Environmental Science
Processes & Impacts

Accepted Manuscript

ROYAL SOCIETY OF CHEMISTRY

rsc.li/process-impacts

Occupational exposure to airborne contaminants during offshore oil drilling

14/05-15

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Running title: Oil drilling and airborne exposure

Abstract

The aim was to study exposure to airborne contaminants in oil drillers during ordinary work. Personal samples were collected among 65 drill floor workers on four stationary and six moveable rigs in the Norwegian offshore sector. Air concentrations of drilling mud were determined based on measurements of the non-volatile mud components Ca and Fe. The median air concentration of mud was 140 µg/m3. Median air concentrations of oil mist (180 µg/m^3), oil vapour (14 mg/m^3) and organic carbon (46 µg/m^3) were also measured. All contaminants were detected in all work areas (drill floor, shaker area, mud pits, pump room, other areas). The highest air concentrations were measured in the shaker area, but the differences in air concentrations between working areas were moderate. Oil mist and oil vapour concentrations were statistically higher on moveable rigs than on stationary rigs, but after adjusting for differences in mud temperature the differences between rig types was no longer of statistical significance. Statistically significant positive associations were found between mud temperature and the concentrations of oil mist (Spearman's R = 0.46) and oil vapour (0.39), and between viscosity of base oil and oil mist concentrations. Use of pressure washers was associated with higher air concentrations of mud. A series of 18 parallel stationary samples showed a high and statistically significant association between concentrations of organic carbon and oil mist (r = 0.98). This study shows that workers are exposed to airborne non-volatelized mud components. Air concentrations of volatile mud components like oil mist and oil vapour were low, but were present in all the studied working areas.

Keywords: drill floor workers, oil mist, mud, shale shaker, drilling fluid

Environmental impact

This study showed low concentrations of oil mist and oil vapour in the work room atmosphere of offshore drill floor workers. The differences in air contaminant concentrations between the shaker area and other areas were smaller than expected. The air sampling program in this study was restricted to ordinary work, in contrast to other studies. A method for determination of airborne drilling mud components was developed based on non-volatile mud components, showing the presence of airborne mud in all examined areas. Parallel filter samples of organic carbon (OC) and oil mist could suggest that the possibility of OC sampling should be explored further for determination of particulate hydrocarbon components.

Introduction

Offshore oil drilling from moveable or stationary rigs is conducted either for exploration or development of oil fields. Drilling fluid (mud) is used to remove drill cuttings from the drill hole. Mud returning to the rig is pumped to shale shakers with vibrating screens in order to remove cuttings before the mud is reused or stored in tanks (mud pits). Mud is a complex mixture of chemicals with components intended for lubrication as well as stabilization and pressure control of the well. Drilling fluids are either water or oil based. The latter typically consists of approximately 50% base oil by weight, while barite, brine, emulsifiers and other chemicals account for the rest (1).

Drill floor workers in the Norwegian offshore sector usually conduct work tasks alternating between the drill floor, the mud pit, in the pump room and in the shaker area. The shaker area consists of the shaker room with the shale shakers, the shaker cabin from which the shakers are monitored and sometimes a separate room for mud sampling. Mud runs in open or partly open systems in the shaker area, and particles generated from the mud may contaminate the work room atmosphere. Mud is mostly handled in closed systems at other work places, but occasional mud spills may be a source for air contamination. Diesel engines e.g. power generators, cranes and cement units, are also used on oil rigs. Thus, drill floor workers may be exposed to diesel fuel combustion products when working on the drill floor.

Oil drilling has been conducted for more than 150 years, and about 3500 oil drilling rigs are currently (2013) in operation throughout the world (2). Although oil companies have their own surveillance programs, scientific publications presenting data on occupational airborne exposure during oil drilling are sparse (3-6). These publications have shown that the total

hydrocarbon air concentrations based on personal samples collected from the North Sea oil fields, are ranging from 10 – 200 mg/m^3 at the drill floor and from 20 – 450 mg/m^3 in the shaker area in the late 1980s. Later studies indicated oil mist air concentrations below 1 mg/m^3 in personal samples. In addition, a larger study from the Norwegian offshore sector reported air concentrations of oil mist ranging from lower than the detection limit (DL) to 48 mg/m^3 in personal samples and from 0.020 to 120 mg/m^3 in stationary shaker room samples, while oil vapour concentrations measured by charcoal tubes ranged from DL to 164 mg/m^3 in personal samples and from 0.23 to 350 mg/m^3 in stationary shaker room samples (7, 8). However, these personal samples were probably predominantly collected during work in the shaker area, and may thus not be representative for the air concentrations to which drill floor workers may be exposed during work. Geometric mean (GM) oil mist concentrations up to 0.5 mg/m^3 and oil vapour concentrations up to 37 mg/m^3, based on air samples collected by personal sampling, were reported during drilling with oil based mud during the time period 1985 to 2009 in the Norwegian offshore sector (9-11). Studies targeted to assess exposure both to oil mist and oil vapour and to other, non-volatile mud components, have to our knowledge not been performed.

Adverse pulmonary effects associated with exposure to oil mist have been reported in the mechanical industry (12-14). In contrast, no studies assessing pulmonary effects during oil drilling have been published. The chemistry of the oil based products used during oil drilling is complex, e.g. several mud additives have irritative or corrosive properties (1). Thus, it is imaginable that exposure to airborne mud potentially may cause other adverse airway effects than what is reported in studies from the mechanical industry. However, exposure to oil mist is common in both industries. Diesel engine emissions have been shown to have adverse effects on the respiratory system (15).

