortality cases, detailed data on smoking and a better retrospective archive of exposure data. NIOSH used a linear extrapolation model and calculated an extra cancer mortality risk. The NIOSH risk assessment estimates an excess lifetime risk of lung cancer death of 6 per 1,000 workers at 1 µg Cr VI/m³ (the previous REL) and approximately 1 per 1,000 workers at 0.2 µg Cr VI/m³ (the revised REL) (Park et al. 2004). The basis for the previous REL for carcinogenic Cr VI compounds was the quantitative limitation of the analytical method available in 1975.

See the NIOSH criteria document for details of the calculations.

DECOS 2016

DECOS has drafted a guideline for the calculation of risks of (developing or dying from) lung cancer as a consequence of occupational exposure. DECOS is of the opinion that data from only a limited number of cohorts are suitable for a reliable risk assessment.(DECOS, 2016) In this regard DECOS shares the opinion of AGS and NIOSH. These are the American 'Baltimore cohort' (Braver, Infante, & Chu, 1985; Gibb et al., 2000; Hayes et al., 1979), the American 'Painesville cohort' (Luippold et al., 2003; Mancuso, 1997), and an American (Texas & North Carolina)(Luippold et al., 2005) and a European cohort (Leverksen & Uerdingen)(Birk et al., 2006) involving employees participating in a 'multiplant study' (Mundt et al., 2002). These four cohorts consist of employees in the chromate production industry, show an increased lung cancer risk (except the study by Luippold et al. (2005), exclude smoking as cause of lung cancer and have used a well-documented database of exposure measurements.

Seidler et al. selected five studies to establish an exposure-effect relationship (Gibb et al., 2000; Park et al., 2004; Park & Stayner, 2006) from the Baltimore cohort); (Crump et al., 2003) and (Luippold et al., 2003) from the Painesville cohort). In a subsequent meta-analysis an average dose-effect relationship was calculated, applying linear exposure-response models, for the Crump (2003) and the Park (2004) studies (characterized by a weighted average β value of 1.75). Thereafter, Seidler et al. (2013) calculated an extra lung cancer risk for Cr VI compounds of 4 per 10,000 (4×10^{-4}) after 40 year occupational exposure to 0.1 µg/m³ and 4 per 1,000 (4×10^{-3}) after 40 year occupational exposure to 1 µg/m³. See the study by (Seidler et al., 2013) for details of the calculation. DECOS considered it important that the calculations are based on multiple studies when possible (and thus not only by the study of Park (2004) as has been done in the risk assessment by NIOSH (2013)). Therefore DECOS prefers the study by Seidler et al. as starting point for its further risk assessment.

As a first step DECOS evaluated the calculations by Seidler et al. Based on the average slope of the dose-effect relationship of the two selected studies in the meta-analysis an extra risk is using mortality data from the Netherlands' population (from 2000 to 2010), separated by age and sex). Moreover, the cancer risk values are calculated taking into account a higher age (end of cohort at 100 years). This results into extra risks of respectively:

- 4 per 100,000 at exposure to 0.0104 µg/m³
- and 4 per 1,000 at exposure to 1.04 µg/m³.

These exposure levels are almost equal to those calculated by Seidler et al. DECOS

noted that the expected higher risks at higher age are probably compensated because male and female mortality data are combined in the DECOS calculation. When using only male mortality data, as was done by Seidler et al., the DECOS calculation would lead to an approximately 28% lower exposure level.

In addition, DECOS noted that the calculated exposure of $1 \mu\text{g}/\text{m}^3$ at an extra risk of 4 per 1,000 (based on the Seidler et al. data) equals the exposure calculated by the RAC-ECHA (also based on the Seidler et al. data) and the AGS (based on the data by Birk et al.).

DECOS estimates that the additional lifetime cancer risk for Cr VI compounds amounts to:

- 4×10^{-5} for 40 years of occupational exposure to $0.01 \mu\text{g}/\text{m}^3$
- and, 4×10^{-3} for 40 years of occupational exposure to $1 \mu\text{g}/\text{m}^3$.

