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Offshore field experiments with in-situ burning of oil: Emissions and burn efficiency

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ABSTRACT

In situ burning (ISB) is an oil spill response technique including ignition and burning to remove oil on the water surface. The technique rapidly and effectively removes large portions of the oil. However, the combustion process causes a large smoke plume and leaves a viscous residue in the water. During six large-scale experimental burns in the North Sea in 2018 and 2019, the smoke plume, released oil and contained residues were analysed. The objectives were to document the content of particles and gases in the smoke plume, properties of both the released oils and residues, and the effectiveness of the burns. Oseberg crude oil, Ultra Low Sulphur Fuel Oil (ULSFO), Intermediate Fuel Oil (IFO180) and Marine Gas Oil (MGO) were released into a fire-boom and ignited. Particles and gases in the smoke plume were monitored using drones with several sensors. Soot particle monitoring indicated that more than 90% of the particles produced during the burns were <1 μm. Soot fallout was mainly limited to visible smoke, and the particle concentration was highest directly under the smoke plume and declined with distance from the burn. Gas monitoring in the smoke indicated low concentrations of SO_2 and NO_X (<2 ppm), and the concentrations of CO_2 and CO were within air quality standards. Black Carbon produced relative to the amount of oil burned was 10–18%. The burn efficiency varied and were estimated to 80–91% for Oseberg, >90% for MGO, and <60% for both ULSFO and IFO180. The present paper addresses the results of the smoke plume monitoring, properties of the ISB residues and the burn efficiency.

1. Introduction

In-situ burning (ISB) is, together with mechanical recovery and use of chemical dispersants, one of the main strategies for combatting oil on the sea surface. ISB can potentially remove large amounts of oil from the sea surface and may be the most effective recovery option in certain situations, e.g. in ice infested areas in the Arctic. The suitability of ISB depends to a large degree on the initial characteristics and weathering state of the oil, and the weather conditions (Mullin and Champ, 2003). However, ISB produces emissions to the air and burn residue at sea, causing public concern on environmental issues and human health. ISB has a narrow window of opportunity, as it must be carried out as soon as possible after the initial release as weathering and oil emulsification reduce the ignitability and burn efficiency.

Controlled in-situ burning has been used successfully to remove oil from spills in ice-affected waters in several large-scale field trials since the 1970s (summarized in Buist et al., 2013a). In more recent ISB field trials in the Barents Sea in 2008 and 2009 (Sørstrøm et al., 2010) and as a part of the EU Horizon project GRACE in Greenland in 2018, (Jørgensen et al., 2019), no monitoring of the smoke plume was reported. These field trials have mostly been related to potential oil spills in the Arctic, and ISB as a response option has rarely been used on marine oil spills on open water. However, its successful use during the Gulf of Mexico Deepwater Horizon (Macondo) response in 2010 where approximately 400 burns were completed, resulting in an estimated range of approximately 35 000 to 49 000 tons of oil burned at sea, has generated interest in use also in other areas than the Arctic (Allen et al., 2011). The most cited project regarding monitoring of gases in smoke during large scale ISB field experiments is the Newfoundland Offshore Burn Experiment (NOBE) in 1993, burning 29 and 48 m^3 crude oil (e.g. Fingas et al.,

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1995a). Emissions from ISB, both with crude oils and diesel, have also been studied in several experiments in smaller scale conducted in Mobile, Alabama, U.S. (Fingas et al., 1996a, 1996b, 1998). Monitoring was also performed in smoke produced from the burning oil well fires in Kuwait in 1991 (Campara and Humprey, 1992). However, according to Fraser at al. (1997), the burn conditions during well fires are very different from ISB of oil on water. Hence, the two types of burn are not comparable, as the well fire burns were more efficient compared to burning oil on water.

The Norwegian Clean Seas Association for Operating Companies (NOFO) and the Norwegian Coastal Administration (NCA) cooperate closely to consider ISB as a response method in Norwegian waters. With some exceptions, NOFO together with the NCA conduct "Oil-on-water" (OOW) field experiments in Norwegian waters annually, usually in June. The main objective of OOW is to verify and further develop oil spill response technology and methods, and OOW offers NOFO and NCA the opportunity to verify new equipment and methods under various weather conditions and with different oil types. In 2016, 2018 and 2019 various aspects of ISB were introduced to qualify ISB operationally for a future oil spill response method in Norwegian waters (Faksness et al., 2020). During OOW in 2016, the main goals were to investigate if free floating crude oil will ignite and burn on open water and whether use of herders could be beneficial in conjunction with ISB on open water. The experience and results from these experiments were reported in Faksness et al. (2020), Singsaas et al. (2017), and were summarized in Cooper et al. (2017). Based on the results and the predominating weather conditions on the Norwegian continental shelf, NOFO and NCA do not see the use of herders as a key component in ISB operations on open water (Faksness et al., 2020).

During OOW in 2018 and 2019, the main purpose was to address aspects of in-situ burning related to human health, environmental impact and operational issues. The main objectives were to monitor soot and gases in the smoke plume using drones with sensor packages, and to document the effectiveness of ISB and the oil residue properties. Finally, the durability of fire booms and ignition with the use of a drone were to be verified.

The present paper addresses results of the smoke plume monitoring, properties of the ISB residues and the burn efficiency. There were several concepts that had not been tested in the field during ISB of oil previously: Igniting the oil slick with the use of a drone, using drones with sensor packages to monitor soot and gases in the smoke, and to be able to collect the residue after the burn in a net that was connected to the boom. More detailed chemical characteristics of the ISB residues are discussed in Faksness et al. (2020), toxicity of the ISB residues in Faksness et al. (2021) and Keitel-Gröner et al. (2021), and the potential for human exposure during ISB in Szwangruber et al. (2021). The operational aspects of these ISBs are described and discussed in Jensen et al. (2021).

2. Materials and methods

2.1. Permit

Prior to conducting OOW, the Norwegian Environment Agency must approve the experiments. NOFO has been responsible for applying to the Norwegian Environment Agency for a release permit for experimental purposes. The Norwegian Environment Agency announces the application for public hearing by publishing it on their website and sending it to other governmental agencies and stakeholders (e.g. the Institute of Marine Research and the Directorate of Fisheries). If approved, specific requirements and conditions such as site location, maximum discharge volumes, weather conditions, time period, environmental monitoring, presence of remote sensing and oil recovery equipment in preparedness on site are stated in the permit for discharge for experimental purposes.

