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Exposure to Fibres, Crystalline Silica, Silicon Carbide and Sulphur Dioxide in the Norwegian Silicon Carbide Industry

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Objectives: The aim of this study was to assess personal exposure to fibres, crystalline silica, silicon carbide (SiC) and sulphur dioxide in the Norwegian SiC industry.

Methods: Approximately 720 fibre samples, 720 respirable dust samples and 1400 total dust samples were collected from randomly chosen workers from the furnace, processing and maintenance departments in all three Norwegian SiC plants. The respirable dust samples were analysed for quartz, cristobalite and non-fibrous SiC content. Approximately 240 sulphur dioxide samples were collected from workers in the furnace department.

Results: The sorting operators from all plants, control room and cleaning operators in Plant A and charger, charger/mix and payloader operators in Plant C had a geometric mean (GM) of fibre exposure above the Norwegian occupational exposure limit (OEL) (0.1 fibre cm^{-3}). The cleaner operators in Plant A had the highest GM exposure to respirable quartz (20 μg m^{-3}). The charger/mix operators in Plant C had the highest GM exposure to respirable cristobalite (38 μg m^{-3}) and the refinery crusher operators in Plant A had the highest GM exposure to non-fibrous SiC (0.65 mg m^{-3}). Exposure to the crystalline silica and non-fibrous SiC was generally low and between 0.4 and 2.1% of the measurements exceeded the OELs. The cleaner operators in Plant A had the highest GM exposure to respirable dust (1.3 mg m^{-3}) and total dust (21 mg m^{-3}). GM exposures for respirable dust above the Norwegian SiC industry-specific OEL of 0.5 mg m^{-3} were also found for refinery crusher operators in all plants and mix, charger, charger/mix and sorting operators in Plant C. Only 4% of the total dust measurements exceeded the OEL for nuisance dust of (10 mg m^{-3}). Exposure to sulphur dioxide was generally low. However, peaks in the range of 10–100 p.p.m. were observed for control room and crane operators in Plants A and B and for charger and charger/mix operators in Plant C.

Conclusion: Workers in the SiC industry are exposed to a mixture of several agents including SiC fibres, quartz, cristobalite, non-fibrous SiC and sulphur dioxide. Exposure levels were generally below the current Norwegian OELs; however, high exposure to fibres and respirable dust still occurs in the furnace department.

Keywords: cristobalite; exposure assessment; fibres; quartz; respirable dust; silicon carbide; sulphur dioxide; total dust

INTRODUCTION

Silicon carbide (SiC) is produced by mixing quartz sand and petrol coke in an electric resistance furnace (Smoak *et al.*, 1978). Small-scale production of SiC was started by Edward Goodrich Acheson in the 1891 and has risen steadily since then (Smoak *et al.*, 1978). The global SiC production capacity was 1 010 000 metric tons in 2002, of these the Norwegian plants accounted for ∼8% (US Geological Survey, 2004). Important areas of application are as abrasive grains, construction and refractory materials, for metallurgical purposes, in diesel particle filters and in slicing of silicon wafers for the photovoltaic and semiconductor industry.

In the SiC production process, crystalline silica, SiC fibre, non-fibrous SiC, polycyclic aromatic

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hydrocarbons (PAHs), sulphur dioxide (SO_2) and carbon monoxide (CO) are released into the work environment (Smith *et al.*, 1984; Bye *et al.*, 1985; Dufresne *et al.*, 1987; Scansetti *et al.*, 1992; Petry *et al.*, 1994; Dion *et al.*, 2005). Many of these exposures have been linked to malignant and non-malignant respiratory diseases (Bruusgaard, 1948; Osterman *et al.*, 1989; Marcer *et al.*, 1992; Infante-Rivard *et al.*, 1994; Romundstad *et al.*, 2001, 2002). Several studies have reported an increased risk for pulmonary impairments, pneumoconiosis and lung cancer; however, specific exposure agents have not been linked to these outcomes.

The main objective of this study was to provide an overview of the contemporary dust, fibre and sulphur dioxide exposure levels in the SiC industry in Norway. This information will be used to improve a previously developed retrospective job-exposure matrix (Romundstad *et al.*, 2001), which will be applied in an ongoing epidemiological study on lung cancer and non-malignant respiratory diseases in the Norwegian SiC industry. The results may also be useful for risk assessment.

MATERIALS AND METHODS

SiC production

SiC appears in two different crystalline forms. The hexagonal α-SiC is the main product, while the cubic β-SiC is formed at lower temperatures and is used in the metallurgic industry or recycled into the furnace mix. SiC is produced as either green or black crystals from a mixture of high-grade quartz sand and petrol coke. In the production of black SiC product, reclaimed furnace mix and aluminium oxide may be added to the furnace mix, and sawdust is sometimes added to improve porosity of the furnace mix. The furnace mix is transported to the furnace building and loaded into an electrical resistance furnace with a graphite core in the centre. The furnace mix is heated electrically by the graphite core that functions as a resistance element. Quartz (SiO_2) will react with carbon and form α-SiC and carbon monoxide (CO) at temperatures >1700°C according to the chemical reaction:

$$SiO_2 + 3C \rightarrow SiC + 2CO.$$

After the completion of a furnace cycle (8–10 days), unreacted material is removed and returned to the mix area, while the crude SiC is transported to the sorting area. In the sorting area β-SiC is removed from α-SiC. α-SiC is then crushed and transported to the processing department where it is crushed further and treated chemically with pine oil, sulphuric acid and sodium hydroxide to remove unreacted crystalline silica, silicon and carbon. Metallic impurities are removed by magnetic separation. SiC is then sieved and classified into size fractions (grits) with a mass median particle size ranging from 0.1 to 880 μm. The high temperatures in the furnace will transform quartz into cristobalite, another crystalline form of silica. Sulphur impurities in the coke will lead to emission of sulphur dioxide.

A SiC plant can be divided into three different departments: furnace department where the crude SiC is produced, processing department where the SiC grits are manufactured and maintenance department responsible for maintenance work in all parts of the plant, see Fig. 1 and Table 1.

Plant characteristics

Exposure assessment was performed in all three Norwegian SiC plants. One plant is located in central Norway, while the two other plants are located in the southern part of Norway. The three plants employ a total of ~350 production and maintenance workers. The furnaces are located inside a furnace hall building. Differences between plants are described under the job groups in Table 1.

Sampling strategy

The agents that were measured were fibres, respirable quartz, respirable cristobalite, respirable non-fibrous SiC, respirable dust, total dust and sulphur dioxide. Other agents known to be present in the work atmosphere in the SiC industry are carbon monoxide, PAHs and amorphous silica. Carbon monoxide was not measured, as this gas was not expected to induce chronic respiratory effects. Amorphous silica was not analysed due to analytical limitations. PAHs were not quantified due to relative low levels reported in other studies (Dufresne *et al.*, 1987; Petry *et al.*, 1994).

Walk-through surveys of the plants were performed by one of the authors and information on jobs and tasks was collected. Workers were then divided into job groups performing similar tasks in similar work conditions. The jobs were categorized as described in detail in Table 1.

A random sample of workers from each group was invited to participate in the study and all except one agreed to participate. Exposure to dust and gas was determined by means of personal sampling. The aim was to measure two or more agents for each person for at least 2 days. Workers were interviewed after sampling for their perception of the work conditions and respirator use. There were no criteria given for stating normal/worse/better working conditions other than the workers' own perception of the work on that specific day

The sampling duration for sulphur dioxide, total dust full-shift samples and respirable dust was close to a full work shift (6–8 h). Sampling duration for total dust short-term and fibre samples was limited

