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Report

Offshore field experiments to operationalize in situ burning as a response method in Norwegian waters

Summary of experience and results from "Oil-on-water" in 2016, 2018, and 2019

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SUMMARY
The Norwegian Clean Seas Association for Operating Companies (NOFO) and the Norwegian Coastal Administration (NCA) perform "Oil on water" (OOW) in Norwegian waters on an annual basis, usually in June. The objective with OOW is to verify and further develop the oil spill response. In 2016, 2018, and 2019, in situ burning (ISB) was tested out as a possible strategy for oil spill response using different oil types.

During OOW in 2016, a series of experiments were conducted to demonstrate the use of herders followed by ISB in open water conditions. ISB was the main activity during OOW in 2018 and 2019. ISB experiments with different oil types were performed and two types of fire booms were tested (DESMI Pyroboom and Elastec/American Fireboom). Ignition was done by use of a "Pyrodrone" (DESMI). 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. The University of Bergen measured level of toxic gases and particles for potential for human exposure under ISB as a basis for working out recommendations to protect personnel.

The present report summarizes experience and results from the ISB field experiments in 2016, 2018 and 2019.

MANAGEMENT SYSTEM CERTIFICATION
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List of abbreviations and expressions

Abbreviation	Explanation	Abbreviation	Explanation
AED	Aerodynamic equivalent diameter	NR	Not reusable (filter mask)
ASHB	Analysis of spreading and herding for burning	OC	Organic carbon
BC	Black carbon	OEL	Occupational exposure limit
BE	Burn efficiency	OOW	Oil on water
BTEX	Benzene, toluene, ethylbenzene, xylenes	Oseberg Fireboom	Refers to experiment where Oseberg crude was burned in a Fireboom
CV	Copepodite stage 5	Oseberg Pyroboom	Refers to experiment where Oseberg crude was burned in a Pyroboom
DCM	Dichloro methane	P1	Low efficiency (filter mask)
DWH	Deepwater Horizon (oil spill in Gulf of Mexico in 2010)	P2	Medium efficiency (filter mask)
GC	Gas chromatograph	P3	High efficiency (filter mask)
GC/FID	Gas chromatograph with flame ionisation detector	PAH	Polycyclic aromatic hydrocarbons
GC/MS	Gas chromatograph with mass spectrometer	PID	Photoionization detector
IARC	International Agency for Research on Cancer	PM	Particulate matter
IFO	Intermediate fuel oil	PP	Polypropylene
ISB	In situ burning	PyroDrone	Drone with igniter
ITA	Integrated time area	R	Reusable (filter mask)
Kow	Octanol-water coefficient	SLCP	Short lived climate pollutant
LOD	Limit of detection	SVOC	Semi-volatile organic compounds
MBA	Maximum burn area	THC	Total hydrocarbons
MGO	Marine gas oil	TPH	Total petroleum hydrocarbons
MOB	Man overboard	TS-6535	ThickSlick 6535 (herder)
N/A	Not applicable or not available	TU	Toxic unit
NCA	Norwegian Coastal Administration	TVOC	total volatile organic compounds
ND	Not detected	UiB	University of Bergen
NIOSH	National Institute for Occupational Safety and Health	ULSFO	Ultra low sulphur fuel oil
NOBE	Newfoundland offshore burn experiment	USV	Unmanned surface vessel
NOFO	Norwegian Clean Seas Association for Operating Companies	WAF	Water accommodated fraction

Executive summary

With few exceptions, Norwegian Clean Seas Association for Operating Companies (NOFO) and Norwegian Coastal Administration (NCA) perform "Oil on water" (OOW) in Norwegian waters annually, usually in June. The main objective with OOW is to verify and further develop oil spill response methods. OOW gives NOFO and NCA the opportunity to verify new equipment and methods using different oil types under various weather conditions. In situ burning (ISB) experiments were performed in 2016, 2018, and 2019 in order to operationalize ISB as a possible response method in Norwegian waters. These experiments included use of herders, ignitors (hand-held or from drone), validation of fire booms, and estimation of burning efficiency. On behalf of NCA and NOFO, SINTEF, Maritime Robotics, and the University of Bergen performed monitoring in the smoke plume, at the surface as well as on vessels. Dedicated drones and workboats were used to measure harmful gas levels to estimate the risk for human exposure during the burns.

During OOW 2016, one of the experiments were performed with three releases of Grane Blend crude oil. The main goals of the ISB experiment was to investigate if free floating oil would ignite and burn in open water and whether herders could be useful in conjunction with ISB in open water. Two slicks were herded before ignition, while the third "reference" slick was not treated with herder. Hand-held igniters (gelled gasoline and flare) were used to ignite the slicks.

The ISB experiment demonstrated that uncontained oil slicks with a sufficient thickness can be ignited and burn efficiently in calm open water, and that oil slicks may be contracted by herder sprayed from a MOB-boat around the periphery. However, also the untreated slick was ignited and burned successfully. 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 in open water.

Smoke from the burns were sampled by a drone and the total particle concentration (particles less than 2.5 µm (PM2.5)) corresponded to estimated levels of 57 to 137 mg/m^3 when the drone was actually in the smoke plume (Norwegian Occupational Exposure Limit (OEL)= 10 mg/m^3). At the same time, concentration of PM2.5 particles was low in the MOB boat (approx. 1 km downwind from the burn). In the smoke plume particulate PAHs were detected at levels approaching the Norwegian OELs.

ISB was the main activity during OOW 2018 and 2019. The objectives were to demonstrate ignition of an oil slick from drone, measure amount of residue and effectiveness of ISB in containment booms, monitor concentrations of soot and gases in the smoke plume using drones with sensor packages, and monitor harmful substances related to ISB to identify necessary safety measures for response personnel. Seven experimental burns with different oil types were performed and two types of fire booms were tested (DESMI Pyroboom and Elastec American Fireboom). The oils were released (approximately 6 m^3 of each) and contained by the fireboom before ignited using a "Pyrodrone" (DESMI) to operate an ignitor fuelled with a mixture of gelled diesel (80%) and gasoline (20%). ISBs with pre-weathered Oseberg Blend, marine gas oil (MGO), an Ultra Low Sulphur Fuel Oil (ULSFO) and a heavy fuel oil (IFO 180) were performed. 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 on shore prior to the offshore experiment. Both firebooms, Pyroboom and American Fireboom, suffered too much damage after one burn to be reused.

The ambient CO_2 level was approximately 400 ppm, and during the burns the CO_2-concentrations in the smoke plume monitored to be up to 420 ppm (above ambient level). In 2018, higher CO concentrations than in 2019 were measured. Less sensitive sensors were used in 2018, which could have had impact on the readings. In 2018 maximum CO level was 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 and 2 ppm for IFO180. 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).

The soot particle monitoring during all burns in 2018 and 2019, both in the smoke plume and on sea level, indicated that by mass more than 90% of 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 penetrate into the blood stream and potentially harm other vital organs. The monitoring on sea level showed that the soot fallout was concentrated and mainly limited to visible smoke, and that the particle concentrations were highest directly under the smoke plume, i.e. up to 200 m from the burn. Particle concentrations declined with increasing distance from the burn site and decreased shortly after the fire extinguished.

In the smoke plume several PAH components in the particulate phase, some of them carcinogenic, were detected at levels approaching the Norwegian OEL. Particulate PAH is bound to the soot-particles, and when moving away from the smoke plume the exposure to PAH decreased similarly to reported for the particles. Human exposure to PAH onboard vessels both upwind and downwind from the burning was very low during these conditions with relatively short burning time. However, it is recommended that personnel close to and downwind of smoke plumes from oil fires should use facemasks with P3 filters. On the other hand, this finding illustrated that the particles were concentrated mainly within the visible smoke. The results strongly indicate that on the vessels placed upwind from the smoke plume, the burning has no harmful effect on the air quality.

The estimated amount of Black Carbon (BC, soot) produced relative to the amount of oils burned were 10% for Oseberg 2018, 11% for ULSFO, 12% for MGO, 13% for IFO180, and 14% and 18% from the two burns with Oseberg in 2019, which are within the range reported from other ISBs (2-20%). The estimated total emission of BC to air from the four experimental ISB performed in 2019 was 2.4 tons or contributed with 0.075% of the total emission to air in Norway in 2016.

In 2018 and 2019, a net capturing the residue after burning was connected to the firebooms. After ISB, the net was transferred to a container on the vessel and weighed onshore. In 2018, two sections (30 m) of the PyroBoom was destroyed during the burn and disconnected prior to burning ULSFO. The boom was used without a net during ISB of ULSFO, and only a small part of the residue was recovered after the burn. The surveillance plane LN-KYV was in the air during the release of Oseberg, and estimated the boom leakage to be 400 L. In addition, approximately 100 kg residue was on the boom after burning. Estimated BE was 80% for Oseberg (gravimetric) and 49-57% for ULSFO (estimated from chemical analysis of residue and a combination of heat flux and gas concentrations). For the burns in 2019, estimated BE is based on the weight of the residues only. 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 taking into account leading to some overestimation of BE. Estimated BE were 87% for Oseberg Fireboom, 91% for Oseberg Pyroboom, and 64% for IFO180. No residue was collected for MGO due to high BE (>95%). It was also observed that there was more loss of the IFO residue than the other oils when lifting the net from the sea to the container on deck. The collection of residues after each burn was successfully completed in 2018 and 2019 using a net mounted to the booms.

Density and viscosity of the ISB residues were higher compared to the unburned oils. Compared with unburned oils, the depletion in the total PAH concentration (including decalins and naphthalenes) in the ISB residues were reduced with approximately 85% and 75%, respectively for the two burns with herders in 2016, and with more than 80% for Oseberg and about 50% for ULSFO during OOW in 2018.The depletion in the total PAH concentrations during OOW 2019 was 77% for Oseberg Fireboom, 90% for Oseberg Pyroboom, 63% for MGO and 33% and 77% for the two residues of IFO180. Unburned ULSFO contained less lower boiling point components, such as decalins and naphthalenes than the other oils.

Total emissions of semi volatile organic compounds (SVOC) or PAHs (including decalins and naphthalenes) during ISB were calculated based on the concentrations from the measurements in soot particles and residue. The highest amount of soot (845 kg) was produced during the Oseberg Fireboom burn where 6 m^3 oil were released and the lowest amounts of soot were produced during the burns of ULSFO (5.8 m^3 released) and IFO180 (4.2 m^3 released), 334 and 336 kg, respective. The estimated BE was lower in these two burns than in the other burns. The lower soot amount during burning of IFO180 could be due to that the drone was only 12 minutes in the air, while it was more than 30 minutes in the air when burning Oseberg and ULSFO. However, the flight pattern was more random in 2018 when ULSFO was burned.

The residues of Oseberg 2018 burn, Oseberg Fireboom 2019 burn and MGO contained similar total amount of PAHs (approximately 4 kg, of which ca 2.8 kg were naphthalenes and 2-3 ring PAH). Two burn residues of IFO180 were analysed, reflecting their difference in BE. The total amount of PAHs varied from 8.7 kg PAH in the most burned residue (6.4 kg being naphthalenes and 2-3 ring PAH) to 24 kg (20 kg being naphthalenes and 2-3 ring PAH). The lowest amount of PAHs was quantified in the residue of Oseberg Pyroboom burn in 2019 (1.2 kg, of which 0.8 kg naphthalenes and 2-3 ring PAH). The results indicated that residues of the oils with less BE contained higher content of SVOCs than the residues of oils with higher BE, such as Oseberg Pyroboom.

Although BE varied within the burns, ISB of weathered, non-emulsified crudes and MGO seem to be applicable. Prior to burning a heavy bunker oil, however, an assessment should be performed on whether using ISB or not. The BE from IFO180 was approximately 50% leaving a relatively large amount of residue with a consistence much more challenging to handle than the unburned oil.

Learnings and operational findings are summarized in Chapter 5.

1 Introduction

In order to burn oil spilled on water, three elements must be present: Fuel, oxygen and a source of ignition. The oil must be heated to a temperature above its flash point, i.e. to the temperature at which a sufficient amount of hydrocarbons are vaporized to support combustion in the air above the slick. It is the hydrocarbons vapours above the slick that burn, and not the oil itself. The fire point is the temperature a few degrees above the flash point at which the oil is warm enough to supply vapours at a rate sufficient to support continuous burning (Buist et al., 2013a)

The key parameter that determines whether or not the oil will burn is oil slick thickness. If the slick is thick enough, it acts as an insulator and keeps the burning surface at a high temperature by reducing heat loss to the underlying water. As the slick thins, increasingly more heat is passed through it, eventually enough heat is transferred through the slick to allow the temperature of the surface to drop below its fire point, at which time the burn stops.

Controlled in-situ burning (ISB) has proven effective for oil spills in ice conditions and has been used successfully to remove oil from spills in ice-affected waters in several large-scale field experiments since the 1970s (summarized in Buist et al., 2013b). ISB is a response option that has rarely been used on marine oil spills, but its successful use during the Gulf of Mexico Deepwater Horizon (DWH) response in 2010 (Allen et al., 2011) has generated interest in use also in other areas than the Arctic.

The Norwegian Clean Seas Association for Operating Companies (NOFO) and the Norwegian Coastal Administration (NCA) are cooperating closely to operationalize ISB as a response method in Norwegian waters. With a few exceptions, NOFO and NCA conduct "Oil on water" experiments (OOW) in Norwegian waters on an annual basis, usually in June. The main objective with OOW is to verify and further develop oil spill response methods. OOW gives 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 ISB was tested out as a possible strategy for oil spill response (NOFO (2016), Engen et al., (2018 and 2019)).

During OOW 2016 (NOFO, 2016), one of the experiments were performed with three releases of Grane Blend crude oil (4 - 6 m^3 oil each). The main goals of the ISB experiment were to investigate if free floating oil would ignite and burn in open water and whether herders could be used in conjunction with ISB on open water (Cooper et al. (2017), Singsaas et al. (2017)). Two slicks were herded before ignition, while the third "reference" slick was not treated with herder. Hand-held igniters (gelled gasoline and flare) were used to ignite the slicks. The ISB experiments demonstrated that oil slicks in calmer open waters ignite and burn efficiently and that oil slicks may be contracted by herder sprayed from a MOB-boat around the periphery of an oil slick. However, also the untreated slick was ignited and burned.

ISB was the main activity during the field experiments OOW in 2018 and 2019 (Engen et al., 2018, 2019). The objectives were to demonstrate igniting the oil slick from drone, measure amount of residue and effectiveness of ISB in booms on open water, monitor concentrations of soot and gases in the smoke plume using drones with sensor packages, and monitor harmful substances related to ISB to identify necessary safety precaution for response personnel. Six experimental ISB with different oil types were performed and two types of fire booms were tested (DESMI Pyroboom and Elastec/American Fireboom). The oils were released (approximately 6 m^3 in each experiment) and contained into the fireboom before ignited by use of a "Pyro-drone" (DESMI) with a gelled ignitor consisting of diesel (80%) and gasoline (20%). ISBs with pre-weathered Oseberg Blend, marine gas oil (MGO), an Ultra Low Sulphur Fuel Oil (ULSFO) and a heavy fuel oil (IFO 180) were performed. In addition to the 6 ISBs, an emulsified pre-weathered Oseberg Blend with 52% water did not ignite, although a sample of the emulsion (4 L) was easily to ignite and burned at ideal

conditions onshore prior to the offshore experiment. The operational aspects of these ISBs are described and discussed in Jensen et al. (2020). 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 burned residues were collected from the sea surface and in addition, the University of Bergen measured the potential for human exposure under ISB.

The present report summarizes the experience and results from the ISB field experiments in 2016, 2018 and 2019 previously reported in Singsaas et al. (2017), Faksness and Krause (2018), and Faksness et al. (2019a). Characterisation of air pollutants emitted from ISB and the potential for human exposure are presented and discussed in Chapter 4 (Szwangruber et al. (2020)).

2 Materials and methods

2.1 Discharge permit

Prior to conducting OOW, the Norwegian Environment Agency must approve the experiments. NOFO has been responsible for preparing and submitting the discharge permit application to the Norwegian Environmental Agency. The content in an application is i.a.:

- A detailed plan describing each of the experiments, including the release requirements
- Documentation to justify each experiment and volumes of oil and other substances planned to be used
- Description of marine wildlife (fish, seabirds and sea mammals) at the site (the area and time of year is chosen considering marine wildlife, fishing activity, helicopter traffic and petroleum activity)
- Description of the discharges (e.g. oil types and volume) and assessment of their potential for environmental effects
- Plan for surveillance of the marine wildlife – experiments can be moved or postponed if accumulations of seabirds and / or marine mammals are observed prior to the experiments (according to predefined criteria)
- Competence of involved personnel
- Remote sensing (e.g. surveillance planes, drones, satellite images, IR-cameras, oil detecting radars)
- Risk reducing measures, i.a.:
    - Surveillance of marine wildlife
    - Oil spill recovery equipment on site
    - Contingency plan for oil recovery
    - Remote sensing (e.g. surveillance planes)
    - Oil drift modelling and weather forecasts

The Norwegian Environment Agency (NEA) puts the application up for public hearing by publishing it on their web-site and sending it to other governmental agencies and stakeholders (e.g. Institute of Marine Research and Directorate of Fisheries). Their comments, together with NEA's own considerations, form the basis for the final approval or disapproval. If approved, specific requirements and conditions for the discharge permit is stated in the approval.

For an ISB experiment, preferred wind speed is typically within 5 m/s, but conditions could be better or worse depending on the wind speed increasing, being constant over some time or decreasing. As a consequence, NOFO applied for and got permission to conduct the burns at a maximum of 8 m/s wind. This gave enough room on site to consider whether conditions were acceptable for each burn. The permit also specifies site location for the experiments, time period, environmental monitoring, presence of remote sensing and oil recovery equipment in preparedness on site.

2.2 Test site

The field experiments were conducted at the Frigg field in the North Sea in mid-June. Frigg was a natural gas field on the boundary between Norway and UK and was in production from 1978 to 2004. The water depth in the area is approximately 100 m and the location of the test site is shown in Figure 2.1.

Figure 2.1 *The North Sea with the location of the Frigg field where the "Oil-on-water" field experiments took place (Map from https://cop.nofo.no/)*

2.3 The field experiments

The experimental large scale ISBs planned and carried out are detailed in Table 2.1. Wind and wave conditions during the burns show that some burns were done at more than 5 m/s wind speed. The emulsified Oseberg 200°C+ with more than 50% water did not ignite and will not be discussed further in the report.

Table 2.1 *The experimental large scale ISB performed under OOW in 2016, 2018 and 2019. In 2016, the slicks were ignited several times during the burning time.*

Year	Volume	Oil type	Boom	Burning time	Wind and waves
2016	6 m^3	Grane Blend (HISB 4.1)	No boom, used herder	Ca 26 min	3-4 m/s, non-breaking
2016	4.2 m^3	Grane Blend (HISB 4.2 ref)	No boom, no herder	Ca 32 min	3-4 m/s, non-breaking
2016	4 m^3	Grane Blend (HISB 4.3)	No boom, used herder	Ca 8 min	5 m/s, some breaking
2018	6 m^3	Oseberg Blend 200°C+	Desmi Pyroboom	43 min	6-7 m/s, 1.1 m waves
2018	5.8 m^3	ULSFO	Desmi Pyroboom	48 min	4-5 m/s, 1.2 m waves
2019	6 m^3	Oseberg Blend 200°C+	American Fireboom	63 min	4-5 m/s, 2.4 m waves
2019	4.2 m^3	IFO 180	American Fireboom	37 min	4-5 m/s, 1.1 m waves
2019	5.6 m^3	Oseberg Blend 200°C+	Desmi Pyroboom	44 min	4-5 m/s, 2.4 m waves
2019	6 m^3	Marine gas oil (MGO)	American Fireboom	28 min	6-7 m/s, 1 m waves
2019	6 m^3	Oseberg Blend 200°C+, 52% water	American Fireboom	Did not ignite	5-6 m/s, 1m waves

An overview over the data collected and the analytical methods used are given Table 2.2.

Table 2.2 Overview over the data collected and the analytical methods used during the ISB experiments.

	OOW 2016			OOW 2018		OOW 2019			
	HISB 4.1	HISB 4.2	HISB 4.3	Oseberg Pyroboom	ULSFO Pyroboom	Oseberg#1 Fireboom	Oseberg #2 Pyroboom	IFO180 Fireboom	MGO Fireboom
Maps with GPS trackings				X	X	X	X	X	X
Wind speed	X	X	X	X	X	X	X	X	X
Air temperature				X	X	X	X	X	X
Heat flux				X	X	X	X	X	X
In smoke									
Drone flight heights				X	X	X	X	X	X
PM 1, 2.5, 4, 10 and total				X	X	X	X	X	X
PM 2.5	X	X	X	X	X	X	X	X	X
NOx				X	X	X		X	X
SO_2				X	X	X		X	X
CO				X	X	X		X	X
CO_2				X	X	X		X	X
Soot on filters	X			X	X	X	X	X	X
Black Carbon				X	X	X	X	X	X
Soot on sea (SVOC)				X	X				
PM 2.5 on sea				X	X	X	X	X	X
In residue									
Density	X	X	X	X	X	X	X	X	X
Viscosity	X*			X	X	X	X	X	X
GC/FID (THC)	X			X	X	X	X	X	X
GC/FID (evaporative loss)	X	X							
GC/MS (SVOC)	X**	X**		X	X	X	X	X	X
Gravimetric (BE)				X		X	X	X	
Estimated BE	X	X	X	X	X	X	X	X	X
Human exposure (UiB)									
PM 1, 2.5, 4, 10, total				X	X	X	X	X	X
PM 2.5	X	X	X	X	X	X	X	X	X
TVOC/BTEX				X	X	X	X	X	X
Filter/XAD (21 comp PAH)	X	X	X	X	X				

** Only one sample*

*** In another project (Faksness et al., 2019b)*

2.3.1 Field experiments in 2016

Three experimental releases of Grane Blend crude oil to sea were performed for verification of the use of herder (ThickSlick 6535 (TS-6535)) and ISB in open water conditions. Two slicks were herded before ignition, while the third "reference" slick was not treated with herder. A fourth experiment was performed in breaking wave conditions with release of 5 litres of herder alone to study the potential dampening effect on capillary waves.

Two vessels were allocated to the experiments: KV Sortland, a Norwegian coastguard vessel within the "Barentsea-class" was responsible for the oil releases. An unmanned surface vessel (USV) with an Aerostat (OceanEye® with visual and Infra-Red (IR) video cameras) were stationed and launched from KV Sortland. From MS Strilborg, a support and response vessel, two MOB (Man Over Board) boats were used for sampling (surface oil and water column), air monitoring, the herding and ignition operations, and in containment and recovery of burn residue. More details are given in Section 5.3.2 and in Singsaas et al. (2017).

Monitoring strategy

One of the MOB-boats was primarily allocated for surface oil sampling and water column monitoring. Surface oil slick thickness measurements (synchronized to aerial survey) using a Plexiglas cylinder for oil/water samples (> 3 mm), PP-pads (polypropylene) for gravimetric quantification (< 3 mm), and Teflon net (< 3µm) for GC or spectrophotometric quantification. Surface oil sampling for physical/chemical characterization of oil properties (viscosity, density, water content, dispersibility, evaporative loss), sampling of burned residues (density, viscosity, GC).

The air measurements during the three burns were taken at three locations for PM2.5-particles, total particles and for PAH in the total particle fraction and in the vapour phase: In the smoke plume by a drone (MR QUAD), in the closest vessel using an USV, and on a drone operator located on deck on MS Strilborg. The particle fraction was measured by a SidePak™ Aerosol Monitor AM510, and for the PAHs a "sampling train" that consists of a 37 mm filter cassette with a glass-fibre-filter for sampling with aerosol/particles in series with an adsorbent tube for sampling of vapour (BTEX). It was attached to a pump with an air flow of 0.2 L/min. More details are given in Section 5.2.

Two video drones (DJI Inspire 1) were used to document the different aspects of the ISB experiments. In addition, three remote sensing aircrafts participated with a range of sensors that was used in the detection of herder and oil slicks, and to document the burns.

2.3.2 Field experiments in 2018 and 2019

In 2018 and 2019, seven large-scale experimental in situ burns (ISB) were planned (detailed in Table 2.1). The oils physical properties are given in Table 3.2.

The main vessel MS Strilborg was deploying and towing the firebooms and releasing the oil. A net to contain the residue after burning was connected to the booms before they were deployed on water. A heat flux sensor (mounted on the rail on MS Strilborg), the Pyro-drone and two MOB-boats were also 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 more was operated from OV Utvær. In 2019, both drones monitoring the smoke were operated from the fishing boat "Bøen". More details regarding operational challenges when performing the experiments are given in Jensen et al. (2020).

SINTEF, in cooperation with Maritime Robotics, performed an extensive monitoring of the smoke plume, using two drones (Figure 2.2) 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 3L/min. In addition, samples of burned residues were collected from the sea surface. The University of Bergen measured the potential for human exposure by monitoring the particle distribution and concentration in the smoke fallout using i.a. the same type of DustTrak as on the drones (more details in Section.5.3.1).

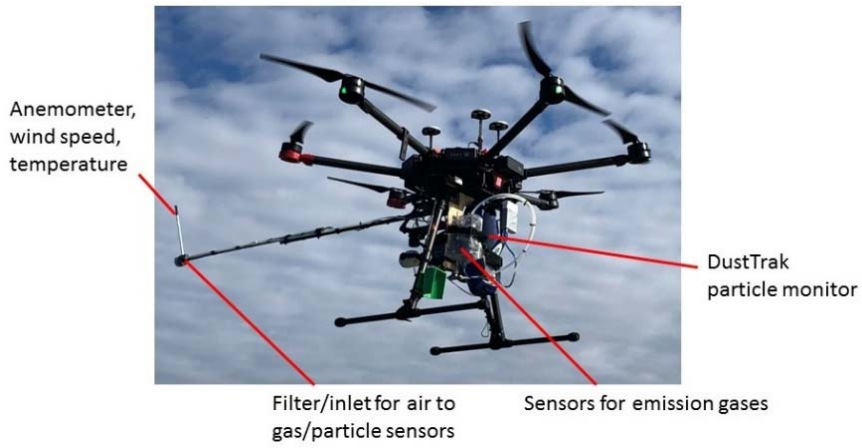

Figure 2.2 *Drone (DJI Matrice 600 Pro) equipped with monitoring instruments and sensors (two identical equipped drones were used)*

Monitoring strategy

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 were improved from 2018 to 2019, as a random sampling were 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. One of the MOB-boats was used to monitor the potential for human exposure. The monitoring was performed up to 400 m downwind from the fire (more details in Section 5.3.1)

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 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.

In 2019, the flight patterns were improved. The drones flied in a pre-defined pattern in the smoke plume. A vertical cross section of the plume 100 meters downwind of the fireboom was chosen as the primary objective for both drones. Another vertical cross section 300 meters 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.

