

# Occupational exposure to air pollutants emitted from in situ burning of offshore oil spills: a large-scale field study

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## ABSTRACT

**Background:** In-situ burning (ISB) could be an effective cleanup method during spills. This study aims to study occupational exposure to pollutants emitted from offshore, large-scale ISB-experiments among personnel on vessels involved in ISB.

**Materials and methods:** Six experimental ISBs after release of 4.2–6 m<sup>3</sup> crude or refined oils were performed. Air measurements on three vessels were taken of particulate matter (PM) of different size fractions, polycyclic aromatic hydrocarbons (PAH) and volatile organic compounds (VOC).

**Results:** One vessel was located upwind (about 80–140 m) from the burning oil while two work boats were positioned 200–400 m downwind. One of the work boats moved back and forth transverse to the smoke plume while the other followed the edge of the smoke plume downwind. During the burn period (28–63 min) the range of mean concentrations of PM<sub>2.5</sub> particles in the closest work boat downwind from the burn (0.068–0.616 mg/m<sup>3</sup>) was considerably higher than in the upwind vessel (0.0198–0.029 mg/m<sup>3</sup>) and in the work boat moving downwind at the edge of the visible smoke (0.007–0.078 mg/m<sup>3</sup>). The particles were mainly in the PM<sub><1</sub> fraction. In the work boat closest to the burn the mean concentration of particulate PAH and VOC was 0.046–0.070 ng/m<sup>3</sup> and < limit of detection –17.1 ppm, respectively.

**Conclusions:** The mean PM<sub>2.5</sub> levels in the closest vessel varied between 4 and 41 times higher than the 24-hour Norwegian Air Quality Criteria for the general population, indicating that the particulate exposure may impose a health risk for personnel up to 400 m downwind from an ISB. Exposure to VOC and PAH among crew on board vessels both upwind and downwind from the burning was low during these conditions. However, it is recommended that crew on vessels close to and downwind of smoke plumes from oil fires should use half-masks with P3 filters.

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**Key words:** oil cleanup, particles, particulate matter (PM)<sub>2.5</sub>, polycyclic aromatic hydrocarbon, volatile organic compound

## INTRODUCTION

As a potentially effective and cost-effective cleanup method during offshore oil spills [1], in-situ burning (ISB) could be a favourable alternative under the right circumstances. Effi-

ciency of ISB can reach up to 95% for thick, non-weathered and non-emulsified oil slicks [2]. ISB may be a quick response method eliminating the need for storage and subsequent disposal of considerable volumes of oil and water recovered



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**Table 1.** Oil types, volumes, burn time and climatic conditions

Year	Sample	Oil	Oil type	Volume [m <sup>3</sup> ]	Burn [min]	Temperature <sup>1</sup> [°C]	Wind [m/s]	Relative <sup>1</sup> humidity [%]
2019	A	Oseberg blend	Light crude	6	63	14	4–5	77
	B	Oseberg blend	Light crude	5.6	44	11	4–5	95
	E	IF 180 – 1% S <sup>2</sup>	Heavy fuel	4.2	37	14	4–5	74
	F	Marine gas oil	Distillate fuel	6	28	15	6–7	75
2018	C	Oseberg blend	Light crude	6	43	10	6–7	81
	D	ULSFO	Residual fuel	5.8	48	11	4–5	65

<sup>1</sup>Information collected from Norwegian Centre for Climate Services for Heimdal gas processing centre located 30 km south of the in-situ burning burns. Mean values of the weather parameters are given for the respective burn periods; <sup>2</sup>Heavy fuel oil; ULSFO – ultra low sulphur fuel oil

mechanically. However, burning of oil also involve several adverse consequences, with air pollution being one of the most significant ones [3] and often also producing a viscous residue.

In-situ burning involves exposure of people in the close vicinity to acutely elevated levels of particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) [4]. Particulate matter produced due to incomplete combustion of oil prevails as the primary health concern among the air pollutants resulting from ISB [4] including the risk of detrimental effects on respiratory and cardiovascular systems [5]. Particulates are commonly divided into three categories based on their aerodynamic equivalent diameter (AED). Particles with an AED > 2.5 µm are commonly defined as “coarse”, those between 0.1 and 2.5 µm as “fine” and < 0.1 µm as “ultrafine”. Combustion of oil normally results in high concentrations of fine and ultra-fine particles [3]. Over the years, the focus in PM-measurements has shifted towards the smaller particles as they are considered more hazardous to human health than the larger particles [6]. Acute health effects related to VOCs comprise irritation of airways, eyes and skin, while long-term exposure might, for some VOCs like benzene, lead to cancer [7]. PAHs, a collective term for compounds that consist of two or more aromatic benzene rings, are causally associated with lung, skin, and bladder cancer [8].