The aim of this work was to characterize the workers exposure to air contaminants during ordinary work when drilling with oil based mud, for the use in a health study of drill floor workers. The air concentrations of oil mist and oil vapour were assessed by personal sampling. Calcium (Ca) and iron (Fe) as markers of non-volatilized airborne mud components (NVM) were also determined. Elemental carbon (EC) was determined to assess potential exposure to diesel exhaust particulate matter. Samples for measurement of EC were also analyzed for organic carbon (OC), which was used to indicate airborne exposure to particulate hydrocarbons during whole shifts. A further aim was to assess the impact of drilling related variables on the measured air contaminant concentrations.

Materials and methods

Study design

Air sampling was restricted to drill floor workers exposed during ongoing offshore oil drilling with oil based mud. Health examinations were carried out at the heliport outside the town of Stavanger (Norway) from where the drill crew members were shuttled by helicopters to and from the respective offshore installations. Thus, only companies using this heliport for the transport of personnel offshore were eligible for inclusion. Four drilling and three operator companies met this criterion and were approached with the request to participate. All companies agreed, resulting in the potential inclusion of drill floor workers from up to seven moveable and four stationary oil drilling rigs.

Each drill crew had a shift rooster consisting of 14 consecutive days of work offshore, followed by four weeks off work. Each rig had six drill crews, of which always two crews worked on the rig in a 12 hours on and 12 hours off work schedule. Once a week, one crew was replaced with a new crew. Each crew included three drill floor workers. Thus, 198 drill floor workers were potentially available for the study. As only a maximum of two drill floor workers could be health examined at the heliport before helicopter transportation offshore due to time restraints, the maximum eligible number of drill floor workers was 132. Drill floor workers were consecutively recruited at random through the participating companies until 65 drill floor workers from a total of four stationary and six moveable rigs had been included, thereby fulfilling the aim of enrolling 64 drill floor workers.

The study was approved by the Regional Ethical Committee for Medical Research in Norway (REC South East). Participation in the study was voluntary and an informed written consent was obtained from all participants.

Air sampling strategy

The air sampling strategy was designed to collect exposure data for use in a study of pulmonary health. Air samples of oil mist, oil vapour and NVM were collected in parallel by personal sampling during two separate sampling periods of two hours. These samples were intended to be collected when work in the shaker area was anticipated. Samples of the liquid drilling mud and the corresponding base oil used at the time of air sampling were also collected. Air samples of EC and OC were collected by personal sampling during a whole shift of eight to 12 hours at shifts when the worker mostly was working on the drill floor.

The samplers were mounted in the breathing zone of the participants. The workers were instructed to carry out their normal work tasks during sampling. Offshore personnel (medics or safety contacts) administered the air sampling. Written instructions and support were given by the Norwegian National Institute of Occupational Health (NIOH). The drilling parameters well section (defined by drill hole diameter), base oil, mud flow, rate of penetration (ROP, drilling progress) and mud temperature specified for each sampling period, were collected from the companies. During sampling the participants were required to record workplaces and some specified work tasks. These tasks were shaker screen inspections and use of pressure washers during the two hour sampling, and smoke room visits during the EC/OC sampling. The question of shaker screen inspections was however frequently misinterpreted, and thus not considered in the statistical analysis. The rigs were equipped with open and in one case semi encapsulated shakers (Thule RigTech VSM 300 and 100, Axiom AX-1, Mi Swaco BEM-650 and DM-3, Derrick DP 626).

To compare sampling methods, two hours stationary samples of oil mist, oil vapour and OC were collected in parallel in a shaker room during two consecutive days of drilling. For each sample pair, the sampling position and time were the same. The sampling positions varied between pairs, some close to and some away from typical breathing zones. This stationary sampling was administered by personnel from NIOH.

Air sampling equipment

Oil mist and vapour were collected with a 37 mm closed-face cassette (CFC) (EMD Millipore Corporation, Billerica , MA, USA) loaded with a glass fiber filter, followed by a cellulose acetate (CA) filter and a backup charcoal tube containing 150 mg sorbent (front section: 100

mg, back section: 50 mg) in sequence. NVM was collected using a 37 mm Millipore cassette equipped with 5.0 μm pore-size polyvinyl chloride (PVC) filter (PVC502500, EMD Millipore Corporation) and a cellulose pad filter support. EC and OC were collected on pre-heated quartz filters (Pallflex Tissue Quartz 2500 QAT-UP, Pall Corporation, Port Washington, NY, USA) using a 37 mm standard aerosol cassette without a cellulose back-up pad.

Oil mist and vapour were sampled at an air flow rate of 1.4 L/min. The samplers for NVM and EC/OC were fitted with thoracic cyclones (GK2.69, BGI Instruments, Waltham, MA, USA) and operated at an air flow rate of 1.6 L/min. Explosion proof air pumps were used (SKC 224-PCMTX4 and SKC 224-PCTX4, SKC Inc. Eighty Four, PA. USA). Air flow rates were measured before and after each sampling period with a calibrated rotameter, type Brooks 2-65 MM (Emerson Electric Co., Hatfield, PA, USA). After use, cassettes and tubes were sealed and stored in refrigerators.