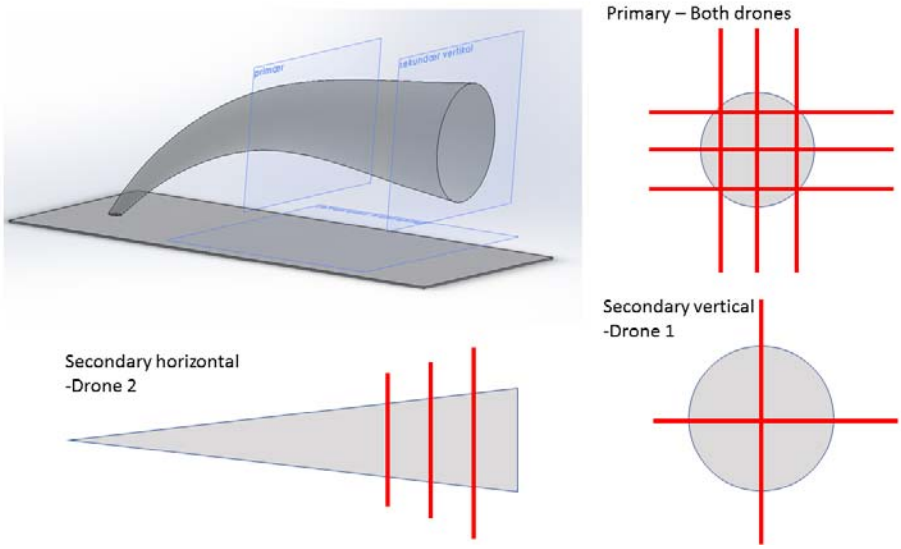

Figure 2.3 Planned monitoring strategy for drones in the smoke plume (OOW 2019)

2.4 Sample processing and analysis

An overview of all collected samples by SINTEF is given in Appendix A, including the analysis performed on the selected samples.

2.4.1 Physical properties of the ISB residues

Viscosity and density of the ISB residues were measured. In 2016, it was reported that the rheometer was not able to measure viscosities with a share rate of 10 s^{-1} with a lower temperature than 30 ^{o}C. In 2018 and 2019, viscosities were measured as temperature sweeps (1 ^{o}C/min) from 65 ^{o}C down to -3 ^{o}C with a shear rate of 10 s^{-1}. The density for the residues was measured at 50 ^{o}C (2016) or 80 ^{o}C (2018 and 2019) and re-calculated to 15 ^{o}C (ASTM, 1980).

2.4.2 Sample preparation and chemical analysis

An aliquot of the unburned oils and their ISB residues were weighed directly into a graduated flask (10 mL). Dichloro methane (DCM) was used as a solvent. The residues were heated at 50 ^{o}C for approximately 2 hours to get them as homogenous as possible prior to weighing.

Total amount of soot particles on the filters were measured by weighing the filters prior to and after exposure (in the laboratory). The filters were extracted with DCM and aided with sonication.

The extracts were added internal standards for quantitative analysis on gas chromatograph with flame ionisation detector (GC/FID) and gas chromatograph with mass spectrometer (GC/MS). For GC/FID the internal standards o-terphenyl and 5α-androstane were added, 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). Total Petroleum Hydrocarbons, 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 semi-volatile compounds (SVOC), including decalins, naphthalenes, and PAHs, were performed on selected samples (modified US EPA, 2007).

In 2016, no quantitative analysis on the oils and residues were performed, only qualitative GC/FID-analysis to estimate evaporative loss. However, residues from two of the burns have later been analysed and quantified as described above as a part of another project (Faksness et al., 2019b).

Methods and monitoring related to human exposure are described in Section 4.2.

2.5 Estimating burning efficiency

To estimate burning efficiency (BE) of ISB on open water is challenging as it is difficult to collect all the residue to e.g. use a gravimetric method. In 2016 different approaches were evaluated, but all of them include a high degree of uncertainty and the results presented should be regarded as best estimations.

2.5.1 Estimating burning efficiency by different approaches

In 2016, different approaches were considered to estimate the burning efficiency (Singsaas et al., 2017):

- "Analysis of Spreading and Herding for Burning" (ASHB): Analyse the amount of oil (as an area or derived volume) that was present as oil thicker than 1 mm (regarded as minimum thickness for successful ignition). It includes analysis of a large amount of pictures and videos, combined with a few oil thickness measurements, and depends upon how much oil was released and its spreading into areas of thick and thin oil, how much of thick oil was surrounded by herder, what happened to the area of the thick oil after herding, and how much oil (area, thickness and amount) was available for, or exposed to, ignition.
- "Integrated time area" (ITA): The flame area is estimated, integrated over the duration of the burn(s) and is multiplied by the assumed burn rate (3 mm/min for Grane crude). The amount of oil estimated to have burned are then calculated. The ITA approach produces estimates only, due to uncertainties associated not only with interpretation of the aerial imagery, but also associated with the assumed burn rate of 3 mm/min.
- Maximum burn area (MBA): The maximum burn area is determined, then multiplied by the assumed burn rate and the duration of time over which more than 50% of the maximum burn rate is aflame:

  MBA burn volume = burn rate x maximum flame area x (E_{50} - I_{50})

  Where E_{50} represents the time at which the burn diminishes to half its maximum area and I_{50} represents the time at which the spreading burn reaches half its maximum area. This method was tentatively rejected due to the incomplete video and photographic coverage that was available for analysis to determine an actual maximum area.
- Gravimetric method: Relies on the ratio of the mass of oil burned to the initial oil mass. The following equation may be used to calculate the overall efficiency for a burn:

  Overall burn efficiency (mass %) = ((initial oil net weight – residue net weight)/(initial oil weight)) x 100 %

  Uncertainty arises from the assumptions that all mass loss is resulting from burning and not from other factors as evaporative loss and boom leakage, and that all remaining oil and residue following the burn is retrieved and weighted. This method was rejected at the outset in 2016 due the logistical difficulty in ensuring all of the residue would be recovered.

In 2018 and 2019, the gravimetric method was used. A net to contain the residue after burning was connected to the booms before they were deployed (left photo, Figure 2.4). After ISB, the net capturing the residue was transferred to a container on the vessel and weight onshore. Figure 2.4 shows the boom on sea, before the oil was applied (middle photo) and after burning (right photo).

Figure 2.4 *The net connected to the boom shown prior to deployment to sea (left photo), before oil was applied (middle) and after ISB (right photo).*

2.5.2 Estimating burning efficiency through controlled laboratory burns

In a previous project performed by the collaborating laboratories SINTEF Ocean and SL Ross Environmental research Ltd, a laboratory methodology for estimation of BE based on chemical analysis of burned residues was developed (Faksness et al., 2019b).

The laboratory burning at SINTEF was 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 from a heating element in the conic oven, with an initial temperature of 575 ^{o}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). The water-cooled tray was placed on a scale, allowing us to follow the weight reduction during the burn. The burns were stopped to give known BE of approximately 50%, 70% and 90% weight loss. The remaining residue was collected and weight to get an exact amount of oil burned off. 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 has formed basis for quantifying BE (component loss) of the residues generated in the field for the specific oils. Controlled laboratory burns of Grane Blend (OOW 2016), Oseberg 200 ^{o}C+, ULSFO, IFO180 and MGO were performed and calibrations curves from GC/FID established.

ISB residues from i.a. OOW 2016 and OOW 2018 were used to verify the developed methodology. Faksness et al. (2019b) 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. Using the detailed SVOC profile from the GC/MS analysis to estimate BE did not work out, as hopane itself appears to have evaporated. This has also been observed by Han et al. (2019).

The established calibration curves from the GC/FID were used to estimate the BE for all offshore burns, except MGO.

2.6 Black Carbon

Black Carbon, commonly known as soot, is the dark, light absorbing part of the particles (PM2.5), 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 transferred to soot, CO_2 and CO. The amount of carbon in crude, diesel and bunker are approximately 85%, and it can be used to estimate an oil concentration from the monitoring of CO_2, CO and soot. The share BC is calculated as the percentage of soot versus the estimated amount of burned oil.

No gas analysis nor calculations of black carbon were performed in 2016.

2.7 Exposure measurements

Materials and methods used to investigate the potential for human exposure of air pollutants emitted from ISB are described in Section 4.2.

3 Results and discussion

There were other objectives for the experiments in 2016 than in 2018 and 2019. Testing of herders on a free-floating oil slick was the main objective in 2016, while ISB in fire booms and ignition with drones were the main objectives in 2018 and 2019. Monitoring in the smoke plume with drones were performed all three years, but with different monitoring strategies. An overview of the data collected is shown in Table 2.2. Results from the data collected by the University of Bergen on potential for human exposure are presented and discussed in Section 4.4.

Results from the six ISBs conducted during OOW in 2018 and 2019 are presented and discussed here. The same strategy for sampling and monitoring were followed in these fires. All vessels, including the drones, were equipped with GPS, and an overview over the different units' positions during the burns are shown in Figure 3.1.

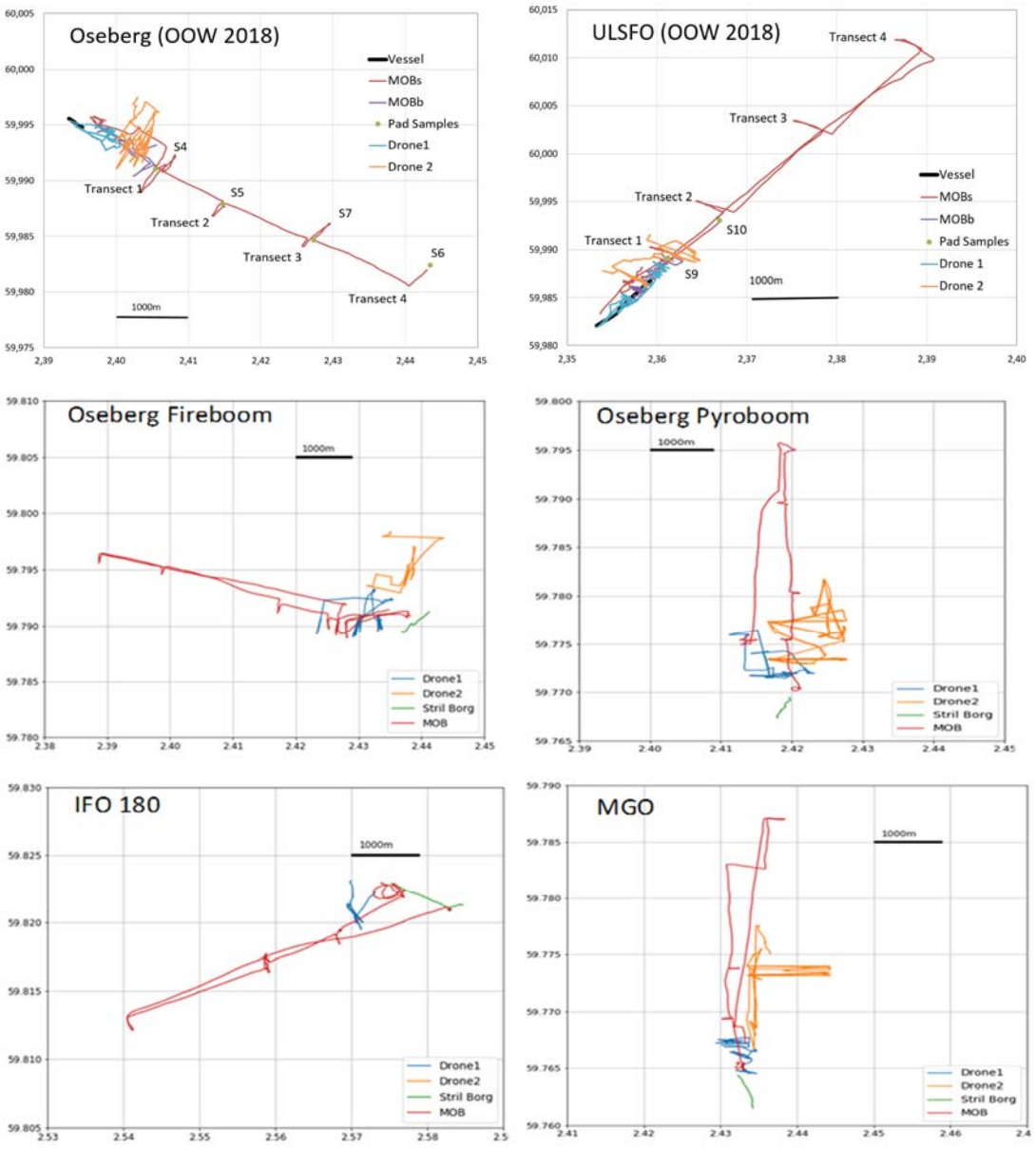

Figure 3.1 *Maps showing the GPS trackings from the drones, the response vessel (MS Strilborg) and the MOB-boats during ISB in 2018 and 2019 (latitude on x-axis and longitude on y-axis).*

The plan was that Drone 1 (blue lines) should fly in the area closest to the burn (<500 m), and Drone 2 (orange lines) follow the plume as far as possible (up to 2 km from the fire). The tracks from the MOB boats (red lines) indicated the visual distribution of the smoke plume, approximately 4.5 to 5 km during the burns. The tracks of the second MOB-boat are not shown from 2019, but it monitored particle matters in up to 200 m from the fires. The position of "Strilborg" (black line in 2018 and green line in 2019) is also indicated in Figure 3.1.

3.1 Monitoring of the dimensions of the smoke plumes

Figure 3.2 illustrates the flying altitudes for the drones during monitoring in the smoke plume. The figures indicate that Drone 2 was shorter time in the air than Drone 1. In 2018, no soot samples (filter) were collected of Drone 2. In 2019, there was a crash-landing of Drone 2 on deck after 30 min into the Oseberg#1 Fireboom burn, so only Drone 1 was available, and it flied up to approximately 1 km. During the IFO burn, Drone 1 was in the air for only 12 min (from 6 to 18 min), and Drone 2 did not fly. By mistake, the gas monitoring data from Drone 1 during the second Oseberg burn (Oseberg#2, Pyroboom) was deleted. Still, the data set collected is comprehensive and has given us valuable knowledge of the smoke generated during ISB of oils.

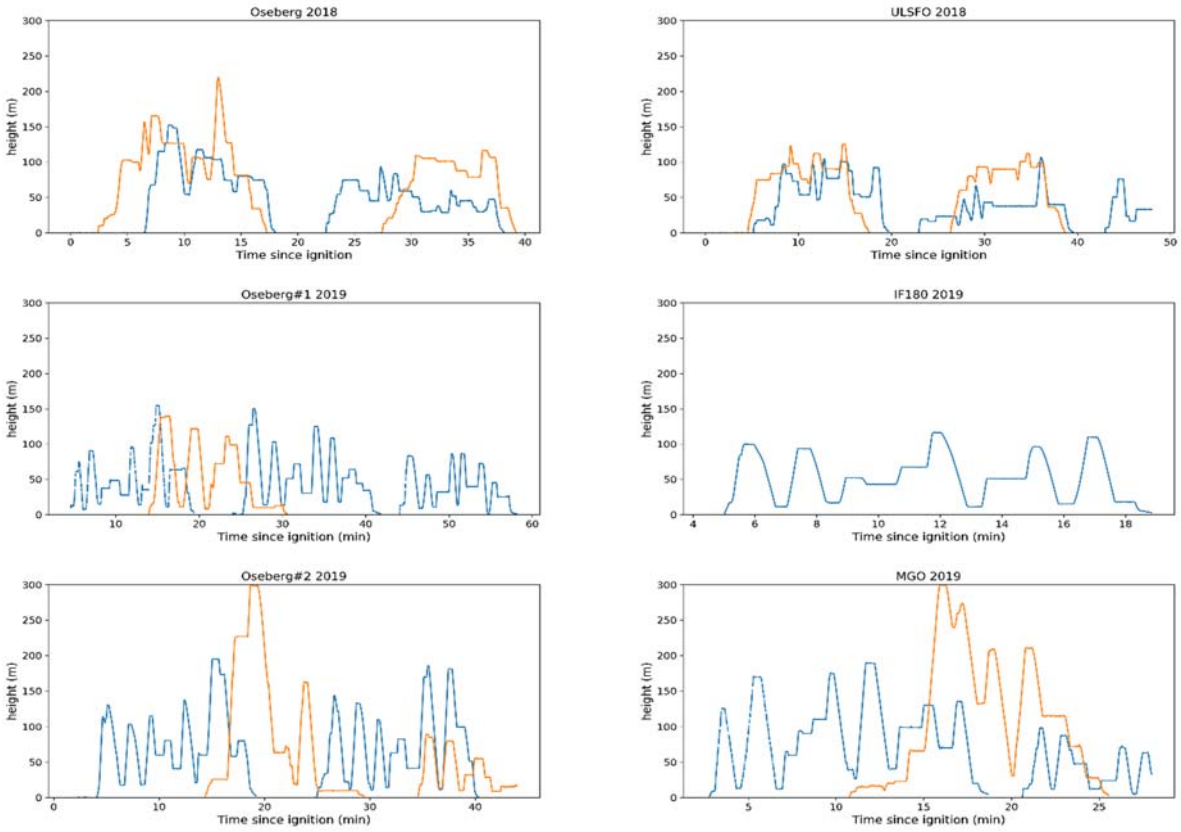

Figure 3.2 *Flying altitudes for the drones during monitoring in the smoke plume (drone 1 is blue and drone 2 is yellow). Time after ignition is shown on the x-axis. Drone 2 did not fly during ISB of IFO180.*

A set of vertical and horizontal transects where used to calculate the size of the smoke plume. Figure 3.3 shows an example of measured travelled distance plotted against measured total particle concentration. The distance is defined as the distance interval where measured particle concentrations are higher than 0.2 mg/m^3. This interval is also used for averaging concentrations of particles and gas. Unfortunately, the flight patterns were less systematic in 2018, so this data were not processed.

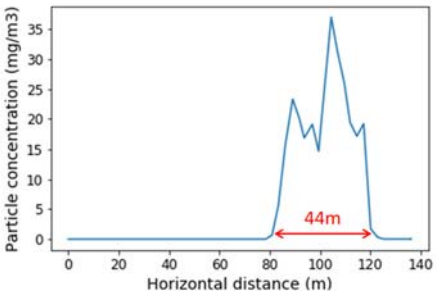

Figure 3.3 *Example of how particle concentration and distance travelled is used to measure the dimensions of the smoke plume.*

The time intervals drone 1 was in the air and the estimated dimensions of the smoke plumes are detailed in Table 3.1. Figure 3.4 shows the recorded vertical and horizontal plume dimensions as function of time for the burns. The length of the markers shows how long the entire mapping of the plume geometry took. The cross-sectional area is calculated as the area of an oval with the recorded height and width as the axis diameters.

Table 3.1 *Overview over the time intervals drone 1 was in the air and estimated smoke plume dimensions during OOW 2019.*

OOW 2019		Time interval in the air		Smoke plume dimensions		
Burn	Date	Start	Stop	Vertical (m)	Horizontal (m)	Areal (m^2)
Oseberg#1 Fireboom	June 15	11:17:19	11:26:09	51	68	2723
Oseberg#1 Fireboom	June 15	11:38:22	11:52:07	41	57	1840
Oseberg#1 Fireboom	June 15	11:57:14	12:08:58	35	61	1693
Oseberg#2 Pyroboom	June 19	08:37:10	08:44:01	67	90	4742
Oseberg#2 Pyroboom	June 19	08:44:29	08:46:27	76	114	6798
Oseberg#2 Pyroboom	June 19	08:47:05	08:50:08	62	147	7077
Oseberg#2 Pyroboom	June 19	08:59:35	09:05:34	44	99	3382
IF180	June 15	20:06:05	20:11:35	41	74	2413
IF180	June 15	20:11:58	20:17:50	70	124	6860
MGO	June 19	16:36:30	16:42:28	92	94	6782
MGO	June 19	16:42:42	16:49:35	85	94	6330
MGO	June 19	16:54:40	16:56:54	25	31	604

The dimensions and heights of the smoke plume varies as shown both in Table 3.1 and Figure 3.4. There will be natural variations during the burns, such as wind speed and direction, that will have influence on the smoke plume dimensions as seen in the photos in Figure 3.5, but also variations in the time and where the drones were in the plume.

As illustrated in Figure 3.5, the operation of the boom was different in 2018 and 2019, which also could have influenced the smoke plume. In 2018, the fire boom was spread out by using a flexible paravane (surface kite), which required a certain minimum speed through the water to get sufficient lifting force. In 2019, the paravane was skipped by having the ship tow the fire booms by sailing sideways through the water. This change made it possible to reduce the towing speed, and at the same time the fire booms were operating at the leeward side of the vessel, reducing both the wind and the waves for the boom and the fire (Jensen et al., 2020).

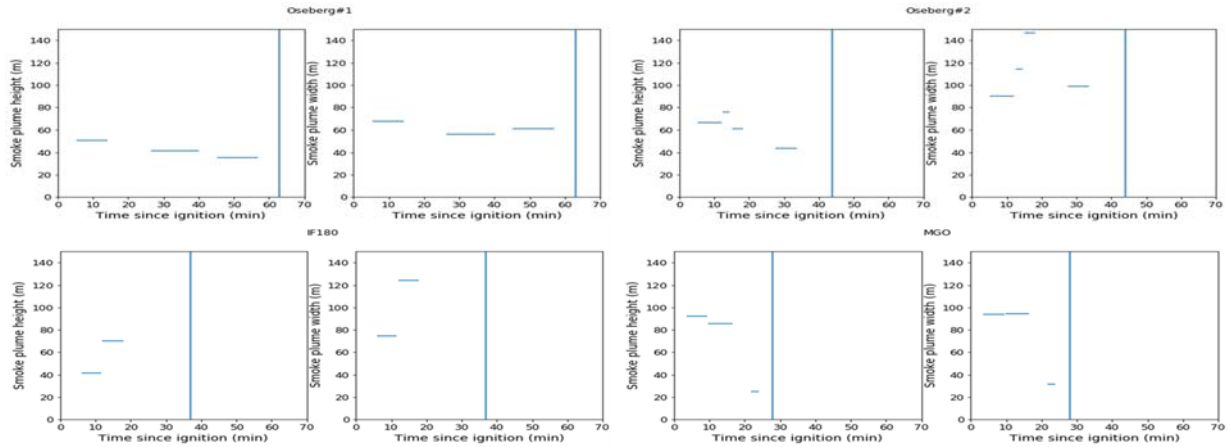

Figure 3.4 *Smoke plume height (left graph) and width (right graph) vs flight time during ISB of Oseberg Fireboom (left upper figures), Oseberg Pyroboom (right upper figures), IFO180 (lower left figures), and MGO (lower right figures), respective. Vertical blue lines indicate when the fire extinguished and the horizontal lines the time the plume was mapped. All data from OOW 2019.*

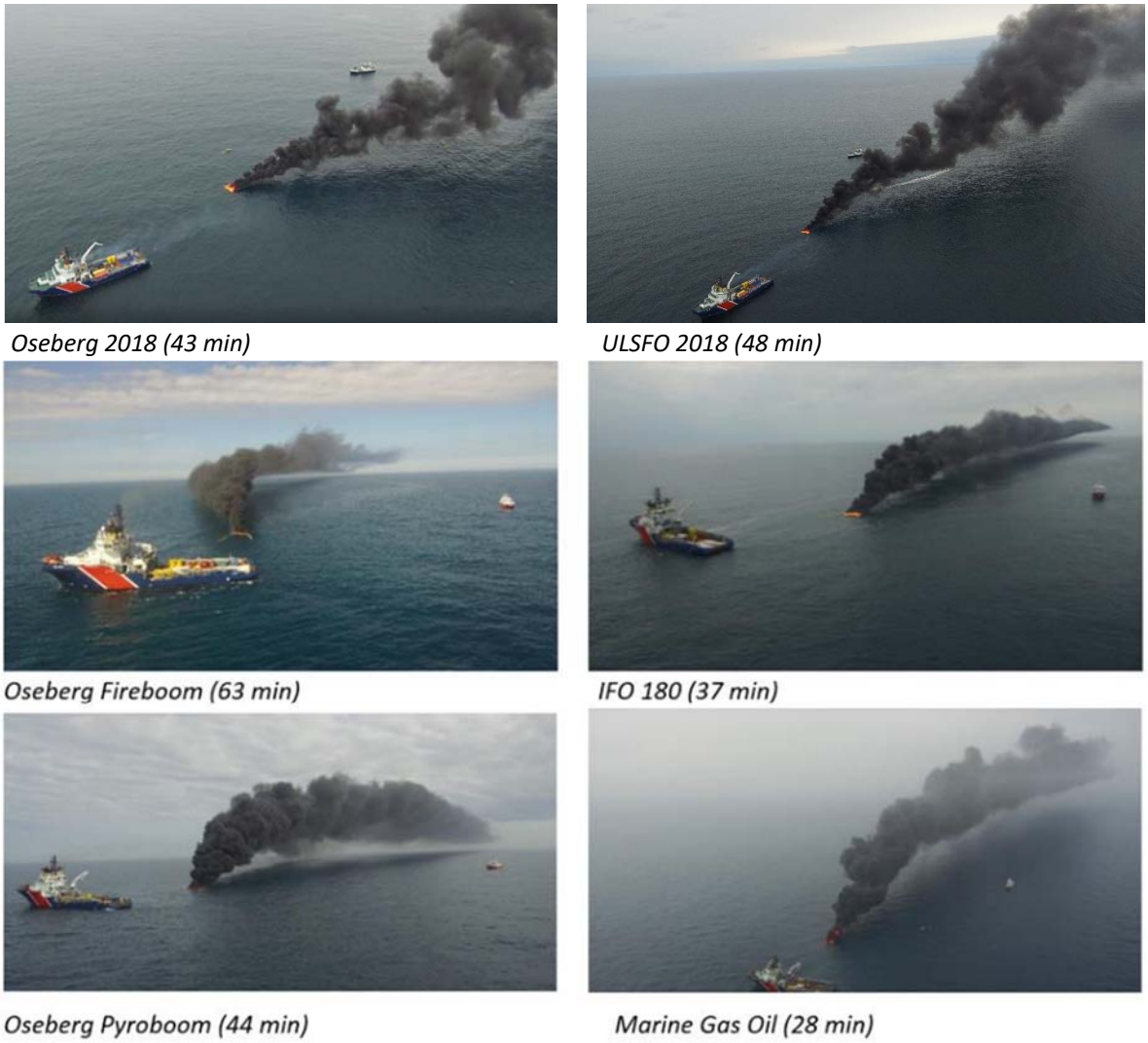

Figure 3.5 *Photos of the smoke plume taken by the PyroDrone (burning times given).*

3.2 Temperature and heat-flux

The drones were equipped with sensors for i.a. wind speed and temperature. The monitored data from the drones are shown in Figure 3.6. In addition, measured amount of PM2.5 (particles less than 2.5 µm) and heat flux are shown. Heat flux can be defined as the rate of heat energy transfer through a given surface and is expressed as W/m^2. The surface refers to the area of the heat flux sensor itself (2.6 cm x 2.6 cm).

As described above, the booms were operated differently in 2018 and 2019. In 2018, the heat-flux sensor was located starboard stern, and in 2019, the heat-flux monitor was mounted on the starboard rail of Strilborg, positioned approximately right in front of the fire.