Previous research has focused on the dispersion [9, 10], physical properties [11] and chemical composition of the smoke plume from ISB [12, 13] as well as on the oil residues [14, 15]. Air pollution concentrations at sea level during offshore ISB have been estimated by use of exposure models based on measurements taken during the Deepwater Horizon oil spill in 2010 [16]. Mesoscale experiments [9, 17, 18] have also been helpful in modelling potential human exposure to air pollutants during ISB. Fingas [4] reported that although such models provide an important tool for assessing the impact of smoke both before and after a burn, they are not intended to replace monitoring. However, only few measured data on pollutants on surface vessels during offshore ISBs has been published [19].

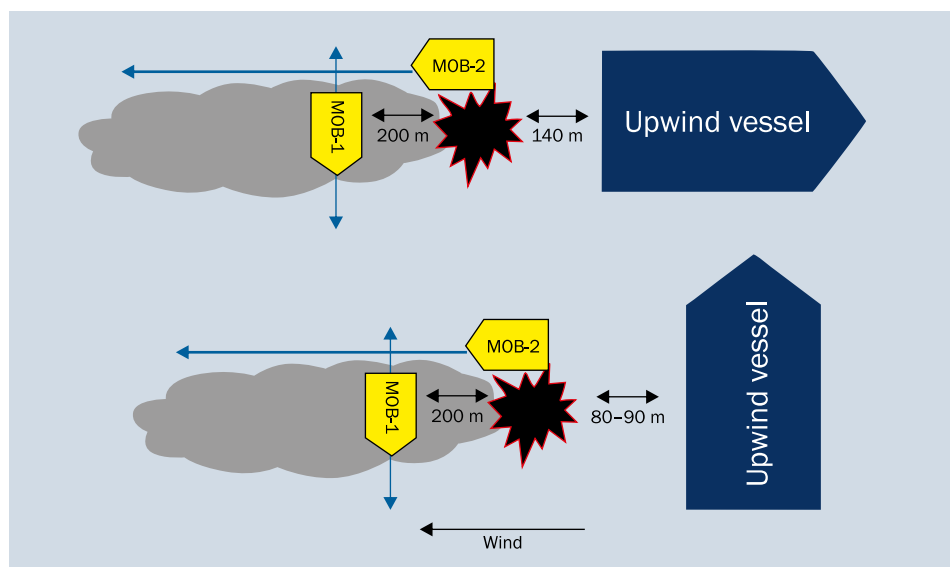
This paper aims to investigate selected pollutants emitted from offshore oil fires as occupational hazards among workers on vessels involved in ISB, and to compare these exposures to relevant limit values. The study focuses on quantitative measurements of PM, PAHs and VOCs on vessels at sea level, emitted from in-situ burning of both crude and refined oils in large-scale experiments carried out in the North Sea.

## MATERIALS AND METHODS

### IN SITU BURNING EXPERIMENTS

The Norwegian Clean Seas Association for Operating Companies (NOFO) and the Norwegian Coastal Administration (NCA) normally perform annual “Oil on water” (OOW) verifications in Norwegian waters. In-situ burn experiments were performed in OOW 2018 and 2019 to verify ISB as a possible response method for the Norwegian continental shelf. These experiments were performed in cooperation with SINTEF Ocean Maritime Robotics AS, DESMI and the University of Bergen, and included use of fire-booms, drones for ignition of oil and air sampling [20]. This paper presents results from air measurements during totally six experimental ISBs with four different oil types. The oils were released in volumes of 4.2 to 6 m<sup>3</sup>, and were contained into a fire-boom before ignited by use of a “Pyro-drone” using gelled mixture of diesel (80%) and gasoline (20%). Pre-weathered crude Oseberg Blend and three fuel oils; marine gas oil (MGO), an ultra-low sulphur fuel oil (ULSFO) and a heavy fuel oil (IFO 180) were used (Table 1). The main vessel was in charge of deploying and towing the fire-booms and releasing the oil. From the main vessel, two work boats (MOB-1 and MOB-2) were used for sampling surface oil, air monitoring, and recovery of burn residue. The personnel in the work boats were instructed to use half-masks with P3-filters during the experiments.