2.2. The field experiments

The field trials were conducted at the former Frigg field in the Norwegian part of the North Sea in mid-June. The experiment area is located approximately 150 km from the Norwegian coast and the water depth is around 100 m. Selected photos from the field experiments are shown in the Supplementary Information (SI, Fig. S9).

In total, seven large-scale experimental in-situ burns (ISB) were planned (detailed in Table 1). The burnings took place in wind speeds from 3 to 7 m/s and wave heights from 1.0 to 2.4 m. Experimental burns with different oil types were performed and two types of fire booms were used (DESMI Pyroboom and Elastec/American Fireboom). The oils were released (approximately 6 m^3 in each experiment) and contained into the fire boom before being ignited by use of DESMI PyroDrone with a gelled ignitor consisting of diesel (80%) and gasoline (20%). ISBs with pre-weathered Oseberg Blend (200 °C+), marine gas oil (MGO), Ultra Low Sulphur Fuel Oil (ULSFO), and a heavy fuel oil (IFO 180) were performed. In addition, an emulsified pre-weathered Oseberg Blend with 52% water did not ignite, although a sample of the emulsion (4 L) was easy to ignite and burned at ideal conditions onshore prior to the offshore experiment. To prepare pre-weathered oil, fresh Oseberg Blend was heated to 200 °C+ in a large-scale chemical facility (Indus AS, Indre Arna, Norway). Pre-weathered Oseberg 200 °C+ corresponds to approximately 0.5–1 day of weathering on the sea surface (Daling and Strøm, 1999). The physical properties of the oils are given in Table 2. SINTEF, in cooperation with Maritime Robotics, performed an extensive monitoring of the smoke plume, using dedicated drones with sensors for emission gases and soot particle distribution. Samples of burn residues were collected from the sea surface and in addition, the University of Bergen measured the potential for human exposure during the burns.

The vessel MS Strilborg deployed and towed the fire booms and releasing the oil. This vessel is 75 m long, operates with two MOB/work boats, and has a main deck well suited for this type of operation. Specially designed nets to contain the residue after burning were connected to the booms before they were deployed. In 2018, the fire boom was spread out by using a flexible paravane (Ro-Kite), which required a minimum speed through the water to get sufficient lifting force. In 2019, the paravane was skipped by having the ship tow the fire booms sideways through the water, using the length of the hull to regulate the width of the boom opening. This change made it possible to reduce the towing speed, and at the same time operating the fire booms at the leeward side of the vessel, reducing both wind and waves for the boom and the fire. More details regarding operational challenges when performing the experiments are given in Jensen et al. (2021). However, parts of the fire booms directly exposed to fire, could not be reused after being brought on board the vessel to install a new residue net after a burn.

Table 1
The experimental large scale ISBs performed under OOW in 2018 and 2019.

Year	Volume	Oil type	Boom	Burn time	Wind and waves
2018	6 m^3	Oseberg Blend 200 °C+ (2018)	Desmi Pyroboom	43 min	6–7 m/s, 1.1 m
2018	5.8 m^3	ULSFO	Desmi Pyroboom	48 min	4–5 m/s, 1.2 m
2019	6 m^3	Oseberg Blend 200 °C+ (#1)	American Fireboom	63 min	4–5 m/s, 2.4 m
2019	4.2 m^3	IFO 180	American Fireboom	37 min	4–5 m/s, 1.1 m
2019	5.6 m^3	Oseberg Blend 200 °C+ (#2)	Desmi Pyroboom	44 min	4–5 m/s, 2.4 m
2019	6 m^3	Marine gas oil (MGO)	American Fireboom	28 min	6–7 m/s, 1 m
2019	6 m^3	Oseberg Blend 200 °C+, 52% water	American Fireboom	Did not ignite	5–6 m/s, 1 m

Table 2
Density (g/mL) and viscosity (cP) for unburned oils and their ISB residues. Density for Oseberg and IFO are measured at 80 °C and recalculated to 15 °C. Viscosity are at 10 °C from the temperature sweep (shear rate 10 and 1 °C/min).

SINTEF ID	Oil	Flash point (°C)	Density (g/mL)	Viscosity (cP, 10 s^{-1})
2018–4052	Oseberg 200 °C+ (unburned)	78	0.891	750
2018-5303-S1	Oseberg 2018 (ISB residue, on sea, in boom)		0.968	138 000
2018-5303-S3	Oseberg 2018 (ISB residue, scraped off boom)		0.969	145 000
2018-5303-S8	Oseberg 2018 (ISB residue, from net in container)		0.969	118 000
2018–3881	ULSFO (unburned)	82	0.917	9030
2018-5304-S1	ULSFO (ISB residue, on sea, in boom)		0.944	142 000
2018-5304-S4	ULSFO (ISB residue, in sea, in boom)		0.949	201 000
2018-5304-S6	ULSFO (ISB residue, scraped off boom)		0.948	101 000
2018-5304-S11	ULSFO (ISB residue, on sea from Utvær)		0.945	131 000
2019-5232-S1	Oseberg 200 °C+ (unburned)	78	0.898	467
2019-5232-S3	Oseberg #1 (ISB residue)		0.954	100 000
2019-5234-S2	Oseberg #2 (ISB residue)		0.957	579 000
2019-5233-S1	IFO 180 (unburned)	89	0.960	12 600
2019-5233-S2	IFO 180 (ISB residue)		1.001	1 010 000
2019-5233-S3	IFO 180 (ISB residue)		0.952	127 000
2019-5235-S1	MGO (unburned)	74	0.847	6
2019-5235-S3	MGO (ISB residue)		0.886	259

A heat flux sensor mounted on the cargo rail, the PyroDrone and two MOB boats were all operated from Strilborg. In 2018, the drone monitoring the smoke plume nearest the burn (<400 m downwind) was operated from Strilborg and the drone monitoring from approximately 400 m and above was operated from OV Utvær. In 2019, both drones monitoring the smoke were operated from the fishing vessel Bøen.

2.3. Monitoring strategy and sampling

An extensive monitoring of the smoke plume was performed using two drones (Fig. S1, Supplementary Information (SI)) with sensors for emission gases (NO_X, SO_2, CO, and CO_2), soot particle distribution (TSI DustTrak DRX Aerosol Monitor Model 8534) and sampling of soot particles. The DustTrak measured the particle fractions (PM) 1, 2.5, 4, and 10 μm. The soot particles were sampled in a closed-faced filter cassette with a PTFE filter (37 mm, 2.0 μm) connected to an MSA Escort Elf Pump with an airflow of 3 L/min. Monitoring of the particle distribution and concentration in the smoke fallout was measured at sea level using the same type of DustTrak as on the drones, to evaluate the potential for human exposure. More details on monitoring of the potential for human exposure are presented in Faksness et al. (2020).