The samples were transported ashore by helicopter and express mailed to NIOH for re-storage in refrigerators until analysis. The samples for determination of EC and OC were sent to Sunset Laboratory Inc. (Tigard, OR. USA) for analysis, while the other samples were analysed at NIOH.

Chemical analysis

Oil mist

The glass fiber and CA filters were folded together as one sample and placed in a glass test tube, added 5 mL of 1,1,2-trichlorotrifluoroethane (Freon® 113) and treated in an ultrasonic bath for 10 min at room temperature. The sample solution was analyzed in a 1 cm quartz cell

within the spectral region 3200 – 2600 cm^{-1} by Fourier transform infrared spectrometry (FTIR) using a Perkin Elmer Spectrum 100 spectrometer (Perkin Elmer Inc. Waltham, MA. USA). The resolution was 4 cm^{-1} and the number of scans was 16. As background, the solution from two blank filters in the same cell was used. The spectrometer was calibrated (5-point linear curve) based on oils corresponding to the samples dissolved in Freon® 113. The DL of oil mist was 0.01 mg/m^3.

Oil vapour

When preparing the tubes for oil vapour measurements, the front section and the backup section were treated separately. The charcoal was transferred to a glass test tube with glass stopper, added 3 mL of carbon disulphide (CS_2), placed in an ultrasonic bath for 10 min at room temperature and finally filtered through glass wool. The CS_2 solution was analyzed using a gas chromatograph (Perkin Elmer AutoSystem XL9) equipped with flame ionization detector (300 °C) and a Chrompack CP-Sil 8 CB capillary column (25m x 0.25mm x 0.25 µm) programmed to increase the temperature from 40 °C to 250 °C at 6 °C/min. A one point calibration was based on standards with the n-alkane nearest to the main peak within the retention time window of the base oil corresponding to the air samples. The n-alkanes used for standard preparations were dissolved in CS_2 and prepared with charcoal added to the solution. The oil vapour DL was 0.10 mg/m^3.

Elemental and organic carbon

EC and OC were measured by use of an OC-EC dual-optical analyzer according to a procedure based on NIOSH Method No. 5040 (16). The laboratory reported DLs were 3 ng/m^3 for EC and 10 $\mu g/m^3$ OC for a 8-12 hour sampling period at an air flow rate of 1.6 L/min with a 1.5 cm^2 punch from the 37 mm filter.

Elemental composition of mud and non-volatilized airborne mud components

The inorganic fraction of the collected mud samples was characterized for the elemental composition. After careful homogenization by shaking, five gram portions of individual mud samples were dried at 200 °C in glass beakers for 7 hours followed by 4 hour dry ashing in a standard laboratory furnace at 550 °C. After cooling to room temperature, the residue was weighed before final grinding to fine powder in an agate mortar.

Three replicate portions of approximately 10 mg each of the grinded residues, were transferred onto 37 mm PVC membrane filters before introducing the filter into teflon autoclaves for leaching in a mixture of 2 mL of aqua regia and 0.5 mL of hydrofluoric acid with microwave-assisted heating (MLS 1200, Teflon Container SV140, 10 bar, Milestone, 556 J. Sorisole, Italy). Before digestion, 10 µg of beryllium chloride was added as an internal standard. The leached sample solutions were diluted to 15 mL with de-ionized water. For measurement of the elemental composition of the leaches, a PerkinElmer Optima Model 7300 DV inductively coupled plasma optical emission spectrometer was used (Perkin Elmer Inc., Waltham, MA, USA).

The filters from the air sampling of NVM were analyzed for Ca and Fe using the same procedure. In-house, commercially available reference filter materials, simulating workroom air concentrations at occupational exposure limit values for individual elements (batches A-3 and B-3) was used to monitor the accuracy and reproducibility of the measurements. For Ca and Fe, the measured values were in excellent agreement with the certified value ($\pm$2%) and the day-to-day variation was within the same range. Measurements of Ca and Fe were carried

out in two different series. Ca DLs were 0.42 and 0.29 µg/filter, and Fe DLs were 0.31 and 0.38 µg/filter.

Airborne mud concentrations (MUD) were estimated based on the air and liquid mud concentrations of both Ca and Fe, and the DLs for MUD ranged from 1.0 to 2.6 µg/m^3 and from 1.1 to 2.3 µg/m^3, respectively, depending on air flow and measurement series.

Statistics

Because most of the distributions were skewed and several observations were < DL for some of the measured air contaminants, non-parametric statistical tests were generally used. Distributions were considered to be normal when skewness was between -2.0 to 2.0. For concentrations below DL, the read values were used as previously suggested (17). Mann-Whitney U-test was used to compare groups and the Spearmans rank correlation test was calculated in order to assess univariate correlations. For correlated continuous variables, where number of concentrations below DL was low and distribution was normal or lognormal, univariate linear regressions were also carried out to quantify the associations between drilling variables and air contaminant concentrations.

MUD concentrations based on Ca (MUD_{Ca}) were estimated by dividing the airborne Ca concentrations (<DL – 69 µg/m^3) by the fraction of Ca (0.8 to 7.3%) in the liquid mud in use during the individual sampling. Fe based MUD concentrations (MUD_{Fe}) were calculated similarly using airborne Fe concentrations (<DL – 28 µg/m^3) and the fraction of Fe in liquid mud (0.53 – 1.5%).