Monitoring of heat-flux from e.g. the two burns with Oseberg in 2019 (#1: Fireboom; 2#: Pyroboom) indicated that the burn intensity was higher during Oseberg Pyroboom. The heat-flux seems to be in the same range during the burns in 2018. In 2019, ISB of MGO had the highest radiant heating and heat-flux, and this was also observed during the burn.

The concentration of particles, PM2.5, seems to be higher in the second monitoring during ISB of ULSFO in 2018 (50-75 mg/m^3 vs 10-20 mg/m^3), while Oseberg 2018 seems to be in the same range as the burns in 2019 (<75 mg/m^3).

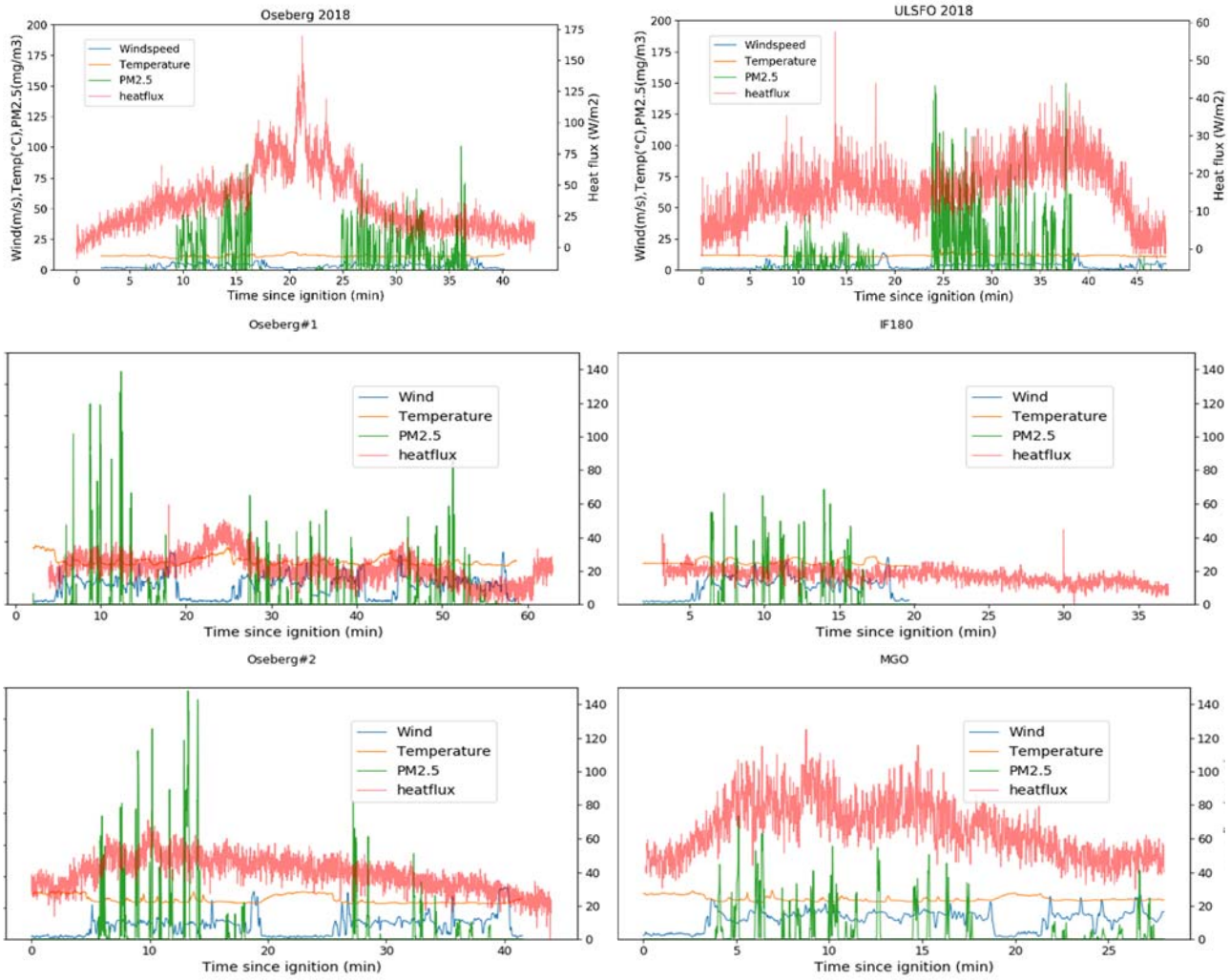

Figure 3.6 *Wind, temperature and PM2.5 monitored in the smoke plume, and heat flux from MS Strilborg. Monitoring from 2018 and 2019. Different scales on the y-axis in 2018 and 2019.*

3.3 Gas monitoring in the smoke plume

No gas monitoring in the smoke plume was performed in 2016.

The monitored CO_2 and CO concentrations are shown in Figure 3.7. The CO_2-concentrations were below 420 ppm (above ambient level) in all burns. In 2018, higher CO concentrations than in 2019 were measured. Other and less sensitive sensors were used in 2018, so it could have had impact on the readings. In 2018 maximum CO level was 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 Fireboom and 2 ppm for IFO180.

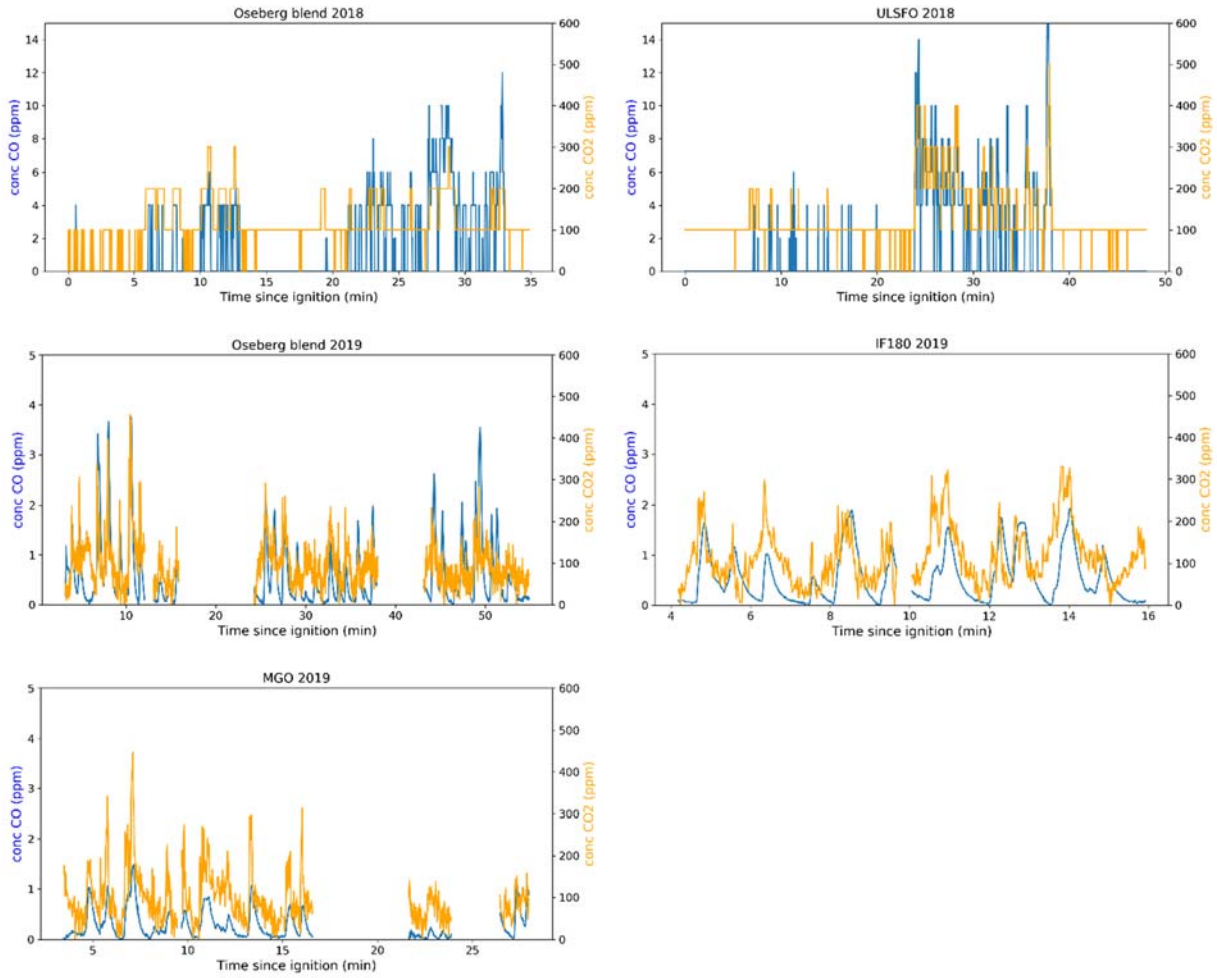

Figure 3.7 *CO (yellow line) and CO_2 (blue line) concentrations during the burnings. CO is shown on left y-axis and CO_2 on right y-axis. As seen in the graphs, less sensitive sensors were used in 2018. Gas monitoring data from Oseberg Fireboom (#1) in 2019, no data from Oseberg Pyroboom (#2).*

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).

It is assumed that gases emitted during an ISB generally do not represent a serious threat to safety of human health. Their concentrations may exceed hazard threshold as they leave the fire, but they decline below these thresholds within very short distances from the fire (Buist et al., 2013a).

The most refereed project regarding monitoring of gases in smoke during ISB field experiments are the Newfoundland Offshore Burn Experiment (NOBE) that took place in 1993, burning 29 and 48 m^3 crude oil

(e.g. Fingas et al., 1995a; 1995b). Fingas et al (1995b) concluded that the concentration of soot and particles in the smoke plume may not be a concern past about 500 m. The combustion gases, including carbon dioxide, sulphur dioxide and carbon monoxide did not reach level of concern, as the level of CO_2 in the plume measured to maximum 629 ppm under the two burns and the other gases were measured only at background level or below the lower detection level.

During DWH more than 400 ISB were performed. Gullett et al. 2017 have later simulated ISB of the Macondo oil in the laboratory and measured the emissions. The CO_2 concentration was in the range of 500 to 2200 ppm, CO up to 30 ppm, and an average PM2.5 of approximately 60 mg/m^3 during burning. These concentrations were higher than measured during our field experiments. SINTEF (Faksness et al., 2018) has also observed in previous laboratory studies performed under controlled conditions in a cone calorimeter 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 plume passed the sensors, while the drones were flying in and out of the smoke plume during the monitoring period.

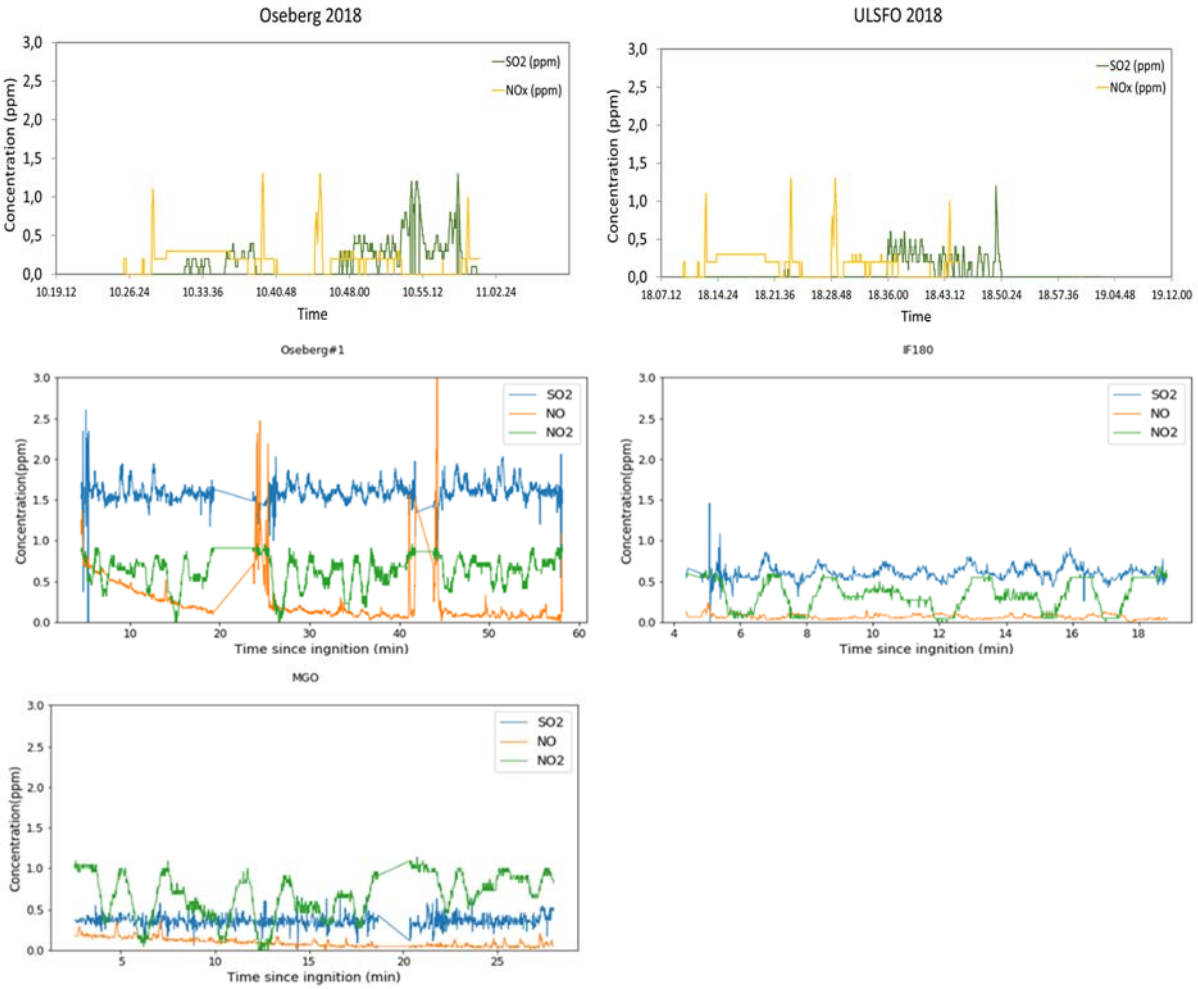

Figure 3.8 *Measured concentrations of SO_2 (green lines), NO_X (2018) and NO (yellow lines), and NO_2 (2019, blue lines) in the smoke plume. Gas monitoring data from Oseberg Fireboom (Oseberg#1) in 2019, not from Oserberg Pyroboom (Oseberg#2). Different sensors were used in 2018 and 2019.*

3.4 Soot particles on the sea surface

Both MOB-boats were equipped with DustTraks to monitor particulates just above the sea surface. As indicated in Figure 3.1, one of the MOB-boats (MOB-2 or MOB-S) followed the smoke plume up to 4.5 to 5 km during the burns. In 2018, pad samples from the sea surface were collected when a "peak" was detected by the DustTrak. In 2019, no pad-samples were taken as the DustTrak indicated low concentrations on background level. The MOB boat returned to the boom when the burn extinguished. The measured levels were low and indicated that the particles seems to be mainly bounded to visible smoke. It has earlier been observed visually during ISB in ice infested areas, e.g. in the Barents Sea or in fjord ice in Svalbard, that the ice close to the burn were contaminated with soot after ISB. However, no observations on longer distances from the burn or any monitoring of soot particles were performed during these experiments.

Results from the air measurements in surface vessels to evaluate the potential for human exposure are reported and discussed in Chapter 4.

3.5 Concentration and size distribution of soot particles in the smoke plume

The soot particle monitoring during all burns in 2016, 2018 and 2019, booth in the smoke plume and on sea level, indicated that more than 90% of the particles produced during the burns were in the fine 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 penetrate into the blood stream and potentially harm other vital organs.

The strategy for the sampling in the smoke plume was different in 2016, 2018 and 2019. In 2016, a SidePak was used and only PM2.5 was monitored with an upper measurement range of 20 mg/m^3 that was exceeded and the reported average PM2.5 levels underestimated (Singsaas et al., 2017). The concentration of soot particles was measured in different size bins using a DustTrak in 2018 and 2019. To calculate a flux of soot particles, a concentration representative to a cross sectional area of the smoke plume was needed. In Figure 3.9 the total particle concentration with time since 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 drone transects through the smoke in the pre-defined pattern shown in Figure 2.3, indicated as a more straight peak for each transect.

For 2018, a few intervals are shown, all with relatively high concentrations. The results indicate that the particle concentration was 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 peaks 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 > 0.2mg/m^3) are used in the calculation of the soot particle flux. The results indicated that there were detected more particles in the smoke during both burns with Oseberg than with IFO180 and MGO, and that the highest particle concentration was monitored during the burn with Oseberg Fireboom. However, the drone was longer time in the smoke during the Oseberg burn than IFO180 and MGO (more than 30 min vs 12 and 15 min, respective).

Results from the air measurements in surface vessels to evaluate the potential for human exposure are reported and discussed in Chapter 4.

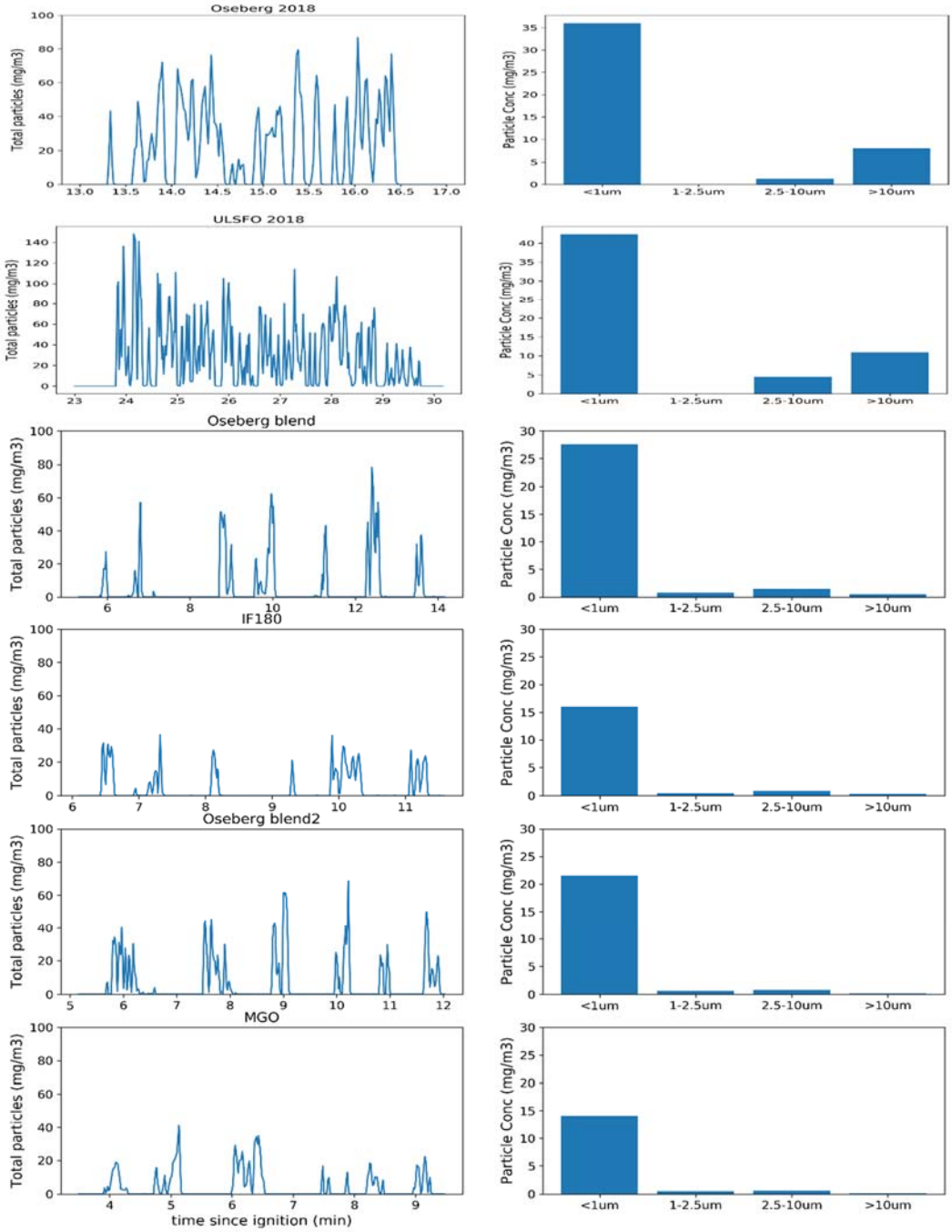

Figure 3.9 *Left: Particle concentration in the smoke plume during the burns. Right: Size distribution of smoke particles for all burns. In 2018 a less systematic flight pattern was followed, and the drone spent more time in the smoke than passing through it as in 2019. Oseberg Blend refers to Oseberg#1 (Fireboom) and Oseberg Blend2 to Oseberg#2 (Pyroboom), both from 2019.*

3.6 Physical properties of oils and residues

The oils and ISB residues physical properties are given in Table 3.2. The available data from OOW 2016 is also included.

The densities were less than 1 for all samples, except for one of the IFO180 residues (1.001). This indicate that the residues would not sink in sea water, unless they were exposed to heavier particles or similar. In Leirvik and Faksness (2019), ISB residues from ULSFO and IFO180 (meso scale laboratory burns) were exposed to sand particles and swells to study the potential for sinking. The results showed that the IFO180 had the potential for sinking, while ULSFO was not sinking.

Table 3.2 *Density (g/mL) and viscosity (cP) for unburned oils and their ISB residues. In 2016, density in ISB residues was measured at 50°C and recalculated to 15°C, and viscosity was measured at 30°C at shear rate 10 s^{-1}. For samples from 2018 and 2019, densities were measured at 80°C and recalculated to 15°C, and viscosities were given 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})
2016-0157	Grane Blend (unburned)	45*	0.899	64
2016-0149	Grane residue release 4.1 A		0.978	620 000
	Grane residue release 4.1 B		0.967	
2016-0150	Grane residue release 4.2		0.952	
2018-4052	Oseberg 200°C+ (unburned)	78	0.891	750
2018-5303-S1	Oseberg residue (on sea, in boom)		0,968	138 000
2018-5303-S2	Oseberg residue (scraped off boom)		0,971	
2018-5303-S3	Oseberg residue (scraped off boom)		0,969	145 000
2018-5303-S8	Oseberg residue (from net in container)		0,969	118 000
2018-3881	ULSFO (unburned)	82	0,917	9030
2018-5304-S1	ULSFO residue (on sea, in boom)		0,944	142 000
2018-5304-S4	ULSFO residue (in sea, in boom)		0,949	201 000
2018-5304-S6	ULSFO residue (scraped off boom)		0,948	101 000
2018-5304-S11	ULSFO 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 Fireboom (residue)		0.954	100 000
2019-5234-S2	Oseberg #2 Pyroboom (residue)		0.957	579 000
2019-5233-S1	IFO180 (unburned)	89	0.960	12 600
2019-5233-S2	IFO180 (residue)		1.001	1 010 000
2019-5233-S3	IFO180 (residue)		0.952	127 000
2019-5235-S1	MGO (unburned)	74	0.847	6
2019-5235-S3	MGO (residue)		0.886	259

**) 150 °C+*

It was reported in Singsaas et al. (2017) that the residue from the ISB in 2016 had an extreme high viscosity. The rheometer was not able to measure viscosities with shear rate 10s^{-1} at lower temperature than 30°C (620 000 mPas or cP). A shear rate of 2 s^{-1} at 13 °C, gave a viscosity of 20-25 million mPas or cP. For the residues sampled in 2018 and 2019, the viscosities were measured using a temperature sweep of 1°C/min at shear rate 10.

In 2018, residues after ISB were collected randomly in the booms, and in addition scraped off from the booms after they were on deck. The densities and viscosities measured in the ISB residues of Oseberg were in the same range, approximately 134 000 cP and 0.970 g/mL. For residue samples after ISB of ULSFO, the densities were in the same range (approximately 0.947), while the viscosities varied from 101 000 to 201 000 cP (average 144 000 cP).

In 2019, it was planned to collect three residues samples in the boom after each burn, one from the left side, on from the right side and one in the middle (close to apex). All samples were analysed on GC/FID, while

viscosity and density were measured for at least one of them. The GC chromatograms were visually compared, and in all burns, except IFO180, there were relatively similar evaporative loss for the samples collected in different positions in the boom after ISB. One of the ISB residues of IFO180 was more burned off than the other two samples. This is illustrated in Figure 3.10, and also from the viscosity and density measurements (Table 3.2). The viscosity in the most burned sample was approximately 10 times higher (1 010 100 vs 129 000 cP at 10^{o}C) and the density 1.00 vs 0.95. The progress in the two burns with Oseberg was not the same, the first (in Fireboom) burned for 63 min and the second (in Pyroboom) burned for 44 min. This was also reflected in the residue's physical properties, as the viscosities were 579 000 cP and 100 000 cP (shear rate 10s^{-1}).

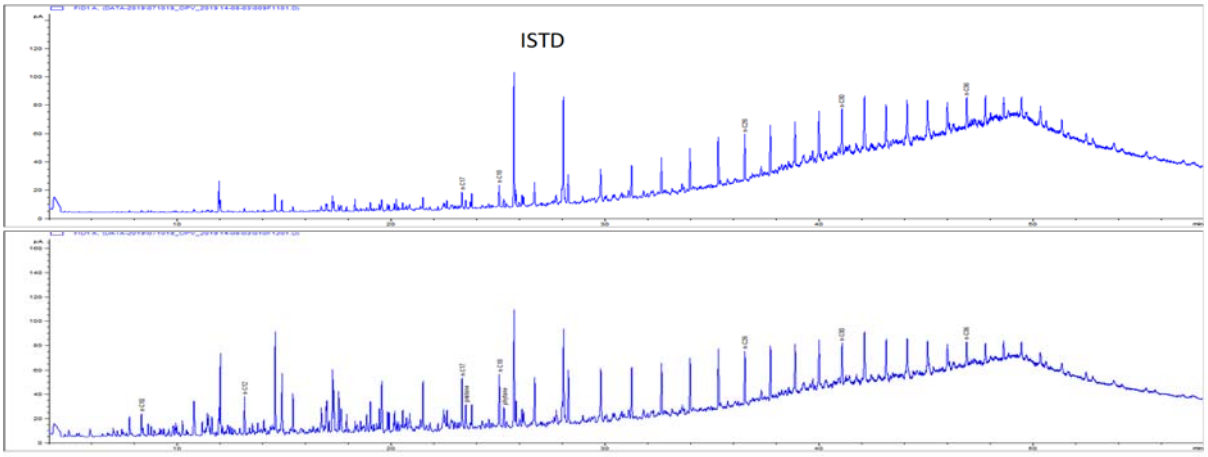

Figure 3.10 *GC chromatograms of residues after ISB of IFO 180 sampled in two different positions in the boom (left side and middle). The two large peaks are added internal standards (ISTD)*

3.7 Chemical composition of the residues and in the soot particles

As a minimum, three residue samples were collected in the boom after each ISB. All samples were analysed on GC/FID (Appendix B, Figure B 1 to Figure B 30), while at least one from each burn were analysed on GC/MS for quantification of SVOC. As mentioned earlier, no SVOC-analysis were done after OOW in 2016, but residues from two of the burns have later been analysed (Faksness et al., 2019b) and are reported in the Appendices.