The same procedure was followed for experiments in OOW 2018 (two burns) and 2019 (four burns). During these burns, the oil was contained on the water surface by different fire-resistant oil booms towed in a U-formation. Air measurements were taken on three vessels: The main ves-



**Figure 1.** Illustration of the experimental setup in “Oil on water” (OOW) in 2018 (upper part) and 2019 (lower part). Black area indicates the burning oil and grey area indicate the smoke plume

**Table 2.** Analytes and sampling equipment

Location	Analyte	Units	Sampling method	Particle size [ $\mu\text{m}$ ]
MOB-1 <sup>1</sup>	PM <sub>&lt;1</sub>	particles/cm <sup>3</sup>	P-Trak Ultrafine Particle Counter (8525)	0.02 to 1
	PM <sub>1</sub>	mg/m <sup>3</sup>	DustTrak DRX Aerosol Monitor (8534)	0.1 to 15
	PM <sub>2.5</sub>	mg/m <sup>3</sup>		
	PM <sub>4</sub>	mg/m <sup>3</sup>		
	PM <sub>10</sub>	mg/m <sup>3</sup>		
	“Total” dust	mg/m <sup>3</sup>		
	VOC	ppm	MiniRAE 3000 Photoionisation Detector	NA
MOB-2 <sup>2</sup>	PM <sub>2.5</sub>	mg/m <sup>3</sup>	SidePak Personal Aerosol Monitor (AM510) + 2.5-micron impactor	0.1 to 2.5
Upwind vessel	PM <sub>2.5</sub>	mg/m <sup>3</sup>	DustTrak II Aerosol Monitor (8532) + 2.5-micron impactor	0.1 to 2.5
MOB-1 and upwind vessel	PAH	$\mu\text{g}/\text{m}^3$	37 mm cassette with a Teflon filter (SKC 225-1713) + XAD-2 sorbent tube (SKC 226-30-04) at 2.0 L/min (SKC pump)	“Total” dust fraction

<sup>1</sup>Work boat moving downwind transverse to the smoke plume; <sup>2</sup>Work boat moving downwind at the edge of the visible smoke; PAH – polycyclic aromatic hydrocarbons; PM – particulate matter; VOC – volatile organic compounds; NA – not available

sel located upwind (about 80–140 m) from the oil and two work boats (MOB-1 and MOB-2) located downwind (Fig. 1). MOB-1 was positioned about 200–400 m (the boat was in constant longitudinal movement) downwind from the oil burn and moved back and forth transverse to the smoke plume (Fig. 1). In OOW 2018, the distance between MOB-1’s and Oseberg oil was about 400 m and gradually decreased to about 200 m as the burn progressed. The distance was considerably closer (200 m) upon the burning of ULSFO. In OOW 2019 MOB-1 was generally closer to the oil burns than in 2018, being kept at approximately 200 m behind the oil during all the burns. MOB-2 started each experi-

ment out in the immediate vicinity of the oil and moved thereafter longitudinally to the plume all the way to the end of visible smoke. It kept its course along the edge of the smoke plume, transecting it 3–4 times for measurements directly under it.

## AIR MEASUREMENTS

During the six ISBs, air measurements were taken outdoors on the main vessel located upwind from the burn and on the two work boats located downwind (Table 2). All measurements were carried out in the open sea (N59°59′ E002°27′) and under good weather conditions, i.e. wind

speed  $\approx$  4–7 m/s, air temperature  $\approx$  10–15 °C, relative humidity  $\approx$  65–95% and no/negligible precipitation.

### Particulate matter

Particulate matter of different particle-size fractions was sampled continuously with direct-reading instruments from TSI Inc. (Shoreview, Minnesota, USA); DustTrak DRX Aerosol Monitor (8534), SidePak Personal Aerosol Monitor (AM510) and P-Trak Ultrafine Particle Counter (8525) (Table 2). Sampling commenced upon ignition of each oil slick. Measurements were logged at 1 second intervals.

### Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons-sampling was undertaken in OOW 2018 on board the upwind vessel, as well as in the two downwind vessels MOB-1 and MOB-2. Two parallel samples were taken in MOB-1 during each of the two burns. In addition two parallel 12-hour samples including the two burns were taken on MOB-1, MOB-2 and the upwind vessel. PAHs were not measured in OOW 2019.