A variable for pressure washer use was calculated by dividing the registered time spent using pressure washers on the respective sampling time. A variable for cuttings volume (m^3/h) was calculated by multiplying ROP by the area of the drill hole. Analyzes for base oil differences were based on viscosity at 40°C for the four base oils used during sampling (Sipdrill 2/0 [1.8 cSt], Clarisol NS [4.8 cSt], EDC 95-11 [3.5 sSt] and EDC 99DW [2.3 cSt]).

The two-sided level of statistical significance was set to 0.05. All data analysis except percentiles was performed using SPSS version 21 (18). Interpolated percentiles are presented to show distribution within the data set, and the statistical package R (quantiles definition 7) was chosen for these calculations (19, 20).

Results

The personal sampling program resulted in 61 samples of oil mist and oil vapour collected among 37 persons at 48 different sampling days, 58 samples of MUD from 35 persons and 44 sampling days, and 40 samples of OC/EC from 40 persons and 36 sampling days. The samples were distributed between ten rigs and six drilling sections (6", 8 ½", 10 ¼", 12 ¼", 17 ½"and 24").

The median oil mist, oil vapour, MUD_{Ca} and MUD_{Fe} concentrations determined in all samples collected by 2 hours personal sampling were 180 µg/m^3, 14 mg/m^3, 140 µg/m^3 and 140 µg/m^3, respectively. The median air concentration of OC in whole shift samples was 46 µg/m^3 (Table 1). EC was measured above the DL in seven out of 40 samples with a median air concentration of 2.0 µg/m^3 in these samples (range 0.31 – 4.7) (not tabulated). Statistically significantly higher concentrations of oil mist and oil vapour were measured on moveable rigs

as compared to stationary rigs. After adjusting for differences in mud temperature, the differences in oil mist and oil vapour concentrations were no longer of statistical significance ($p=0.99$ for oil mist, $p=0.14$ for oil vapour) (not tabulated). No statistically significant differences were found for MUD or OC concentrations between the two rig types. Comparison of the rig age for the moveable rigs (median construction year 1990, range 1981 – 2009) and the stationary rigs (median 1988, range 1982 – 1998) showed no statistically significant differences in construction years between the two rig types (not tabulated).

The air concentrations of oil vapour were statistically significantly higher in samples collected by personal sampling during work in the shaker area only, as compared to samples collected partly in the shaker area or samples collected outside the shaker area (Table 2). Although not of statistical significance, the air concentrations of oil mist and MUD were also higher in samples collected in the shaker area only. Oil mist, oil vapour and MUD were also identified in samples collected from subjects who reported not to have worked in the shaker area at all during sampling. In full shift samples with an average sampling time of 8 h 51 min the OC air concentrations were similar whether the workers had worked in the shaker area or not.

There were no statistically significant associations between time spent in the shaker area and any of the components presented in Table 1 (results not shown). Time spent in different work areas was recorded for 38 whole shift samples. On average 25% of the work time was spent in the shaker area, 47% on the drill floor, 9% in the mud pits and pump rooms and 19% in other places (not tabulated).

Associations were found between mud temperature and air concentrations of oil mist and oil vapour in personal samples collected in the shaker area (Table 3). Base oil viscosity was

positively associated with oil mist concentrations measured in this area, and the use of pressure washer was associated with the airborne MUD concentrations. The median MUD_{Ca} air concentration among subjects who had used pressure washer was 230 $\mu g/m^3$(<DL – 2300, n=22) as compared to 100 $\mu g/m^3$ (<DL –260, n=10) among those reporting not to have used pressure washer during sampling (p=0.003) (not tabulated). The corresponding air concentrations were 240 and 65 $\mu g/m^3$ when MUD_{Fe} was considered (p=0.009). No significant correlations were observed between any of the airborne contaminant concentrations in the shaker area and mud flow, section, ROP or estimated cuttings volume, or between EC levels and smoke room visits (results not shown). Figure 1 shows the association between mud temperature and the concentration of oil mist and oil vapour measured in personal samples collected in the shaker area.

The median concentration of oil mist was nearly 2.5 times higher than the concentration of OC in samples collected in parallel by stationary sampling for two hours in the shaker room (Table 4). The correlation between the concentrations of oil mist and OC was high (r = 0.98, Figure 2). Based on the regression equation calculated between the two variables, the ratio between the concentrations of oil mist and OC was 1.7 : 1 at the OC concentration of 210 $\mu g/m^3$ and 4.7 : 1 at the OC concentration of 12000 $\mu g/m^3$, representing the minimum and maximum measured OC concentrations. As OC accounts for approximately 85% of the atomic weight of oils with carbon numbers close to the base oils, these ratios can be recalculated to 1.4 : 1 and 4 : 1, respectively, by adding the weight of hydrogen. Two parallel samples were discarded due to pump failure. No EC was detected in these stationary samples.

Discussion

This is to our knowledge the first study where air concentrations of MUD have been assessed during oil and gas drilling with oil based mud. The air concentrations of MUD and oil mist were similar. Exposure to oil mist and oil vapour was higher on moveable rigs than on stationary rigs. The air concentrations of oil mist, oil vapour and MUD were higher inside than outside the shaker area. Drill floor workers were occasionally exposed to diesel exhaust as indicated by the presence of EC. Air concentrations of OC and oil mist were highly correlated in the stationary samples when sampled in parallel, the oil mist concentrations being generally higher than OC.