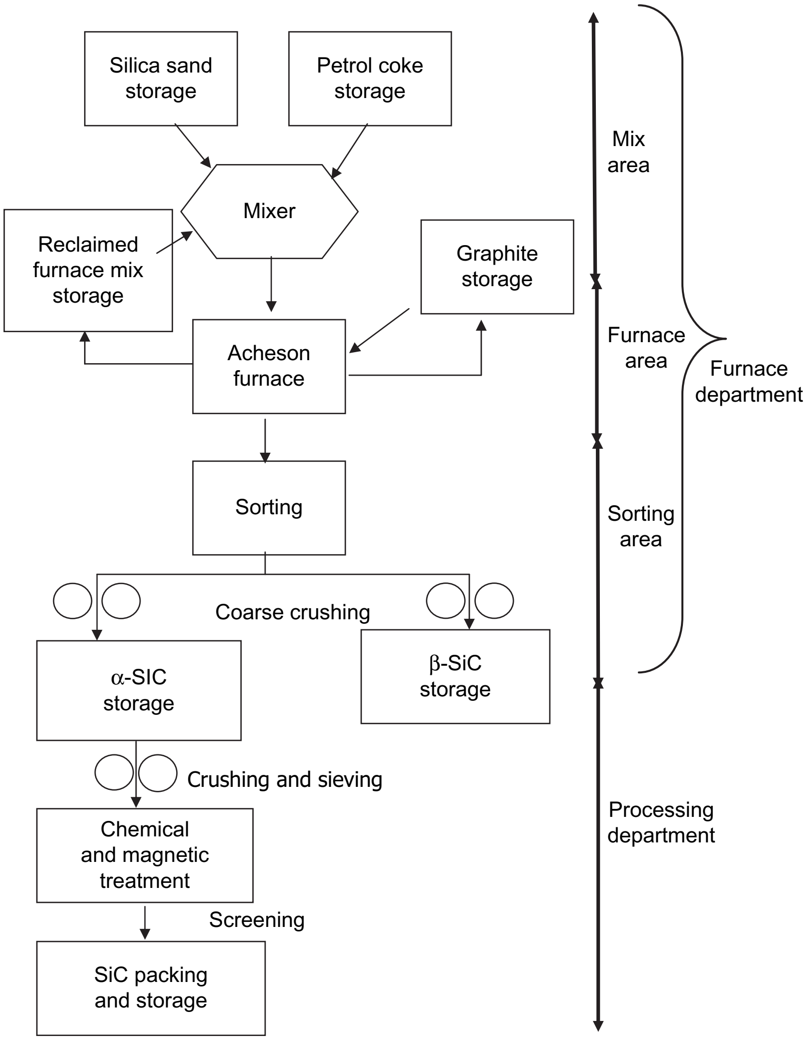

Fig. 1. Flow diagram over the SiC production.

to 0.5–3.5 h to avoid particle overload of the filter used for fibre analyses.

The sampling was performed between November 2002 and December 2003 and included two sampling periods of two work weeks (total 10 days). One sampling period was during autumn/winter (November–February) and the second period during spring/summer (May–August).

The work was organized as daytime only, two-shift schedule per day (morning and afternoon) or three-shift schedule per day (morning, afternoon and night). Sampling was evenly divided on morning and afternoon shifts. In addition, four night shifts per agent per job group were included in each plant.

Sampling methods and analysis

Total dust full-shift samples were collected on 37-mm cellulose acetate filters (Millipore Corporation, Bedford, NY, USA), with a 5.0-µm pore size, whereas the total dust short-term samples were collected on 37-mm Teflon (polytetrafluoroethylene) filters (Millipore Corporation). Both filters were fitted in 37-mm closed-faced aerosol filter cassettes (Millipore Corporation) applying a sampling flow rate of 2 l min^{-1}. Respirable dust was collected on 37-mm cellulose acetate filters with a pore size of 5.0 µm (Millipore Corporation) using a cyclone (Casella T13026/2, London, UK) at a sampling flow rate of 2.2 l min^{-1}. The particle mass was measured with a microbalance Sartorius Micro MC 210 P (Sartorius AG, Goettingen, Germany), with a detection limit of 0.06 mg. The detection limit with 8-h sampling time was therefore 0.063 mg m^{-3} for total dust and 0.057 mg m^{-3} for respirable dust. The amount of quartz, cristobalite and non-fibrous SiC in the respirable dust was determined by the use of X-ray powder diffractometry, applying Philips PW1729 X-ray generator, Phillips PW 1710 diffractometer control and Phillips APD software. The crystalline silica was determined by the use of standard methods (Bye, 1983; NIOSH, 1998) with

Table 1. Occupational job groups in the Norwegian SiC industry

Job groups	Description of work
Furnace department	
Mix operator (Plants A and C)	The mix operator is in charge of the mix building where the furnace mix is made from quartz sand, coke and recycled furnace mix. He supervises the process from a control room, but regular rounds inside the mixing plant are necessary. Raw materials are transported on elevators and transport bands and when there are jams or leaks, the mix operator has to clean up.
Charger (Plant C)	The charger operator is involved in construction of furnaces. He inserts insulation material between the elements in the furnace wall. He assists the crane operator in assembling the furnace and loads it with furnace mix and graphite while standing beside the furnace giving directions or inside the furnace steering the gondola when the graphite core is laid down. He also helps the crane operator to change equipment on the crane. He waits in the control room in the mix building when there is an intermission in the work.
Charger/mix operator (Plant C)	In the second sampling period, the plant had combined the charger and mix operator jobs into one job done by one person on each shift.
Crane operator (Plants A, B and C)	The crane operator works in fresh air-supplied closed cabins located close to the roof of the furnace plant. The crane transports furnace mix to furnaces being constructed and removes fully and partially reacted materials from the furnaces. Sometimes the operator has to leave the cabin in order to do manually work on the furnaces.
Payloader operator (Plants A, B and C)	The payloader operator transports raw materials (petrol coke and quartz sand) from storage rooms to elevators connected to the furnace building. When the elevators jams up or spills, he cleans up. Usually that means getting out of the payloader and doing it manually. He is also involved in emptying of the furnace by removing unreacted furnace mix from the furnace floor. He transports crude SiC from the furnace hall to the sorting building (Plant A) and transports coarse crushed SiC to the processing department. The payloader vehicles used are closed cabin vehicles.
Control room operator (Plants A, B and C)	The control room operator controls the furnaces and the dust release to the environment from a control room. He spends much of his time in the control room, but performs inspection rounds in the furnace plant and works in cranes and on furnace plant floor occasionally. He also has to connect and disconnect the furnace to the power line. The control room is either situated in the furnace building (Plant B) or in a separate building close to the furnace building (Plants A and C).
Cleaning operator (Plant A)	The cleaning operator performs manual cleaning of the area where reclaimed furnace mix is stored.
Sorting operator (Plants A, B and C)	The sorting operator sorts the furnace product so that partially reacted material is removed from the fully reacted SiC. The sorting department is either situated in a separate building (Plant A) or inside the furnace building (Plants B and C). The operators in Plants A and B work in closed cabin vehicles most of the time, most with fresh air supply. The operator in Plant C works in a closed cabin vehicle or in a fresh air-supplied room situated inside the furnace plant.
Processing department	
Refinery crusher operator (Plants A, B and C)	The crusher operator is the first operator to come in contact with the SiC transported from furnace department. He controls the crushing process. Other tasks are performed as well, depending on plant (e.g. sieving, cleaning and truck driving).
Refinery other operator (Plants A, B and C)	Other refinery workers grind, clean and screen the SiC from the furnace plant into various sizes. The product is then either transported to the fines area for further processing or packed into bags ready for sale.
Fines operator (Plants A, B and C)	The fines operator crushes, grinds, cleans and screens the SiC from the refinery area further into various sizes. The end product is packed into 25 or 1000 kg bags and stored ready for sale.
Maintenance department	
Mechanics (Plants A, B and C)	The mechanics do mechanical maintenance work in the furnace department, processing department, outdoor and in repair shops.
Electricians (Plants A, B and C)	The electricians do electrical maintenance work in the furnace department, processing department, outdoors and in the repair shop.

some modifications due to the presence of graphite in samples from the furnace hall. Graphite interferes with quartz in the analyses and was removed by high-temperature ashing (700°C). The detection limit for quartz was 5 μg, which amounts to 5.2 μg m^{-3} with 8-h sampling time, and for cristobalite 10 μg, which amounts to 10.4 μg m^{-3} with 8-h sampling time. Non-fibrous SiC was determined by a corresponding X-ray method developed in our laboratory (E Bye *et al*, in press). Pure SiC products from the three plants were used for calibration purposes. The detection limit for SiC was 12 μg which amounts to 0.013 mg m^{-3} with 8-h sampling time. Due to the detection limits of the XRD analytical methods, dust samples were combined if there was not enough dust to ensure sufficient material for analysis (>0.7 mg). Samples were combined within plant and job groups, preferably from the same persons. The detection limits apply to the combined samples and the detection limit for the individual samples would be lower depending on the amount of dust in the sample. The total number of samples was 680 and they were combined into 272 analyses.