A summary of the chemical analysis (concentrations of TPH and SVOC) for the unburned oils and ISB residues are given in Table C 1 to Table C 5 in Appendix C and in the soot in Table D 1 to Table D 4. A list of the SVOC components, the component grouping, and their abbreviations are shown in Appendix E.

Results from the detailed SVOC-analysis are given in Table C 9 to Table C 13 (Appendix C) for the unburned oils and their residues, and in Table D 6 and Table D 7 (Appendix D) for the soot samples. The results are placed together in Figure 3.11 and Figure 3.12. 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 PAH, 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)). The final chemical composition of the residue will depend on the initial oil type and the efficiency of the burning.

The SVOC composition of unburned Oseberg and the residues from the three burns are shown in Figure 3.11. The same batch of oil was burned, but e.g. 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 (Fireboom) lasted 19 minutes longer (63 vs 44 min) than the second burn (Oseberg Pyroboom). The SVOC results shows that more of the SVOC components disappeared during ISB when burning Oseberg Pyroboom than Oseberg Fireboom, indicating that the last burn was more efficient. The Oseberg burn in 2018 lasted for 43 min, i.e. the same as Oseberg Pyroboom in 2019. More 4-6 ring PAH were detected on the soot filter collected in 2018 than on the filters from 2019. These components are considered to be pyrogenic PAHs (i.e. combustion derived) 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 so-called reference filters (not been in the smoke) in 2019, and as the results are corrected for background, this could have influenced the results reported.

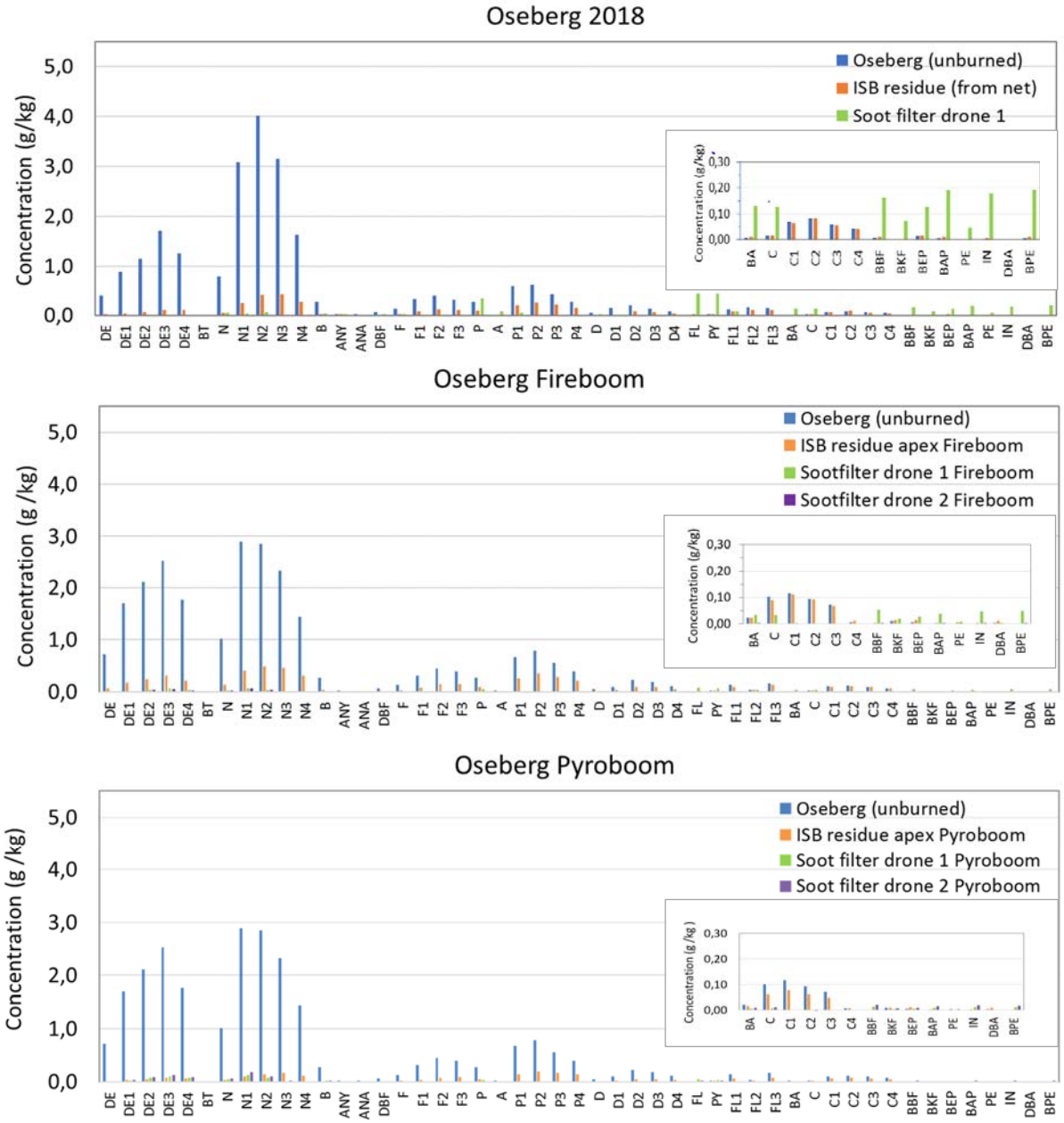

Figure 3.11 *SVOC in unburned oils, ISB residue and in soot for the three burns with Oseberg 200°C+ (residue in g analyte/kg oil and soot in g analyte/kg soot). Enlargement of 5 to 6 ring PAHs shown. Abbreviations and component groups given in Appendix E.*

Compared with unburned oils, the depletion in the total PAH concentration (including decalins and naphthalens) in the ISB residues were reduced with approximately 85% and 75%, respective for HISB1 and HISB in 2016, and with more than 80% for Oseberg and about 50% for ULSFO during OOW in 2018 The depletion in the total PAH concentrations during OOW 2019 was 77% for Oseberg Fireboom, 90% for Oseberg Pyroboom, 63% for MGO and 33 and 77% for the two residues of IFO180. Unburned ULSFO contained less lower boiling point components, such as decalins and naphthalenes than the other oils (Figure 3.12).

In 2016, PAH in the vapor phase and in the soot were measured in the smoke plume. The results are discussed in section 4.2.2.

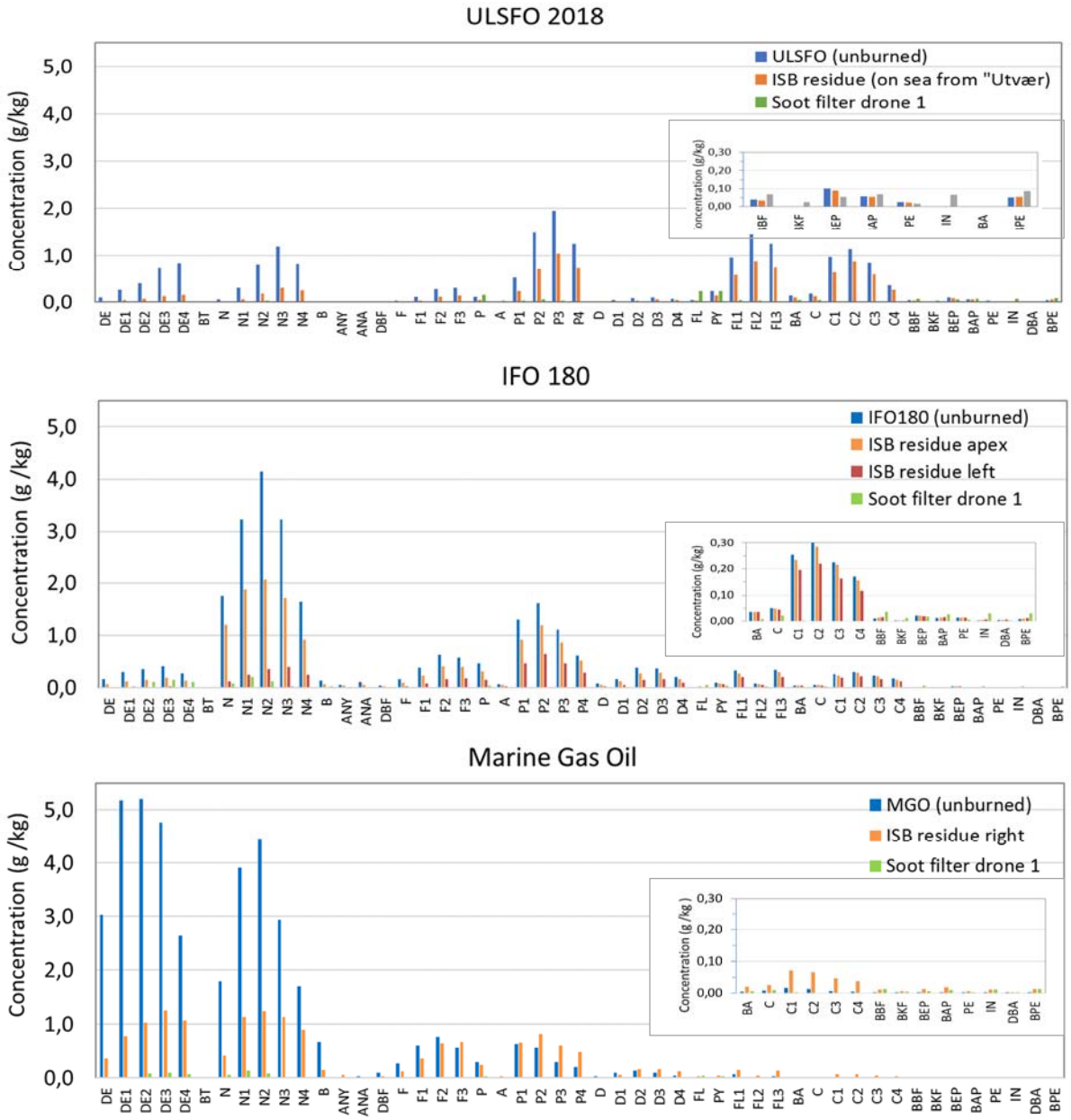

Figure 3.12 *SVOC in unburned oils, ISB residue and in soot for ULSFO, IFO180 and MGO (residue in g analyte/kg oil and soot in g analyte/kg soot). Enlargement of 5 to 6 ring PAHs shown. Abbrevations and component groups given in Appendix E.*

3.8 Acute toxicity of ISB residues

According to a review paper by Fritt-Rasmussen et al. (2015), few studies have investigated the toxicity of burn residues. E.g. Blekinsopp et al. (1999) and Daykin et al. (1994) found that the burn reside was not more toxic than the weathered oil itself.

Faksness and Altin (2019) have studied acute toxicity of the ISB residue of ULSFO from OPV 2018. Water accommodated fraction (WAF) of unburned ULSFO and its ISB residue were studied with emphasis on chemistry and acute toxicity. Low-energy WAFs were prepared with an oil-to-water ratio of 1 to 40 to evaluate the potential impact of ISB residue to the environment. The primary consumer, the copepod *Calanus finmarchicus* were tested: Both *Calanus* CV (late copepodite stage) and nauplii to WAF of unburned oil and only nauplii to WAF of burn residue. The total WAF concentrations were low, 1.104 ppm in WAF of unburned (fresh) ULSFO and 0.332 ppm in WAF of ISB residue. The oil and WAF of ISB residue still contained volatiles, and this was unexpected. However, the residue after a burn could contain both burned and unburned oil, and here the residue was heated and homogenized before the WAF was prepared.

Calanus nauplii were tested both for WAF of fresh oil and ISB residue, and the results indicate that the nauplii stage is more sensitive to WAF of fresh oil than the late copepodite (CV) stage. The nauplii have limited fat reserves and are therefore less protected than the grown organisms where heavier components (PAHs) will be stored temporary in the fat reserves and in that way be physiological unavailable. Specific toxicity is normalized to the total WAF concentration and has been the traditional approach for expressing toxicity and indicated that WAF of ISB residue was more toxic to nauplii than WAF of fresh oil. However, as mentioned above, the WAF concentration is relatively low (0.332 ppm). Acute toxicity, expressed as toxic unit (TU), was predicted based on the chemical composition of the WAFs and the K_{ow} for the individual components. A TU> 1 for the total WAF implies that it is expected to cause more than 50% mortality in the test organisms. TU for both WAFs were below 1, WAF from fresh oil was 0.63 and for WAF from ISB residue was 0.44. The calculations indicate that especially the PAHs were contributing to the toxicity.

It has been assumed the residue after an ISB does not contain water soluble components that can dissolute into the water. However, as seen in the present study, as the residue after an ISB could contain a mixture of burned and unburned/less burned oil, the concentration and composition of water-soluble components from the residue could reach a level that may have an impact on marine organisms. A potential impact on the environment will depend of several factors, e.g. burning effectiveness, residue properties, dilution rate in water. Faksness et al. (2011) measured the water-soluble oil components in the water during a 6-day experimental release of Troll crude oil (7 m^3) in the marginal ice zone in the Barents Sea in 2009. The highest concentrations of water soluble oil components measured close to the oil slick (3 m depth) was 30 ppb, which is 10 times lower that the WAF concentrations of the ISB-residue tested here.

The acute toxicity to *Calanus* nauplii of the burned residues of IFO180 and MGO from OPV 2019 will be tested using the same methods during 2020. In addition, the toxicity testing of ISB residue of Oseberg from OPV 2018 will be tested on shrimps.

3.9 Burn efficiency

To estimate BE of ISB on open water has been challenging as it is difficult to collect all the residue.

In 2016, the residues were spread over a large area on sea. The comparison of the estimated volumes oil subjected to burning (ignited) from the ASHB approach with estimated volume of oil burned was based on the ITA approach (Table 3.3) and showed comparable figures indicating no significant difference in burn efficiency between the different experiments. The majority of the oil subjected to burning was burned, but

the high degree of uncertainty precludes any meaningful analysis of the percentage of oil burned (burn effectiveness) in each experiment (Singsaas et al., 2017).

Table 3.3 *Comparison of estimated volumes of oil subjected to burning (ignited) for det ISB with herders during OOW 2016. The estimates were based on ASHB analysis with estimated volumes of oil burned based on the ITA approach (Vol = volume).*

	Vol oil on sea (m^3)	Approx vol of oil subject to burning (ASHB approach) (m^3)	Estimated volume of oil burned (ITA approach) (m^3)	Estimated burn efficiency range (%)
Grane Blend HISB 4.1	6.0	3.5 (range 2.5 -4 .4)	3.4 (range 2.5- 4.3)	30-80
Grane Blend HISB 4.2 (no herder)	4.2	1.4 (range 1.1 – 1.7)	1.2 (range 0.9 – 1.5)	Up to 45%
Grane Blend HISB 4.3	4.0	0.8 (range 0.6 – 1.0)	0.8 (range 0.6 – 1.0)	Up to 45%

In 2018 and 2019, a net capturing the residue after burning was connected to the booms. After ISB, the net was transferred to a container on the vessel and weight onshore. Table 3.4 gives results from the weighing and estimated BEs calculated.

In 2018, a boom leakage was observed after releasing the Oseberg oil. The surveillance plane LN-KYV estimated that it was approximately 400 L, and it was estimated that approximately 100 kg was sticking to the boom after burning. The net was weight on shore and 523 kg residue was left in the net. Two sections (30 m) of the PyroBoom was destroyed during the burn and disconnected prior to burning ULSFO. However, with two sections gone, the residue net could not be attached to the boom. The PyroBoom had to be used without a net during ISB of ULSFO and a second vessel OV Utvær used its integrated sweeping arms to recover the residue after the burn, but too much residue passed the mechanical recovery system and only 60 kg were recovered.

Table 3.4 gives results from the weighing and estimated BE. For the burns in 2019, estimated BE is solely based on the weight of the residues. Estimated BE were 87% for Oseberg Fireboom, 91% for Oseberg Pyroboom, and 64% for IFO180. No residue was collected for MGO, and a visual estimate of remaining residue in the boom indicated a BE >95%. All these estimates are assumed to be too high, as photos taken by the Pyro-drone prior to and during ISB showed that there was visible boom leakage in all burns (Figure 3.23 in Faksness et al., 2019a). It was also observed that there was more loss of the IFO residue than the other oils when lifting the net from the sea into the container on deck. Nevertheless, the collection of residues after each burn was considered to be successfully completed in 2018 and 2019 using net.

Table 3.4 *Estimated weight and BE after OOW in 2018 and 2019. For OOW 2019, factors such as boom leakage, loss when transferring the net from sea to a container on deck, and residue sticking on the boom after ISB, are not taken into account in calculations of BE. For OOW2018, these factors are estimated in the amount of residue for Oseberg (Vol = volume).*

Oil	Vol 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 Fireboom	6.0	5389	697	4692	87
Oseberg Pyroboom	5.6	5030	466	4564	91
IFO 180	4.2	4031	1449	2582	64
MGO	6.0	5083	ca 260	ca 4823	>95

As a supplement, regression curves establish from the controlled burns in the laboratory were used to estimate the BE of the offshore burns (Faksness et al., 2019a). Even though the scale of the burns and the oil film thickness in laboratory burns versus field ISB were different, laboratory burns seemed to be a good supplement to improving the estimates of BE to get more reliable BE from offshore burns. For Oseberg, three ISBs have been performed the last two years. Estimated BE for all burns are included, and the results from 2019 show that there were differences in BE, depending on where in the boom the samples were collected. However, the variation between the three samples from each burn were small (±2%) for Oseberg, and the average BE were 69% and 75% (Fireboom and Pyroboom). BE in 2018 was higher, and was estimated to 84%, which correlated well with the collected residue, estimated boom leakage and oil on the boom (approximately 80%). In the residues of IFO180, 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. "Calibration curves" for Oseberg and IFO180 are given in Figure 3.13.

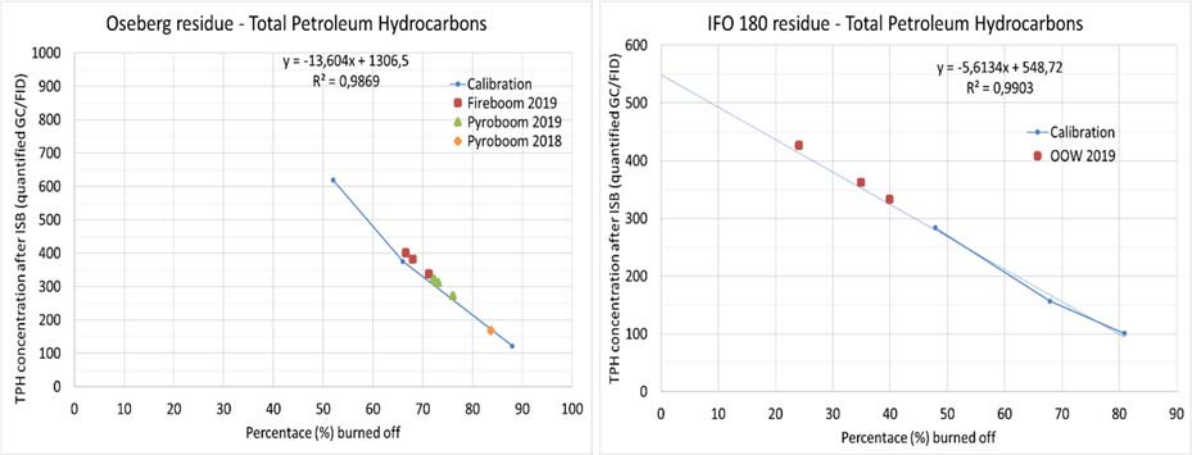

Figure 3.13 *Correlation between TPH concentration quantified from GC/FID and percent oil burned off in the laboratory experiments ("calibration", blue line) and ISB-residue samples of Oseberg and IFO180. Three samples of each residue are shown from 2019, and one of Oseberg in 2018 (Pyroboom 2018).*

In Table 3.5, estimated BE in burn residues from the field experiments were calculated based on the "calibration curves" established in Faksness et al. (2019) and have been compared with the estimated BE reported. Based on the comparison between the field burned oils and the laboratory burns, it is suggested that the estimated BE calculated from the "calibration curves" are a good supplement to get more reliable BE than only using e.g. the ITA approach or a gravimetric method.

Table 3.5 *Estimation of BE (%) based on calculated TPH concentration from GC/FID for laboratory tests (in cone calorimeter). Estimated BE reported after field testing are also given (from Table 3.3 and Table 3.4.*

Oil burned	Experiment	Sample description	Estimated BE (%) ("Calibration" curve)	Previously estimated BE (%) (reported)
Grane Blend	OPV 2016 HISB1	HISB1	64	57 - 98
Grane Blend	OPV 2016 HISB2	HISB2	56	53 - 90
ULSFO	OPV 2018 (S11)	From OV "Utvær (S11)	47	49 - 57
Oseberg 200 °C+	OPV 2018	Pyroboom	84	80
Oseberg 200 °C+	OPV 2019	Fireboom	69	87
Oseberg 200 °C+	OPV2019	Pyroboom	75	91
IFO 180	OPV 2019	Left and apex in boom	24 and 40	64

3.10 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.

Black Carbon is a Short-Lived Climate Pollutant (SLCP) of particular concern in the Arctic (lifetime less than 15 years). 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 Black Carbon produced relative to the amount of oil burned were estimated and were approximately 10% for Oseberg 2018, 11% for ULSFO (2018), 12% for MGO, 13% for IFO180, 14% for Oseberg Pyroboom, and 18% for Oseberg Fireboom (Figure 3.14). 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., 2013b). In the Macondo spill in 2010, it was estimated that 42000 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.

Total emission of BC to air in Norway in 2011 was 5100 tonnes of which 12 % was from the oil and gas industry (Aasestad, 2013). According to Arctic Council (2019), the BC emissions in Norway were reduced to 3200 tons in 2016 and are predicted to be 2700 tons in 2025. The estimated total emission of BC to air from the four experimental ISB performed in 2019 was 2.4 tons or 0.075% of the total emission to air in 2016.

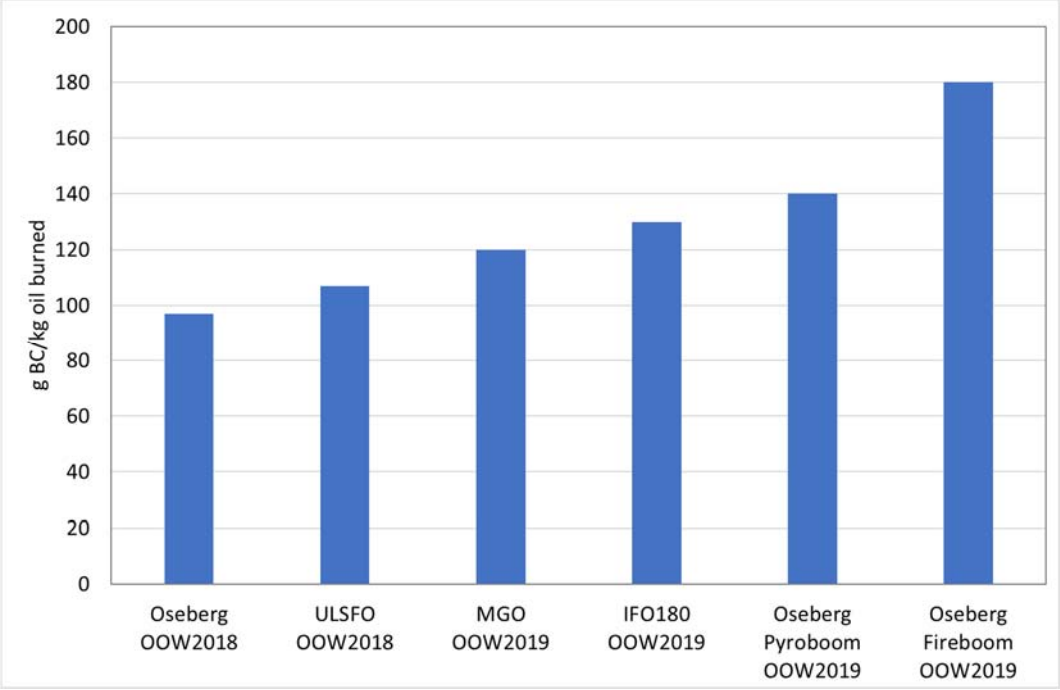

Figure 3.14 *Black carbon in soot from ISB during OOW in 2018 and 2019 (in g BC/kg oil burned). No data on BC in 2016. Amount oil burned based on data in Table 3.4.*

3.11 Estimates of total emissions in soot and residues

Total amounts of gasses, soot and residues produced during the ISB experiments in 2018 and 2019 have been estimated, but the data from 2016 was not sufficient to perform these calculations. In the calculations, the estimated amounts of oil burned from Table 3.4 was used. Based on known amount of carbon in the oils (85%), the amount of total carbon in the burned oil was calculated. The relative composition of soot, CO and CO_2 were documented through the gas and soot measurements. It is calculated an average composition for the monitoring performed throughout the individual burns. If total amount 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.

Figure 3.15 illustrates total emissions in the smoke, both total amounts and total amounts of carbon produced from soot, CO and CO_2. Oseberg Pyroboom (2019) is not shown due to missing gas monitoring data. As expected, CO_2 contributed most to the smoke, and it was estimated a somewhat higher total amount produced during 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 (totally about 7500 kg). The drone was only 12 min in the smoke during burning of IFO180. Amounts SO_2 and NOx was so low that they are not shown in the figure (e.g. 9 kg SO_2 and 2 kg NO for Oseberg Fireboom). The estimates indicate that from the total amount carbon produced, 4000 kg was produced during ISB of Oseberg and MGO, and approximately 2400 kg during ISB of ULSFO and IFO180.