The air contaminant concentrations measured by personal sampling in this study may represent current exposure during ordinary work as drill floor worker during drilling with oil based mud in the Norwegian offshore sector. We have no knowledge of any factors systematically affecting the recruitment or dropouts of participants. The study design did not systematically favour the selection of some drilling conditions on behalf of others. Even though the collection of more samples was planned, each base oil and each drill section from 8 ½ to 17 ½“ were represented by several samples of each measured air contaminants. Previously reported oil mist and vapour concentrations are, in contrast, often based on samples collected to assess compliance with limit values or to document effect of technical control measures (5, 7, 11). Exposure to oil mist and oil vapour in this study was low when compared to occupational exposure limits (OEL) in Norway of 0.6 and 30 mg/m^3 (12 h TWA), respectively, as well as the OEL of 5 mg/m^3 for inhalable oil mist from refined mineral oil (8 h TWA) recommended by the Scientific Committee on OEL, European Commission of Employment, Social Affairs and Inclusion (21-23). Studies addressing

possible health effects due to inhalation of oil mist and oil vapour exposure during oil drilling are lacking. Thus, the above OELs are based on studies from other industries than oil drilling.

Exposure to oil mist and oil vapour was higher when working on moveable rigs than on stationary rigs. Previous studies suggested the reasons to be the older age and smaller shaker rooms of the moveable rigs (7, 8). However, when the oil mist concentrations measured on the two rig types were adjusted for differences in mud temperature, the differences in oil mist and oil vapour concentrations were no longer of statistical significance. The different rig types were also of comparable age. This suggests that differences in oil mist and oil vapour exposure found between rig types mainly are related to differences in mud temperatures.

The possibility that mechanically generated MUD contributes to contamination of the work room atmosphere has rarely been addressed, but one study indicated the presence of airborne mud particles during drilling with water based mud (4). Also other studies have discussed the possibility of mechanical generation of mud, but without presenting any data (3, 24, 25). The present study shows the occurrence of MUD in the work room atmosphere, both inside and outside the shaker area. The concentrations were significantly associated with the use of high pressure washers. Drill floor workers use pressure washers to clean liquid mud from shaker screens and to clean mud spills from the drill floor. This may explain the presence of airborne NVM during this work. Drill floor workers are apparently also exposed to NVM outside the shaker area. However, too few samples were accompanied with information on the use of pressure washers on the drill floor to draw any firm conclusions. Another source of NVM may be dust from occasional manual dry mixing of drilling mud chemicals. This procedure is located outside the shaker area and may sometimes be done by

drill floor workers. As long as the measured air concentrations of Ca and Fe were higher in the shaker area than outside, dry mixing is most likely not a major source of these agents.

Ca and Fe were used as markers for the determination of MUD in air. Air sampled in the Southern Bight of the North Sea had concentrations of Ca from 0.12 to 0.45 μg/m^3 (26). The fraction of Ca containing particles in the air was also found to be lower far from shore in the North Sea compared to what was found in the Southern Bight (27). Thus, Ca from sea air is not likely to have a significant impact on the workroom air concentrations found in the present study. Fresh water is used for pressure washing. The maximum allowable content of Fe in fresh water is according to Norwegian legislation 0.2 mg/L, while the Ca content is recommended by Norwegian Institute of Public Health to be between 15 to 25 mg/L to control corrosive properties of the water (28, 29). If fresh water used for pressure washing was the main source of Ca and Fe in air, a ratio of about 1:100 between Ca and Fe concentrations would be expected. The ratio is about 1:2, suggesting that used fresh water is not a main source of airborne Ca and Fe.

The simultaneous determination of oil mist and MUD makes this the first study where it is possible to evaluate the importance of mechanical formation versus thermal formation of airborne particles during oil drilling. The association between oil mist concentrations and mud temperature shown in earlier as well as in the present study suggests that vaporization and subsequent condensation of mud oil components occur (7, 9, 30). If this would be the only significant mechanism of particle generation, air concentrations of oil mist should exceed air concentrations of MUD by far. On the other hand, mechanical generation of airborne contaminants may cause both volatile and non volatile airborne mud components with a composition similar to the liquid mud. Mechanically generated airborne contaminants from

oil based mud should therefore consist of approximately 50% base oil. In the present study the ratios between air concentrations of oil mist and MUD were 1.3 : 1 on average, indicating that both generation mechanisms significantly contributed to the air concentrations.

The work room air in the shaker area has generally been considered to be the most important source for oil mist and oil vapour exposure, in particular after the mud tanks were covered. This is reflected in the high number of air samples collected from shaker areas compared to other work room atmospheres during drilling (11). Stationary sampling showed that oil mist and oil vapour concentrations in the shaker room can be highly variable, ranging up to 44 and 230 mg/m^3, respectively, indicating that the shaker room atmosphere is non-homogenous with respect to oil mist and oil vapour concentrations. Thus, personal exposure may not necessarily be particularly high even during long term work in the shaker room. It is in this context important to emphasize that according to the companies in this study, usually only about 1/3 of drill floor workers' daily work is carried out in the shaker area during ongoing drilling. The drill floor workers were apparently also exposed to oil mist when they reported not to perform any work in the shaker area. Previous studies have reported median air concentrations in personal samples of oil mist between 0.22 and 0.50 mg/m^3 and oil vapour between 11 and 37 mg/m^3 from shaker areas (7, 11), which is similar to the median oil mist concentration of 0.23 mg/m^3 and oil vapour of 17 mg/m^3 measured after personal sampling in the shaker area only in this study. Substantially higher concentrations have been measured in personal samples previously (3, 9, 10).