Fibres were collected on 25-mm cellulose acetate filters (Millipore Corporation) with a pore size of 1.2 μm using an open-face aerosol filter cassette of conducting polypropylene (Gelman Sciences, Ann Arbor, MI, USA) at a sampling flow rate of 1 l min^{-1}. The fibres were counted with a light microscope according to World Health Organization (WHO) counting criteria (WHO, 1997) with a detection limit of four fibres which amounts to 0.016 fibres cm^{-3} with a sampling time of 2 h.

The samples were collected in parallel with a cyclone and a total dust cassette, or a fibre cassette and a short-term total dust cassette placed side by side on the worker. The two parallel cassettes were connected to the same high-flow pump through a hose with a Y-passage (SKC Inc., Eighty Four, PA, USA).

Sulphur dioxide was measured with direct-reading electrochemical sensors with a data-logging facility built into the instrument (PAC III Dräger Aktiengesellschaft, Lübeck, Germany). An averaging period of one reading every 10 s was selected. The detection limit was 0.2 p.p.m. for each 10-s period.

Quality control

One field blank was taken to the plants per day for every 10 particulate samples, with at least one blank per day. The average mass change of 1-day blanks were subtracted from the mass change for samples collected that day. The quality control procedures for the gravimetric measurements also included measuring two weights, at the beginning of each weighing session. The Norwegian Metrology Service calibrated the balances annually. The response factors of the electrochemical sensors were calibrated before each sampling period with calibration gas obtained from Hydrogass Norge AS, Oslo, Norway. Crystalline silica analyses were controlled by participation in an inter-laboratory proficiency-testing programme (Grunder, 2003).

Data analysis

Using cumulative probability plots, the exposure data were found to be best described by lognormal distributions and were $\log_{10}$ transformed before the statistical analyses. Standard measures of central tendency and distributions [arithmetic mean (AM), geometric mean (GM) and geometric standard deviation] were calculated. The GM was also calculated using mixed effect models, as was the 95th percentile. The mixed effects models were constructed with the exposure as the dependent variable. Exposure determinants were treated as fixed effects, whereas worker was treated as random effects. For sulphur dioxide measurements the highest value recorded for a 10-s averaging period within a work shift was registered as the maximum peak value.

Values below the limit of detection were treated as follows: readable values above the background noise level were directly applied in calculations and modelling, while non-readable values were substituted with the lowest readable value divided by the square root of two (Eduard, 2002).

The significance of differences in exposure levels among the job groups and plants was evaluated using *post hoc* tests with Bonferroni adjustment. In order to investigate whether the short-term samples were representative of full-shift exposure, we calculated the ratio of the adjusted GMs of short-term and full-shift total dust samples for each job group in all three plants.

The software package SPSS version 15.0 for Windows (SPSS Inc., Chicago, IL, USA) and SAS version 9.1 (SAS Institute Inc., Cary, NC, USA) was used for statistical analysis.

RESULTS

All measurements were carried out between November 2002 and December 2003. Most of the workers (77%) were monitored on more than one occasion. Results are shown in Tables 2–9 and Figs 2 and 3, and the GM referred to in the following text is the GM adjusted with mixed effect models.

Fibres

Most of the fibre sampling (90%) was initiated during the first half of the shift due to practical considerations. A total of 40% of the samples were below the detection limit. However, the fibre count was zero in only 9% of the samples. The fibre exposure levels are shown in Fig. 2 and Table 2. Highest GM of fibre exposures was found in the furnace and sorting areas in all plants, and the cleaning operators in Plant A had the highest exposure to fibres (2.7 fibres cm^{-3}). The control room, cleaning and sorting operators in Plant A, sorting operators in Plant B and charger, charger/mix, payloader and sorting operators in Plant C had all GM exposures of 0.1 fibres cm^{-3} or more. The sorting operators had significantly higher exposure in Plant C compared to the

Table 2. Summary of fibre levels by plant and job group, exposure intensity in samples collected with 0.5–3.5 h sampling time

Job group	Fibres (fibres per cm^3)																				
	Plant A							Plant B							Plant C						
	Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]	
	N[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]	*N*[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]	*N*[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]
Furnace																					
Mix	14	3	0.11	0.097	1.8	0.096	0.25								10	5	0.072	0.046	3.0	0.047	0.22
Charger															10	4	0.43	0.36	2.0	0.36	0.82
Charger/mix															11	5	0.39	0.31	2.2	0.31	0.88
Payloader	10	2	0.12	0.086	2.5	0.086	0.37	5	1	0.037	0.025	2.9	0.025	0.098	18	6	0.58	0.24	4.3	0.24	2.4
Crane	21	8	0.18	0.082	2.9	0.081	0.25	19	7	0.056	0.036	3.0	0.037	0.16	14	7	0.082	0.039	4.3	0.037	0.28
Control room	21	5	0.87	0.46	3.8	0.46	2.2	20	5	0.11	0.062	2.5	0.061	0.61	19	8	0.12	0.080	2.8	0.078	0.48
Cleaning	2	1	2.8	2.7	1.6	2.7	3.7														
Sorting	19	5	0.21	0.13	2.8	0.13	0.66	21	4	0.32	0.19	2.7	0.18	1.1	21	9	0.50	0.43	1.9	0.43	0.97
Processing																					
Refinery																					
Crusher	29	14	0.029	0.022	2.4	0.022	0.073	15	2	0.058	0.037	2.5	0.040	0.21	19	6	0.032	0.021	2.7	0.019	0.097
Other	29	13	0.050	0.030	2.4	0.031	0.12	27	13	0.019	0.015	2.3	0.015	0.044	32	8	0.019	0.013	2.7	0.013	0.048
Fines	36	21	0.015	0.011	2.2	0.011	0.044	60	23	0.010	0.007	2.3	0.007	0.034	49	19	0.014	0.011	2.2	0.011	0.035
Maintenance																					
Mechanics	48	18	0.057	0.034	2.9	0.035	0.16	47	16	0.050	0.017	4.0	0.017	0.24	27	9	0.092	0.049	3.0	0.051	0.42
Electrician	21	7	0.15	0.086	2.6	0.085	0.39	22	7	0.096	0.041	3.0	0.043	0.23	10	5	0.025	0.017	2.6	0.018	0.059

The Norwegian OEL for SiC fibre is 0.1 fibre per cm^3 (The Norwegian Labour Inspection Authority, 2007).
[a]Adjusted with mixed effect models.
[b]Number of measurements.
[c]Number of persons.
[d]Geometric standard deviation.
[e]95th percentile.

Table 3. Summary of respirable quartz levels by plant and job group, exposure intensity in samples collected with 6–8 h sampling time

Job group	Respirable quartz (μg m^{-3})																				
	Plant A							Plant B							Plant C						
	Unadjusted					Adjusted[a]		Undjusted					Adjusted[a]		Unadjusted					Adjusted[a]	
	N[b]	K[c]	AM	GM	GSD[d]	GM	P95[e]	N[b]	K[c]	AM	GM	GSD[d]	GM	P95[e]	N[b]	K[c]	AM	GM	GSD[d]	GM	P95[e]
Furnace																					
Mix	13	3	14	13	1.5	13	22								9	4	15	10	2.4	9.6	30
Charger															9	5	10	8.0	2.0	8.0	58
Charger/mix															10	5	21	13	2.9	12	12
Payloader	7	2	4.0	3.3	2.0	3.1	7.9	5	1	NA	NA	NA	NA	NA	17	9	3.5	2.5	2.4	2.5	33
Crane	23	7	NA	NA	NA	NA	NA	17	5	3.6	2.1	3.5	2.1	11	13	5	3.4	1.1	3.1	1.1	6.5
Control room	19	6	3.0	2.5	2.0	2.3	7.0	19	5	2.6	1.9	2.4	1.9	11	19	7	2.1	1.7	2.0	1.7	6.5
Cleaning	2	1	23	20	2.1	20	34														
Sorting	20	5	NA	NA	NA	NA	NA	18	4	2.4	1.2	4.3	1.2	8.7	18	9	6.6	4.3	3.4	4.4	22
Processing																					
Refinery																					
Crusher	29	11	2.8	1.2	4.9	1.2	9.0	13	3	1.7	0.51	7.2	0.49	8.4	19	6	2.6	1.8	2.8	1.9	9.8
Other	27	11	NA	NA	NA	NA	NA	26	14	1.8	0.90	4.5	0.88	6.1	31	8	2.3	0.93	6.5	1.1	6.5
Fines	20	14	NA	NA	NA	NA	NA	56	22	1.5	0.42	7.8	0.44	5.1	48	15	NA	NA	NA	NA	NA
Maintenance																					
Mechanics	47	17	1.8	0.67	5.3	0.75	5.1	48	18	17	1.5	5.2	1.5	45	28	9	NA	NA	NA	NA	NA
Electrician	20	7	2.3	1.5	2.8	1.5	8.0	20	7	17	2.3	7.3	2.4	123	10	5	NA	NA	NA	NA	NA

The Norwegian OEL for respirable quartz is 100 μg m^{-3} (The Norwegian Labour Inspection Authority, 2007).
NA, not applicable, all measurements below limit of detection (5.2 μg m^{-3} for 8-h sampling time).
[a]Adjusted with mixed effect models.
[b]Number of measurements.
[c]Number of persons.
[d]Geometric standard deviation.
[e]95th percentile.