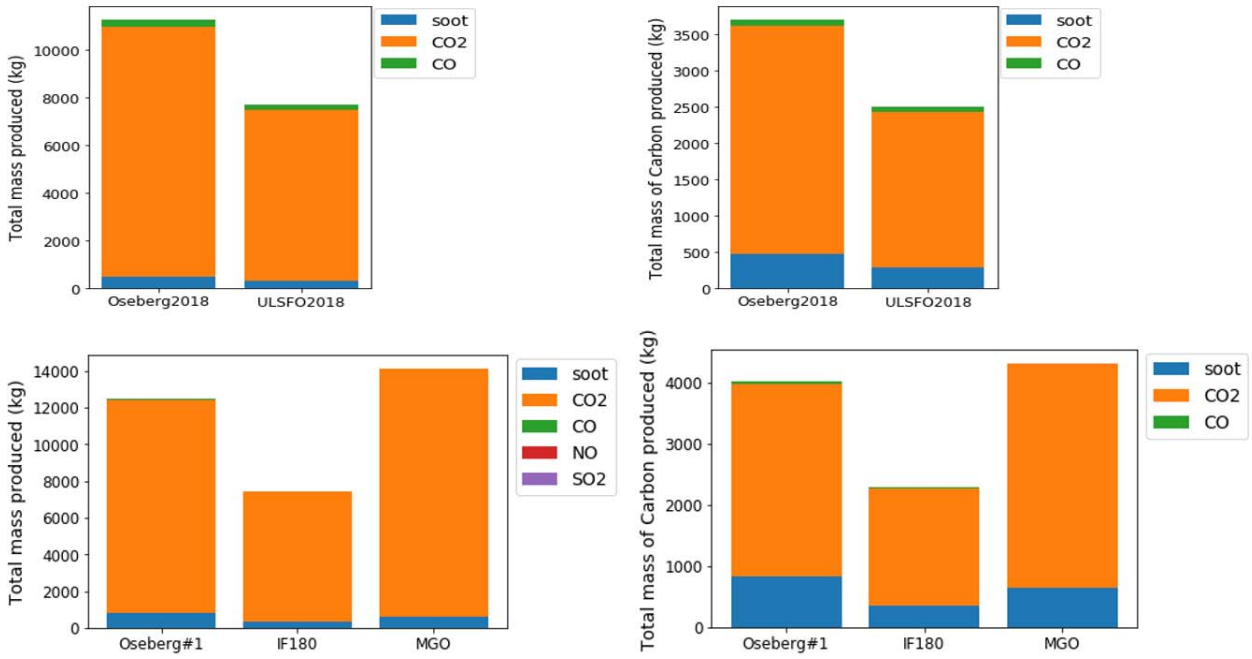

Figure 3.15 *Estimated total emissions in the smoke produced during the burn: Total amounts of measured components emitted during the burns (left graph) and total amount of carbon in the released soot, CO_2 and CO (right graph). No gas measurements available from Oseberg Pyroboom. The estimats are based on amount burned oil (Table 3.4).*

In Figure 3.16, total emissions from each component group (described in Appendix E) was calculated based on the concentrations from the PAH measurements in soot particles and residue.

In the left figure, estimated amounts (in kg) of each component group in total amount of soot produced during ISB (drone 1 from each experiment) are shown. The calculations are based on the concentrations in

soot given in Table D 1 (2018) and Table D 2 (2019), estimated amount BC in Table D 5 (Appendix D), and amount burned oil from Table 3.4. It was assumed that BC was 100% soot. The highest amount of soot (845 kg) was produced during ISB of Oseberg Fireboom (Table D 5), 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 PAH). However, as mentioned in section 3.7, there were higher concentrations measured on the so-called reference filters (not been in the smoke) in 2019, and as the results are corrected for background, this could have influenced the results reported. The soot generated in the burn of Oseberg Fireboom contained 784 g SVOCs (437 g 4-6 ring PAH). The results indicated that the lowest amounts of soot were produced during the burns of ULSFO and IFO180 (334 and 336 kg, respectively). The SVOC concentration in the soot was similar, 474 g in soot from ULSFO (354 g 4-6 ring PAH) and 427 g in soot from IFO180 (109 g 4-6 ring PAH). The estimated BE was lower in these two burns than in the other burns.

In the right graph in Figure 3.16, estimated amounts (in kg) of each component group in the burn residue samples is shown. The calculations are based on the concentrations given in Table C 6 to Table C 8 (Appendix C) and amount residue in Table 3.4. The residues of Oseberg 2018, Oseberg Fireboom and MGO contained similar total amount of SVOC (approximately 4 kg, of which ca 2.8 kg were the most water soluble and bioavailable components (naphthalenes and 2-3 ring PAH)). Two burn residues of IFO180 are shown, reflecting their difference in BE. The same amount of residue is used in both calculations (1449 kg). In the least burned residue, the total amount of SVOC was 24 kg (of which 20 kg was naphthalenes and 2-3 ring PAH). There was 8.7 kg SVOC in the most burned residue (of which 6.4 kg were naphthalenes and 2-3 ring PAH). Burn residue of ULSFO contained 22 kg total SVOC (8.4 kg naphthalens and 2-3 ring PAHs, and 12 kg 4.6 ring PAH). The lowest amount of SVOCs was quantified in the residue of Oseberg Pyroboom (1.2 kg, of which 0.8 kg naphthalenes and 2-3 ring PAH).

The results indicated that residues of the oils with less BE contained higher content of SVOCs than the residues of oils with higher BE, such as Oseberg Pyroboom.

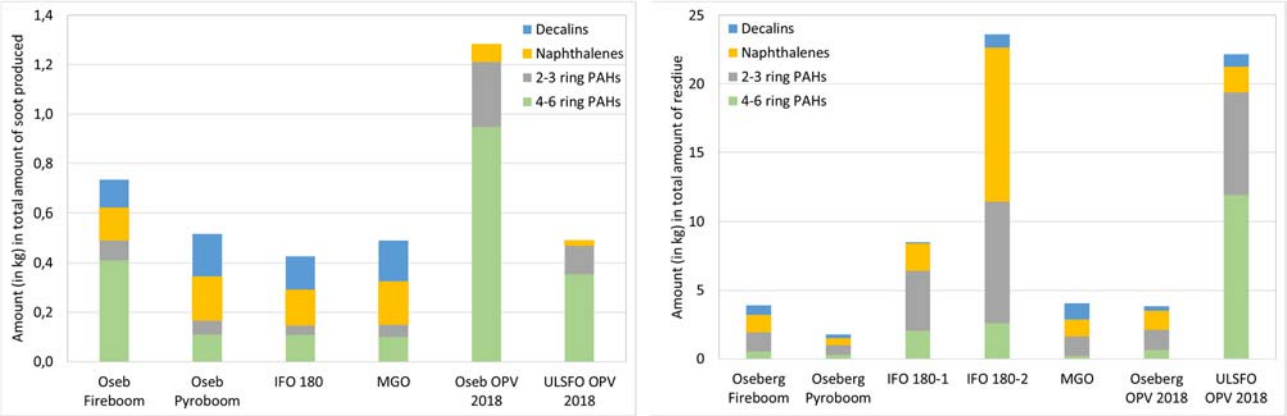

Figure 3.16 *Estimated amounts (in kg) of each component group (given in Appendix E) in total amount of soot produced during ISB (left graph) and estimated amount (in kg) in total amount of residue after ISB (two residue samples are shown for IFO180 to illustrate the difference). Composition of unburned oils are given in Table C 6 to Table C 8 (Appendix C).*

3.12 Conclusions

During OOW 2016, one of the experiments were performed with three releases of Grane Blend crude oil. The main goals of the ISB experiment was to investigate if free floating oil would ignite and burn in open water and whether herders could be used in conjunction with ISB in open water. Two slicks were herded before ignition, while the third "reference" slick was not treated with herder. Hand-held igniters (gelled gasoline and flare) were used to ignite the slicks. The ISB experiment demonstrated that oil slicks in calmer open waters can be ignited and burn efficiently and that oil slicks may be contracted by herder sprayed from a MOB-boat around the periphery. However, also the untreated slick was ignited and burned successfully. Based on the results and the predominating weather conditions on the Norwegian continental shelf, NOFO and NCA, do not see herders as a key component in ISB operations in open water.

Six successful burns were completed during OOW in 2018 and 2019, where the oils were released into a fireboom and then ignited from a Pyro-drone or by a hand-held igniter. Pre-weathered Oseberg crude and fresh ULSFO, IFO180 and MGO were burned. It was performed a comprehensive monitoring of particles and gases in the smoke plume using dedicated drones and ISB residues were collected for chemical characterisation. An emulsified pre-weathered Oseberg Crude oil (52% water) did not burn.

Comparing the PAH content (including naphthalenes and decalins) in the residues after ISB with the unburned oils, showed that the concentrations of the most bioavailable and water soluble PAHs in the oils, such as naphthalenes and 2-3 ring PAHs, were reduced during the burns, but that the content of more heavy, typically pyrogenic 5-6 ring PAH, increased. Compared with unburned oils, the depletion in the total PAH concentration in the ISB residues varied from 33% for the least burned residue of IFO180 to 90% for Oseberg Pyroboom. The lowest total amount of PAHs was quantified in the residue after ISB of Oseberg Pyroboom (1.2 kg), which also had the highest BE. Highest amount of PAHs was estimated in the least burned IFO180 residue (24 kg) and ULSFO (22 kg). The results showed that residues of oil with lower BE contained higher contents of PAHs than the residues of oils with higher BE, such as Oseberg Pyroboom. The final chemical composition of the residues depends on the initial oil type and the efficiency of the burning.

The monitoring in the smoke plume indicated low concentrations of SO_2 (<2ppm) and NO_X (<1.5 ppm). The concentrations of CO_2 and CO were below 420 ppm and 3.6 ppm, respectively. As expected, the particle concentrations were high in the smoke plume, but the levels declined rapidly when the drone left the smoke plume. The major part (> 90%) of the measured particulates was in the fine particle fraction (PM<1) which includes the ultrafine particles (<0.1 µm). The high concentrations of PM<1 and particulate PAH are mainly limited to visible smoke and the concentrations decline with increasing distance from the burn site. The highest amount of soot was produced during ISB of Oseberg Fireboom (845 kg), which contained 784 g PAHs, whereof 437 g 4-6 ring PAHs. The results indicated that the lowest amounts of soot were produced during the burns of ULSFO (334 kg) and IFO180 (336 kg), with a similar PAH amount (approximately 450 g). The BE was lower in these two burns, but the amount of soot collected with the drones also depends on the time the drones were in the smoke plume.

The amount of BC produced relative to the amount of oil burned were 10% for Oseberg 2018, 11% for ULSFO, 12% for MGO, 13% for IFO180, and 14% and 18% from the two burns with Oseberg in 2019, which were within the range reported from other ISBs (2-20%). The estimated total emission of BC to air from the four experimental ISB performed in 2019 (21.8 tons of oil released, 16.7 tons burned) was 2.4 tons or would have contributed with 0.075% of the total emission of 3200 tons of BC to air in Norway in 2016. E.g. during the Macondo spill in 2010, it was estimated that 42000 tons of oil was burned, and Perring et al. (2011) estimated that between 600 and 2100 tons BC was released to the atmosphere (4% of the total amount burned).

The BE varied within in the slick and from one burn to another. For oils (e.g. heavy bunker oils) and emulsions, a thorough assessment should be performed on whether using ISB or not. BE was estimated to be between 80-91% 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 IFO180, and especially for IFO180, the BE varied within the slick (approximately from 30 to 60%). The ISB residues had different consistence, which also were reflected in their viscosities. E.g. residue after burning MGO was still liquid (viscosity of 259 cP), while the residue of IFO180 had a viscosity of more than 1 mill cP, resulting in a very sticky residue which will be much more challenging to collect. A laboratory test with ISB residues of ULSFO and IFO180 were performed to study their potential of sinking. The ISB residues were exposed to sand particles and swell, and the results indicated that IFO180 residue may sink, while ULSFO was not sinking. Oseberg was not tested.

The burn efficiency is not only dependent on the oil type, but also factors original slick thickness, degree of emulsification and weathering, area coverage of the flame, wind speed and wave choppiness. Three burns with the same Oseberg oil showed that the properties of the residues varied, from between 100 000 to 145 000 for Oseberg 2018 and Oseberg Fireboom to 579 000 cP for Oseberg Pyroboom, which also had highest BE.

4 Characterization of air pollutants emitted from in situ burning of offshore oil spills – potential for human exposure

4.1 Introduction

Burning of oil carries several adverse consequences, with air pollution being one of the most significant ones. ISB involves potential exposure of people in the close vicinity to acutely elevated levels of particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) among others.

Particulate matter produced due to incomplete combustion of oil is the primary health concern among the air pollutants resulting from ISB (Fingas, 2017). Particulates are commonly divided into three categories based on their aerodynamic equivalent diameter (AED). Particles with a diameter >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 results normally in high concentrations of fine and ultrafine particles.

There are rather extensive research gaps regarding the effects of oil spill cleanup operations on human health. Research on emissions from full-scale ISB is scarce as it is usually only made possible after an oil spill, but ISB is not always executed. Most of the available data is over 20 years old (e.g. Fingas et al., 1995b), except for the studies about the Deepwater Horizon oil spill (Nance et al., 2016).

Mesoscale experiments (Gullett et al., 2017) have been helpful in modelling of human exposure to air pollutants during ISB, but a lack of actual data from personal exposure remains. Over the years, the focus in PM-measurements has shifted towards the smaller particles as they are believed to be the most harmful to human health (Meng et al., 2013), making the older occupational hygiene studies of ISB (Booher and Janke, 1997; Fingas et al., 1998) less relevant.

A lot of the previous research focuses on the spread, physical properties and chemical composition of the smoke plume as well as oil residues. The studies, however, generally lack the occupational health perspective. This part of the report deals with investigating the potential of PM emitted from offshore oil fires as occupational hazard to workers on vessels involved in ISB. The measurements focus on quantitative measurements of PM and to a lesser extent also PAHs and VOCs at sea level, emitted from in-situ burning of both crude and refined oils.

4.2 Materials and Methods

Air measurements in surface vessels were taken during a total of nine controlled ISBs. All of them were carried out in the open sea (N59°59’ E002°27’) and under good weather conditions, i.e. wind speed ≈ 3-7 m/s, air temperature ≈ 10-17°C and no/negligible precipitation. The parameters measured each of the years are outlined in Table 4.1. Sampling instruments are listed in Table 4.2.

Table 4.1 Parameters measured

Year	**PM** (aerodynamic diameter in µm)				**VOC**	**PAH**
2019	Upwind vessel	MOB-1	MOB-2	In smoke plume	MOB-1	-
	2.5	<1, 1, 2.5, 4, 10, ≤15	2.5	-		
2018	2.5	<1, 1, 2.5, 4, 10, ≤15	2.5	-	MOB-1	MOB-1 + MOB-2 + upwind vessel
2016	-	-	2.5	2.5	-	Smoke plume + upwind vessel

Table 4.2 Analytes and sampling equipment

Analyte	Location	Units	Sampling method	Particle size [µm]
PM<1	MOB-1	particles/ cm^3	P-Trak Ultrafine Particle Counter (8525)	0.02 to 1
PM1, PM2.5, PM4, PM10, Total	MOB-1	mg/m^3	DustTrak DRX Aerosol Monitor (8534)	0.1 to 15
PM2.5	MOB-2 and in smoke plume	mg/m^3	SidePak Personal Aerosol Monitor (AM510) + 2.5-micron impactor	0.1 to 2.5
PM2.5	Upwind vessel	mg/m^3	DustTrak II Aerosol Monitor (8532) + 2.5-micron impactor	0.1 to 2.5
PAH	MOB-1, in smoke plume and in upwind vessel	$µg/m^3$	37mm closed-faced cassette with a Teflon 2µm pore-size filter (SKC 225-1713) + XAD-2 sorbent tube (SKC 226-30-04) + 2.0 l/min (2016 drone, 2018) or 0.2 l/min (2016 upwind) SKC pump	Total
VOC	MOB-1	ppm	MiniRAE 3000 Photoionization Detector	N/A

4.2.1 Particulate Matter

Particulate matter in each location was sampled continuously with various direct-reading instruments from TSI Inc. (Shoreview, MN, USA) as indicated in Table 4.2. Measurements were logged at 1 second intervals, and the average particle concentrations over the respective burning periods were calculated. Sampling commenced upon ignition of each oil slick. In this paper, the measured PM fractions are presented as "up to" a given AED, e.g. PM2.5 includes all particles with a diameter ranging from the lower detection limit for a given instrument up to 2.5 µm.

4.2.2 Polycyclic Aromatic Hydrocarbons (PAH)

In 2016 PAHs were measured upwind and in the smoke plume onboard a drone. One sample was taken in each of the two locations during the entire of each of the three burns. Due to technical complications, a pump with a low flow rate of 0.2 L/min was used upwind, increasing the uncertainty of the measurements. A more comprehensive sea-level PAH-sampling was undertaken in 2018, with sampling trains onboard the upwind vessel, MOB-1 and MOB-2. Two parallel samples were taken in MOB-1 during the entire of each of the two burns, in addition to two parallel 12-hour (including the two burns) samples. Two parallel 12-hour (including the two burns) samples were also collected on both the upwind vessel and MOB-2. Flow rate of all the pumps was set to 2.0 L/min. PAHs were not measured in 2019.

Total particles on the Teflon filter was analyzed gravimetrically (mg on filter; limit of detection 0.1 mg ±10%), and average air concentration (mg/m^3) was found by dividing by the air volume through the filter during the

sampling period. The total particle fraction sampled by this method/sampling head does not have a defined cut-point for particle size. However, the sampler is widely used in US and Norway and resembles the inhalable sampler (50% cut-point = 100 µm), but it underestimates the larger of the particles defined as inhalable.

21 PAH compounds (PAH21), in the particulate fraction on the Teflon filters and biphenyl and naphthalene in the vapor phase sampled on XAD-2 sorbent tube were desorbed and analyzed by gas chromatography/mass spectroscopy (GC/MS), with detection limits of 0.1 µg/m^3 (±30%). PAHs were analyzed according to NIOSH 5515, issue 2.

4.2.3 Volatile Organic Compounds (VOC)

VOC levels were measured in 2018/19 with a direct-reading photoionization detector (PID) MiniRAE3000 (RAE Systems Inc., San Jose, CA, USA). The PID, with a 10.6 eV lamp, was Isobutylene-calibrated. Sampling commenced during oil release prior to ignition.

4.3 Experimental setup

The types and amounts of oil used, along with the corresponding burning times are listed in Table 4.3. Oil samples G and H had a secondary ignition and burn in addition to the main one.

Table 4.3 *Oil types, volumes and burn time. Grane Blend has lower density and is less asphaltene rich than a "pure" Grane (density approx. 0.90 vs 0.95), but is still a heavy crude compared to other Norwegian crudes.*

Year	Sample name	Oil name	Oil type	Volume [m^3]	Burn [min]
2019	A	Oseberg Blend Fireooom	Light crude	6	63
	B	Oseberg Blend Pyroboom	Light crude	5.6	44
	E	IF 180 - 1% S Fireboom	Heavy fuel	4.2	37
	F	Marine Gasoil Fireboom	Distillate fuel	6	28
2018	C	Oseberg Blend Pyroboom	Light crude	6	44
	D	ULSFO Pyroboom	Residual fuel	5.8	48
2016	G	Grane Blend + Herder (HISB 4.1)	Heavy crude	6	4 + 10
	H	Grane Blend (HISB 4.2 ref)	Heavy crude	4.2	7 + 10
	I	Grane Blend + Herder (HISB 4.3)	Heavy crude	4	18

4.3.1 OOW 2019 and 2018

The same procedure was followed for burnings in 2019 (total of 4) and 2018 (total of 2). During these burns, the oil was contained on the surface of water by different U-shaped fire-resistant oil booms. The measurement strategy for these six ISBs focused on the different PM-fractions. The priority in sampling was given to concentrations of air pollutants at sea level as these are of occupational health interest and are regulated by law. Measurements were taken on a total of three vessels: MS Strilborg upwind (about 140 - 150 m) from the oil and two MOB ("man-over-board") boats. Figure 4.1 illustrates the experimental setup of the OOW 2019 and 2019.

In each case, MOB-1 was positioned about 200-400 m (the boat was in constant longitudinal movement) downwind from the oil slick and moved back and forth transverse to the smoke plume. In 2018, the distance between MOB-1's and Oseberg oil was about 400 m and gradually decreased as the burn progressed. The distance was considerably closer to 200 m upon the burning of ULSFO. In 2019 MOB-1 was generally closer to the oil fire than in 2018, being kept at approx. 200 m behind the oil during all the burnings.

MOB-2 started each experiment 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.

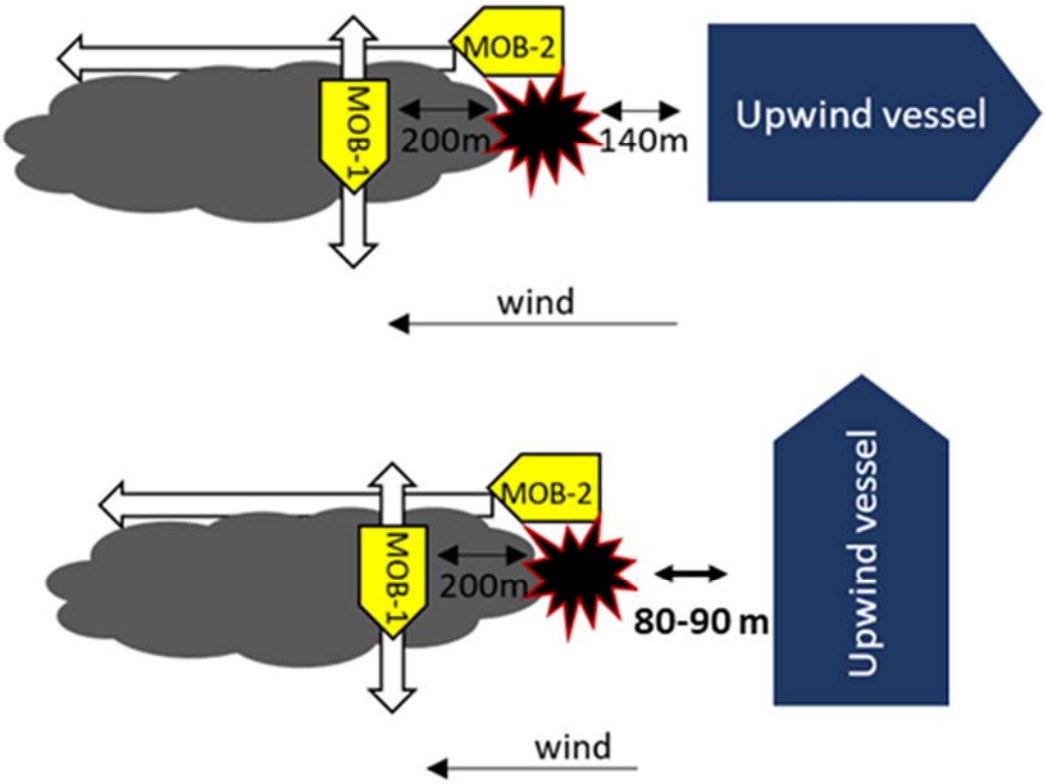

Figure 4.1 Illustration of the experimental setup in 2018 & 2019

4.3.2 OOW 2016

The experimental setup in 2016 (Figure 4.2) differed from the one in 2018 and 2019. In 2016 the oil was free-floating on the surface of water and only the fine fraction (PM2.5) was measured both at sea level (MOB-2) and in the smoke plume (drone). In the first and last experiment in 2016 a herder (ThickSlick 6535) was used to concentrate the oil slick to a burnable thickness.

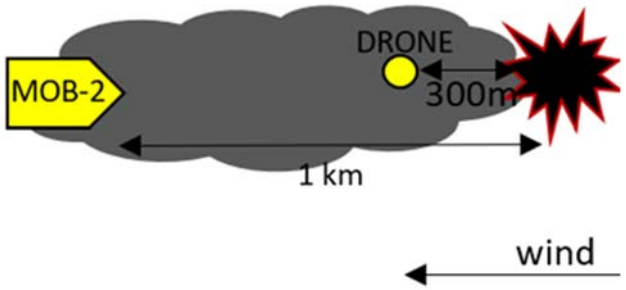

Figure 4.2 Illustration of the experimental setup in 2016 (free floating oil slick, no booms)

4.3.3 Norwegian Occupational exposure limits and Norwegian Air Quality Criteria

As indicated in Table 4.4 The Norwegian Occupational Exposure Limit (OEL) for nuisance dust over an 8-hour workday is 10 mg/m^3 for total dust/particulate fraction and 5 mg/m^3 for respirable dust fraction (aerodynamic diameter <4 µm) https://www.arbeidstilsynet.no/globalassets/regelverkspdfer/forskrift-om-tiltaks--og-grenseverdier (Vedlegg 1) (in Norwegian).

It should be noted that this limit does not account for additional adverse effects of VOCs or PAHs emitted from the oil combustion and adsorbed/absorbed by the particles. The 8-hours OEL for the 21 PAHs in particulate fraction is 0.04 mg/m^3, naphthalene 50 mg/m^3 and biphenyl 1 mg/m^3. All the OELs need to be adjusted by a factor of 0.6 for a 12-hour workday. The Norwegian Air Quality Criteria for PM2.5-particles among the general population are 15 µg/m^3 (24 hours) and 8 µg/m^3 (year), and correspondingly 30 µg/m^3 and 20 µg/m^3 for PM10 https://www.fhi.no/nettpub/luftkvalitet/svevestov/svevestov/ (in Norwegian). The Norwegian Air Quality Criteria for benzo(a)pyrene (B[a]P) as a measure for PAH is 0.1 ng/m^3 as an yearly mean value https://www.fhi.no/nettpub/luftkvalitet/pah/pah/?term=&h=1 (in Norwegian).

Table 4.4 Norwegian Occupational Exposure Limits and Air Quality Criteria

	Norwegian Occupational Exposure Limit (8 hours)	Norwegian Air Quality Criteria for the general population	
		24 hours	Annual mean
Total dust/particles	10 mg/m^3		
Respirable dust/particles (<4 µm)	5 mg/m^3		
Σ21 PAHs in particulate fraction	0.04 mg/m^3		
Naphthalene	50 mg/m^3		
PM2.5-particles		15 µg/m^3	8 µg/m^3
PM10-particles		30 µg/m^3	20 µg/m^3
Benzo(a) pyren (B[a]P)			0.1 ng/m^3

4.4 Results

When analysing the results, one should bear in mind that the smoke plume generated during an ISB may constitute of two smaller vortices with a gap in-between (Morton, 1997) as shown in Figure 4.3. Thus, the individual measured PM-concentrations deviate considerably from their calculated mean value. It is especially noticeable in the PM-measurements from MOB-1 in 2018/19, which in each case resulted in a recognizable pattern of concentration peaks separated by valleys with even time intervals. An example of this is shown in Figure 4.4 from 2019.

Figure 4.3 Typical smoke plume during ISB.

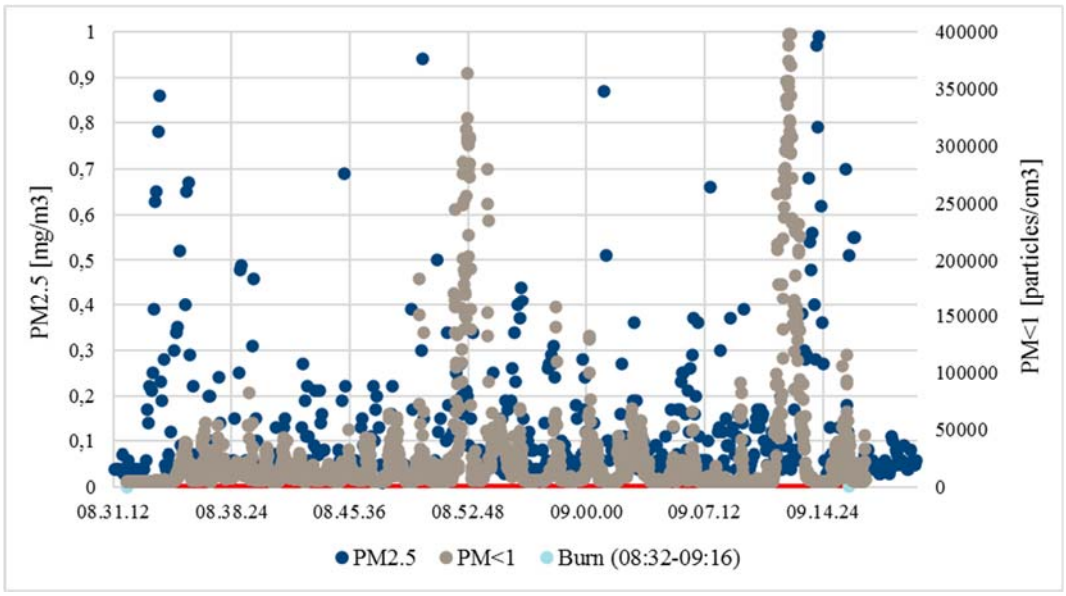

Figure 4.4. Typical results for the particle fractions $PM_{2.5}$ and $PM_{<1}$measured in MOB-1 during a burn of Oseberg Blend.