As oil is burned, gas and smoke particulates are produced. The main objective of the drone sampling was to quantify the generation of gas and smoke particulates from the fire. To quantify the total flux of particulates and gas through a cross-section of the smoke plume, the following parameters were measured: The width and height of the plume, the velocity of gas and particles through the cross section (wind speed), and the concentration of particulates and gas. All vessels and drones were equipped with GPS, and an overview over the different units' positions during the burns are shown in Fig. S3 (SI). In 2018, Drone 1 was operating close to the burn (up to 400 m) and Drone 2 was operating from approximately 400 m to 1 km from the burn. In 2019, the drones flew in a pre-defined pattern in the smoke plume (Fig. S2, SI). A vertical cross section of the plume 100 m downwind from the fire boom was chosen as the primary objective for both drones. Another vertical cross section 300 m downwind was a secondary objective for one of the drones. Transecting under the plume was set as a secondary objective for the other drone. The drones typically did three vertical and three horizontal transects to map the size and shape of the primary cross-sectional area. The plan was that Drone 1 (blue lines) should fly in the area closer to the burn (<400 m), and Drone 2 (orange lines) was to follow the plume as far as possible (up to 2 km from the fire). Due to a hard landing of Drone 2 after 30 min into the Oseberg #1 (2019) burn, only Drone 1 was operational, so it flew to approximately 1 km. During the IFO 180 burn, Drone 1 was in the air for only 12 min (from 6 to 18 min), and Drone 2 did not sample. The tracks from one of the MOB boats (red lines) indicate the visual distribution of the smoke plume, approximately 4.5–5 km during the burns. The tracks of the second MOB boat are not shown, but this boat monitored particulate matter approximately 200–400 m from the fires. The position of Strilborg (green line) is also indicated in Fig. S3 (SI).

Oil (1 L) was sampled from the tanks when the oil was released on sea, representing the unburned oil. The sampling strategy in the booms after the burns was improved from 2018 to 2019, as a random sampling was performed in 2018. In 2019, three residue samples were collected after the burn, located on the left side, in the middle (apex), and on the right side in the boom using one of the MOB boats. The second MOB boat was used to monitor the potential for human exposure up to 400 m downwind from the fire.

2.4. Sample processing and analyses

All samples were analysed in the SINTEF laboratory in Trondheim. The samples were stored on deck onboard Strilborg and stored at <5 °C after arrival to the laboratory.

2.4.1. Physical properties of the ISB residues

Viscosity and density of the unburned oils and the ISB residues were measured. Viscosities were measured as temperature sweeps (1 °C/min) from 65 °C down to −3 °C with a shear rate of 10 s^{-1}. The density for the residues was measured at 80 °C and extrapolated to 15 °C (ASTM, 1980).

2.4.2. Sample preparation and chemical analysis

An aliquot of the unburned oils and their ISB residues were weighed (70–90 mg) directly into a graduated flask (10 mL). Dichloromethane (DCM) was used as solvent. The residues were heated to 50 °C for approximately 2 h to as assure they were homogenous prior to weighing. Total soot particles on the filters were analysed gravimetrically, whereafter the filters were extracted three times with DCM (20 + 10+5 mL) and aided with sonication. The combined extracts were concentrated to approximately 1 mL.

Internal standards were added to the extracts for quantitative analysis of the total petroleum hydrocarbons (TPH) on gas chromatograph with flame ionisation detector (GC/FID) and semi-volatile components (SVOC) on gas chromatograph with mass spectrometer (GC/MS). For GC/FID *o*-terphenyl and 5α-androstane were added as internal standards, and for the GC/MS analysis naphthalene-d_8, phenanthrene-d_{10}, chrysene-d_{12}, fluorene-d_{10}, and acenaphthene-d_{10} were added.

The GC/FID analyses were performed according to a modification of EPA Method 8015D (US EPA, 2003). TPH (resolved plus unresolved TPH) was quantified by the method of internal standards using the baseline corrected total area of the chromatogram and the average

response factor for the individual C_{10} to C_{40} *n*-alkanes. GC/MS-analysis for quantification of 49 SVOC, including decalins, naphthalenes, and PAHs (Table S1 in SI), were performed on selected samples (modified US EPA, 2007).

2.5. Estimating burning efficiency

To estimate burn efficiency (BE) of ISB on open water is challenging as it is difficult to collect all the residue. Two different approaches were used to estimate burning efficiency (BE) of ISB: A gravimetric method and by estimating BE through a comparison with controlled laboratory burns, and chemical analysis.

2.5.1. Estimating burning efficiency gravimetrically

A net to contain the residue after burning was connected to the fire booms before they were deployed at sea (Fig. S9, SI). After ISB, the net capturing the residue was disconnected from the boom at sea, transferred to a container on board Strilborg and weighed onshore. The net was used both to avoid floating ISB residue sinking after the burn and to get an estimated weight of the residue.

2.5.2. Estimating burning efficiency through controlled laboratory burns

A laboratory method for estimation of BE based on chemical analysis was applied to estimate BE for the offshore burns (Faksness et al., 2019). Controlled laboratory burns of Oseberg 200 °C+, ULSFO, IFO 180 and MGO were performed in a modified cone calorimeter. Approximately 150 mL oil was used, giving an initial oil thickness of 15 mm. To ignite the oil, its surface was exposed to a heating element in the conic oven, with an initial temperature of 575 °C (heat radiation of 25 kW/m^2), and the gases were ignited by a spark igniter. The oil was burned off in a weight controlled, open water-cooled tray (inner diameter of 10.8 cm, inner surface area 91.6 cm^2), allowing us to follow the weight reduction during the burn. The burns were stopped to give samples with known BE of approximately 50%, 70% and 90% weight loss. The remaining residue was collected and weighed to obtain an exact amount of oil burned. Each of the burn residues were analysed by GC/FID and GC/MS, and a "calibration curve" from GC/FID for each oil was prepared, which formed the basis for quantifying BE. ISB residues from i. a. OOW 2016 and OOW 2018 were used to verify the methodology. Faksness et al. (2019) concluded that using GC/FID to quantify TPH in the residues to establish a regression curve between the TPH concentrations and the BE worked out quite well for all oils, except MGO. They reported that for MGO, the amount of TPH from C_{10} to C_{40} was not significantly changed but appeared to increase with increasing BE (lower boiling point n-alkanes were decreasing, but the UCM (unresolved complex materials) was increasing). Using the detailed SVOC profile from the GC/MS analysis to estimate BE did not work, as hopane itself appears to have evaporated. The geochemical biomarker hopane (17α(H), 21β(H)-hopane) used as an internal GC/MS standard is well established in connection to weathering processes such as evaporation and biodegradation (e.g. Prince et al., 1994; Garrett et al., 2000), but Faksness et al. (2019) observed that the abundance of hopane also decreased and was clearly affected by burning when BE exceeded 60–70%. This has also been reported by Han et al. (2019). Even though the scale of laboratory burns versus field ISB were different, the methodology seemed to be a good supplement to existing methods improving the estimates of BE from offshore burns, and the established calibration curves from the GC/FID were used as a supplement to estimate the BE for all offshore burns, except MGO.