Higher oil mist concentrations were associated with higher base oil viscosity. This has been demonstrated in shaker room stationary samples previously (8). The authors suggested that this association was due to higher evaporation from filters for all low viscosity base oils.

Although base oil viscosity may theoretically influence the mechanical formation of oil mist, the study design does not allow any further exploration of this question.

OC was measured in whole shift samples, in contrast to two hours sampling of oil mist and oil vapour. The strong association between OC and oil mist concentrations in stationary samples suggests that OC can be regarded as an indicator of oil mist levels, although not at equivalent concentrations. One possible reason for the different concentrations may be a higher sampling efficiency of coarser particles for the open faced oil mist cassettes compared to the thoracic cyclone fitted OC samplers. The impact of different sampling heads is however difficult to emphasize as long as the particle size mass distribution of the aerosol in the shaker room is not known. The ratio between oil mist and OC in the stationary samples was 1.7 : 1 at the OC concentration level of 210 $\mu g/m^3$, which is within the range of the OC concentration levels measured by personal sampling. Thus adding 70% to the OC personal concentration levels could give a rough estimate of the oil mist levels. This suggests a median full shift oil mist exposure level of around 80 $\mu g/m^3$.

The measured OC concentrations were similar among drill floor workers working partly or not at all in the shaker area. One reason could be that since most of the work shift is spent outside the shaker rooms the contribution to the total exposure from the shaker area would normally be lower than generally anticipated. Exposure to airborne hydrocarbons on the drill floor has received little attention, and hence the knowledge of the magnitude of air concentrations in this area is limited. The results of oil mist, oil vapour and OC measurements presented in this study indicate that airborne exposure outside the shaker area should also be considered for exposure assessment of drill floor workers.

The detection of EC in samples collected at the drill floor indicates that drill floor workers can be exposed to diesel fume emissions, although this was not a regular event during this study. The concentrations of EC were low, but it is imaginable that higher concentrations may occur, e.g. due to weather conditions. Due to the low EC concentrations it is not likely that the measured OC concentrations are confounded by exposure to the organic part of diesel exhaust emissions.

It is difficult to study exposure offshore in the North Sea. Rigs have limited space for overnight stays, and opportunities for helicopter transport are rare and the transport expensive. Thus, one needs to collaborate with personnel offshore who have been instructed to take care of air and mud sampling. A sampling program offshore involving multiple rigs and companies restricted to ongoing drilling with oil based mud is difficult to plan in advance due to the unpredictable nature of drilling progress and changing weather conditions. Altogether, these factors resulted in a lower number of collected air samples than planned. Such difficulties may also be one reason for the striking shortage of scientific publications from this occupational environment. Still, this is probably the most extensive scientific field study yet carried out to assess ordinary work exposure in off-shore drill floor workers during drilling with oil based mud.

Conclusions

The overall exposure to oil mist and oil vapour was relatively low during regular work. Much of the exposure appears to occur outside the shaker area, and should be reflected in workers'

risk assessments. Also the presence of airborne mud particles should receive more attention as several of the involved components in the drilling mud may have irritating properties.

Acknowledgements

This work was financially supported by The Research Council of Norway. We also thank offshore medics and safety contacts for administration of the sampling programs, HR departments for recruiting workers, occupational hygienists for support, and all drill floor workers for their participation. A special thank to the companies who organized three field inspections and thereby added valuable insight in offshore oil drilling. Liv Bente Hatteland and Marita Dahl are acknowledged for taking care of the participants at the heliport.

References

1 OGP/IPIECA Drilling Fluid Task Force. *Drilling fluid and health risk management.* International Association of Oil & Gas Producers /International Petroleum Industry Environmental Conservation Association, Report no. 396, London, UK, 2009.

2 Baker Huges Rig Count, http://www.bakerhughes.com/rig-count, accessed Nov. 15th 2013

3 R. G. Davidson, M. J. Evans, J. W. Hamlin and K. J. Saunders, *Ann. Occup. Hyg*., 1988, **32(3)**, 325-332.

4 A. B. Hansen, E. Larsen, L. V. Hansen, M. Lyngsaae and H. Kunze, *Ann. Occup. Hyg*., 1991, **35(6)**, 651-657.

5 R. W. James, T. Schei, P. Navestad, T. A. Geddes, M.G. Nelson and D. Webster, *SPE Drill. & Completition*, 2000, **15(4)**, 254-260.

6 A. Saasen, M. Berntsen, G. Løklingholm, H. Igeltjørn and K. Åsnes, *SPE Drill. & Completition*, 2001, **16(3)**, 150-153.

7 K. Steinsvåg, M. Bråtveit and B. E. Moen, *Ann. Occup. Hyg., 2006,* **50(2)**, 109-122.

8 M. Bråtveit, K. Steinsvåg, S. Lie and B. E. Moen, *J. Occup. Environ. Hyg.*, 2009, **6(11)**, 679-686.

9 SINTEF, *A low aromatic drilling fluid and the work environment*, Norwegian Institute of Technology, Report no. STF21 A84067, Trondheim, Norway, 1984.

10 Hydro Research Center, *Sampling and analyzing oil mist and oil vapor when using oil based drilling mud. A summery of 1982 -87*, Report no. 88A.AX1, Porsgrunn, Norway, 1988, (Document in Norwegian).