Polycyclic aromatic hydrocarbons was analysed in the “total” particulate fraction sampled by 37 mm closed-faced cassettes fitted with a Teflon 2  $\mu$ m pore-size filter (SKC 225-1713), and in the vapour phase sampled by XAD-2 sorbent tube (SKC 226-30-04). The two sampling media were connected in series, and sampling was performed at a flow rate of 2.0 L/min using a SKC Sidekick Pump (Table 2). The particulates on the Teflon filter were analysed gravimetrically (mg on filter; limit of detection 0.1 mg  $\pm$  10%). Average air concentration (mg/m<sup>3</sup>) was found by dividing by the air volume through the filter during the sampling period. Twenty-one PAH compounds (PAH21) in the particulate fraction and biphenyl and naphthalene in the vapour phase were analysed by gas chromatography/mass spectroscopy (GC/MS), with detection limits of 0.1  $\mu$ g/m<sup>3</sup> ( $\pm$  30%). The 21 PAH-compounds analysed were anthracene, benz[a]anthracene, benzo[a]fluorene, benzo[b]fluorene, benzo[b]fluoranthene, benzo[j]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, benzo[e]pyrene, benzo[ghi]perylene, dibenzo[a,h]anthracene, dibenzo[a,e]pyrene, dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, dibenzo[a,l]pyrene, phenanthrene, fluoranthene, indeno[1,2,3-cd]pyrene, chrysene, pyrene, and triphenylene. PAHs were analysed according to the US NIOSH 5515, issue 2 [21] at Sintef Molab, Norway.

### Volatile organic compounds

Volatile organic compounds levels were measured in OOW 2018 and 2019 with a direct-reading photoionisation detector (PID) MiniRAE3000 (RAE Systems Inc., San Jose, California, USA) located on MOB-1 only (Table 2). The PID, with a 10.6 eV lamp, was isobutylene-calibrated. Measurements commenced during oil release prior to ignition.

## EXPOSURE LIMITS

The particle exposures were compared with the 8-hour Norwegian occupational exposure limit (OEL) for total dust/particulates of 10 mg/m<sup>3</sup> [22], the Norwegian Air Quality Criteria for PM<sub>2.5</sub>-particles among the general population of 15  $\mu$ g/m<sup>3</sup> (24 hours), and correspondingly 30  $\mu$ g/m<sup>3</sup> for PM<sub>10</sub> [23] as well as with the recently revised Air Quality Guidelines from the World Health Organization (WHO) for PM<sub>2.5</sub> of 15  $\mu$ g/m<sup>3</sup> (24 hours) [24].

The sum of the 21 PAHs (EPAH21) was compared with the Norwegian 8-hours OEL for the particulate fraction of 0.04 mg/m<sup>3</sup> while naphthalene and biphenyl in the vapour phase were compared with the OELs of 50 mg/m<sup>3</sup> and 1 mg/m<sup>3</sup>, respectively. All the OELs need to be adjusted by a factor of 0.6 for a 12-hour workday [25]. There is no OEL for VOCs (C6-C10), but the 8-hours OEL for white spirits (C7-C12 with aromatic content < 22%) is 50 ppm.

## DATA HANDLING

The arithmetic mean of the particle concentrations logged at 1 second intervals was calculated over the respective burning periods of the different oils (range: 28–63 min). In calculations of EPAH21 we used limit of detection/2 for PAH-compounds with concentration < limit of detection [26].