2.6. Black carbon

Black Carbon (BC) is the dark, light absorbing part of the particles ($PM_{2.5}$), while Organic Carbon (OC) is the light reflecting part of the particles. Soot is the sum of BC and OC and was measured with the DustTrak instrument in the smoke during the burns. When oil is burned, the carbon in the oil will be transformed into mainly soot, CO_2 and CO (Buist et al., 2013a). The amount of carbon in crude, diesel and bunker is approximately 85%, and it can be used to estimate an oil concentration from the monitoring of CO_2, CO and soot. The share of BC is calculated as the percentage of soot versus the estimated amount of burned oil.

3. Results and discussion

Results from the six ISBs conducted during OOW in 2018 and 2019 are presented and discussed here.

3.1. Smoke emissions

Fig. 1 shows the monitored CO_2 and CO concentrations in the smoke up to approximately 400 m from the fire. The ambient CO_2 level was approximately 400 ppm. During the burns, the CO_2-concentrations in the smoke plume varied and 420 ppm CO_2 (above ambient level) was the highest concentration monitored. In 2018, higher CO concentrations than in 2019 were measured. Other sensors were used in 2018, which might explain the difference. In 2018 maximum CO levels were 12 ppm during ISB of Oseberg and 14 ppm during ISB of ULSFO. In 2019, maximum CO levels were 3.6 ppm for MGO, 2 ppm for Oseberg oil and 2 ppm for IFO 180, again much lower concentrations in 2019 than in 2018. For NO_X and SO_2, the concentrations were in the same range in 2018 and 2019. The smoke emission monitoring indicated that there were produced low concentrations of SO_2 (<2 ppm) and NO_X (<2 ppm).

During the NOBE experiments in 1993 (e.g. Fingas et al., 1995a, 1995b), crude oil was released into a boomed area and ignited with a Helitorch. They concluded that combustion gases, including CO_2, SO_2, NO_X and CO did not reach level of concern, as the level of CO_2 was measured to maximum 629 ppm on ground level under the two burns and the other gases were measured only at background level or below the lower detection level. However, most of the emission data discussed in Fingas et al. (1995b) appear to be from ground stations. Monitoring in the smoke plume during NOBE was obtained aboard a research aircraft from 1.5 km to 30 km downwind from the fire (Ross et al., 1996). The aircraft flew back and forth across the width of the smoke plume at various distances downwind and measured up to 40 ppm excess CO_2 in the smoke about 1.5 km from the fire, and it dropped below 1 ppm approximately 25 km downwind. CO concentrations were low and difficult to quantify. The peak NO_X concentration was 15 ppb, and throughout most of the plume the NO_X concentrations were only a few parts per billion. During OOW, the gas measurements in the smoke were performed closer to the fire (<500 m), and the concentrations were, of course, higher than monitored 1.5 km and longer from the burn during NOBE, but still low. The instruments and monitoring equipment have improved since the NOBE and Mobile burns in the 1990s, e.g. our gas sensors were more sensitive.

Fingas et al. (1995b, 1996b) and Wang et al. (1999) reported that the monitoring performed during NOBE 1993 and Mobile 1994 demonstrated that there was a significant gas separation between the plume and the surface, and that the ground concentration of CO_2 was always greater than those found in the air and in the plume. This is not in accordance with our monitoring during OOW 2018 and 2019. Our monitoring showed that the gases, including CO_2, followed the smoke plume, and that no separate plume was detected by the instrumentation on board the drones. Fingas (2014) summarized in a review of emissions from oil fires based on meso-scale and offshore burns, that in all burns it was found that gas emissions did not exceed any health concerns at distances greater than about 1 km from the burn. Buist et al. (2013b) assumed that gases emitted during an ISB generally do not represent a serious threat to safety of human health. The gas concentrations may exceed hazard threshold as they leave the fire, but they drop below these thresholds within very short distances from the fire. This is in accordance with our observations during OOW (Szwangruber et al., 2021).