11 University of Bergen and UNI Health, *Historical exposure to chemicals in the Norwegian oil and gas industry*, Departmet for Occupational and Envirommental Medicine, Report no. 2/2010, Bergen, Norway, 2010, (In Norwegian).

12 K. Skyberg, A. Rønneberg, J. I. Kamøy, K. Dale and A. Borgersen. *Environ. Res.*, 1986, **40(2)**, 261-273.

13 E. A. Eisen, T. J. Smith, D. Kriebel, S. R. Woskie, D. J. Myers and S. M. Kennedy, *Am. J. Ind. Med.*, 2001, **39(5)**, 443-453.

14 A. Gondouin, P. Manzoni, E. Ranfaing, J. Brun, J. Cadranel, D. Sadoun, J. F. Cordier, A. Depierre and J. C. Dalphin, *Eur. Respir. J.*, 1996, **9(7)**, 1463-1469.

15 A. Sydbom, S. Blomberg, S. Parnia, N. Stenfors, T. Sandström and S-E. Dahlén, *Eur. Respir. J.*, 2001, **17**, 733-746.

16 NIOSH, *Manual of Analytical Methods: Elemental carbon (diesel particulate), Method 5040*, US Department of Health and Human Services, DHHS (NIOSH) 4:1-8, 1998.

17 P. S. Porter and R. C. Ward, *Water Resour. Bull.*, 1991, **27(4)**, 687-697.

18 IBM, SPSS Version 21.

19 R Core Team (2014), R Foundation for Statistical Computing, Vienna, Austria.

20 R. J. Hyndman and Y. Fan, *The American Statistician*, 1996, **50(4)**, 361-365.

21 Norwegian Ministry of Labor and Social Affairs, *Regulation of Occupational Exposure Limits (Forskrift om tiltaks- og grenseverdier)*, 2011

22 Norwegian Ministry of Labor and Social Affairs, *Regulations relating to Conducting Petroleum Activities (Aktivitetsforskriften)*, 2010/2013.

23 SCOEL, *Recommendation from the Scientific Committee on Occupational Exposure Limits for Aerosols of Severely Refined Mineral Oils*, European Commission: Employment, Social Affairs and Inclusion, SCOEL/SUM/163, 2011.

24 I. Eide, *Ann. Occup. Hyg*., 1990, **34(2)**, 149-157.

25 R. Gardner, *Ann. Occup. Hyg*., 2003, **47(3)**, 201-210.

26 F. Bruynseels, H. Storms and R. van Grieken, *Atmos. Environ*, 1988, **22(11)**, 2593-2602.

27 S. Hoornaert, H. van Malderen and R. van Grieken, *Environ. Sci. Thechnol.*, 1996, **30**, 1515-1520.

28 Norwegian Ministry of Labor and Social Affairs, *Regulation of Water Supply and Drinking Water (Drikkevannsforskriften)*, 2001/2004.

29 FHI, *Enough, Good and Safe Drinking Water Offshore, A Guide for Design and Operation of Offshore Drinking Water Installations*, Norwegian Institute of Public Health, Water Report 119, 3rd Edition, Oslo, Norway, 2013.

30 K. Steinsvåg, K. S. Galea, K. Krüger, V. Peikli, A. Sanchez-Jimenez, E. Sætvedt, A. Searl, J. W. Cherrie and M. van Tongeren, *Ann. Occup. Hyg.*, 2011, **55(4)**, 347-356.

Table 1 The median concentration (and range) of air contaminants measured after personal sampling in drill floor workers according to rig type. The number of samples is shown in brackets.

	All samples Median Range	Moveable rigs Median Range	Stationary rigs Median Range	p[a]
Oil mist ($\mu g/m^3$)	180 (<DL-6000) (n=61)	230 (20-1200) (n=38)	130 (<DL-6000) (n=23)	0.03
Oil vapour (mg/m^3)	14 (<DL-120) (n=61)	15 (<DL-62) (n=38)	8.7 (0.6-120) (n=23)	0.048
MUD_{Ca}† ($\mu g/m^3$)	140 (<DL-3100) (n=58)	160 (<DL-3100) (n=36)	130 (<DL-2300) (n=22)	0.71
MUD_{Fe}† ($\mu g/m^3$)	140 (<DL-2400) (n=58)	150 (<DL-840) (n=36)	110 (<DL-2400) (n=22)	0.90
OC ($\mu g/m^3$)	46 (23-320) (n=40)	46 (23-320) (n=28)	43 (23-110) (n=12)	0.23

† Estimated MUD concentration based on the determination of Ca or Fe

[a] p-value calculated between concentrations measured on moveable and stationary rigs

Table 2 The median concentration (and range) of air contaminants measured after personal sampling in drill floor workers according to work area. The total number of samples and number of samples below DL are shown.