4.4.1 Measurements in the smoke plume in 2016

Particles

For evaluation of the results taken by the drone one should take into account that the drone was in the smoke plume for only about 4 - 7 minutes of the total flying times of the drone of 6 to 18 min (Table 4.5).

When assuming zero concentration when the drone was out of the smoke plume the PM2.5 concentration in the smoke plume would be 8.5, 10.8 and 9.9 mg/m^3 for sample G, H and I, respectively. The average values for the drone measurements (PM2.5-values) in Table 4 are, however, underestimated since in shorter periods the levels exceeded the upper measurement range (20 mg/m^3) of the instrument. When drone was outside the smoke plume, the measured values dropped rapidly to <0.05 mg/m^3 (Table 4.5)

The total dust/particle concentration (results from gravimetric analysis of total particles) was very high in two samples taken from the drone (sample H; 34.4 mg/m^3 and sample I; 23.5 mg/m^3), which corresponds to estimated levels of 57 and 137 mg/m^3, respectively when the drone was actually in the smoke plume (Table 4.5).

Table 4.5 *Mean particle concentrations in OOW2016 measured by the drone by direct reading instrument (PM2.5) and by total dust sampler (filter samples).*

Oil sample		PM2.5 average [mg/m^3]	Total particulate/dust [mg/m^3]
G	Grane Blend + Herder	Mean for totally 14 min; 2.5 In the smoke for 4 min; 8.5 Outside smoke for 10 min; 0.025	<LOD
H	Grane Blend	Mean for totally 6 min; 6.6 In the smoke for 4 min; 10.8 Outside smoke for 2 min; 0.043	Mean for totally 16 min; 34.4 In the smoke for 4 min; 137
I	Grane Blend + Herder	Mean for totally 18 min; 3.8 In the smoke for 7 min; 9.9 Outside smoke for 11 min ; 0.038	Mean for totally 17 min; 23.5 In the smoke for 11 min; 57

Polycyclic Aromatic Hydrocarbons (PAH)

The air concentration of the 21 particulate PAH components in the two analysed samples of total particles in the smoke plume in 2016 (sample H and I) were 2.3 and 12 µg/m^3 (Table 4.6), which correspond to estimated levels of about 9 and 29 µg/m^3 in the 4 and 7 minutes the drone was in the smoke plume (Norwegian OEL=40 µg/m^3). The components with highest concentrations were phenanthrene, anthracene, fluoranthene and pyrene. Benzo(a)pyrene, classified by IARC in Group1; certain carcinogenic for humans, was below the level of detection (<0.1 µg/m^3).

The air concentration of PAH components in the vapor phase were found in low concentrations in the two samples (naphthalene: 18 and 37 µg/m^3 and biphenyl: 0.56 and 1.4 µg/m^3) (Table 4.6). The Norwegian OELs are 50 mg/m^3 for naphthalene and 1 mg/m^3 for biphenyl.

Table 4.6 *Mean concentration of PAH- components in vapour and total particles taken from the drone in OOW2016.*

Oil sample		Sampling time [min]	Time in smoke [min]	Naphthalene (vapor) (µg/m^3)	Biphenyl (vapor) (µg/m^3)	ΣPAH21 (particulate) (µg/m^3)
G	Grane Blend + Herder	18	4	<LOD	<LOD	<LOD
H	Grane Blend	16	4	18	0.56	2.3
I	Grane Blend + Herder	17	7	37	1.4	12

The content of PAH in soot-particles (in µg PAH/g particulates) are commonly used as indicators of combustion source contributions to atmospheric pollution. For sample H and I the mean content of PAH/g total particulates (in µg PAH/g total particulates) was 18 for naphthalene,124 for phenanthrene, 60 for fluoranthene, 72 for pyrene and 3 for chrysene. Figure 4.5 from Gullett et al (2016) illustrates that the concentration of PAH-components in particulate matter detected in the smoke plume in OOW 2016, are within the range reported in other studies, i.e. for most components somewhat higher than in the DWH burn, while lower than in some of the other oil burns such as Louisiana and Alberta crude oil in meso-scale (Evans et al., 2001, Fingas et al., 1996). However, there are many factors that contributes to the variability in measured PAH-content including type of oil, temperature, scale of experiment, sampling location, sampling method etc.

The content of PAH (g)/total particulates (kg) in OOW2016 is close to or within the range of the results from OOW 2019 for 2-3 ring PAHs (OOW2016; 0.129 g/kg and OOW2019; 0.023-0.114 g/kg) and for 4-6 rings PAH (OOW2016; 0.151 g/kg and OOW2019; 0.057-0.518 g/kg), while lower for naphthalene (OOW2016; 0.018 g/kg and OOW2019; 0.142-0.429 g/kg).

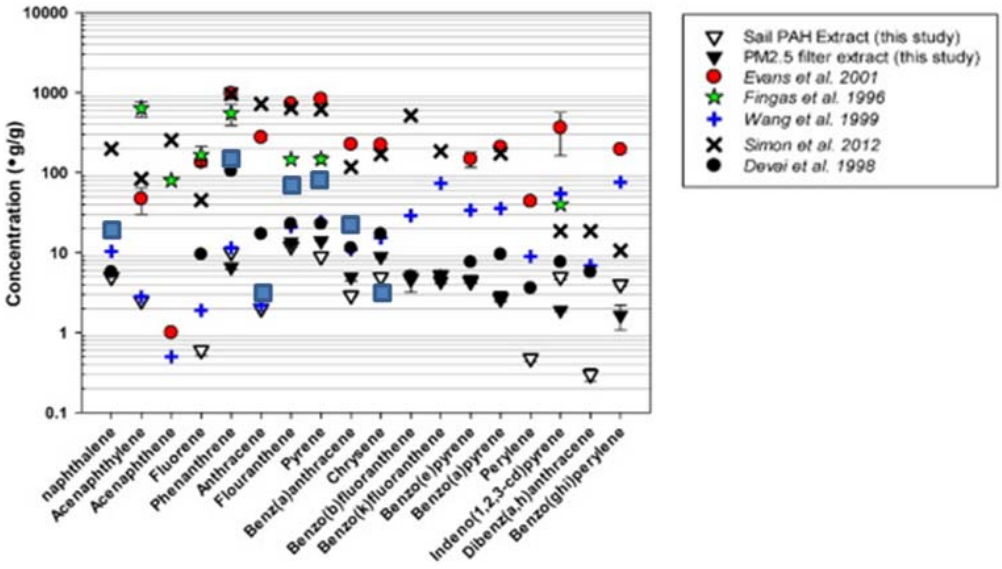

Figure 4.5 *The content of PAH in soot-particles (in µg PAH/g particulates) in OOW2016 (blue-filled squares) compared the previous studies.*

4.4.2 Measurements in the surface vessels; MOB-1, MOB-2 and MS Strilborg

Particles

The average measurement results during each of the burns are listed in Table 4.7. The particle concentrations were highest in MOB-1 that moved back and for the transverse to the smoke plume. The highest peak concentration of the different particle size fractions were measured when the vessels was located directly under the smoke cloud (Figure 4.4) as also indicated by the peaks of the smallest particles (PM<1) in Figure 4.6

The mean concentration of PM2.5-particles in MOB-1 was very low in OOW2016 (0.006-0.012 mg/m^3) compared to the levels in OOW2018 (0.061-0.068) and OOW2019 (0.194-0.616) (Table 4.7). Thus, the mean levels in in MOB-1 in OOW2016 during burning were close to background concentrations before burning, and below the Norwegian Air Quality Criteria. The low concentrations in OOW 2016 is due to the much longer distance between the burn and MOB-1 (about 1 km) compared to 200-400 m in OOW 2018 and 2019. However, the PM2.5 levels in OOW2018 and OOW2019 varied between 4 and 41 times higher than the 24 hour Norwegian Air Quality Criteria for the general population.

The highest concentration was found for MGO followed by Oseberg (sample A), IF180 (E) an Oseberg (B) (Table 4.7). The relatively highest concentration for MGO could be partly related to the higher burning efficiency for this oil. Sample A and B (both Oseberg blend) were collected at the same distance from the fire, but the burn time of A was over 50% longer than B. As a result, the average PM1 concentration for A was 2.2 times higher than B. The generally lower concentrations in OOW2018 compared to OOW2019 is presumably

due to the shorter distance between the burn in OOW2019 (about 200 m) compared to OOW2018 when the distance varied between 200-400m.

The particle concentrations were very low on the upwind vessel MS Strilborg (Table 4.7). The levels measured in MOB-1 were considerably higher than in MOB-2 that moved in the outskirts of the visible smoke (Table 4.7), thus reflecting that exposure to particulates seems to be mainly bounded to visible smoke.

Table 4.7 *Particle concentrations of different size fractions measured by direct reading instruments in OOW2016. OOW2018 and OOW2019.*

Oil sample			PM average [mg/m³] MOB-1					MOB-2	Upwind vessel
			1	2.5	4	10	≤100	2.5	2.5
A	Oseberg Blend	2019	0.421	0.424	0.426	0.431	0.432	0.048	0.02
B	Oseberg Blend	2019	0.190	0.194	0.197	0.200	0.203	0.029	0.02
C	Oseberg Blend	2018	0.067	0.068	0.069	0.071	0.071	0.007	0.02
D	ULSFO	2018	0.061	0.061	0.062	0.063	0.063	0.007	0.03
E	IF 180 - 1% S	2019	0.240	0.245	0.250	0.261	0.265	0.054	0.02
F	Marine Gasoil	2019	0.603	0.616	0.626	0.647	0.653	0.078	0.03
G	Grane Blend + Herder	2016		0.006					
H	Grane Blend	2016		0.007					
I	Grane Blend + Herder	2016		-					

Table 4.8 *The fine particle fraction (PM<1um) measured in MOB-1 in OOW 2018/19*

Oil sample			PM<1 average (max) [particles/cm³]
A	Oseberg Blend (2019)	2019	18 591 (461 000)
B	Oseberg Blend (2019)	2019	23 973 (398 000)
C	Oseberg Blend (2018)	2018	13 620 (500 000)
D	ULSFO (2018)	2018	11 556 (114 000)
E	IF 180 - 1% S (2019)	2019	18 986 (351 000)
F	Marine Gasoil (2019)	2019	22 498 (374 000)

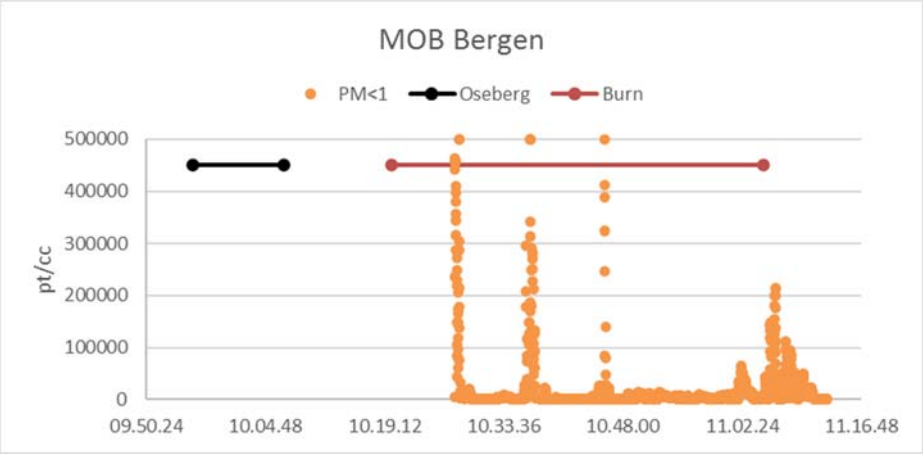

Figure 4.6 *The fine particle fraction (PM<1) from Oseberg (sample C) measured in MOB-1 in OOW2018.*

There were only small differences between the different particle size fractions from PM1 to PM<100. This finding suggests that the finest size fraction, i.e. with aerodynamic diameter <1µm that includes the ultrafine particles, comprises most of the particle matter, independent of the oil type. Measurements taken with particle counter (Table 4.8) confirms the difference in particle levels PM<1 between OOW2018 and 2019 for the smallest particles.

Taken together, MGO seems to cause the highest concentration of particles in the closest vessel during burning which could be due to higher burning efficiency. In situ burning and MGO was associated with 2-3 times higher PM2.5-concentration than Oseberg and IF180. However, this is based only on few experiments, and more detailed studies under stable and comparable conditions are needed to confirm this. The relative position of the vessel to the oils, in addition to the weather/climatic conditions the largest sources of uncertainty in the presented measurements.

Polycyclic Aromatic Hydrocarbons (PAH)

The results in Table 4.9 show very low levels of PAH in all vessels (MOB-1, MOB-2 and Strilborg) when compared to Norwegian Occupational Exposure Limit Values. This include 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 ULFSO. There were no large differences in the full-shift results 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.

The amount of sampled particles/dust on the filters on the drone operators in ISB were below the limit of detection (<0.1 mg) set by the laboratory and was thus not analysed for PAH components.

It is concluded that personal exposure to PAH among crew onboard vessels both upwind and downwind from the burning was very low during these conditions with relatively short burning time.

Table 4.9 Results from measurements of PAH on three vessels in OOW2018.

Location/ vessel	Sample type	Oil sample	Sampling time (min)	Naphthalene (vapor) (µg/m^3)	Biphenyl (vapor) (µg/m^3)	ΣPAH21 (particulate) (µg/m^3)
Upwind/Strilborg	12-hr	C + D; Oseberg Blend+ULFSO	731	1.50	0.180	0.010
Upwind/Strilborg	12-hr	C + D; Oseberg Blend+ULFSO	731	1.50	0.190	0.011
MOB-2	12-hr	C + D; Oseberg Blend+ULFSO	722	0.26	0.039	0.010
MOB-2	12-hr	C + D; Oseberg Blend+ULFSO	722	0.33	0.050	0.010
MOB-1	12-hr	C + D; Oseberg Blend+ULFSO	615	0.47	0.051	0.012
MOB-1	12-hr	C + D; Oseberg Blend+ULFSO	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; ULFSO	82	0.82	0.026	0.049
MOB-1	Oil release + burn	D; ULFSO	82	1.00	0.030	0.046

Volatile Organic Compounds (VOC)

Recorded levels of VOCs were very low during release and burning of the oils. Peaks of VOC concentrations as measured during oil release and ISB are listed in Table 4.10. The PID-instrument was inactive during the experiment with sample A. The maxima were registered due to oil leakage from the fire booms prior to ISBs. Non-detectable or negligible values were detected during all ISBs, with

(decreasing) emissions from MGO lasting the longest. There is no OEL for VOCs (C6-C10), but even the peak levels indicated in Table 5.9 are well below the 8-hour OEL for white spirits (C7-C12 with aromatic content <22%) of 50 ppm.

Table 4.10 Maximum (peak) concentration of VOC measured in MOB-1 during OOW2018 and OOW2019.

Oil sample	Oil sample	Max. VOC concentration [ppm]
A	Oseberg Blend (2019)	-
B	Oseberg Blend (2019)	1.8
C	Oseberg Blend (2018)	0.4
D	ULSFO (2018)	0
E	IF 180 - 1% S (2019)	2.5
F	Marine Gasoil (2019)	17.1

4.5 Personal protection-evaluation of filter masks

The results indicate that the smoke mainly consists of particles <1 µm. This is in line with results from oil burning during the Deepwater Horizon oil spill where the particle size in smoke from burning was in the range of 0.1-1.0 µm, with a top at about 0,4µm (Perring et al., 2011). Similar results were found in the NOBE-burnings where the particle size was mainly in the range of 0.1-1.0 µm, with a top at 0,3µm (Ross et al., 1996). During the last years there has been increased focus on these smallest particles (<1 µm) as they may have adverse effects not only on the lungs, but also on the heart and circulatory system, also at relatively short exposure periods. However, they have not yet any occupational exposure limit or air quality criteria. Preventive measures to reduce exposure to such particles should be considered.

Protective masks of proper quality should be used when exposed to smoke from burning of oil. Particle filters can be used against both solid particles and liquid particles (mists, fine sprays and aerosols). Particle filters are classified according to their efficiency. The filter (or the facepiece it is built into) are marked with the letter P (for particle) and a number to indicate efficiency, or the level of protection provided:
P1 = Low efficiency; P2 = Medium efficiency and P3 = High efficiency. P1 and P2 should not be used against fume unless specified by manufacturer. General requirements for P2 and P3-particle filters in facemasks is that maximum percentage penetration of particles through the filter is <6% and <0.05%, respectively. Thus, the filters should capture/filter 94% and 99.95% of the particles.
Filters are additionally marked:
NR = Not reusable – Designed for a single work shift (eight hours) and must be disposed of safely at the end or R = Reusable.

Laboratory studies have shown that percentage penetration for P3-filters was <0.03% for particles with a medium size of 0.238 µm, which is typical size for smoke particles from burning oil (Rengasamy et al., 2009). The most penetrating particle sizes was 0.03-0.06 µm having a percentage penetration of <0,164%. Similar results were found in a French study (Golanski et al., 2009) where the percentage penetration for P3-filters was about 0.05% for a particle size of 0.1µm.

The persons in the MOB-vessels in OOW2019 had half masks with P3-filters available. Burning of MGO was associated with the highest mean particle concentration (0,6 mg/m^3). When using the published percentage penetration (0.05%) for typical particle sizes (0.3-0.4 µm) in this type of smoke the particle concentration inside the mask would be about 0.3 µg/m^3, which is considerably lower than the PM2.5 Norwegian Air Quality Criteria for the general population, which indicates that when used properly this type of respiratory masks should provide adequate protection and well within the safety criteria for the persons in these MOB-vessels.

However, one should bear in mind that the real protection would probably be lower since at these low particle levels as the penetration of particles through the filter is most likely not the limiting factor since leakages between the skin and the mask probably will contribute relatively more to the inhaled particle concentration.

A Norwegian study in the aluminium industry showed that the real protection for these facemasks/half-masks that were used in OOW2019 varied considerably between persons, with a mean protection of 64% for respirable particles (<4 µm) (Skaugseth et.al., 2004). A similar filter efficiency among persons exposed to smoke from burning of MGO would result in a particle exposure of 0,2 mg/m^3 inside the mask. Leakage of particles between the face and the mask caused by poor fit, contributes to less protection in work situations than in laboratory tests. Thus, such leakage should be reduced as far as possible through education, training and fit testing (The Norwegian Oil and Gas Association, 2011).

4.6 Conclusions and recommendations related to human exposure

- As expected, the concentrations of PM2.5 particles and total particles were high in the smoke plume, by far exceeding the Norwegian Air Quality Criteria, and the Norwegian Occupational Exposure Limits (OEL). The levels of PM2.5 particles declined rapidly when the drone left the smoke plume. The small PM2.5-particles can be inhaled into the deepest part of the lung and are considered as more harmful than the larger particles.
- The concentration of PM2.5 particles in the closest vessel, located about 200-400 meter downwind from the burn, was well above the Norwegian Air Quality Criteria, and was considerably higher than in the upwind vessel (MS Strilborg) as well as in MOB-2 that moved in the outskirts of the visible smoke. This finding illustrates that the particles are concentrated mainly within the boundaries of visible smoke.
- The major part of the measured particulates is in the fine size fraction; PM<1, which includes the ultrafine particles (<0.1 µm). There has been increasing focus on these smallest particles in recent years due to their effects on the respiratory and the cardiovascular system, but they have not yet any limit values.
- On the other hand, the results strongly indicate that on the vessels placed upwind from the smoke plume, there is a negligible effect on the air quality from the burning. Thus, the particles originating from the burning should not represent an additional risk of harmful health effects for the crew on the upwind vessel.
- In the smoke plume several PAH components in the particulate phase, some of them carcinogenic, were detected at levels approaching the Norwegian OEL. Particulate PAH is bound to the soot-particles, and when moving away from the smoke plume the exposure to PAH will decrease similarly as reported for the particles. Personal exposure to PAH among crew onboard vessels both upwind and downwind from the burning was very low during these conditions with relatively short burning time. However, it is recommended that crew on vessels close to and downwind of smoke plumes from oil fires should use facemasks with P3 filters.
- Negligible concentrations of VOCs were measured in the closest vessel during burning. However, previous studies (Gjesteland et al., 2017; 2018) 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 occupational exposure limit during the initial stages the spill. In such cases half-face air purifying respirators with a combination of a particle filter and an organic vapor cartridge, A2 should be used to prevent biological uptake of benzene.

5 Learnings and operational findings

During OOW 2016, 2018 and 2019, nine burns were completed. Free floating slicks and oil in fire booms were ignited from a Pyro-drone or a hand-held igniter. Grane crude, pre-weathered Oseberg crude, and ULSFO, IFO180 and MGO were burned. NOFO and NCA have gained much knowledge through these experiments and some of the main findings are summarized in the table below (Table 5.1).

Table 5.1 Summary of advantages and disadvantages/challenges with in situ burning based on experience from OOW 2016, 2018 and 2019

Advantages	Disadvantages/challenges

• Have the potential to efficiently combat large quantities of oil over a short period of time
• Costs could be relatively low:
  o Especially when not using booms
  o Less need for waste management
  o Less need for cleaning of vessels
• Reduced demand of personnel and logistics
• Might be the best alternative in scenarios with ice
• Rapid response even with limited resources available in remote areas (burning without booms)
	• Generates:
	  o Soot particles (Organic and Black Carbon)
	  o Smoke gases (including long-lived greenhouse gases such as CO_2)
	• Thin oil films cannot be ignited and burned
	• Weathering reduces the ignitability of oils (evaporation and emulsification)
	• HSE issues associated with smoke gases and soot from the burn
	• Strong weather limitations:
	  o Existing fire booms are mainly for low wind and wave conditions.
	  o If herders are used, the time span from application of herder to ignition of the oil is reduced with increasing wind and wave conditions.
	  o Vulnerable to precipitation
	• Limited re-use of fire booms. Logistically challenging and costly to resupply booms.
	• Continuous remote sensing necessary to support the application of herder and ignition of slick.
	• Generally leaving a high viscous and long-lived residue in the environment.

The burnings took place in wind speeds from 3-7 m/s and wave hights from 1.0 to 2.4 m. Our experience is that ISB operations should be carried out with wind speeds below 5 m/s and wave heights below 2 meters. Dependent on the wave type (breaking waves, swell etc.), ISB can also be conducted at slightly higher wind speeds and waves.

The BE varied both between and within the burns slick and from one burn to another. BE was estimated between 80-91% for Oseberg crude. For the fuel oils the BE varied, and was highest for MGO (more than 90%). The two heavier fuels, ULSFO and IFO180, the BE were less than 60%, and especially for IFO180, the BE varied within the slick (approximately 30 to 60 %). Factors such as boom leakage were not taking into account when estimating BE. For oils and emulsions with low BE, an assessment should be performed on whether using ISB or not.

The experiments also demonstrated that oil slicks in calm open waters might be contracted by herder and be ignited. However, free floating oil slicks may ignite and burn also without the use of herders. Based on the results and the predominating weather conditions on the Norwegian continental shelf, NOFO and NCA, do not see herders as a key component in ISB operations.

The parts of the fire booms directly exposed to fire, lasted for only one burn and could not be reused. In a bigger ISB operation, large quantities of booms are required. This implies increased logistic operations and costs.

NOFO and NCA have positive experience in using drones to ignite oil and have verified the use of the Pyrodrone for this purpose.

The amount of BC produced relative to the amount of oil burned were 10-18% from the burns which is in the upper range compared to other studies. The estimated total emission of BC to air from the four experimental ISB performed in 2019 (21.8 tons of oil released, 16.7 tons burned) was 2.4 tons or would have contributed with 0.075% of the total emission of BC to air in Norway in 2016 (latest data available). E.g. during the Macondo spill in 2010, it was estimated that 42000 tons oil was burned, and Perring et al. (2011) estimated that between 600 and 2100 tons BC was released to the atmosphere (4% of the total amount burned).

The major part (> 90% by mass) of the measured particulates was in the fine particle fraction (PM<1), which includes the ultrafine particles (<0.1 µm). If inhaled, the ultrafine particles have harmful effects on the respiratory and cardiovascular system. Particulate PAH is bound to the soot-particles and some are carcinogenic. The high concentrations of PM<1 and particulate PAH are mainly limited to visible smoke and the concentrations decline with increasing distance from the burn site. When performing ISB operations it is crucial to keep personnel away from visible smoke. Personnel located inside, close to or downwind of smoke plumes should use facemask (P3-filters) to avoid inhalation of PM2.5 and smaller particles and particulate PAH. Optimal use of such masks requires education and training of the users as well as proper fit testing. Volatile organic compounds, including benzene, were very low onboard the vessels during OOW 2016, 2018 and 2019. However, previous studies (Gjesteland et al., 2017; 2018) 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 occupational exposure limit during the initial stages of a spill. In such cases, half-face air purifying respirators in combination with particle filter and an organic vapor cartridge A2 should be used to prevent biological uptake of benzene.

The soot fallout was concentrated and mainly limited to visible smoke, and the particle concentrations at sea level were highest under the smoke plume in up to 200 m distance from the burn. The particulate concentrations declined with increasing distance from the burn site and decreased relatively short time after the fire extinguished. However, it has earlier been observed during experimental ISB in e.g. the Barents Sea, that the sea ice close to the burn will be contaminated with soot.

Unlike the particulate matter, the gases emitted during and ISB operation generally do not represent a serious threat to safety and human health, primarily because the concentrations at which they become harmful are much higher than those for the particulate soot. The concentration of gases in the smoke plume may exceed hazard thresholds as they leave the fire, but they decline below these thresholds within very short distance from the fire. The monitoring in the smoke plume indicated low concentrations of SO_2 (<2ppm) and NO_X (<1.5 ppm). The concentrations of CO_2 and CO were below 420 ppm and 4 ppm, respectively, which are well below ambient air quality standards.

The field experiments demonstrated that ISB of weathered, non-emulsified crudes, ULSFO, IF 180 and MGO is applicable in Norwegian waters, however, there are operational and technical restrictions that must be considered prior to burning operations, e.g. should be reflected in contingency plans.