## RESULTS

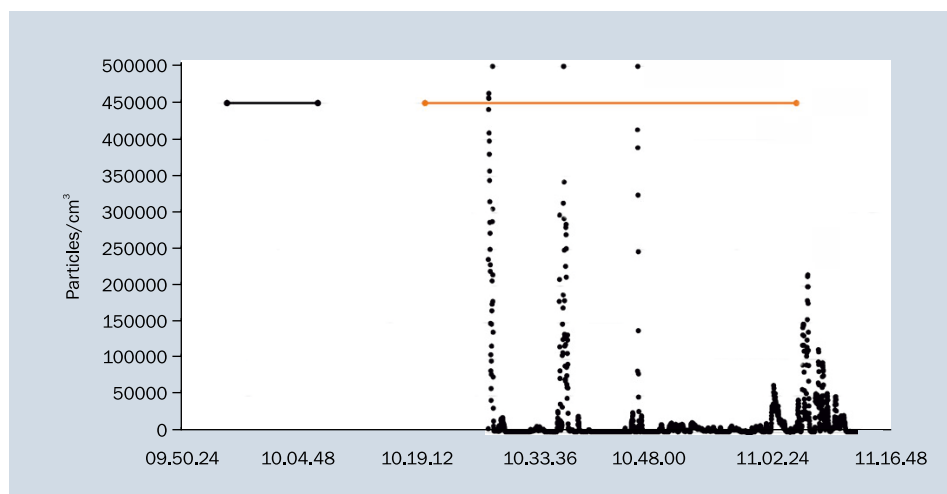
### PARTICLES

Figure 2 shows typical results from continuous measurements of particle fraction PM<sub><1</sub> in MOB-1 during burn of Oseberg Blend. A recognisable pattern of concentration peaks was seen as the boat traversed the smoke plume about 200 m downwind from the burn.

Measurement results during each of the burns are listed in Table 3. The particle concentrations were very low on the upwind vessel, while the levels measured in MOB-1 under the smoke were about ten times higher than in MOB-2 that moved in the outskirts of the visible smoke (Table 3).

The mean concentration of PM<sub>2.5</sub>-particles in MOB-1 was higher in OOW 2019 (0.194–0.616 mg/m<sup>3</sup>) compared to the levels in OOW 2018 (0.061–0.068 mg/m<sup>3</sup>) (Table 3). The mean PM<sub>2.5</sub> levels in MOB-1 varied between 4 and 41 times higher than the 24-hour Norwegian Air Quality Criteria for the general population. Furthermore, the levels of PM<sub>≤100</sub> were low compared to the OEL for total dust of 10 mg/m<sup>3</sup>. The mean levels in MOB-2 were considerably lower, and in OOW 2018 the PM<sub>2.5</sub>-concentration during burning was close to background concentrations before burning. In the main vessel upwind the PM<sub>2.5</sub>-concentration was close to background levels during all burns.

Among the oils the highest concentration was found for MGO followed by Oseberg (sample A), IF180 (E) and Oseberg



**Figure 2.** Example of continuous measurement with number of particles in the  $PM_{<1}$ -fraction (y-axis) from burning of Oseberg (red line) measured in MOB-1 in “Oil on water” (OOW) 2018. Black line indicated the oil release to sea. Time in hh.mm.ss (x-axis)

**Table 3.** Particle-concentrations of different size fractions and maximum volatile organic compounds (VOC)-concentration measured by direct reading instruments in “Oil on water” (OOW) 2018 and 2019

		Vessel								
		MOB-1					MOB-2	UW	MOB-1	
		Particulate matter; Arithmetic mean [ $mg/m^3$ ]							VOC-concentration [ppm]	
Oil sample	Year	$PM_1$	$PM_{2.5}$	$PM_4$	$PM_{10}$	$PM_{\leq 100}$	$PM_{2.5}$	$PM_{2.5}$		
A	Oseberg blend	2019	0.421	0.424	0.426	0.431	0.432	0.048	0.022	Missing
B	Oseberg blend	2019	0.190	0.194	0.197	0.200	0.203	0.029	0.020	1.8
C	Oseberg blend	2018	0.067	0.068	0.069	0.071	0.071	0.007	0.018	0.4
D	ULSFO	2018	0.061	0.061	0.062	0.063	0.063	0.007	0.029	0
E	IF 180 <sup>1</sup>	2019	0.240	0.245	0.250	0.261	0.265	0.054	0.020	2.5
F	Marine gas oil	2019	0.603	0.616	0.626	0.647	0.653	0.078	0.026	17.1

<sup>1</sup>Heavy fuel oil; PM – particulate matter; ULSFO – ultra low sulphur fuel oil; UW – upwind vessel

(sample B) (Table 3). Sample A and B (both Oseberg blend) were collected at the same distance from the burning oil, but the burn time of A was over 50% longer than B, and the average PM concentration for sample A was about 2.2 times higher than for sample B.

There were only small differences between the different particle size fractions from  $PM_1$  to  $PM_{\leq 100}$  on all vessels. The highest peak concentration of the different particle size fractions was measured when MOB-1 was located directly under the smoke cloud as indicated by the peaks of the smallest particles ( $PM_{<1}$ ) (Fig. 2).