7.7.2 Animal data

The carcinogenicity of a number of Cr VI compounds has been investigated in animal studies using various route of exposure; the most informative for the purpose of estimating cancer risks to humans in occupational settings are inhalation, intratracheal instillation and intrabronchial studies. In an inhalation study, in which rats were exposed to sodium chromate (0.025 , 0.05 or $0.1 \text{mg Cr}/\text{m}^3$), increased lung tumours occurred only at the highest dose. In a mouse inhalation study, increased lung tumours were associated with exposure the calcium chromate at the concentration used of ($4.3 \text{mg Cr}/\text{m}^3$). Two mouse inhalation studies showed a nonsignificant increase in lung tumours following exposure to chromium (IV) oxide. These inhalation studies all suffered from some deficiencies in design. Other inhalation studies, some of which investigated less soluble Cr VI compounds, had major deficiencies that prevented any conclusions being drawn. In one intratracheal instillation study, increased lung tumour incidence was reported in rats following exposure to calcium chromate. In the same study, sodium dichromate was associated with increased lung tumour incidence in rats with $1.25 \text{mg}/\text{kg}/\text{week}$ ($0.5 \text{mg Cr}/\text{kg}/\text{week}$) administered as one weekly dose, but not when the same weekly dose was administered in five instillations. Other intratracheal instillation studies had major limitations, which prevented any conclusions being drawn. An intrabronchial implantation study in rats demonstrated elevated lung cancer incidence with calcium chromate, strontium chromate and zinc chromate, but failed to demonstrate evidence for carcinogenicity of poorly soluble compounds (lead chromate or barium chromate) or sodium dichromate, although the method may be inappropriate for highly soluble compounds. On the basis of the animal carcinogenicity data, it is concluded that there is evidence to suggest a potency difference between Cr VI compounds, probably related to solubility and consequently bioavailability. However, the variation in design of the animal studies and, crucially, the scarcity of reliable data for poorly soluble Cr VI compounds precludes definite distinctions being made, either qualitative or quantitative, between Cr VI compounds on the basis of the available animal studies done alone (SCOEL 2004).

Present evaluation by SCOEL

The SCOEL considers that a risk assessment should be made using the best available data and methodology, leading to unbiased risk estimates. Therefore, SCOEL considers that a risk assessment from Cr VI should be made using exposure response studies that made use of Cr VI quantitative exposure estimates. In addition, the exposure response studies should be high quality studies, meaning that these studies do not suffer from strong epidemiological biases and preferably have made adjustments for smoking habits. SCOEL is also convinced that the lifetime excess risk should be calculated on the basis of a lifetable analysis, which gives the most accurate and precise estimate of the risk.

In case of Cr VI a few of such studies are available and these have recently been reviewed (Seidler et al., 2013). They estimated from an average dose-effect relationship,

applying linear models, for the Crump et al., (2003) and the Park et al., (2004) studies (characterized by a weighted average β value of 1.75) which involve the Painesville and Baltimore cohorts. This exposure-response slope was used for linear extrapolation and forms the basis for the SCOEL calculations. SCOEL used European lung cancer and total mortality data, to account for competing risks in a lifetable analysis, and assumed occupational exposure from age 20-60 (40 years) and calculated the excess risk for lung cancer. A latency period of 10 years was assumed. Calculations were made using a lifetable analysis which allows for competing risks (other causes of death) and as a result leads to precise risk estimates.

Risk calculations are shown below in chapter 8.

7.8. Reproductive toxicity

7.8.1. Human data

Studies, which have reported complications in pregnancy and childbirth in women employed in the chromate manufacturing industry, provide unreliable data (Shmitova 1978; Shmitova, 1980). Several investigations of male fertility have focussed on welding as an occupation. Some of these studies report effects on semen quality (Mortensen, 1988) whilst others do not (Bonde & Ernst, 1992; Jelnes & Knudsen, 1988). Furthermore, male-mediated spontaneous abortion among spouses of stainless steel welders has been suggested (Hjollund et al. 2000). However, the general absence of reliable and specific exposure data in these studies precludes any assessment of the relationship to Cr VI.