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A Appendix A Overview collected samples

Table A 1 Samples collected during OV 2016 (by SINTEF)

SINTEF ID	Oil	Sample	Sample description
MC-2016-142		Water	HISB3 - 1 m deep 14.06
MC-2016-143		Water	HISB3 - 3 m deep 14.06
MC-2016-148	Grane	ISB residue	HISB 1 Burn residue
MC-2016-149	Grane	ISB residue	HISB 1 Burn residue
MC-2016-150	Grane	ISB residue	HISB 2 (reference) Burn residue
MC-2016-157	Grane	Oil	HISB 2, prior to burn, 14.06 - 15:55
MC-2016-174		Pad on sea	Teflonpad - Blank 14.06 - 13:35
MC-2016-175		Pad on sea	Teflonpad - Smoke fallout 14.06 - 19:20
MC-2016-176		Pad on sea	Teflonpad - Smoke fallout 14.06 - 19:21
MC-2016-177		Pad on sea	Teflonpad - Smoke fallout 14.06 - 19:22

Table A 2 Samples collected during OOW 2018 (by SINTEF). All samples were collected June 13, 2018.

SINTEF ID	Oil	Sample	Sample description
2018-4052	Oseberg 200+	Oil	Received prior to OOW (1 L)
2018-5303	Oseberg 200+	Oil	Sampled during deployment to sea
2018-5303-S1	Oseberg 200+	ISB residue	On sea in boom
2018-5303-S2	Oseberg 200+	ISB residue	Scraped off several of the boom floating parts on deck
2018-5303-S3	Oseberg 200+	ISB residue	Scraped off one of the boom floating parts on deck
2018-5303-S8	Oseberg 200+	ISB residue	From net in container (from NOFO, ca 5 L)
2018-3881	ULSFO	Oil	Received prior to OOW (2 x 20L)
2018-5304	ULSFO	Oil	Sampled during deployment to sea
2018-5304-S1+S2	ULSFO	ISB residue	On sea in boom, "Low-viscosity sample"
2018-5304-S3	ULSFO	ISB residue	On sea, behind the boom
2018-5304-S4	ULSFO	ISB residue	Lumps, on sea in boom
2018-5304-S5	ULSFO	ISB residue	Collected on sea by "Utvær" (200 mL)
2018-5304-S6+S7	ULSFO	ISB residue	Scraped off one of the boom floating elements on deck
2018-5304-S8	ULSFO	ISB residue	Scraped off the boom skirt on deck
2018-5304-S11-S13	ULSFO	ISB residue	Collected on sea by "Utvær" (from KyV, 3 x 1L)
2018-3941	Oseberg 200+	Soot filter #1	Drone 1: Opened 10:26, closed 11:02
2018-3965	Oseberg 200+	Soot filter #25	Drone 2: Start 10:24, end 10:35
2018-3954	Oseberg 200+	Soot filter #14	Drone 2: Start 10:49, end 11:00
2018-3942	ULSFO	Soot filter #2	Drone 1: Opened 18:17, closed 19:01
2018-3955	ULSFO	Soot filter #15	Drone 2: Start 18:16, end 18:27
2018-3956	ULSFO	Soot filter #16	Drone 2: Start 18:38, end 18:49
2018-3943	Background	Soot filter #3	Not opened or exposed (Strilborg)
2018-3964	Background	Soot filter #24	Not opened or exposed (Utvær)
2018-5303-S4	Oseberg 200+	Pad on sea	MOB-S, kl. 10:44:40 (Pos. 59,99105; 2,405413)
2018-5303-S5	Oseberg 200+	Pad on sea	MOB-S, kl. 10:53:20 (Pos. 59,98791; 2,414697)
2018-5303-S6	Oseberg 200+	Pad on sea	MOB-S, kl. 11:07:45 (Pos. 59,98242; 2,443395)
2018-5303-S7	Oseberg 200+	Pad on sea	MOB-S, kl. 11:01:58 (Pos. 59,98465; 2,427298)

SINTEF ID	Oil	Sample	Sample description
2018-5304-S9	ULSFO	Pad on sea	MOB-S, kl. 18:53:40 (Pos. 59,99305; 2,366919)
2018-5304-S10	ULSFO	Pad on sea	MOB-S, kl. 18:58:00 (Pos. 59,98914; 2,361192)

Table A 3 Collected samples during OOW 2019 (by SINTEF)

SINTEF ID	Date	Oils		Location	Sample volume	Comments
2019-5232-S1	June 15	Oseberg	200^{o}C+	During deployment to sea	ca 900 mL	
2019-5233-S1	June 15	IFO180	Fresh	During deployment to sea	ca 900 mL	
2019-5235-S1	June 19	MGO	Fresh	During deployment to sea	ca 900 mL	Tank tidligere brukt til Oseberg
2019-5236-S1	June 19	Oseberg	200+ emulsion	During deployment to sea, sampled after ca 1m^3	ca 800 mL	Water content measured to 53%
2019-5236-S2	June 19	Oseberg	200+ emulsion	During deployment to sea, sampled after ca 3m^3	ca 800 mL	Water content measured to 51%
SINTEF ID	**Date**	**ISB residue**	**Bom used**	**Location**	**Sample volume**	**Comments**
2019-5232-S2	June 15	Oseberg	American FireBoom	Left side in boom	ca. 500 ml	
2019-5232-S3	June 15	Oseberg	American FireBoom	In boom apex	ca. 1000 ml	2 boxes
2019-5232-S4	June 15	Oseberg	American FireBoom	Right side in boom (1/2)	ca. 500 ml	
2019-5232-S5	June 15	Oseberg	American FireBoom	Right side in boom (2/2)	ca. 500 ml	
2019-5232-S6	June 15	Oseberg	American FireBoom	Scraped off boom (1/2)	ca. 500 ml	
2019-5232-S7	June 15	Oseberg	American FireBoom	Scraped off boom (2/2)	ca. 500 ml	
2019-5232-S8	June 15	Oseberg	American FireBoom	Fra nett (1/2)	ca. 500 ml	
2019-5232-S9	June 15	Oseberg	American FireBoom	Fra nett (2/2)	ca. 500 ml	
2019-5233-S2	June 15	IFO180	American FireBoom	Left side in boom	ca. 500 ml	
2019-5233-S3	June 15	IFO180	American FireBoom	In boom apex	ca. 1000 ml	2 boxes
2019-5233-S4	June 15	IFO180	American FireBoom	Right side in boom	ca. 500 ml	
2019-5234-S1	June 19	Oseberg	Desmi PyroBoom	Left side in boom	ca. 500 ml	
2019-5234-S2	June 19	Oseberg	Desmi PyroBoom	In boom apex	ca. 500 ml	
2019-5234-S3	June 19	Oseberg	Desmi PyroBoom	Left side in boom	Ca 1000ml	2 boxes
2019-5235-S2	June 19	MGO	American FireBoom	Left side in boom	Ca 500 ml	
2019-5235-S3	June 19	MGO	American FireBoom	Left side in boom	Ca 1000 ml	
2019-5236-S3	June 18	Oseberg emulsion	i.a.	i.a.	ca. 500 ml	After test burn at the fire dep on shore
2019-5236-S4	June 20	Oseberg emulsion	i.a.	i.a.	ca. 100 ml	Sampled day after dispersion
2019-5236-S5	June 20	Oseberg emulsion	i.a.	i.a.	ca. 300 ml	Sampled day after dispersion

SINTEF ID	Date	Pad samples	Boom used	Location		
2019-5233-S5	June 15	IFO 180	American FireBoom	ca. 1 km downwind boom		
2019-5233-S6	June 15	IFO180	American FireBoom	ca. 1 km		
2019-5233-S7	June 15	IFO180	American FireBoom	ca. 1 km		
2019-5235-S4	June 19	MGO	American FireBoom	In boom		
SINTEF ID	**Date**	**Soot filter**	**Filter no**			**Comments**
2019-5363	June 15	Oseberg 200+	1			ISB1 Drone 1, 3 flights
2019-5391	June 15	Oseberg 200+	2			ISB1 Drone 2, 1 flight
2019-5392	June 15	IFO180	3			ISB2 Drone 1, 1 flight
2019-5477	June 15	IFO180	4			ISB2 Drone 2, 0 flights
2019-5393	June 19	Oseberg 200+	5			ISB3 Drone 1, 2 flights
2019-5394	June 19	Oseberg 200+	6			ISB3 Drone 2, 2 flights
2019-5395	June 19	MGO	7			ISB4 Drone 1, 2 flights
2019-5396	June 19	MGO	8			ISB4 Drone 2, 1 flight (downwind)
2019-5397		Background	11			Not on drone
2019-5398		Background	12			Not on drone
SINTEF ID	**Date**	**"Residue"**	**Boom used**	**Location**	**Sample volume**	**Comments**
2019-5237-S1	June 12	Soya-emulsion 1	i.a.	i.a.	ca.50 ml	Mix of water and emulsion
2019-5237-S2	June 12	Soya-emulsion 2	i.a.	i.a.	ca. 400 ml	Emulsion. Water content measured to 80% (intial 67%)
SINTEF ID	**Date**	**Water sample**	**Boom used**	**Location**	**Sample volume**	**Comments**
2019-5237-S3	June 12	Soya-emulsion	i.a.	Close to soya emulsion slick	ca. 500 ml	
2019-5237-S4	June 12	Soya-emulsion	i.a.	Close to soya emulsion slick	ca. 500 ml	

Table A 4 *Overview analysed samples and analysis. Residue and soot collected during OPV 2016.*

SINTEF ID	Oil	Sample description	GC/FID	GC/MS	Density	Viscosity	Water-content
MC-2016-142		HISB3 - 1 m deep 14.06	x				
MC-2016-143		HISB3 - 3 m deep 14.06	x				
MC-2016-148	Grane	HISB 1 Burn residue	x		x	x	
MC-2016-149	Grane	HISB 1 Burn residue	x		x		
MC-2016-150	Grane	HISB 2 Burn residue	x		x		
MC-2016-157	Grane	HISB2, prior to burn, 14.06 - 15:55	x		x	x	x
MC-2016-174		Teflonpad - Blank 14.06 - 13:35	x				
MC-2016-175		Teflonpad - Smoke fallout 14.06 - 19:20	x				
MC-2016-176		Teflonpad - Smoke fallout 14.06 - 19:21	x				
MC-2016-177		Teflonpad - Smoke fallout 14.06 - 19:22	x				

Table A 5 *Overview analysed samples and analysis. Residue and soot collected during OPV 2018.All samples were collected June 13, 2018.*

SINTEF ID	Oil	Sample description	GC/FID	GC/MS	Density	Viscosity	Water-content
2018-4052	Oseberg	Received prior to OOW	x	x	x	x	
2018-5303-S1	Oseberg	On sea in boom	x	x	x	x	x
2018-5303-S2	Oseberg	Scraped off the boom floating parts	x	x	x	x	
2018-5303-S8	Oseberg	From net in container (from NOFO)	x	x	x	x	
2018-3881	ULSFO	Received prior to OOW	x	x	x	x	
2018-5304-S1	ULSFO	On sea in boom, "Low-viscosity sample"	x	x	x	x	x
2018-5304-S3	ULSFO	On sea, behind the boom	x				
2018-5304-S4	ULSFO	Lumps, on sea in boom	x	x	x	x	
2018-5304-S6	ULSFO	Scraped off the boom floating elements	x	x	x	x	
2018-5304-S8	ULSFO	Scraped off the boom skirt on deck	x				
2018-5304-S11	ULSFO	Collected on sea by "Utvær" (from KyV)	x	x	x	x	
2018-3941	Oseberg	Filter: Drone 1: From 10:26 to 11:02		x			
2018-3942	ULSFO	Filter: Drone 1: From 18:17 to 19:01		x			
2018-3943	Background	Filter: Not opened or exposed (Strilborg)		x			
2018-5303-S4	Oseberg	Pad on sea, MOB-S, kl. 10:44		x			
2018-5303-S5	Oseberg	Pad on sea, MOB-S, kl. 10:53		x			
2018-5303-S6	Oseberg	Pad on sea, MOB-S, kl. 11:07		x			
2018-5303-S7	Oseberg	Pad on sea, MOB-S, kl.11:01		x			
2018-5304-S9	ULSFO	Pad on sea, MOB-S, kl. 18:53		x			
2018-5304-S10	ULSFO	Pad on sea, MOB-S, kl. 18:58		x			

Table A 6 Overview analysed samples and analysis. Residue and soot collected during OPV 2019.

SINTEF ID	Date	Oil samples		Viscosity	Density	GC/FID	GC/MS	Gravimetry
2019-5232-S1	June 15	Oseberg	200 ^{o}C+	x	x	x	x	
2019-5233-S1	June 15	IFO180	fresh	x	x	x	x	
2019-5235-S1	June 19	MGO	fresh	x	x	x	x	
2019-5236-S1	June 19	Oseberg	200 ^{o}C+ emulsion	x	x			
	Date	**ISB residue**	**In boom**					
2019-5232-S2	June 15	Oseberg Fireboom	Left			x		
2019-5232-S3	June 15	Oseberg Fireboom	Middle	x	x	x	x	
2019-5232-S4	June 15	Oseberg Fireboom	Right (1/2)			x		
2019-5233-S2	June 15	IFO180	Left	x	x	x	x	
2019-5233-S3	June 15	IFO180	Middle	x	x	x	x	
2019-5233-S4	June 15	IFO180	Right			x		
2019-5234-S1	June 19	Oseberg Pyroboom	Left			x	x	
2019-5234-S2	June 19	Oseberg Pyroboom	Middle	x	x	x	x	
2019-5234-S3	June 19	Oseberg Pyroboom	Right			x		
2019-5235-S2	June 19	MGO	Left			x		
2019-5235-S3	June 19	MGO	Right	x	x	x	x	
	Date	**Soot filter**	**Filter no**					
2019-5363	June 15	Oseberg 200+	1, ISB1 Drone 1			x	x	x
2019-5391	June 15	Oseberg 200+	2, ISB1 Drone 2			x	x	x
2019-5392	June 15	IFO180	3, ISB2 Drone 1			x	x	x
2019-5477	June 19	Oseberg 200+	5, ISB3 Drone 1			x	x	x
2019-5393	June 19	Oseberg 200+	6, ISB3 Drone 2			x	x	x
2019-5394	June 19	MGO	7, ISB4 Drone 1			x	x	x
2019-5395	June 19	MGO	8, ISB4 Drone 2			x	x	x
2019-5397		Background filter	11, not on drone			x	x	x
2019-5398		Background filter	12, not on drone			x	x	x

B Appendix B GC chromatograms of oils and residues

B.1 Oil on water 2016

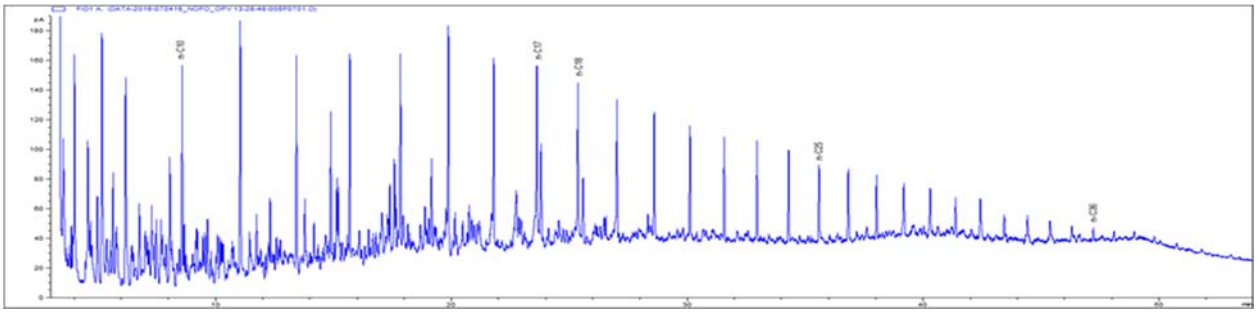

Figure B 1 Grane Blend fresh crude oil (SINTEF ID 2016-84)

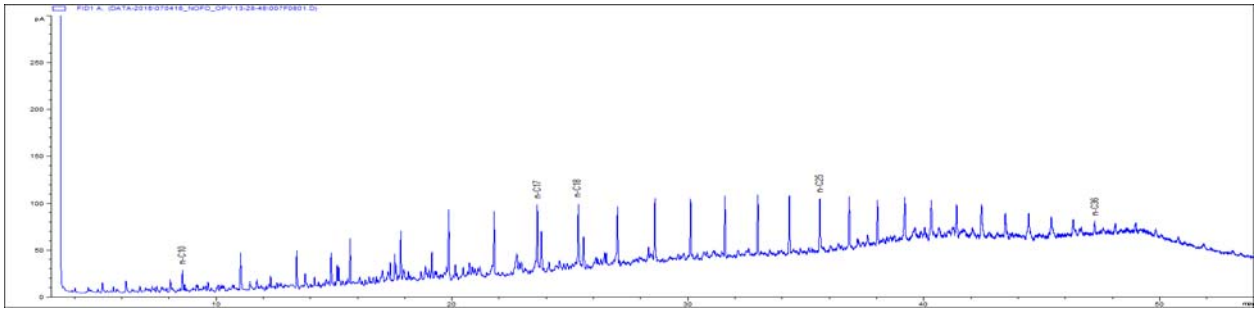

Figure B 2 Grane Blend: ISB residue June 14, 2016: No boom, used herder (HISB 4.1 A, SINTEF ID 2016-148)

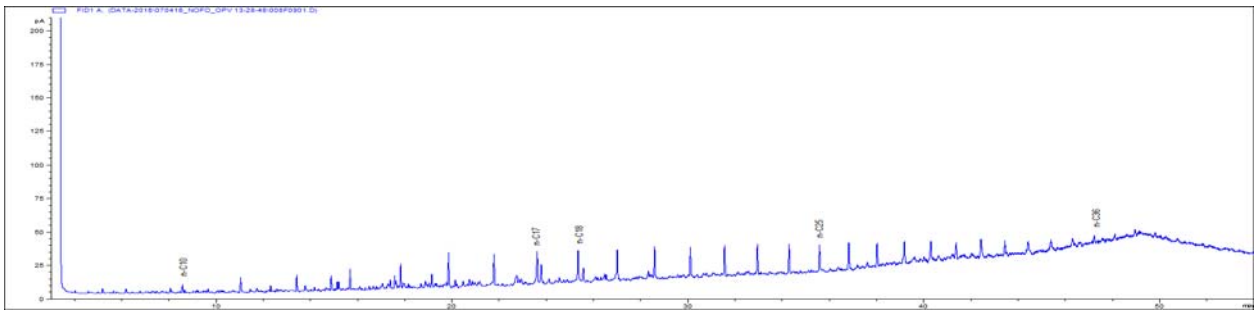

Figure B 3 Grane Blend: ISB residue June 14, 2016: No boom, used herder (HISB 4.1 B, SINTEF ID 2016-149)

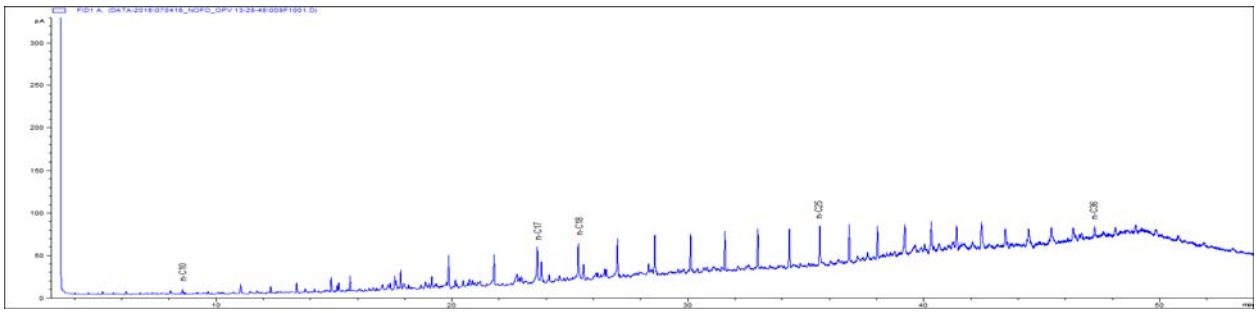

Figure B 4 Grane Blend: ISB residue June 14, 2016: No boom, ignited without herder (HISB 4.2, SINTEF ID 2016-150).

No ISB residue from HISB 4.3 analysed on GC/FID (Grane Blend ignited with herder, no boom).

B.2 Oil on water 2018

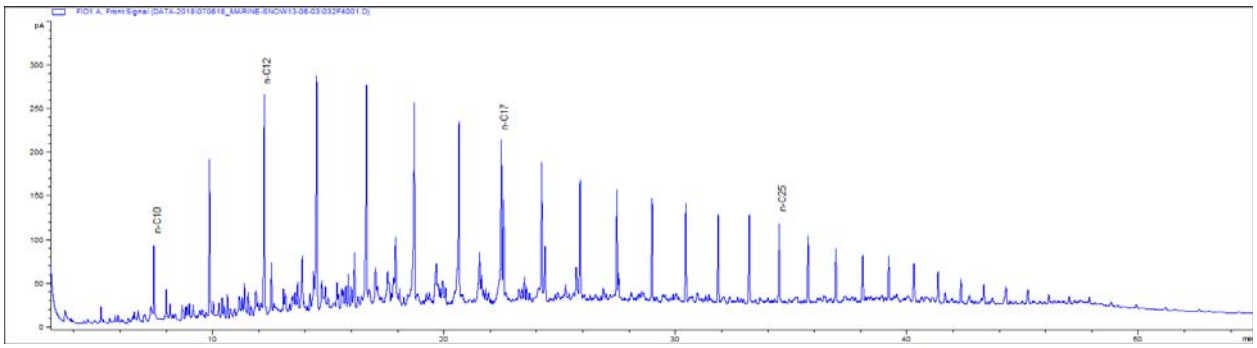

Figure B 5 *Oseberg 200 ^{o}C+, unburned oil, received prior to OOW 2018 (SINTEF ID 2018-4052)*

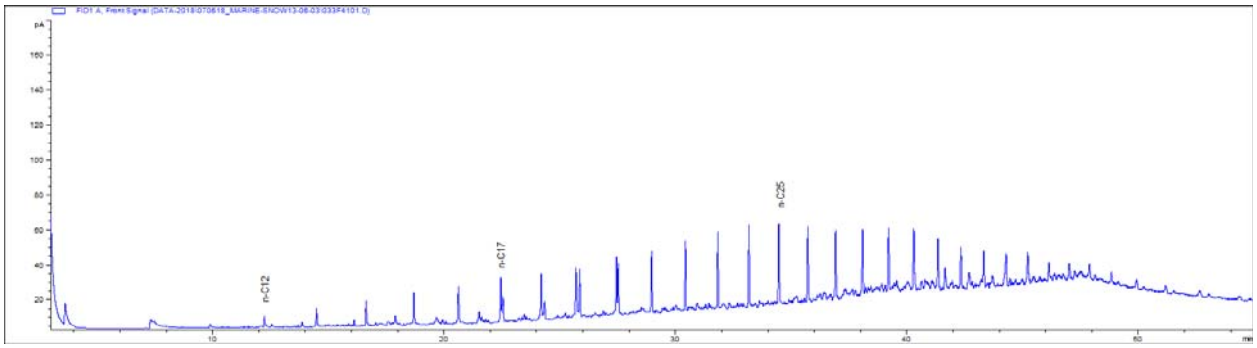

Figure B 6 *Oseberg ISB June 13, 2018: ISB residue sampled in boom on sea (2018-5303-S1)*

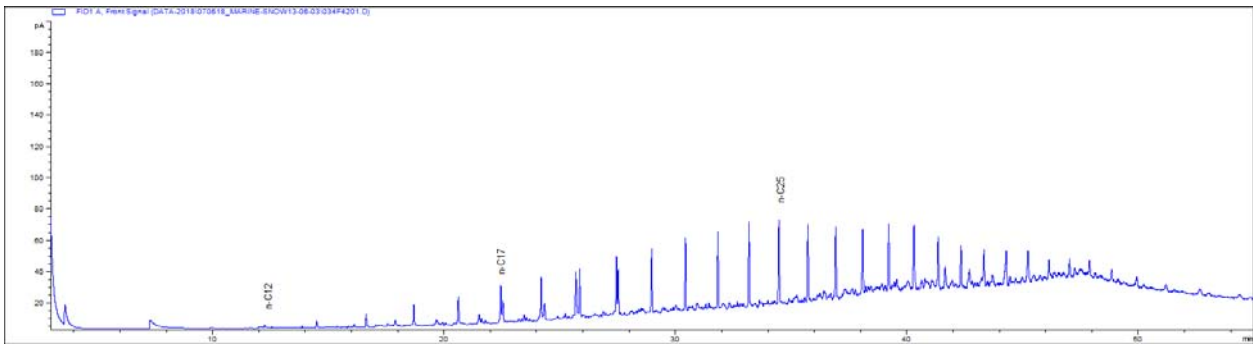

Figure B 7 *Oseberg ISB June 13, 2018: ISB residue scraped off boom on deck (2018-5303-S2)*

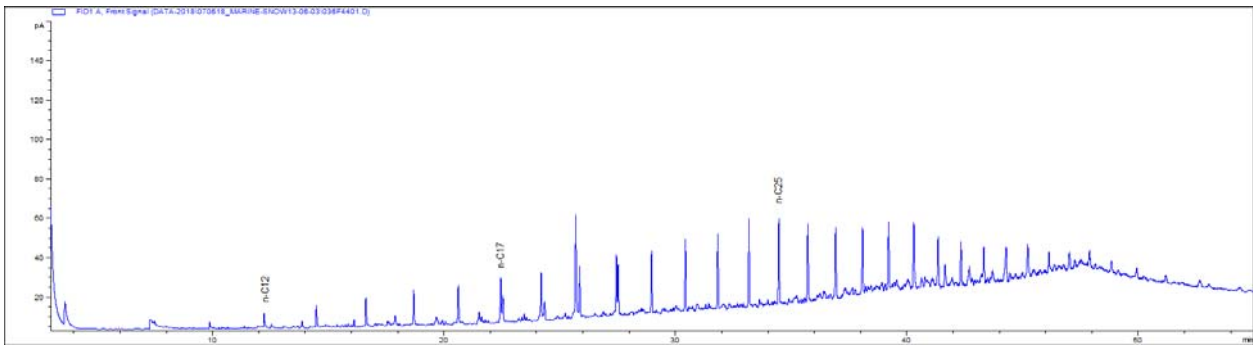

Figure B 8 *Oseberg ISB June 13, 2018: ISB residue from NOFO: Collected from the net after weighed in Stavanger (2018-5303-S8)*