### POLYCYCLIC AROMATIC HYDROCARBONS

The results in Table 4 show small differences in PAH-concentrations between the vessels, and very low levels compared to Norwegian OELs. This includes both the full-shift (12-hour) measurements and the measurements that

were taken during the actual release and burning of the two oils Oseberg and ULSFO. The results from the 12-hour measurements of EPAH21 ( $0.011 \mu g/m^3$ ) corresponds to < 0.03% of the Norwegian OEL, while the highest measured concentrations of naphthalene ( $1.5 \mu g/m^3$ ) and biphenyl ( $0.19 \mu g/m^3$ ) detected were < 0.003% and < 0.02% of the respective OELs.

### VOLATILE ORGANIC COMPOUNDS

Recorded levels of VOCs in MOB-1 were low during release and burning of the oils. Peaks of VOC concentrations as measured during oil release and ISB are listed in Table 3. These peaks were registered due to oil leakage from the fire booms prior to ISBs. Non-detectable or negligible values were detected during all ISBs. The peak levels indicated in Table 3 are well below the 8-hour OEL for white spirits (C7-C12) of 50 ppm.

**Table 4.** Results from measurements of polycyclic aromatic hydrocarbons on three different vessels in “Oil on water” (OOW) 2018

Location/vessel	Sample type	Oil sample	Sampling time [min]	Naphthalene (vapour) [ $\mu\text{g}/\text{m}^3$ ]	Biphenyl (vapour) [ $\mu\text{g}/\text{m}^3$ ]	$\Sigma\text{PAH}_{21}^1$ (particulate) [ $\mu\text{g}/\text{m}^3$ ]
Main vessel/upwind	12-h	C + D; Oseberg blend+ULSFO	731	1.50	0.180	0.010
Main vessel/upwind	12-h	C + D; Oseberg blend+ULSFO	731	1.50	0.190	0.011
MOB-2	12-h	C + D; Oseberg blend+ULSFO	722	0.26	0.039	0.010
MOB-2	12-h	C + D; Oseberg blend+ULSFO	722	0.33	0.050	0.010
MOB-1	12-h	C + D; Oseberg blend+ULSFO	615	0.47	0.051	0.012
MOB-1	12-h	C + D; Oseberg blend+ULSFO	615	0.55	0.046	0.011
MOB-1	Oil release + burn	C; Oseberg blend	68	0.50	0.040	0.060
MOB-1	Oil release + burn	C; Oseberg blend	68	0.82	0.049	0.070
MOB-1	Oil release + burn	D; ULSFO	82	0.82	0.026	0.049
MOB-1	Oil release + burn	D; ULSFO	82	1.00	0.030	0.046

<sup>1</sup>The sum of 21 polycyclic aromatic hydrocarbons (PAH) compounds in the particulate fraction; ULSFO – ultra low sulphur fuel oil

## DISCUSSION

The concentration of  $\text{PM}_{2.5}$  particles in the closest vessel, located about 200–400 m downwind from the burn, was well above the Norwegian Air Quality Criteria and the guideline from WHO, and considerably higher than in the upwind vessel as well as in work boat that moved in the outskirts of the visible smoke. A major part of the measured particulates was in the  $\text{PM}_{<1}$  particle fraction. The concentration of PAH on the vessels both upwind and downwind from the burns was very low. Furthermore, negligible concentrations of VOCs were measured in the closest vessel during burning.

The mean concentration of  $\text{PM}_{2.5}$ -particles in the work boat moving 200–400 m downwind from the burn (range: 0.068–0.616  $\text{mg}/\text{m}^3$ ) was somewhat higher than measured at ground-level 500 m from the Newfoundland offshore burn experiment of 29–48  $\text{m}^3$  oil (0.05–0.13  $\text{mg}/\text{m}^3$ ), but it was considerably lower than in a remotely controlled vessel located only 100 m downwind from the burn (12.3–14.3  $\text{mg}/\text{m}^3$ ) [19]. In 14 onshore mesoscale ISB-experiments of crude oil (1.3–11.8  $\text{m}^3$ ) in Mobile, Alabama the mean concentration of particles at ground level stations at 66 m downwind was 0.299  $\text{mg}/\text{m}^3$  but varied considerably (range: 0.03–3.1  $\text{mg}/\text{m}^3$ ) due to high variability in microscale winds and turbulence [27]. Variations in the positioning of the ground/sea level monitoring stations/vessels relative to the burn and differences in weather conditions will contribute to the variability in measured particle concentrations. Care should also be taken when comparing results from the different studies as different monitoring instruments have been used. In the NOBE and Mobile studies the RAM (real-time aerosol monitors) instrument differed in specifications from the particle monitor presently used, including the cut-point for particle size (0.1–20  $\mu\text{m}$  vs. 0.1–100  $\mu\text{m}$ ).