7.8.2. Animal data

A number of studies have investigated the effect of chromates on reproduction in animals. Parenteral administration of maternally toxic doses of chromium trioxide (3.9mg Cr/kg and above) to pregnant hamsters during gestation resulted in resorption and embryotoxicity (increased foetal resorption; subcutaneous oedema, delayed skeletal ossification and cleft palate in surviving embryos) (Gale, 1974; Gale 1978). Doses, which caused no maternal toxicity, caused cleft palate, hydrocephalus and delayed skeletal ossification in hamsters (2.6mg Cr/kg), but failed to induce embryotoxicity in rats (2mg Cr/kg). (Gale & Bunch, 1979; Mason et al, 1989). Repeat injection studies of sodium chromate in male rats (1- 4mg Cr/kg for 5 days) caused a reduction in body weight, a reduction in testicular weight, atrophy of seminiferous tubules and reduced sperm count. Caution is needed in the interpretation as the relevance of these studies on reproduction as the route of introduction by parenteral administration would avoid the normal reducing route for Cr VI by the oral or inhalation routes.

7.9. Mode of action and adverse outcome pathway considerations

As opposed to many other metal compounds, in case of Cr VI the formation of DNA adducts appears to play an important role in generating genomic instability and thus tumor formation (Hartwig, 2013; Wise & Wise, 2012). Under physiological conditions, Cr VI enters the cell as the anionic tetrahedral species chromate, CrO_4^{2-} , via anion transport systems such as the sulfate carrier, and is intracellularly reduced to Cr III, described by the so-called "uptake-reduction" model. Within the cell, reduction does not require enzymatic steps but is mediated by direct electron transfer from ascorbate and non-protein thiols such as glutathione and cysteine; during this process, potentially toxic intermediates such as oxygen and sulfur radicals are generated, dependent on the intracellular reductant. In case of poorly water soluble Cr VI compounds such as barium chromate and lead chromate, uptake is mediated via endocytosis. DNA lesions generated after exposure towards Cr VI consist of two categories, namely oxidatively induced DNA damage and DNA lesions resulting from Cr III-DNA interactions. With respect to the formation of ROS during the intracellular reduction process, the induction of oxidatively

damaged DNA by Cr VI appears to be restricted to high exposure concentrations, and its relevance on physiological conditions has been questioned. In contrast, especially ternary Cr-DNA adducts may be of special importance for chromate-induced carcinogenicity, where Cr bridges DNA and small molecules such as cysteine, histidine, glutathione or ascorbate, presumably arising from preformed Cr-ligand complexes during the reduction process. Under physiological conditions, ascorbate appears to be the major reductant, and especially ternary adducts formed from Cr-ascorbate are potent premutagenic DNA lesions. One other additional aspect of chromate-induced carcinogenicity is the induction of genomic instability, as evident by simultaneous occurrence of microsatellite instability and chromosome instability in Cr VI-induced tumors. This may be a consequence of disturbed DNA mismatch repair (MMR). Thus, Cr VI-induced DNA lesions lead to aberrant MMR, and upon chronic exposure to toxic doses of Cr VI the selective outgrowth of MMR-deficient clones exerting a high degree of genomic instability has been postulated. In summary, Cr VI acts directly genotoxic by inducing specific DNA lesions, which are not easily repaired; genomic instability is increased via mismatch-repair deficient cell clones which survive on the expense of hypermutability. Even though a fraction of Cr VI may be reduced extracellularly to Cr III, this fraction is currently not quantifiable. Due to the direct genotoxic mode of action, a linear dose-response relationship is assumed.

7.10. Lack of specific scientific information

On the basis of the animal carcinogenicity data, it is concluded that there is evidence to suggest a potency difference between Cr VI compounds, probably related to solubility and consequently bioavailability. However, the variation in design of the animal studies and, crucially, the scarcity of reliable data for poorly soluble Cr VI compounds precludes definite distinctions being made, either qualitative or quantitative, between Cr VI compounds on the basis of the available animal studies done alone.

The genotoxicity of Cr VI compounds has been widely investigated in assays for different genetic endpoints and has, with a few possible exceptions, been uniformly positive in in vitro assays for mutagenicity and clastogenicity, with evidence of in vivo expression of these effects in some compounds. The possible exceptions are lead and barium chromate and these two compounds have required solubilisation to elicit positive results in bacterial cell assays or to enhance their genotoxic activity in mammalian cells. Although there appears to be a difference in genotoxic potential between the various Cr VI compounds tested based on solubility, positive results were obtained with the poorly soluble compounds in some assays. It is therefore not possible to exclude any compounds tested from possessing some mutagenic or clastogenic potential.

8. CANCER RISK ASSESSMENT

On the basis of all the available evidence, it was concluded by SCOEL that Cr VI compounds are carcinogens with no threshold, carcinogen group A.