During the Gulf of Mexico Deepwater Horizon (DWH) response in

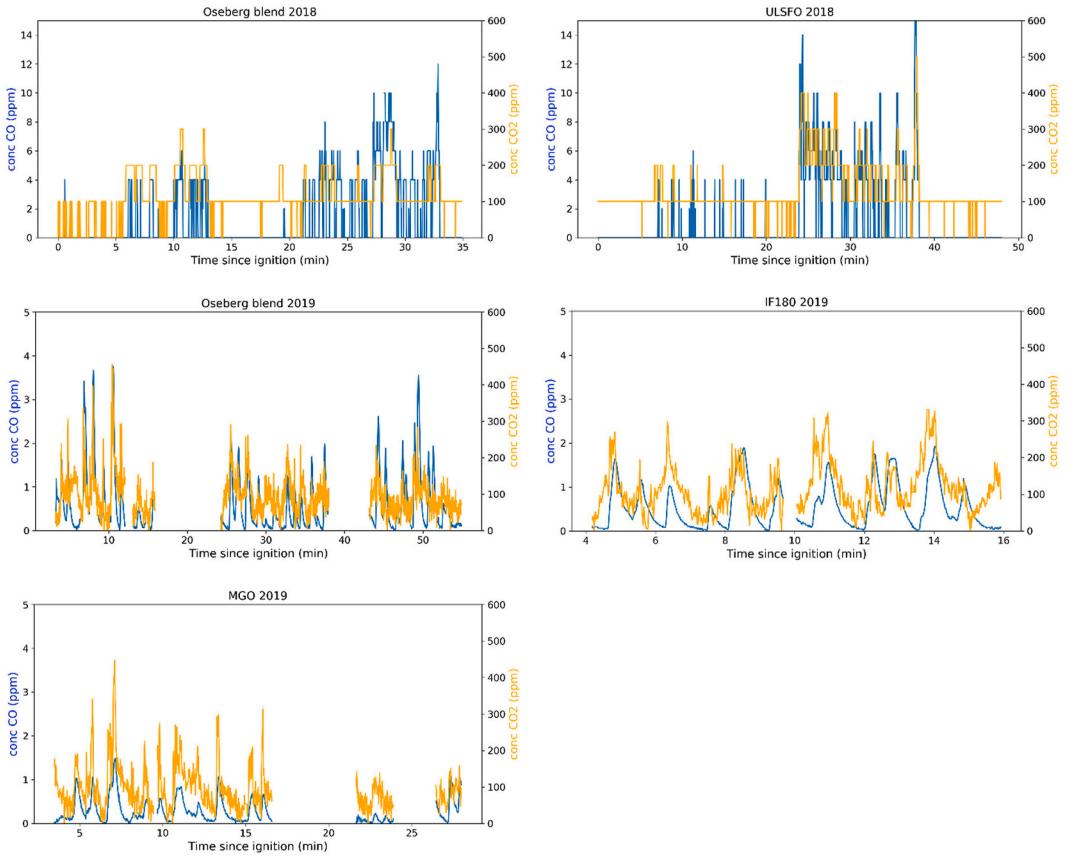

Fig. 1. CO (yellow line) and CO_2 (blue line) concentrations (in excess of ambient) during the burnings. CO is shown on left y-axis and CO_2 on right y-axis. As seen in the graphs, other sensors were used in 2018. No gas monitoring data from Oseberg #2 (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2010 more than 400 ISB were performed. Gullett et al. (2017) have later conducted ISB of the DWH oil in the laboratory and measured the emissions. The CO_2 concentration was in the range of 500–2200 ppm, CO up to 30 ppm, and an average $PM_{2.5}$ of approximately 60 mg/m^3 during burning. These concentrations were higher than measured during our field experiments. In a previous laboratory study performed by SINTEF under controlled conditions in a cone calorimeter (Faksness et al., 2018), it was observed that the gas and soot concentrations were higher than measured in the field, but in the same range or higher than reported in Gullett et al. (2017). In the laboratory, the entire smoke

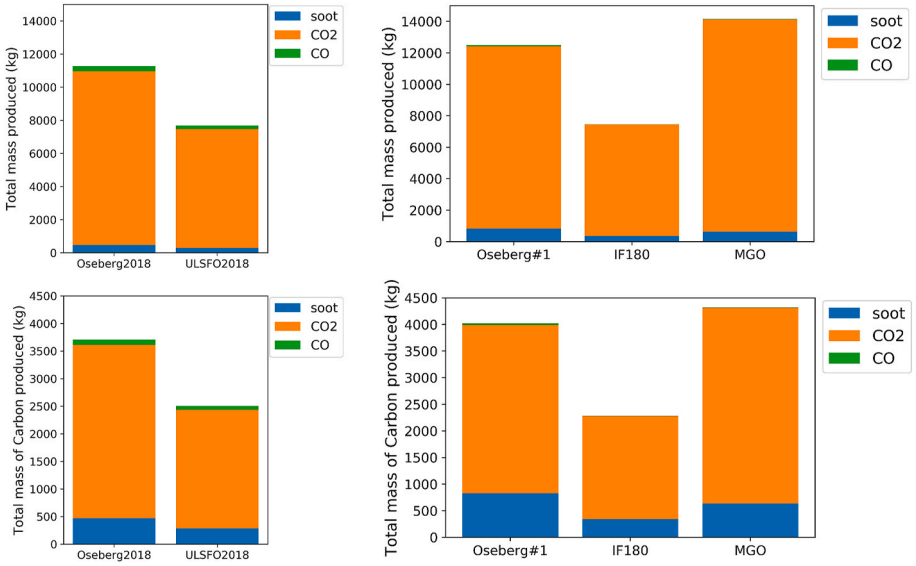

Fig. 2. Estimated total emissions in the smoke produced during the burn: Total amounts of measured components emitted during the burns (left graph) and total amount of carbon in the released soot, CO_2 and CO (right graph). No gas measurements available from Oseberg #2. The estimates are based on amount of burned oil (Table 3).

plume passed the sensors, while the drones were flying in and out of the smoke plume during the monitoring period. The smoke yield can also be affected by fire size, weathering, wind and wave conditions.

In the present study an average composition from the monitoring performed throughout the individual burns was calculated. If total amount of carbon produced during ISB and the relative composition of the compounds that contain carbon are known, total amount of soot, CO and CO_2 can be estimated as shown in Fig. 2, which illustrates total emission in the smoke. As expected, CO_2 contributed most to the smoke, and it was estimated a somewhat higher total amount produced during one ISB of MGO (totally approximately 14 000 kg) than Oseberg (totally approximately 12 000 kg both in 2018 and 2019). Lowest total amount produced was from ULSFO and IFO 180 (totally about 7500 kg). The drone was only 12 min in the air during burning of IFO 180, which probably have influenced the results. Amounts of SO_2 and NO_X were low in all burns, e.g. 9 kg SO_2 and 2 kg NO_X for Oseberg #1 (2019). The estimates indicated that from the total amount of carbon produced, 4000 kg were produced during ISB of Oseberg and MGO, and approximately 2400 kg during ISB of ULSFO and IFO 180, but the estimated BE was lower in these two burns than in the other burns.

3.2. Soot particles on the sea surface and in the smoke plume

The monitoring of soot particles, both in the smoke plume (Fig. 3) and at sea level, indicated that more than 90% of the particles produced during the burns were in the finest particle fraction (PM < 1.0 μm), which includes the ultrafine particles (<0.1 μm). Due to their small size, ultrafine particles can be inhaled deeply into the lungs, enter the alveoli, and may enter the blood stream and potentially harm other vital organs. The potential for human exposure during the burns is evaluated and discussed in detail in Szwangruber et al. (2021).