Table 4. Summary of respirable cristobalite levels by plant and job group, exposure intensity in samples collected with 6–8 h sampling time

Job group	Respirable cristobalite (μg m^{-3})																				
	Plant A							Plant B							Plant C						
	Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]	
	N[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]	*N*[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]	*N*[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]
Furnace																					
Mix	13	3	NA	NA	NA	NA	NA								9	4	36	12	4.7	11	148
Charger															9	5	31	22	2.4	23	102
Charger/mix															10	5	46	38	2.0	35	98
Payloader	7	2	4.9	1.5	8.9	0.99	20	5	1	NA	NA	NA	NA	NA	17	9	26	15	2.8	15	116
Crane	23	7	1.6	0.55	3.4	0.55	10	17	5	4.2	3.0	2.4	2.9	14	13	5	12	2.2	3.7	2.1	135
Control room	19	6	3.9	3.1	2.0	2.9	11	19	5	3.5	2.2	2.6	2.1	16	19	7	5.6	4.7	1.9	4.7	14
Cleaning	2	1	29	29	1.2	29	33														
Sorting	20	5	NA	NA	NA	NA	NA	18	4	27	12	3.5	12	115	18	9	19	17	1.5	17	39
Processing																					
Refinery																					
Crusher	29	11	NA	NA	NA	NA	NA	13	3	9.9	6.4	2.7	6.4	36	19	6	4.1	2.5	2.7	2.6	24
Other	27	11	NA	NA	NA	NA	NA	26	14	3.1	1.6	3.3	1.6	13	31	8	NA	NA	NA	NA	NA
Fines	20	14	NA	NA	NA	NA	NA	56	22	NA	NA	NA	NA	NA	48	15	NA	NA	NA	NA	NA
Maintenance																					
Mechanics	47	17	1.4	0.50	6.0	0.52	2.6	48	18	2.8	0.87	6.0	0.74	9.8	28	9	1.7	0.31	12	0.33	6.5
Electrician	20	7	NA	NA	NA	NA	NA	20	7	1.7	0.80	4.0	0.79	7.1	10	5	NA	NA	NA	NA	NA

The Norwegian OEL for respirable cristobalite is 50 μg m^{-3} (The Norwegian Labour Inspection Authority, 2007).
NA, not applicable, all measurements below limit of detection (10.4 μg m^{-3} for 8-h sampling time).
[a]Adjusted with mixed effect models
[b]Number of measurements.
[c]Number of persons.
[d]Geometric standard deviation.
[e]95th percentile.

Table 5. Summary of respirable non-fibrous SiC levels by plant and job group, exposure intensity in samples collected with 6–8 h sampling time

Job group	Respirable non-fibrous SiC (mg m^{-3})																				
	Plant A							Plant B							Plant C						
	Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]	
	N[b]	K[c]	AM	GM	GSD[d]	GM	P95[e]	N[b]	K[c]	AM	GM	GSD[d]	GM	P95[e]	N[b]	K[c]	AM	GM	GSD[d]	GM	P95[e]
Furnace																					
Mix	13	3	0.014	0.009	2.6	0.010	0.72								9	4	0.066	0.036	3.0	0.034	0.22
Charger															9	5	0.075	0.067	1.7	0.068	0.16
Charger/mix															10	5	0.18	0.14	2.1	0.13	0.53
Payloader	7	2	0.17	0.047	6.9	0.033	0.071	5	1	0.046	0.044	1.4	0.044	0.052	17	9	0.046	0.032	2.4	0.032	0.17
Crane	23	7	0.014	0.008	2.6	0.008	0.097	17	5	0.019	0.015	2.2	0.015	0.052	13	5	0.016	0.004	3.2	0.004	0.16
Control room	19	6	0.044	0.038	1.8	0.035	0.097	19	5	0.034	0.022	2.5	0.022	0.16	19	7	0.011	0.008	2.1	0.008	0.029
Cleaning	2	1	0.54	0.49	1.9	0.49	0.77														
Sorting	20	5	0.10	0.086	1.7	0.083	0.26	18	4	0.48	0.24	3.1	0.22	3.6	18	9	0.35	0.31	1.7	0.31	0.68
Processing																					
Refinery																					
Crusher	29	11	0.89	0.65	2.4	0.65	2.1	13	3	0.54	0.36	2.5	0.39	2.1	19	6	0.69	0.45	2.4	0.46	3.8
Other	27	11	0.11	0.087	2.0	0.087	0.30	26	14	0.26	0.11	3.6	0.11	1.2	31	8	0.38	0.22	2.8	0.27	1.4
Fines	20	14	0.12	0.083	2.3	0.081	0.41	56	22	0.29	0.16	3.1	0.18	0.98	48	15	0.29	0.22	2.0	0.22	0.84
Maintenance																					
Mechanics	47	17	0.098	0.054	3.0	0.053	0.40	48	18	0.14	0.076	3.1	0.079	0.52	28	9	0.075	0.039	2.8	0.042	0.28
Electrician	20	7	0.068	0.052	2.2	0.052	0.17	20	7	0.12	0.068	2.5	0.067	0.55	10	5	0.086	0.038	3.9	0.038	0.33

There is no Norwegian OEL for respirable SiC; however, American Conference of Industrial Hygienists have suggested a threshold limit value of 3 mg m^{-3} (ACGIH, 2007).
[a]Adjusted with mixed effect models.
[b]Number of measurements.
[c]Number of persons.
[d]Geometric standard deviation.
[e]95th percentile.

Table 6. Summary of respirable dust levels by plant and job group, exposure intensity in samples collected with 6–8 h sampling time

Job group	Respirable dust (mg m^{-3})																				
	Plant A							Plant B							Plant C						
	Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]	
	N[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]	*N*[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]	*N*[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]
Furnace																					
Mix	13	3	0.45	0.41	1.6	0.41	0.99								10	4	1.2	0.72	2.7	0.72	4.2
Charger															9	5	0.80	0.70	1.7	0.70	1.8
Charger/mix															10	5	1.1	0.99	1.7	0.93	1.8
Payloader	7	2	0.54	0.40	2.2	0.38	1.7	5	1	0.24	0.23	1.4	0.23	0.32	18	9	0.33	0.22	2.7	0.21	1.3
Crane	23	7	0.17	0.12	2.2	0.12	0.50	17	5	0.26	0.23	1.7	0.23	0.45	14	5	0.25	0.13	2.5	0.12	2.0
Control room	18	5	0.28	0.25	1.6	0.25	0.55	19	5	0.28	0.24	1.8	0.24	0.76	19	7	0.20	0.17	1.8	0.17	0.40
Cleaning	2	1	1.3	1.3	1.1	1.3	1.4														
Sorting	20	5	0.22	0.19	1.6	0.19	0.49	20	4	0.79	0.48	2.8	0.45	3.1	19	9	1.4	0.75	2.2	0.74	13
Processing																					
Refinery																					
Crusher	29	11	1.1	0.86	2.0	0.85	2.00	13	3	0.82	0.63	2.1	0.68	2.6	19	6	0.80	0.55	2.3	0.56	4.3
Other	27	11	0.23	0.21	1.6	0.20	0.41	27	15	0.43	0.27	2.5	0.28	1.7	31	8	0.54	0.40	2.2	0.45	1.4
Fines	30	17	0.81	0.19	3.0	0.20	0.65	56	22	0.49	0.30	2.7	0.34	1.3	49	15	0.37	0.30	1.8	0.30	1.0
Maintenance																					
Mechanics	49	17	0.31	0.25	1.9	0.25	0.77	48	18	0.59	0.41	2.4	0.40	1.5	28	9	0.28	0.22	2.0	0.23	0.85
Electrician	20	7	0.24	0.21	1.7	0.21	0.49	23	7	0.28	0.21	2.2	0.21	0.82	10	5	0.21	0.18	1.7	0.18	0.54

The Norwegian OEL for respirable dust is 0.5 mg m^{-3} in the furnace department and 5.0 mg m^{-3} in other areas (The Norwegian Labour Inspection Authority, 2007).
[a]Adjusted with mixed effect models.
[b]Number of measurements.
[c]Number of persons.
[d]Geometric standard deviation.
[e]95th percentile.