The difference in particle concentrations between the three vessels in our study indicates that the particles are concentrated mainly within the boundaries of visible smoke, and that there is a negligible effect on the air quality from the burning on vessels placed upwind from the smoke plume. The generally lower concentrations in OOW 2018 compared to 2019 in MOB-1 is presumably due to the shorter distance to the burn in OOW 2019 (about 200 m) compared to OOW 2018 when the distance varied between 200 m and 400 m. Thus, particulate concentrations declined with increasing distance from the burn, and it also decreased relatively short time after the fire was extinguished. Similar findings have also been reported in Buist et al. [28] and are in accordance with the suggestion by Fingas et al. [18] that particulate matter is a matter of health concern only close to the fire and directly under the plume.

In situ burning of MGO was associated with 2–3 times higher  $\text{PM}_{2.5}$ -concentration in the closest vessel than when burning the crude oil Oseberg and the heavy fuel oil IF180. In line with this, Fingas [4] reported that the concentrations of particulates in emissions from burning diesel are approximately four times that from similar sized crude oil burns at the same distance from the fire. One may speculate whether the higher burning efficiency of MGO (< 90%) than for Oseberg (80–91%) and IF180 (< 60%) [20] could be one of the reasons for this finding. On the other hand, the difference in particle concentration between the two samples of Oseberg blend in OOW 2019 might be associated with the longer burning time and larger volume of oil in the sample with highest  $\text{PM}_{2.5}$ -concentration.

The  $\text{PM}_{2.5}$  levels on the closest vessel in OOW 2018 and OOW 2019 varied between 4 and 41 times higher than the 24-hour Norwegian Air Quality Criteria for the general popu-

lation. However, the levels of  $PM_{\leq 100}$  were low compared to the OEL for total dust of  $10 \text{ mg/m}^3$ . Independent of the oil type, the small difference between the particle size fractions from  $PM_1$  to  $PM_{\leq 100}$  indicate that the smoke mainly consists of particulate matter in the  $< PM_1$  size fraction that includes the ultrafine particles. These findings are in accordance with results from oil burning during the Deepwater Horizon oil spill where the particle size in smoke from burning was in the range of  $0.1\text{--}1.0 \mu\text{m}$ , with a peak at about  $0.4 \mu\text{m}$  [29]. Similar results were found in the NOBE-burnings where the particle size was mainly in the range of  $0.1\text{--}1.0 \mu\text{m}$ , with a peak at  $0.3 \mu\text{m}$  [3]. During the last years there has been increased focus on these smallest particles ( $< 1 \mu\text{m}$ ) as they may have adverse effects not only on the lungs, but also on the heart and circulatory system, at relatively short exposure periods [30]. In addition to having a larger, porous surface area, which makes them prone to further adsorption of harmful substances, they also dominate over large particles in particle number concentrations [31]. However, these particles do not yet have any OEL or air quality criteria. Nevertheless, preventive measures to reduce exposure to such particles should be considered to reduce potential health effects. Thus, crew on vessels close to and downwind of smoke plumes from oil fires should use half-masks with P3-filters. Laboratory studies have shown that percentage penetration for P3-filters was  $< 0.03\%$  for particles with a medium size of  $0.238 \mu\text{m}$ , which is typical size for smoke particles from burning oil [32]. Burning of MGO was associated with the highest mean particle concentration ( $0.6 \text{ mg/m}^3$ ). When using a percentage penetration of  $0.05\%$  for typical particle sizes ( $0.2\text{--}0.4 \mu\text{m}$ ) in this type of smoke the particle concentration inside the mask would be about  $0.3 \mu\text{g/m}^3$ , which is considerably lower than the  $PM_{2.5}$  Norwegian Air Quality Criteria for the general population and indicates that when used properly this type of respiratory masks should provide adequate protection for the personnel. However, the real protection would probably be lower since the penetration of particles through the filter is not the only limiting factor since leakages between the skin and the mask may contribute significantly to the inhaled particle concentration. Such particle leakage should be reduced as far as possible through education, training and fit testing.