Both MOB boats were equipped with DustTraks to monitor particulates just above the sea surface. As indicated in Fig. S3 (SI), one of the MOB boats followed the smoke plume up to 5 km during the burns, and the other MOB boat was located from 200 to 400 m downwind from the burn and moved back and forth to transverse to the smoke plume. We found that the highest concentration of the different particle size fractions was measured when the MOB boat was located directly under the

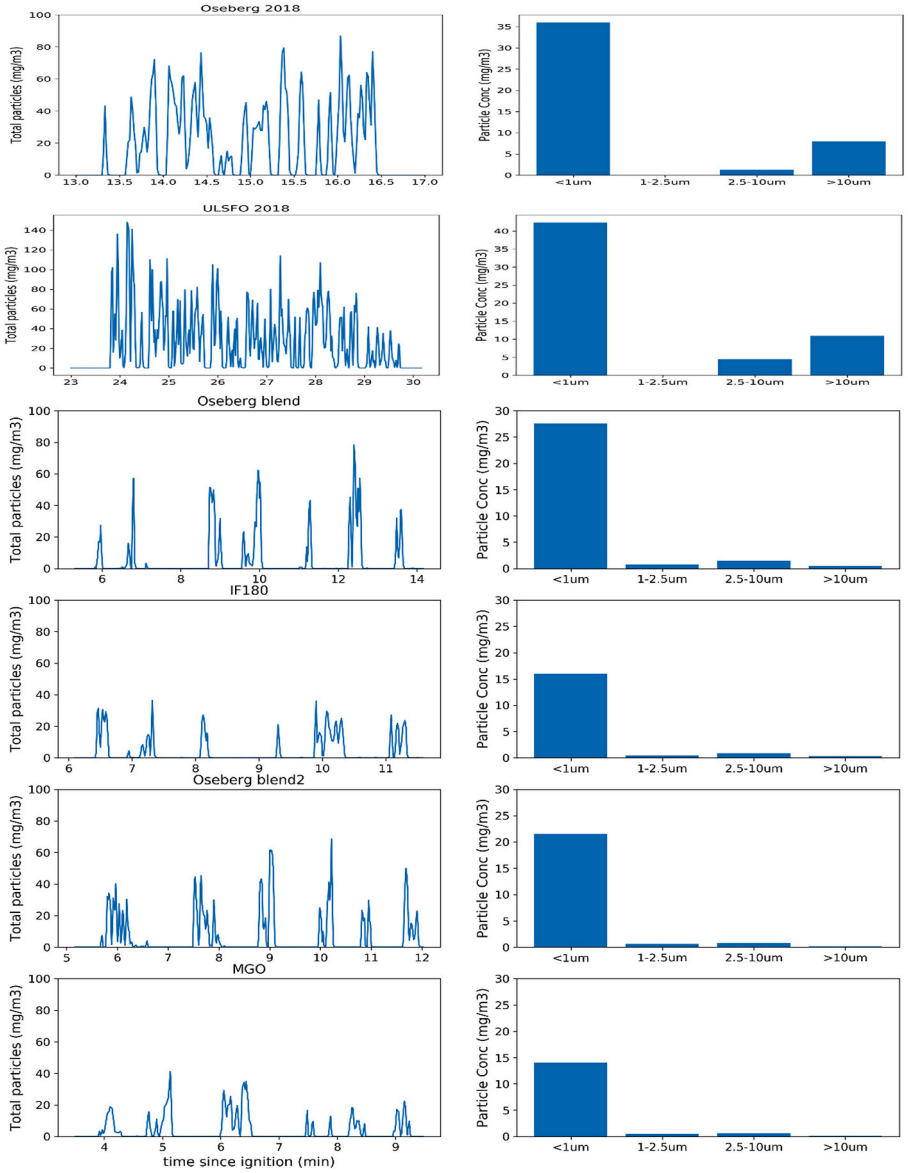

Fig. 3. Left: Particle concentration in the smoke plume during the burns. Right: Size distribution of smoke particles for all burns. In 2018 a less systematic flight pattern was followed, and the drone spent more time in the smoke than passing through it as in 2019. Oseberg Blend refers to Oseberg #1 (2019) and Oseberg Blend 2 to Oseberg #2 (2019).

smoke plume. The concentrations were considerably lower (more than 10 times) on board the MOB boat that followed the smoke plume and moved at the outskirts of the smoke. This reflected that the soot fallout was concentrated and mainly limited to visible smoke, and that the particle concentrations at sea level were highest directly under the smoke plume when monitoring from 200 to 400 m from the burn. It was also observed that the particulate concentrations decreased with increasing distance from the burn site and decreased relatively short time after the fire was extinguished (Szwangruber et al., 2021). This has also been reported in e.g. Buist et al. (2013b).

The strategy for the sampling in the smoke plume was different in 2018 and 2019, but the concentration of soot particles was measured using a DustTrak both times. To calculate a flux of soot particles, a concentration representative to a cross-sectional area of the smoke plume was needed. In Fig. 3, the total particle concentration with time from ignition is shown for all burns. In 2018, the drone spent more time in the smoke than passing through it as in 2019. In 2019, the sampling strategy was improved, as the drone transected through the smoke in the pre-defined pattern illustrated in Fig. S2 (SI), indicated as a straighter peak pattern for each transect. For 2018, a few intervals are shown, all with high concentrations. The results indicate that the particle concentration was slightly higher during the monitored interval for ULSFO than for Oseberg. It seems that more particles larger than 10 μm were detected during the 2018 burns, but it is not possible to say if this was caused by the different monitoring strategies or the burns themselves. For 2019, the six separated peak groups in the left figures are from three horizontal and three vertical transects of a cross section of the smoke plume. An average of concentrations within the peaks (concentrations >0.2 mg/m^3) are used in the calculation of the soot particle flux. The results indicated that more particles were detected in the smoke during both burns with Oseberg (#1 and #2) than with IFO 180 and MGO, and that the highest particle concentration was monitored during the Oseberg #1 burn, which lasted 20 min longer than the Oseberg #2 burn.

The particle size distribution was monitored both in the smoke and at ground level during NOBE in 1993 (Fingas et al., 1995b). Data collected on Rams (real-time aerosol monitors) indicated that particulates were at moderate levels under the plume and dropped to background levels about 1 km downwind from the fire. They concluded that the concentration of particulates in the smoke plume may not be a concern beyond about 500 m, which is in accordance with our findings. From 1.5 km to 30 km downwind from the fire, the particle size distribution in the smoke and in the ambient air were measured continuously by instruments mounted beneath the wing of a research aircraft (Ross et al., 1996). Particle size distributions in the smoke indicated a peak in the accumulation mode around 0.3 μm, and that 65% of the total mass comprised of particles <3.5 μm. From the Mobile 1994 experiments (Fingas et al., 1996b), it seems that monitoring of particulates in the smoke plume was unsuccessful. However, monitoring at ground level indicated that the diesel burns produced four times more particulate matter (PM_{10}) than for similar-sized crude oil spills. In our experiments, the observed particulate concentration in the smoke plume during the MGO burn was not higher than during the other burns. Monitoring at sea level is discussed in Szwangruber et al. (2021). However, the particle size monitoring instruments are more advanced than in the 1990s (NOBE and Mobile burns) as todays instruments give more detailed size distribution in different bins of the particulate matter.