Table 7. Summary of total dust full-shift levels by plant and job group

Job group	Total dust (mg m^{-3})																				
	Plant A							Plant B							Plant C						
	Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]	
	N[b]	K[c]	AM	GM	GSD[d]	GM	P95[e]	N[b]	K[c]	AM	GM	GSD[d]	GM	P95[e]	N[b]	K[c]	AM	GM	GSD[d]	GM	P95[e]
Furnace																					
Mix	13	3	1.5	1.0	3.7	1.1	3.3								9	4	3.9	3.0	2.1	2.8	10
Charger															8	5	4.6	4.1	1.7	4.2	7.4
Charger/mix															10	5	9.3	7.6	1.8	7.3	24
Payloader	7	2	2.7	1.3	3.6	1.1	10	5	1	1.2	1.1	1.8	1.0	1.9	18	9	2.0	1.3	2.6	1.3	6.7
Crane	23	7	0.85	0.37	2.7	0.37	2.5	17	5	1.5	1.1	2.2	1.1	5.2	13	5	0.72	0.29	3.5	0.29	5.6
Control room	19	6	1.3	1.2	1.7	1.1	2.8	20	5	1.3	1.1	2.0	1.0	3.0	19	7	1.3	1.1	2.0	1.1	3.5
Cleaning	2	1	22	21	1.3	21	25														
Sorting	20	5	1.1	0.82	2.1	0.82	3.9	20	4	5.0	2.9	3.2	2.7	17	18	9	5.3	4.8	1.6	4.5	11
Processing																					
Refinery																					
Crusher	28	11	7.4	4.8	2.5	4.8	30	12	3	4.0	3.2	2.0	3.5	9.8	19	6	4.7	3.4	2.2	3.5	23
Other	25	11	1.4	1.1	1.9	1.1	3.5	27	14	2.5	1.2	3.1	1.1	9.3	31	8	2.7	2.1	2.1	2.4	6.3
Fines	32	17	9.2	3.0	4.3	2.9	47	57	23	3.7	1.7	4.3	1.9	11	49	15	3.3	2.2	2.2	2.2	7.4
Maintenance																					
Mechanics	48	17	1.5	1.0	2.5	1.0	4.7	47	18	3.1	2.0	2.8	2.0	7.9	28	9	1.8	1.3	2.3	1.4	6.7
Electrician	20	7	1.3	0.95	2.3	0.97	3.2	23	7	2.0	1.1	3.1	1.1	7.7	10	5	1.8	0.88	3.0	0.88	9.3

The Norwegian OEL for total dust is 10 mg m^{-3} (The Norwegian Labour Inspection Authority, 2007).
[a]Adjusted with mixed effect models.
[b]Number of measurements.
[c]Number of persons.
[d]Geometric standard deviation.
[e]95th percentile.

Table 8. Summary of total dust short-term levels by plant and job group, exposure intensity in samples collected with 0.5–3.5 h sampling time

Job group	Total dust short-term (mg m^{-3})																				
	Plant A							Plant B							Plant C						
	Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]		Unadjusted					Adjusted[a]	
	N[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]	*N*[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]	*N*[b]	*K*[c]	AM	GM	GSD[d]	GM	P95[e]
Furnace																					
Mix	13	3	2.3	1.4	2.9	1.5	8.6								10	5	3.0	1.3	3.0	1.3	20
Charger															10	4	7.3	6.9	1.4	6.9	11
Charger/mix															11	5	6.2	5.1	1.7	5.3	23
Payloader	10	2	2.2	1.1	3.6	1.1	7.9	5	1	6.7	2.3	6.3	2.3	22	18	6	2.3	1.2	3.3	1.2	8.5
Crane	20	8	0.57	0.42	1.9	0.42	2.2	19	7	0.84	0.52	3.0	0.61	2.9	14	7	0.52	0.38	2.4	0.37	1.5
Control room	21	5	1.9	1.3	2.5	1.3	4.2	19	5	1.5	1.2	1.9	1.2	4.6	18	8	1.2	0.81	2.7	0.85	4.7
Cleaning	1	1	3.9	3.9		3.9	3.9														
Sorting	19	5	1.5	1.0	2.3	0.99	7.1	20	4	4.3	2.7	2.6	2.5	13	21	9	7.5	5.4	2.1	5.2	23
Processing																					
Refinery																					
Crusher	25	14	5.3	3.8	2.4	3.6	13	15	2	5.0	3.7	2.4	3.6	13	19	6	2.3	1.7	2.2	1.6	9.1
Other	28	12	1.3	0.98	2.3	0.87	3.4	27	13	1.3	0.94	2.3	0.95	4.1	32	8	2.4	1.8	2.3	1.9	8.0
Fines	31	21	5.8	2.4	4.2	2.5	24	60	23	2.7	1.3	3.5	1.5	9.0	49	19	3.1	1.8	2.8	1.8	11
Maintenance																					
Mechanics	47	18	1.2	0.75	2.8	0.76	3.8	47	16	2.0	1.1	3.2	1.0	7.5	27	9	1.9	1.4	2.3	1.4	4.6
Electrician	21	7	0.85	0.65	2.0	0.63	2.7	22	7	1.1	0.41	4.4	0.43	2.4	10	5	0.74	0.34	3.2	0.36	4.1

[a]Adjusted with mixed effect models.
[b]Number of measurements.
[c]Number of persons.
[d]Geometric standard deviation.
[e]95th percentile.

Table 9. Summary of sulphur dioxide exposure levels by plant and job group, actual concentrations after 6–8 h sampling time

Job group	Sulphur dioxide (p.p.m.)																							
	Plant A								Plant B								Plant C							
						Maximum peak value[a]								Maximum peak value[a]								Maximum peak value[a]		
	N[b]	*K*[c]	GM	GSD[d]	GM	GM[e]	GM	P95[f]	*N*[b]	*K*[c]	GM	GSD[d]	GM[e]	GM	GM[e]	P95[f]	*N*[b]	*K*[c]	GM	GSD[d]	GM[e]	GM	GM[e]	P95[f]
Furnace																								
Mix	12	3	0.001	11	0.001	0.45	0.45	2.3									10	4	0.008	3.4	0.007	0.63	0.62	3.0
Charger																	10	4	0.37	2.1	0.37	5.0	5.0	11
Charger/mix																	10	5	0.37	1.9	0.37	6.9	7.1	18
Payloader	9	2	0.002	15	0.002	0.72	0.72	3.6	5	1	0.006	25	0.006	0.42	0.42	0.90	18	7	0.065	2.8	0.065	0.74	0.73	2.2
Crane	23	8	0.016	3.6	0.016	2.3	2.3	8.1	22	6	0.28	2.3	0.28	9.6	9.6	19	12	6	0.013	3.7	0.013	2.0	2.0	6.7
Control room	20	6	0.036	3.6	0.036	3.2	3.2	58	20	5	0.27	2.9	0.27	13	13	36	17	8	0.061	2.6	0.061	4.0	4.0	17
Cleaning	1	1	NA	NA	NA	NA	NA	NA																
Sorting	3	2	NA	NA	NA	NA	NA	NA	19	4	0.19	4.0	0.19	2.7	2.7	24	20	9	0.12	4.1	0.12	2.0	2.1	6.0

The Norwegian OEL for sulphur dioxide is 2 p.p.m. (The Norwegian Labour Inspection Authority, 2007).
NA, not applicable, all measurements below limit of detection, a measurement is below the limit of detection when all its 10-s reading periods are <0.2 p.p.m.
[a]Maximum observed peak value for a 10-s averaging period within shift measurements.
[b]Number of measurements.
[c]Number of persons.
[d]Geometric standard deviation.
[e]GM adjusted with linear mixed effect models.
[f]95th percentile adjusted with linear mixed effect models.