	Work area	n/n<DL	Median Range	90th percentile
Oil mist ($\mu g/m^3$)	Only shaker	27/1	230 (<DL-1200)	378
	Partly shaker	17/0	170 (10-6000)	310
	No shaker	11/0	130 (20-250)	240
	Not recorded	6/0	190 (60-1100)	700
Oil vapour (mg/m^3)	Only shaker[a,b]	27/0	17 (1.1-62)	35
	Partly shaker	17/0	11 (0.6-120)	27
	No shaker	11/1	12 (<DL-22)	22
	Not recorded	6/0	11 (1.9-61)	50
MUD_{Ca}† ($\mu g/m^3$)	Only shaker	27/8	180 (<DL-2300)	1300
	Partly shaker	16/7	95 (<DL-1600)	700
	No shaker	9/5	67 (<DL-3100)	1100
	Not recorded	6/1	260 (<DL-800)	640
MUD_{Fe}† ($\mu g/m^3$)	Only shaker	27/14	160 (<DL-2400)	800
	Partly shaker	16/12	95 (<DL-670)	380
	No shaker	9/7	50 (<DL-840)	540
	Not recorded	6/1	220 (<DL-420)	420
OC ($\mu g/m^3$)	Only shaker	-		
	Partly shaker	22/0	47 (26-110)	77
	No shaker	16/0	44 (23-320)	72
	Not recorded	2/0	41 (40-41)	41

† Estimated MUD concentration based on the determination of Ca or Fe

[a] p = 0.049 between "only shaker" and "partly shaker";

[b] p = 0.041 between "only shaker" and "no shaker"

Table 3 Spearman's rank correlations coefficients calculated between the concentrations of air contaminants measured after collection by personal sampling in the shaker area or partly in the shaker area, mud temperature, viscosity of base oils in use and time of pressure washer use. Number of observational pairs is shown in brackets.

	Oil vapour	MUD_{Ca}	MUD_{Fe}	Mud temperature	Base oil viscosity	Pressure wash.[a]
Oil mist	0.58** (44)	0.37* (40)	0.16 (40)	0.46* (29)	0.37* (44)	0.10 (33)
Oil vapour		0.52** (40)	0.28 (40)	0.39* (29)	-0.16 (44)	0.24 (33)
MUD_{Ca}			0.73** (43)	-0.13 (30)	-0.14 (43)	0.58** (32)
MUD_{Fe}				-0.17 (30)	-0.23 (43)	0.46** (32)
Mud temperature					-0.07 (30)	-0.04 (24)
Base oil viscosity						-0.37* (34)

a. fraction of time spent using pressure washer out of total sampling time; *$p<0.05$; **$p<0.01$

Table 4 The concentrations of oil mist, oil vapour and OC measured after 2 hours stationary sampling in parallel in a shaker room

	N	Median	Range	90th percentile
OC ($\mu g/m^3$)	18	320	210-12000	7600
Oil mist ($\mu g/m^3$)	18	1100	250-44000	36000
Oil vapour (mg/m^3)	18	33	10-230	190

Legend to figures

Figure 1
The associations between mud temperature and oil vapour (A) and oil mist (B) concentrations, respectively, in the shaker area measured after personal sampling.
Samples marked ◇ are from stationary rigs, △ are from moveable rigs.

Figure 2
The association between oil mist and organic carbon measured after stationary sampling in parallel in a shaker room. Sample conditions: Moveable rig type, drill section: 17 ½", mud temp. range: 34 - 60°C.

Figures

Figure 1

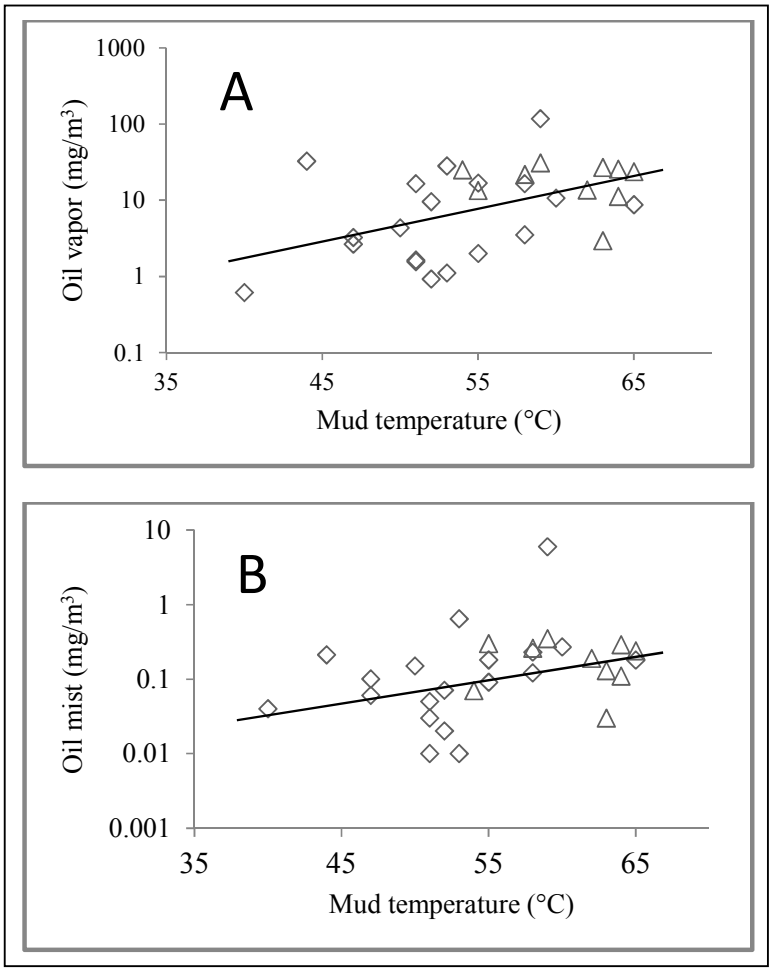

Figure 2