3.3. Properties of ISB residues

All residue samples were analysed on GC/FID to get an indication of evaporative loss during ISB. At least one sample from each burn was analysed on GC/MS for quantification of SVOC (discussed in next section) and measurement of viscosity and density.

In 2018, residues after ISB were collected randomly in the booms and in addition scraped off from the booms after they were placed on deck. Comparing GC chromatograms visually indicate that the evaporative loss seem to be similar within the same burn. The densities and viscosities measured in the ISB residues of Oseberg were in the same range, approximately 0.970 g/mL and 134 000 cP (Table 2). For residue samples after ISB of ULSFO, the densities were in the same range (approximately 0.947 g/mL), while the viscosities varied from 101 000 to 201 000 cP (average 144 000 cP).

In 2019, three residue samples in the boom were collected after each burn. The GC chromatograms were visually compared, and in all burns, except for IFO 180, there were relatively similar evaporative loss for the samples collected in different positions in the boom after ISB. One of the ISB residues of IFO 180 was more burned off than the other two samples. This is illustrated in Fig. S4 (SI), and also from the viscosity and density measurements (Table 2). The viscosity in the most burned sample was approximately 10 times higher (1 010 100 vs 129 000 cP at 10 °C) and the density 1.00 vs 0.95 g/mL. The progress in the two burns with Oseberg was not the same, the first (#1, in Fireboom) burned for 63 min and the second (#2, in Pyroboom) burned for 44 min. This was also reflected in the residue's physical properties, as the viscosities were 100 000 cP (Oseberg #1) and 579 000 cP (Oseberg #2). The ISB residues had different consistencies, which were also reflected in their viscosities. As an example, residue after burning MGO was still liquid (viscosity of 259 cP), while the residue of IFO 180 had a viscosity of more than 1 mill cP, resulting in a very sticky residue.

The densities were less than 1 kg/L for all samples, except for one of the IFO 180 residues (1.001 kg/L). This indicate that the residues would not sink in sea water unless they were exposed to heavier particles or similar. A laboratory test with ISB residues of ULSFO and IFO 180 were performed to study their potential of sinking in seawater (Leirvik and Faksness, 2019). The ISB residues were exposed to sand particles and swell for 5 h. The results indicated that IFO 180 residue had the potential for sinking, while ULSFO was not sinking (MGO and Oseberg were not tested).

3.4. PAHs in ISB residues and soot particles

The SVOC composition of unburned Oseberg and the residues from the three burns are provided in Fig. S6 (SI). The same batch of oil was burned, but the concentrations of naphthalenes in the unburned oil are slightly higher in 2018 than in 2019, while the concentration of decalins were higher in 2019. In 2019, the first Oseberg burn (#1) lasted 19 min longer (63 vs 44 min) than the second burn (Oseberg #2). The SVOC results shows that more of the SVOC components disappeared during the Oseberg #2 burn than Oseberg #1, indicating that Oseberg #2 was more efficient. The Oseberg burn in 2018 lasted for 43 min, i.e. the same as Oseberg #2 in 2019. Fig. S7 (SI) shows the SVOC composition in the fuel oils burned. Unburned ULSFO contains less low boiling point components, such as decalins and naphthalenes, than the other oils, which resulted in a lower depletion of SVOC components in the residue of ULSFO than e.g. Oseberg (approximately 50% vs 80%) in OOW 2018. Comparing the residues with the unburned oils, showed that the concentrations of the most bioavailable and water-soluble components in the oils, such as naphthalenes and 2–3 ring PAHs, were reduced during ISB, but that the content of more heavy, typically pyrogenic, 5–6 ring PAHs (i.e. combustion derived), increased. An increase in heavy, high-ring numbered PAHs as a result of burning has also been reported by others (e.g. Wang et al. (1999), Faksness et al. (2012), and Fritt-Rasmussen et al. (2013)). Comparing the total amounts of SVOC (components listed in Table S1, SI) in the released oil with the amounts in the ISB residues and soot, indicated that more than 96% of the PAHs were destroyed during burning of Oseberg and MGO, and approximately 80% during burning of ULSFO and IFO 180. Wang et al. (1999) reported an average destruction efficiency for PAHs greater than 99% when burning diesel, which is in accordance with our findings. The final chemical composition of the residue will depend on the initial oil type and the efficiency of the burning.

The drones were equipped with a filter cassette connected to a pump

(air flow 3 L/min) for sampling of soot particles. More 4–6 ring PAHs were detected on the soot filter collected in 2018 than on the filters from 2019. These components are considered to be pyrogenic PAHs and some of the enrichment can be attributed to the formation of these PAHs during the ISB. However, there were higher concentrations measured on the reference filters (not been in the smoke (background)) in 2019, and as the results are corrected for background, this could have influenced the results reported. Estimated amounts (in kg) of each component group (described in Table S1, SI) in total amount of soot produced during ISB (Drone 1 from each experiment) were calculated and are shown in Fig. S8. The calculations are based on the PAH concentrations in soot, estimated amount BC, and amount burned oil. The highest amount of soot (845 kg) was produced during ISB of Oseberg #1 (2019), but the results indicated that the soot from Oseberg (2018) (435 kg) contained more SVOCs than the soot in the other burns (1209 g, including 944 g 4–6 ring PAHs). The results indicated that the lowest amounts of soot were produced during the burns of ULSFO and IFO 180 (334 and 336 kg, respectively), which also had the lowest BE. The SVOC concentration in the soot was similar, 474 g in soot from ULSFO (354 g 4–6 ring PAHs) and 427 g in soot from IFO 180 (109 g 4–6 ring PAHs). The amount of soot collected with the drones also depends on the time the drones were in the smoke plume, and it was only 12 min in the air during burning of IFO 180.

3.5. Burn efficiency

To estimate BE of ISB on open water has been challenging as it is difficult to collect all the residue. After ISB, a net capturing of the residue was transferred to a container on the vessel and weighed onshore.