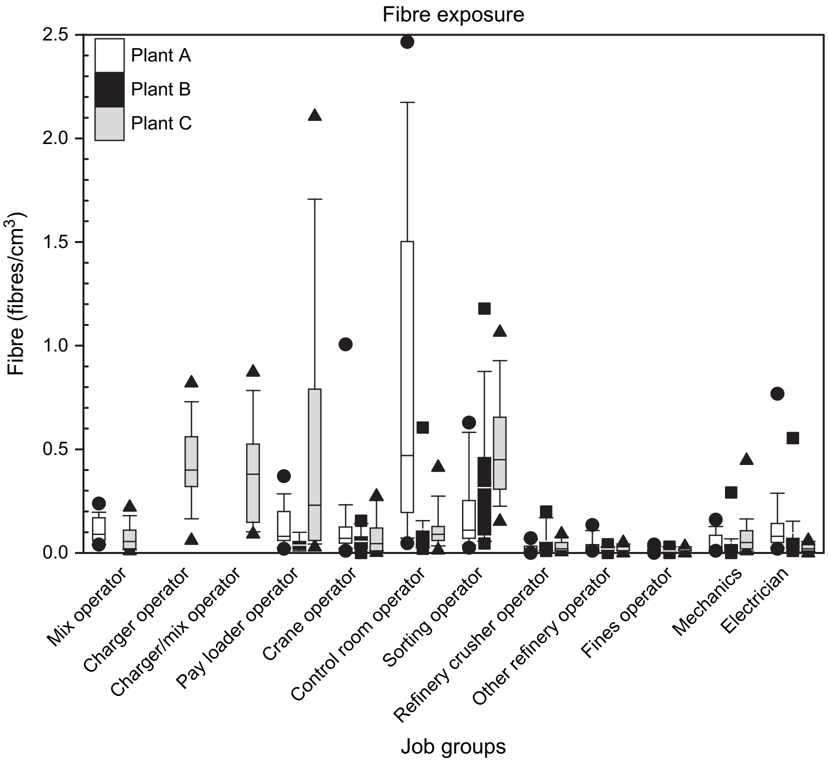

Fig. 2. Box plot of fibre exposure in fibre per cm^3 for job groups in Plants A, B and C. The exposure for the cleaning operator is not included due to too few exposure measurements. The box bounds the 25th and 75th percentiles, encompasses 50% of the data and includes the median (solid line within the box). Dispersion of the data above and below this range is marked by whiskers that extend to the 10th and 90th percentiles. Points above or below the whiskers represent the 95th and 5th percentiles.

other plants ($P < 0.05$). Control room operators had significantly higher exposure to fibres in Plant A compared to the two other plants ($P < 0.05$). The Norwegian occupational exposure limit (OEL) for SiC fibres of 0.1 fibre cm^{-3} was exceeded by 53% of the samples from the furnace department and 17% of the samples from the maintenance department (The Norwegian Labour Inspection Authority, 2007). Only 0.2% of the samples from the processing department exceeded the OEL.

Crystalline silica

The cleaning operators in Plant A had the highest GM exposure to respirable quartz (20 μg m^{-3}). The GM exposure of the mix operators in Plants A and C and charger/mix and charger operators in Plant C varied between 13 and 8.0 μg m^{-3}, while all other job groups had a GM exposure of <5 μg m^{-3} (Table 3). The sorting operators in Plant C had a significantly higher exposure to quartz than the sorting operators in the two other plants ($P < 0.05$). The quartz exposures were generally low and <1% of the samples exceeded the OEL of 100 μg m^{-3} (The Norwegian Labour Inspection Authority, 2007). The samples exceeding the OEL were all from the maintenance department in Plant B.

The job group exposed to the highest levels of respirable cristobalite was the charger/mix operators in Plant C (GM = 35 μg m^{-3}) (Table 4). GM exposures >10 μg m^{-3} were found among the cleaning operators in Plant A, sorting operators in Plants B and C and the mix, charger and payloader operators in Plant C. The mix operators, crane and sorting operators had significantly lower exposure in Plant A compared to the two other plants ($P < 0.01$). The OEL of 50 μg m^{-3} was exceeded in 2.1% of the samples (The Norwegian Labour Inspection Authority, 2007).

The crystalline silica exposures for workers in the processing department and in the maintenance department were generally low. More than 90% of the cristobalite samples from each of these departments were below the detection limit and the corresponding results for quartz exposure levels in these departments were 65 and 58%, respectively.

Respirable non-fibrous SiC

The highest GM exposure to respirable non-fibrous SiC was found among the crusher operators (GM = 0.39–0.65 mg m^{-3}) and the cleaning operators in Plant A (GM = 0.49 mg m^{-3}) (Table 5). The mix, sorting and fines operators had a significantly lower

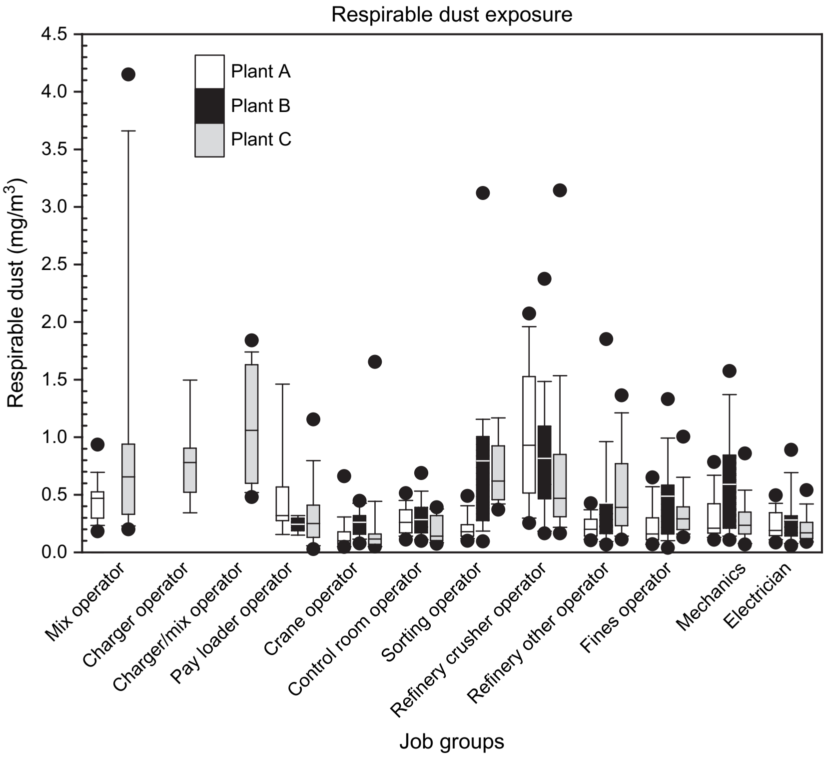

Fig. 3. Box plot of respirable dust exposure in mg m^{-3} for job groups in Plants A, B and C. The exposure for the cleaning operator is not included due to too few exposure measurements. The description of the box plots is the same as in Fig. 2.

exposure in Plant A compared to the two other plants ($P < 0.05$). The control room operators had a significantly lower exposure in Plant C compared to the two other plants ($P < 0.001$). Norway does not have a specific OEL for respirable non-fibrous SiC. The American Conference of Industrial Hygienists has recommended a threshold limit value of 3 mg m^{-3} (ACGIH, 2007) and only 0.4% of the measurements exceeded this limit.

Quantified crystalline components

The respirable dust in the furnace department contained on average 18% SiC, 1.1% quartz and 2.1% cristobalite. In the respirable dust from the processing department, we found 57% SiC, 0.2% quartz and 0.1% cristobalite, while the respirable dust in the maintenance department contained 21% SiC, 0.5% quartz and 0.2% cristobalite.