The air concentration of PAH was very low compared to OELs, and there were only small differences in the full-shift levels of PAH between the three vessels even though the direct reading instruments showed larger particle-concentrations in MOB-1 than in the two other vessels during burning. Particulate PAH is bound to the soot-particles, and when moving away from the smoke plume the exposure to PAH is expected to decrease similarly as reported for the particles. Since the concentrations in all vessels were  $< 0.03\%$

of the Norwegian OELs for the respective PAH-compounds it is concluded that personal exposure to PAH among crew on board vessels both upwind and downwind from the burning was very low during these conditions with relatively short burning time. Our findings are in accordance with the results from PAH measurement at sea-level during the NOBE burns reporting low air concentrations of PAH [19] as well as 66 m downwind from the onshore Mobile ISBs [27] and 30 m downwind from oil burns in Calgary [33]. However, different sampling methodology and sets of analysed PAH components precludes direct comparison of concentration levels.

The low levels of VOCs on the vessels were expected since the oils used were either a pre-weathered crude oil or different fuel oils, and not fresh crude oils with high levels of volatile hydrocarbons. The highest peak level of VOC was found for the distilled fuel oil (MGO), which is associated with the higher volatility and lower viscosity of this oil compared to the other oils tested. There is no OEL for VOCs, but even the peak levels measured during the burnings were well below the 8-hour OEL for white spirits of  $50 \text{ ppm}$  ( $275 \text{ mg/m}^3$ ). Previous studies also found VOCs at low levels as close as 30 m to 150 m downwind from the fire, suggesting they are not a major health concern [2, 33]. Evaporation of VOCs from an unburned crude oil is considered more hazardous than VOCs produced in combustion [2, 28]. Previous studies [34, 35] have shown that personnel located close and downwind from a bulk spill of fresh light crude oil at sea can be exposed to benzene levels exceeding the OEL during the initial stages of the spill. In such cases half-face air purifying respirators with a combination of a particle filter and an organic vapour cartridge, A2 should be used to prevent biological uptake of benzene.

The relative position of the vessel to the oils, in addition to the weather/climatic conditions, is among the largest sources of uncertainty in the presented measurements. Despite logistical constraints and unpredictable weather associated with field experiments in open sea, the measurements were carried out in a relatively narrow weather window with low wind speed ( $4\text{--}7 \text{ m/s}$ ), moderate air temperature ( $10\text{--}15 \text{ }^\circ\text{C}$ ) and no or negligible precipitation. Relative humidity varied in the range  $65\text{--}95\%$ , and according to Jayaratne et al. [36] the DustTrak instrument overestimates the particle concentration due to particle growth by water absorption when relative humidity is above  $78\%$ , with an about  $50\%$  overestimation at  $90\%$  relative humidity. In our study relative humidity exceeded  $78\%$  in two of the burns ( $81\%$  and  $95\%$ , respectively). At the highest relative humidity ( $95\%$ ) the particle concentration was lower than when burning the same oil at a relative humidity of  $77\%$ , indicating that other factors had considerably more impact on the particle concentration. Furthermore, the positioning of the vessels was largely the same for the individual

burns. However, at the start of the burns the most exposed work boat was closer to the burn in 2019 than in 2018, which is reflected in a higher particle concentration in 2019 than in 2018. Our results are based on relatively few experiments, and more detailed studies under similar conditions are needed to study potential differences in exposure between oil types. We have compared the results of our measurements of particles and PAH to OEL's and Air Quality Criteria set for 8 or 24 hours, although, in most cases, our measurements had considerably lower duration. Nevertheless, such comparison still gives an indication on when precautions should be taken when exposed to emissions from ISB.

## CONCLUSIONS

The findings show that the particles from the burns are mainly in the  $PM_{<1}$  fraction, which includes the ultrafine particles ( $< 0.1 \mu m$ ). The higher particle-concentration when burning distillate fuel oil compared to crude oil and heavy fuel oil might be associated with the higher burning efficiency. The particles are concentrated within the boundaries of visible smoke. At the measured concentrations they may impose a health risk for personnel up to 400 m downwind from an ISB operation, but not for the personnel upwind. The mean exposure to PAH and VOC among personnel on board vessels both upwind and downwind from the burning was low during these conditions, and the concentrations will most likely not reach OEL at sea level. Nevertheless, since PAH is carcinogenic the exposure should be kept at low as possible. We recommend that personnel close to and downwind of smoke plumes from oil fires should use half-masks with P3 filters to prevent inhalation small particles ( $< PM_{2.5}$ ) and particulate PAH. Efficient use of such masks requires training of the users and proper fit testing.

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