The SCOEL considers that a risk assessment should be made using the best available data and methodology, leading to unbiased risk estimates. Therefore, SCOEL considers that a risk assessment from Cr VI should be made using exposure response studies that made use of Cr VI quantitative exposure estimates. In addition, the exposure response studies should be high quality studies, meaning that these studies do not suffer from strong epidemiological biases and preferably have made adjustments for smoking habits. SCOEL is also convinced that the lifetime excess risk should be calculated on the basis of a lifetable analysis, which gives the most accurate and precise estimate of the risk.

In case of Cr VI a few of such studies are available and these have recently been reviewed (Seidler et al., 2013). They estimated from an average dose-effect relationship, applying linear models, for the Crump et al., (2003) and the Park et al., (2004) studies

(characterized by a weighted average β value of 1.75). SCOEL is aware of discussion in the literature on exposure thresholds and non-linear exposure response relations, regarding carcinogenic effects of Cr VI (see for instance Haney et al., 2015). First, the totality of the evidence regarding the mode of action mitigate against the conclusion that there is an exposure threshold. Second, some of the discussion in the epidemiological literature considers that the excess risk is only statistically significant for some of the higher exposed exposure categories. This observation is interpreted as evidence for an exposure threshold. However, the SCOEL does not agree with this interpretation because it focusses only on part of the exposure response curve, is not based on all exposure response information and ignores the statistically significant overall exposure response association (test for trend for the relation). Therefore, reliable published exposure-response slopes were used for linear extrapolation and they form the basis for the SCOEL calculations. SCOEL used European lung cancer and total mortality data, to account for competing risks in a lifetable analysis, and assumed occupational exposure from age 20-60 (40 years) and calculated the excess risk for lung cancer. A latency period of 10 years was assumed. Calculations were made using a lifetable analysis which allows for competing risks (other causes of death) and as a result leads to precise risk estimates.

For the calculations, a lifetable analysis was conducted as described by Goldbohm et al., (2006). Life table calculated risk, represents the excess risk from 40 years of occupational exposure, starting at age 20 and onwards, till a certain age, in this case a near maximum age of 100. Lifetable calculated risks take into account that individuals die of other causes of disease as well, apart from the disease of interest, in this case lung cancer. The following risk estimates were produced for the combined exposure response slopes and the individual studies used in the risk assessment. The confidence interval is based on a pooled standard error of the exposure response slopes:

Table 8: Estimates of excess lung cancer risk at different exposure levels during a work shift

Exposure 8 hour time weighted average	Number of excess lung cancer cases / 1000			
	Point estimate combined exposure response slopes	Confidence interval	(Crump et al., 2003)	(Park et al., 2004)
0.1 $\mu\text{g}/\text{m}^3$	0.4	0.3-0.5	0.2	0.6
1 $\mu\text{g}/\text{m}^3$	4	3.2-4.8	2	6
5 $\mu\text{g}/\text{m}^3$	20	16-24	8	32
10 $\mu\text{g}/\text{m}^3$	39	31-47	15	62
25 $\mu\text{g}/\text{m}^3$	94	76-112	38	146

Exposure at which excess risk benchmark values of 4/1000 and 4/100 000 workers are realised, are similar to the exposure estimates which have recently been published by other organisations and researchers and are presented in an overview produced by the Dutch Expert Committee for Occupational Standards (DECOS, 2016) These benchmarks are in some countries considered as 'acceptable' and 'negligible' risk levels respectively. Although the exposure which corresponds with these risks are similar, differences exist in the approaches taken to calculate these exposure estimates with some other risk assessments (AGS, 2014; DECOS, 2016; Seidler et al., 2013) The differences relate to a) methodology to estimate risk, b) age at which the risk is estimated, c) use of average male and female rates instead of male rates only. The different combinations of assumptions lead in the end to similar estimates as produced by the different sources.

Risk calculations require assumptions and practical choices. SCOEL used averaged male and female rates of lung cancer. Risk calculations based on male rates would have led to higher risk at the same exposure in comparison with a risk assessment based on average rates. Similarly, calculations till age 75 would lead to lower risks compared to the approach taken in this analysis (age 100). The effect of these assumptions has been quantified recently and can vary considerably depending on the combination of assumptions (DECOS, 2016; Seidler et al., 2013).

9. GROUPS AT EXTRA RISK

None identified

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