Respirable dust

The respirable dust exposure levels are shown in Fig. 3 and Table 6. The highest GM exposures to respirable dust (>0.5 mg m^{-3}) were found among cleaning operators in Plant A, mix, charger, charger/mix and sorting operators in Plant C and crusher operators in all plants. When comparing plants, sorting operators in Plant A had significantly lower exposure levels than the sorting operators in the other plants ($P < 0.05$) and the mechanics in Plant B had a significantly higher exposure than the other two plants ($P < 0.05$). The Norwegian OEL for mixed respirable dust is 0.5 mg m^{-3} in the furnace department and furnace-related areas of the SiC industry (The Norwegian Labour Inspection Authority, 2007). A total of 26% of the samples from the furnace department and 15% of the samples from maintenance workers performing maintenance in the furnace department exceeded this limit. Since there is no specific OEL for respirable dust in the processing department, the OEL for nuisance respirable dust of 5 mg m^{-3} was applied here (The Norwegian Labour Inspection Authority, 2007). Only 0.4% of the samples in the processing department and none of the samples from maintenance workers performing maintenance work in the processing department exceeded this limit.

Total dust

Cleaning and crusher operators in Plant A and charger, charger/mix and sorting operators in Plant C had GM exposures to total dust of 4 mg m^{-3} or higher (Table 7). The cleaning operators had four times higher GM exposure than any of the other job groups, but this observation was based on only two measurements. The sorting operators had a significantly lower exposure in Plant A compared to Plants B and C ($P < 0.001$) and the crane operators in Plant B had a significantly higher exposure compared to crane operators in the two other plants ($P < 0.001$). As there is no specific OEL for total dust in the SiC industry, the Norwegian OEL for nuisance total dust of 10 mg m^{-3} was applied here (The Norwegian Labour Inspection Authority, 2007). This OEL does not take into account that the dust might contain harmful components. Four per cent of the samples were above the OEL and two-thirds of these were from the fines or refinery crusher operators.

Table 8 summarizes the total dust short-term exposure levels. The job group GM ratios of short-term to full-shift total dust samples varied from 0.19 to 1.4 in Plant A, 2.3 to 0.55 in Plant B and 0.4 to 1.2 in Plant C. However, the GM ratios for the separate plants were close to 1; 0.9 for Plant A and C and 1.0 for Plant B.

Sulphur dioxide

Sulphur dioxide exposure was assessed for job groups in the furnace hall. The mean exposure to sulphur dioxide over a full shift was generally low. The charger and charger/mix operators had the highest measured GM (0.37 p.p.m.), which is one-fifth of the OEL of 2 p.p.m. (Table 9) (The Norwegian Labour Inspection Authority, 2007). The highest GM for maximum peak value was found among the control room operators in Plant B (13 p.p.m.) (Table 9). The crane and control room operators in Plant B had a significantly higher maximum peak value compared to the same job groups in the other plants ($P < 0.05$). The sorting operators in Plant A had a significantly lower exposure than the sorting operators in the two other plants ($P < 0.001$).

Use of respirators

Respirators were available for all workers. The use of respirators was mandatory for workers in the furnace hall and for some operations in the refinery department (e.g. packing and cleaning). Different types of respirators were used [i.e. disposable half-masks with P2 or P3 particulate filters, half-masks with particulate filter and gas filter for acid gases (SO_2), powered air-purifying respirators, compressed air-fed respirators and self-contained breathing apparatus (when concentrations of CO were high)]. Most of the workers (74%) reported using respirators some or all of the time during the sampling. The use of respirators varied between plants, and 79% of the workers in Plant C used respirators all or some of the time compared to ~50% of the workers in Plants A and B. The use also varied within plants with 78% of the workers in the furnace department using respirators some or all of the time compared to 46% in refinery and maintenance departments. When measurements exceeded the OEL, between 79 and 100% of the workers had used respirators some or all of the time depending on component. The GM exposure for total dust was 79% higher among workers using respirators all the time, and 65% higher among workers using respirators some of the time compared to workers not using respirators. Similar trends were seen for all other agents.

Work conditions

Ninety-three per cent of the workers reported their perception of the work conditions of the shift. Of these, 84% reported that the conditions were normal, 6% reported it to be worse than normal and 10% reported better than normal.

DISCUSSION

The workers in the SiC industry are exposed to many different agents. In the present investigation, relatively high levels of fibres, quartz, cristobalite and sulphur dioxide were found in the furnace department while the highest exposure levels to non-fibrous SiC dust were observed in the processing department. Exposure levels were generally below the current Norwegian OELs, except for operators in the furnace department where 53% of the fibre and 26% of the respirable dust samples exceeded the OEL. Overall the operators reported that 85% of the measurements were performed under what they considered as normal work conditions. Previous studies of personal exposure in the SiC industry have been carried out in Canada and Norway (Smith *et al.*, 1984; Dufresne *et al.*, 1987; Romundstad *et al.*, 2001; Dion *et al.*, 2005). These studies reported exposure levels of one or more of the agents investigated in the present study; however, the job groups studied were not always comparable to the job groups in the present study.

Exposure to fibres was mainly found among workers in the furnace department. Gunnæs *et al.* (2005) found that airborne SiC fibres in the three Norwegian SiC plants mainly consisted of cubic β-SiC. They also found accumulation of the same β-SiC fibres in the outermost layer of the crude SiC. This layer is removed from the α-SiC in the sorting area prior to transport of α-SiC to the processing department. The sorting operators were therefore likely to be exposed to fibres and they were the highest exposed workers in Plants B and C. Compared to earlier studies, the fibre exposure levels found for sorting operators were lower than those reported by Romundstad *et al.* (2001) (AM = 0.8–1.8 fibres cm^{-3}). Dion *et al.* (2005) found similar levels for sorting operators as in Plant C (AM = 0.5

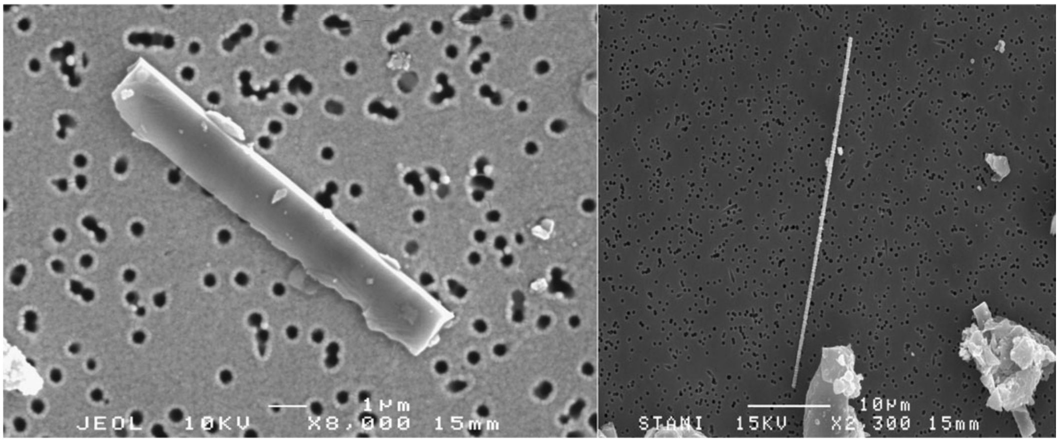

Fig. 4. SEM image of a SiC cleavage fragment to the left and a SiC fibre to the right. The scale bar represents 1 μm on the image to the left and 10 μm on the image to the right. In courtesy of Asbjørn Skogstad, National Institute of Occupational Health, Norway.

fibres cm^{-3}). The charger and charger/mix operators in Plant C were also highly exposed (AM = 0.43 and 0.39 fibres cm^{-3}, respectively) probably because the β-SiC is recycled into the furnace mix and these operators are involved in assembling and loading of furnaces. Romundstad *et al.* (2001) reported an AM of 0.4 fibres cm^{-3} for the charger operators in Plant C, which is similar to what we found. The control room operators in Plant A had a six times higher fibre exposure than the control room operators in the two other plants. This is probably because the control room operators in Plant A supervise the automatic feeder of reclaimed materials to the furnace mix. When there are leaks or jams in this system, the control room operators also cleans up spills. Dion *et al.* (2005) reported a GM of 0.06 fibres cm^{-3} among control room operators, which is similar to Plant B. The cleaning operators in Plant A had a high exposure of fibres, which is probably due to the fibre content of the reclaimed furnace mix that is stored in the area he is responsible for cleaning. The exposure levels of refinery operators were similar to the values reported by Romundstad *et al.* (2001) (AM = 0.04 fibres cm^{-3}) and Dion *et al.* (2005) found similar levels for maintenance operators as observed in Plant A (AM = 0.09 fibres cm^{-3}).