Table 3 gives results from the weighing and estimated BE. BE was 80% for Oseberg 2018 and 49–57% for ULSFO. In 2019, factors such as boom leakage, loss when transferring the net from sea to a container on deck, and residue sticking to the boom after ISB were not counted for when calculating BE. However, we strive to reduce these factors. Estimated BE were 87% for Oseberg #1, 91% for Oseberg #2, and 64% for IFO 180. No residue was collected after ISB of MGO as the residue was still liquid (viscosity 259 cP), and a visual estimate of remaining residue in the boom indicated a BE > 95%. All these estimates are too high, as photos taken by the PyroDrone prior to and during ISB showed that there was visible boom leakage in all burns. We also observed that there was more loss of the IFO 180 residue than the other oils when lifting the net from the sea into the container on deck.

As a supplement, regression curves were established from the controlled burns in the laboratory (Fig. S5, SI) to estimate the BE of the offshore burns (Faksness et al., 2019). Even though the scale of the burns and the oil film thickness in laboratory burns versus field ISB were different, laboratory burns were a good supplement to field measurements of BE. Estimated BE for three burns of Oseberg are included, and the results from 2019 show that there were differences in BE, depending on where the samples were collected in the boom. However, the variation between the three samples from each burn was small (±2%) for Oseberg, and the average BE were 69% and 75% in 2019 (Oseberg #1 and Oseberg #2). BE in 2018 was higher, and were estimated at 84%, which correlated well with BE from the gravimetric method (approximately 80%) based on collected residue, estimated boom leakage and oil on the boom. In the residues of IFO 180, the BE varied from 24 to 40% (average BE was 33% (±8%)). Based on the observations done during OOW, it is suggested that the estimated BE calculated from the "calibration curves" probably are more reliable than the BE solely calculated from the weights of the residues in the net (Fig. S5, SI).

Three burns with the same Oseberg oil showed that the properties of the residues varied from between 100 000 to 145 000 cP for Oseberg 2018 and Oseberg #1 to 579 000 cP for Oseberg #2, which also had the highest BE.

Table 3
Estimated weight and BE after OOW in 2018 and 2019. For OOW 2019, factors, such as boom leakage and residue sticking on the boom after ISB, are not taken into account in calculations of BE. For OOW 2018, these factors are estimated in the amount of residue for Oseberg.

Oil	Volume oil on sea (m^3)	Weight oil on sea (kg)	Weight ISB residue (kg)	Weight burned oil (kg)	Estimated BE (%)
Oseberg 2018	6.0	5346	1000	4346	80
ULSFO 2018	5.8	5319	2287–2819	2500–3032	49–57
Oseberg #1 (2019)	6.0	5389	697	4692	87
Oseberg #2 (2019)	5.6	5030	466	4564	91
IFO 180	4.2	4031	1449	2582	64
MGO	6.0	5083	ca 260	ca 4823	>95

3.6. Black carbon

Black carbon (BC) is the carbonaceous component of particulate matter formed by incomplete combustion of fossil fuels and biomass. Complete combustion would turn all carbon into CO_2. In practice, combustion is never complete, and CO_2, CO, volatile organic compounds, OC (organic carbon) and BC are all formed. Emissions from the same fuel can vary by orders of magnitude, depending on the quality of the combustion.

BC is a short-lived climate pollutant (SLCP) of particular concern in the Arctic (lifetime less than 15 years (Arctic Council, 2011)). Compared to long-lived greenhouse gases such as CO_2, SLCPs remain in the atmosphere for much shorter time periods. BC is not a greenhouse gas but has global warming properties. BC remains in the atmosphere for days to weeks and warms the climate by absorbing both incoming and outgoing solar radiation and by darkening snow and ice after deposition thereby reducing the surface albedo (Arctic Council, 2011).

The amount of BC produced relative to the amount of oil burned were estimated and were approximately 10% for Oseberg 2018, 11% for ULSFO, 12% for MGO, 13% for IFO 180, 14% for Oseberg #2, and 18% for Oseberg #1. Soot yields from dozens of burn experiments conducted in the late 1980s and 1990s, plus the oil fires in Kuwait, range from 2 to 20% of oil burned (Buist et al., 2013a). In the Macondo spill in 2010, it was estimated that 42 000 tons of oil was burned. Perring et al. (2011) estimated that between 600 and 2100 tons BC was released to the atmosphere during the 9 weeks the response action lasted, and that this was equal to 4% of the total amount of oil burned. However, these estimations were done using other instrumentation and methods than during OOW and this may explain the different results.

4. Conclusions

During oil-on-water in 2018 and 2019 ISB of ULSFO, IFO 180, MGO and pre-weathered Oseberg crude oil were carried out on open water. The oils were released into a fire boom and then ignited from a PyroDrone or a workboat. Comprehensive monitoring of particles and gases was performed in the smoke plume using dedicated drones and ISB residues were collected for chemical characterisation.

In the soot monitored in the smoke plume and at sea level, the major part (>90% by mass) of the measured particulates was in the fine particle fraction (PM < 1 μm), which includes the ultrafine particles (<0.1 μm). If inhaled, the ultrafine particles have harmful effects on the respiratory and cardiovascular system. Unlike the particulate matter, the gases emitted during an ISB operation generally do not represent a serious threat to human health, primarily because the concentrations at which the gases become harmful are much higher than measured in the smoke. However, the concentration of gases in the smoke plume may

exceed hazardous thresholds as they leave the fire, but they drop below these thresholds within a very short distance from the fire. Monitoring at sea level showed that the soot concentrations were highest directly under the smoke plume close to the fire but declined with increasing distance from the burn site. The amount of BC produced relative to the amount of oil burned was 10–18% from the burns, which is in the upper range compared to other studies.

The BE varied within the slick and from one burn to another. BE was estimated to be between 80 and 91% for Oseberg crude. For the fuel oils the BE varied and was highest for MGO (more than 90%). The BE was less than 60% for the two heavier fuels, ULSFO and IFO 180. The ISB residues had different consistency, which also were reflected in their viscosities, e.g. residue after burning MGO was still liquid (viscosity 259 cP), while the viscosity of residue from IFO 180 was more than 1 mill cP, resulting in a very sticky residue. The burn efficiency is not only dependent on the oil type, but also on factors like original slick thickness, degree of emulsification and weathering, area coverage of the flame, wind speed and wave choppiness.

There were several concepts that were tested for the first time during these field experiments: Igniting the oil slick with the use of a drone, using drones with sensor packages to monitor soot and gases in the smoke, and to be able to collect the residue after the burn in a net that was connected to the boom.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.112419.

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