Fibres were counted with a light microscope, which does not provide information on the fibre types present or fibres thinner than ~0.25 μm. However, Skogstad *et al.* (2006) characterized fibres from the furnace department in the Norwegian SiC plants by scanning electron microscopy (SEM)–energy dispersive spectroscopy. They found that >93% of the fibres were SiC fibres and that the SiC fibres could be divided into eight categories based on their morphology. They also found that <2% of the fibres in the furnace department were fragments of SiC satisfying the WHO counting criteria for length, diameter and aspect ratio (WHO, 1997). These SiC structures probably originate from cleavage of non-fibrous SiC crystals and were most frequently found in samples of the sorting operators. Figure 4 shows SEM micrographs of a SiC fibre and a SiC cleavage fragment. Samples from the processing department showed that 25% of the fibres were SiC fibres, 57% were cleavage fragments and organic fibres constituted 17% (Skogstad, personal communication). This suggests that the OEL for SiC fibres is not applicable to the samples from the processing department. Skogstad *et al.* (2006) further reported that the GM length of all fibres >5 μm was 9.5 μm with a range of 5.0–900 μm and GM diameter of all SiC fibres was 0.39 μm and ranged from the detection limit of the SEM of 0.07 to 2.90 μm. They found that 33% of the fibres had a diameter between 0.07 and 0.25 μm (Skogstad, personal communication). Thus, a substantial number of fibres were not detected in the light microscope counts. Moreover, as a large proportion of fibres were close to the visibility limit of the scanning electron microscope, it is likely that a substantial number of fibres remained undetected even with the SEM.

Exposure to crystalline silica was generally low, <2% of the samples exceeded the OEL. The highest GM exposures to crystalline silica were found in the cleaning, mix, charger and charger/mix operators who work in close contact with raw materials or furnace mix. Quartz sand is one of the raw materials and is transformed to cristobalite at the high temperature in the furnace. Reclaimed unreacted and partly reacted furnace mix that is reused in the new furnace mix therefore represents a source of cristobalite emission. The exposure to crystalline silica was low in the processing department, with the highest levels among crusher operators. The crusher operators have the first contact with SiC that is transported from the sorting area and are therefore exposed to impurities, e.g. quartz that is removed later in the process. The content of crystalline silica in the respirable dust in the SiC industry has been reported in three Canadian studies. Two of the studies report exposure to both quartz and cristobalite (Dufresne *et al.*, 1987; Dion *et al.*, 2005) and one report the quartz exposure levels (Smith *et al.*, 1984). The GM exposure to quartz was between 2 and 10 times higher for all job groups in the Canadian plants compared to our results. The mix and sorting operators in Plant C had a similar GM cristobalite exposure as the mix and sorting operators in the Canadian studies, while the charger operators in Plant C had a two times higher GM exposure. The GM cristobalite exposure for crane, refinery and maintenance workers were all higher in the Canadian studies compared to our results.

The processing operators had the highest exposure to crystalline non-fibrous SiC. This is as expected since furnace operators are exposed to raw materials and furnace mix, while operators in the processing department are handling mainly pure SiC.

The content of non-fibrous SiC in airborne respirable dust has earlier been studied in two Canadian plants (Dufresne *et al.*, 1987). In general, the observed levels of SiC exposure in the furnace and maintenance operators in the Canadian studies were higher than in our study, while exposure in the refinery department was similar. The proportion of non-fibrous SiC in the respirable dust for sorting operators varied between 41 and 50% in our study, which was fairly similar to the Canadian plants (44–78%). The difference is therefore mainly due to higher dust levels. Other job groups in the furnace department were also exposed to respirable dust with a similar content of SiC in our study (2–10%) as the Canadian study (6–9%). The SiC content of the respirable dust that refinery crusher operators were exposed to was lower in the Canadian study (32%) compared to our results (57–81%). The Canadian results were, however, only based on three samples.

The GM for total dust varied from 0.29 mg m^{-3} for crane operators in Plant C to 21 mg m^{-3} for cleaning operators in Plant A. The GM for respirable dust varied from 0.12 mg m^{-3} for crane operators in Plant A to 1.3 mg m^{-3} for cleaning operators in Plant A. The low exposure of the crane operators is likely because they spend most of their work time inside closed cabins supplied with fresh air. The high exposure found for the cleaning operators was based on only two measurements and could be a chance finding; however, both measurements were reported to be representative for this task.

The measured total dust levels in the furnace department in the present study were 35–86% lower than the levels Romundstad *et al.* (2001) reported from the same plants. The generally lower exposure in the present investigation may partly be explained by introduction of remote controlled equipment and separation of exposure sources from the workers. The exposure levels in the processing department were similar or higher in Plant A, 50% lower in Plant B and ∼25% lower in Plant C compared to the earlier study (Romundstad *et al.*, 2001). Three Canadian studies have reported respirable dust exposure levels in two SiC plants (Smith *et al.*, 1984; Dufresne *et al.*, 1987; Dion *et al.*, 2005). They reported higher levels of respirable dust in crane operators (GM = 0.42 mg m^{-3} compared to GM = 0.12–0.23 mg m^{-3}) and mix operators (GM = 1.01 mg m^{-3} compared to GM = 0.41–0.72 mg m^{-3}). Exposure levels for other job groups were essentially similar with those reported in our study.

The short-term measurements of total dust were considered to be representative for full-shift exposure since the mean ratios of short-term to full-shift total dust samples were close to one. This implies that the fibre measurements which were sampled in parallel with the short-term total dust samples can be considered to be representative for full-shift exposure.

Exposure to sulphur dioxide in the furnace hall was generally low with GM <0.4 p.p.m. and well below the Norwegian OEL of 2 p.p.m. However, short-term peaks in the range 10–100 p.p.m. were observed for control room and crane operators in Plants A and B, charger and charger/mix operators in Plant C. These are all operators that occasionally work near by operating furnaces and may be exposed to the gas produced during the thermal process.

Smith *et al.* (1984) found the exposure to sulphur dioxide among furnace workers in a Canadian SiC plant to be between 1.0 and 1.5 and ≤0.2 p.p.m. for sorting operators and maintenance workers. The exposure to sulphur dioxide in the Canadian study was based on a different sampling technique. Instead of using direct-reading electrochemical sensors as in the present study, the air was drawn through two midget impingers in series, each containing hydrogen peroxide, and SO_2 was measured by titration of the resulting sulphuric acid solution. The sampling system was said to be inconvenient to use and resulted in collection of limited samples. The authors therefore referred to it as tentative SO_2 exposure. The level of sulphur dioxide released is dependent upon the sulphur content of the coke used, which varies depending on the supplier and the availability of low-sulphur coke.

The most important exposure differences between Plants A, B and C was seen for the sorting operators. The operators in Plant A had lower exposure to most components compared to the other plants. This is probably most likely because the sorting area in Plant A was located in a separate building while the sorting area in Plants B and C was located inside the furnace hall. The sorting operators in Plants B and C were thus exposed to the contaminated ambient air in the furnace hall as well.

There was also a large difference between the exposure to cristobalite, total dust and non-fibrous SiC among mix operators. The operators in Plant A had a significantly lower exposure than in Plant C. This can be ascribed to the fact that the mix operators in Plant A only handled raw materials, i.e. quartz and petrol coke. In Plant C, the mix operators handled the reclaimed furnace mixture as well. The differences in exposure for mix operators may also partly be explained by the location of the mix area. In Plant A, it was located in a building ∼100 m away from the furnace hall, while in Plant C it was in a building with entrance from the furnace hall building and the mix operators in Plant C regularly entered the furnace hall.

Respirators were used by 74% of the workers some or all of the time. The actual exposure levels were therefore lower than indicated by the measurements and will also vary according to type of respirators used (e.g. disposable half-masks with P2 particulate filters versus compressed air-fed respirators).

CONCLUSION

SiC workers are exposed to a complex mixture of several agents. The highest exposures to fibres, crystalline silica and sulphur dioxide were found among operators in the furnace department. The cleaner operators in Plant A and charger and charger/mix operators in Plant C were generally the highest exposed job groups in the furnace department. Exposure to non-fibrous SiC and total dust was significantly higher in the processing department compared to the furnace and maintenance departments and the refinery crusher operators were the highest exposed job group. The exposure levels found in this study were comparable to or lower than the levels reported in previous studies. Exposure levels were generally below the current Norwegian OELs. However, 53% of the fibre samples and 26% of the respirable dust samples from the furnace department exceeded the OELs. The results suggest that a better control of exposure is needed.

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