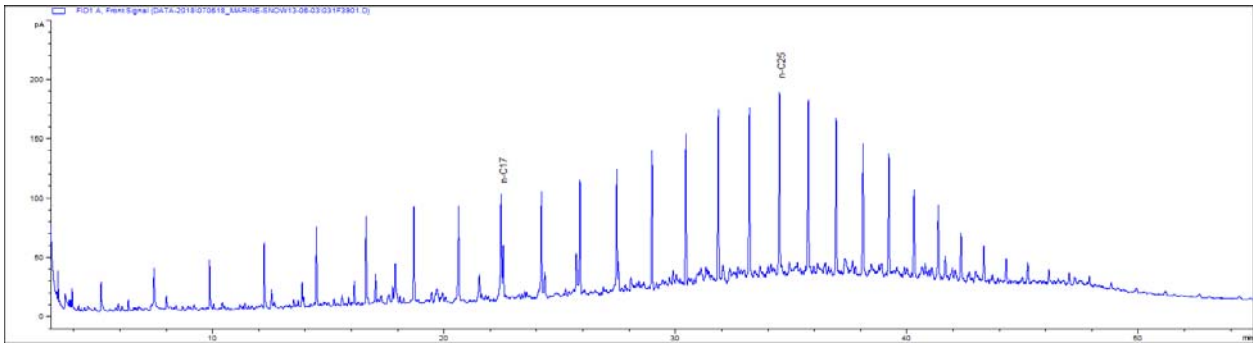

Figure B 9 *ULSFO fresh oil, received from the Norwegian Coastal Administration in April 2018 (2018-3881).*

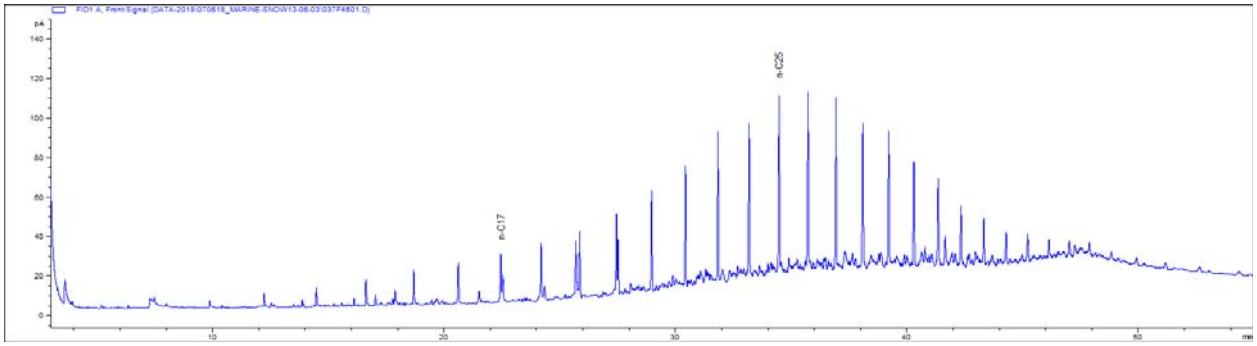

Figure B 10 *ULSFO ISB June 13, 2018: ISB residue ("liquid" sample) collected on sea in boom (2018-5304-S1).*

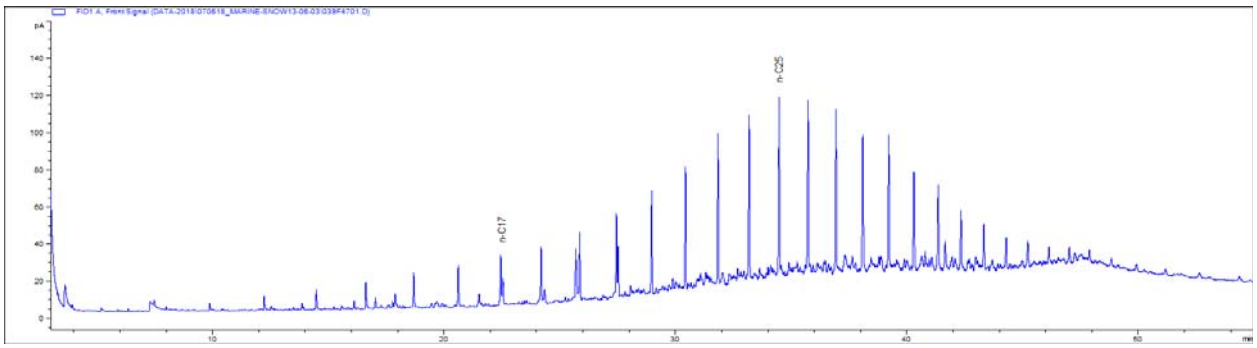

Figure B 11 *ULSFO ISB June 13, 2018: ISB residue (lumps) collected on sea in boom (2018-5304-S3).*

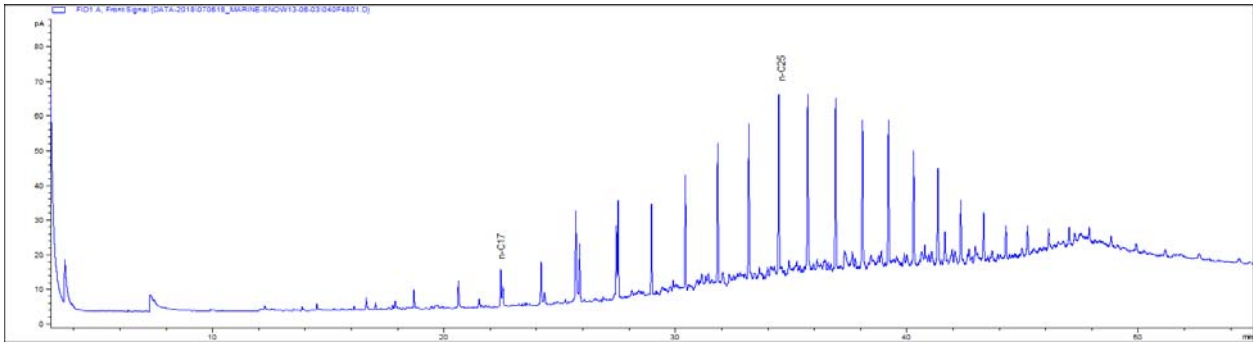

Figure B 12 *ULSFO ISB June 13, 2018: ISB residue (lumps) collected on sea behind the boom (2018-5304-S4).*

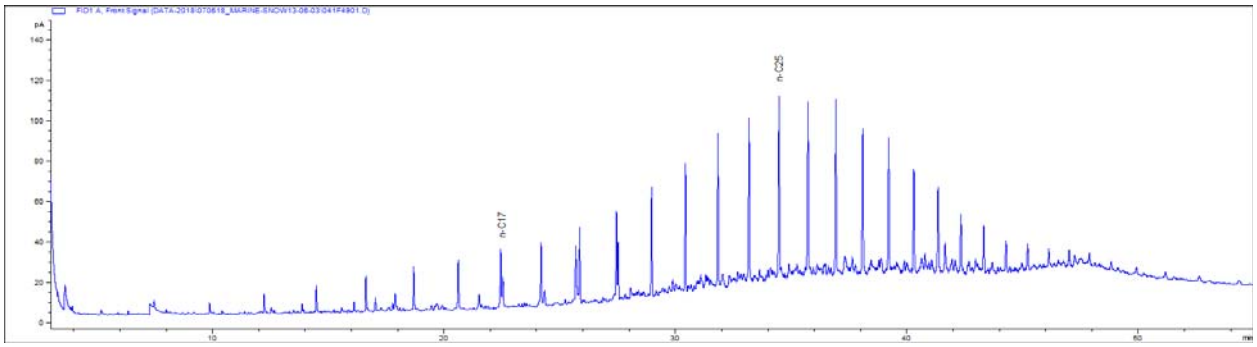

Figure B 13 *ULSFO ISB June 13, 2018: ISB residue scraped off boom on deck (2018-5304-S6).*

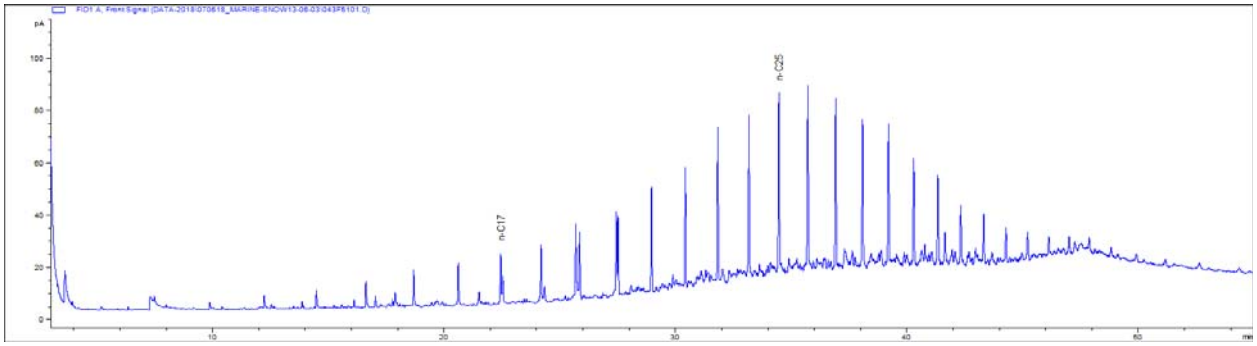

Figure B 14 *ULSFO ISB June 13, 2018: ISB residue scraped off skirt on boom on deck (2018-5304-S8)*

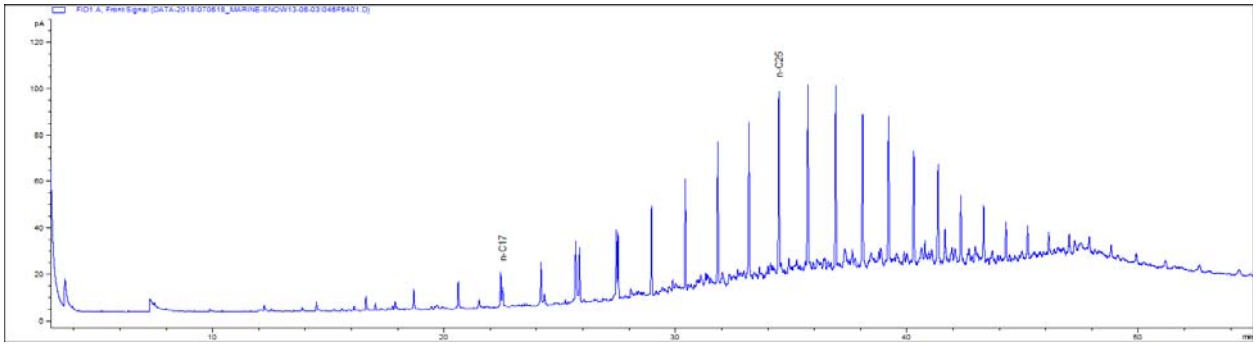

Figure B 15 *ULSFO ISB June 13, 2018: ISB residue collected by "Utvær" (free floating on sea) (from NCA, SINTEF ID 2018-5304-S13)*

B.3 Oil on water 2019

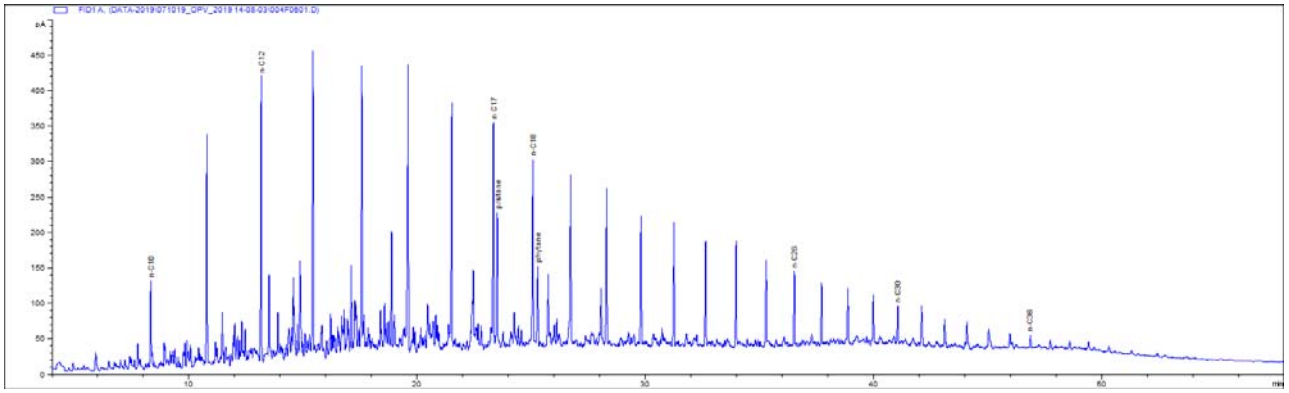

Figure B 16 Oseberg 200 ^{o}C+: Unburned oil sampled during deployment on sea, June 15 (2019-5232-S1)

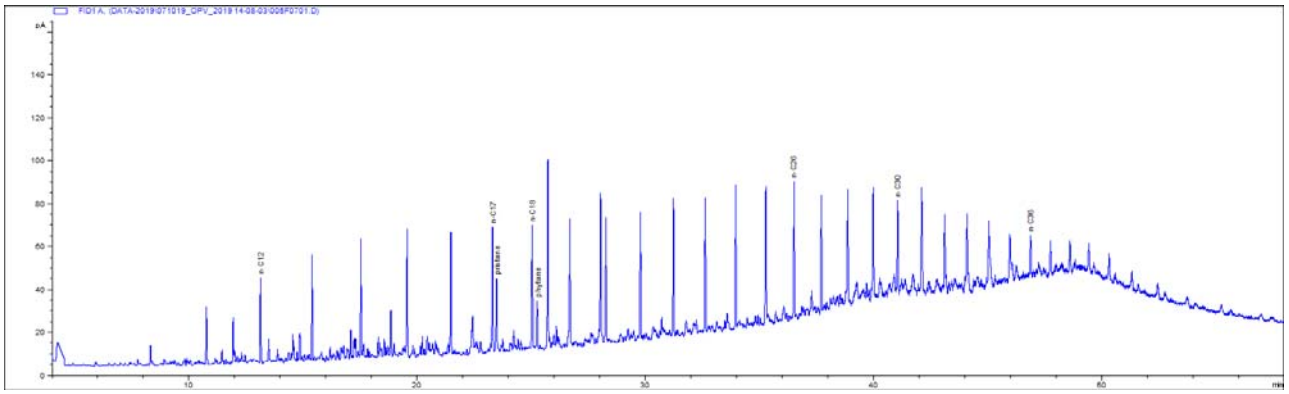

Figure B 17 Oseberg 200 ^{o}C+: ISB residue, June 15 in American Fireboom, left side in boom (2019-5232-S2)

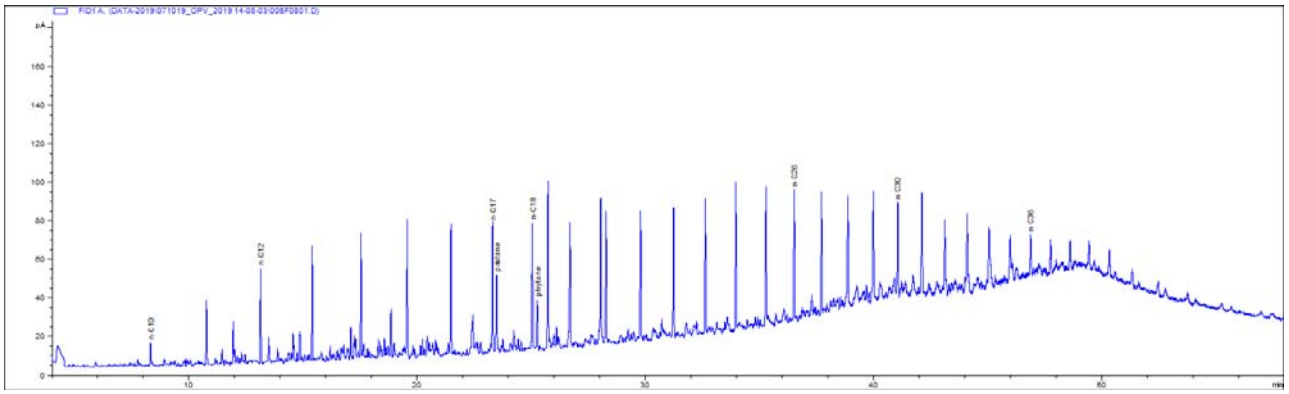

Figure B 18 Oseberg 200 ^{o}C+: ISB residue June 15 in American Fireboom, in boom apex (2019-5232-S3)

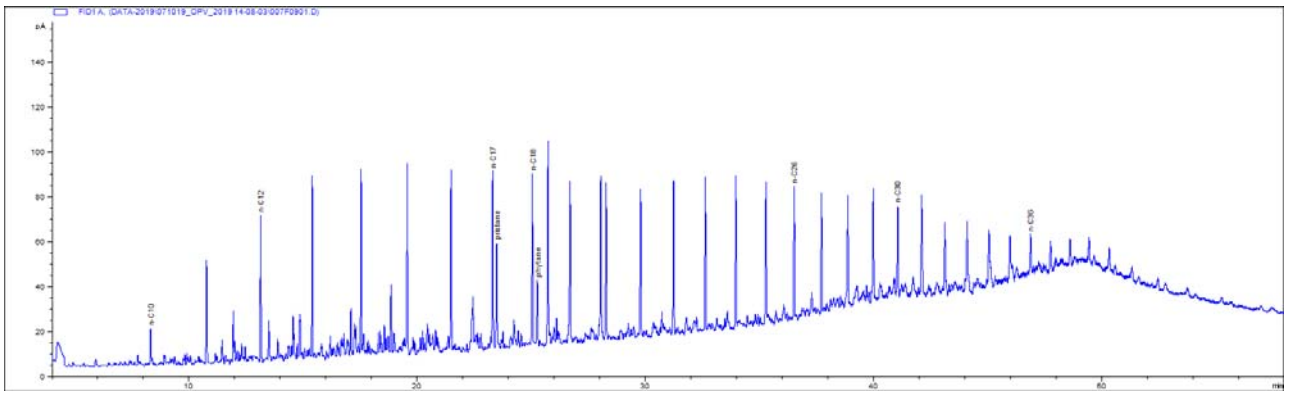

Figure B 19 Oseberg 200 ^{o}C+: ISB residue June 15 in American Fireboom, right side in boom (2019-5232-S4)

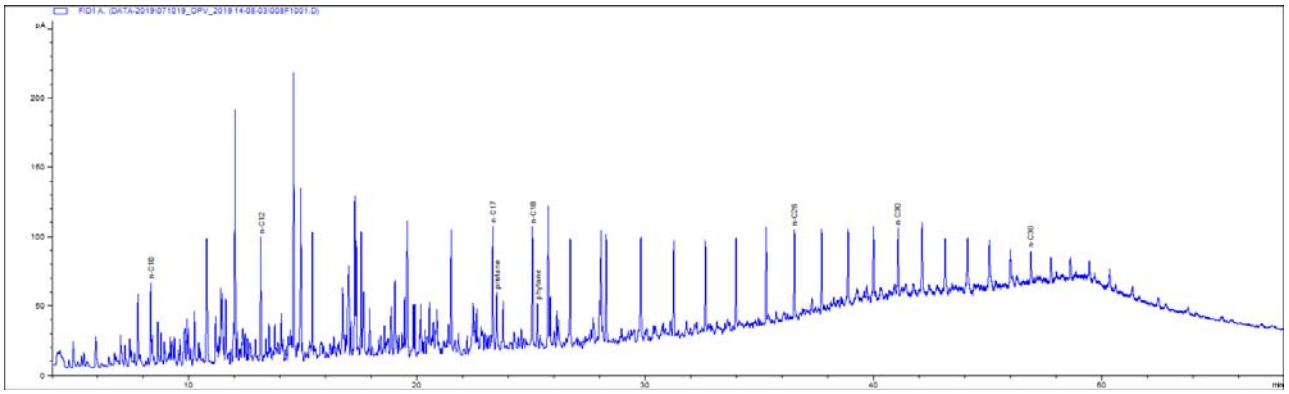

Figure B 20 IFO 180: Fresh oil sampled during deployment on sea, June 15, 2019 (2019-5233-S1)

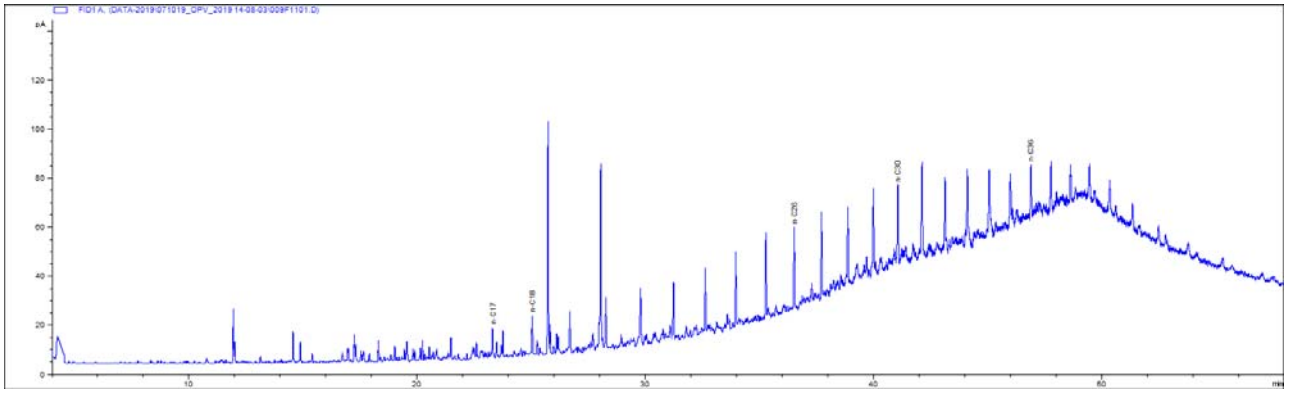

Figure B 21 IFO 180: ISB residue June 15 in American Fireboom, left side in boom (2019-5233-S2)

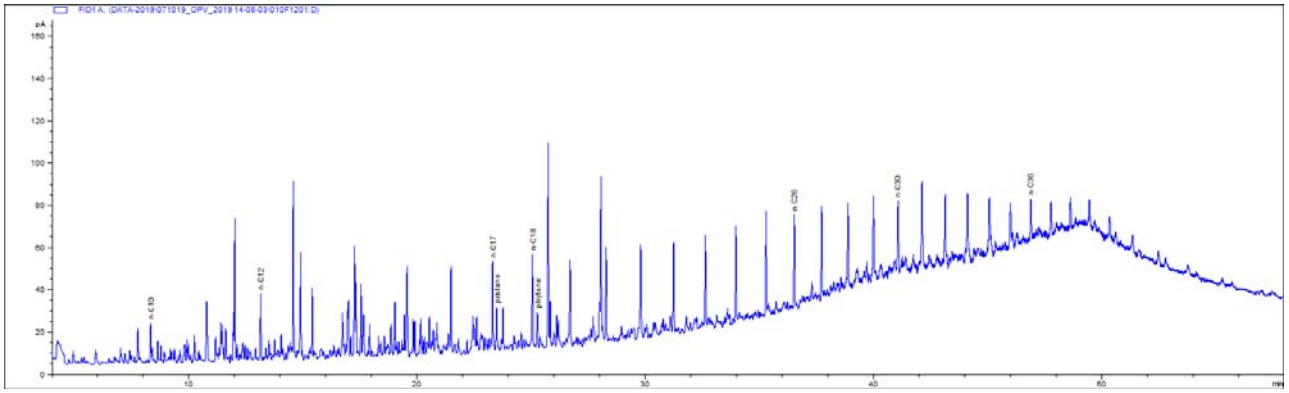

Figure B 22 IFO 180: ISB residue June 15 in American Fireboom, in boom apex (2019-5233-S3)

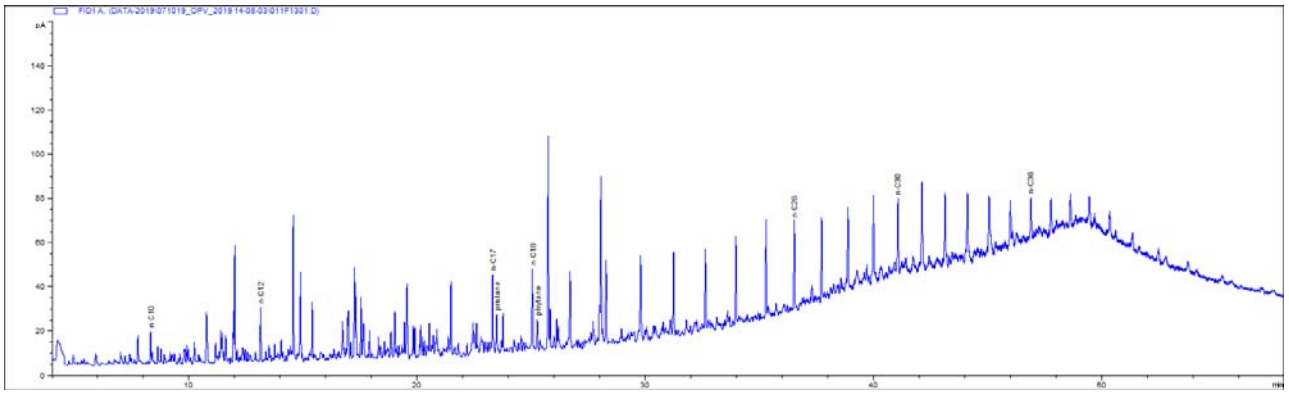

Figure B 23 IFO 180: ISB residue June 15 in American Fireboom, right side in boom (2019-5233-S4)

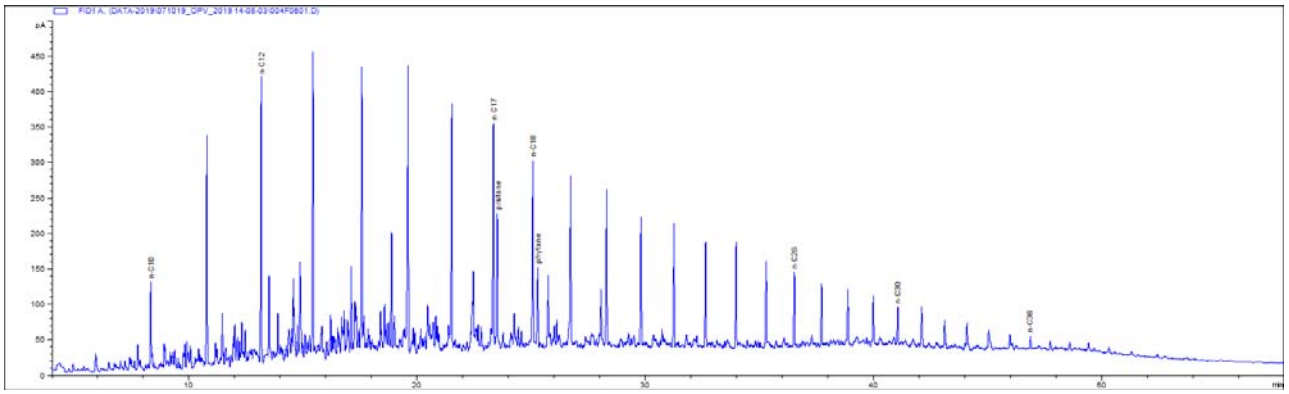

Figure B 24 Oseberg 200 ^{o}C+: Unburned oil sampled during deployment on sea, June 15, 2019 (2019-5232-S1)

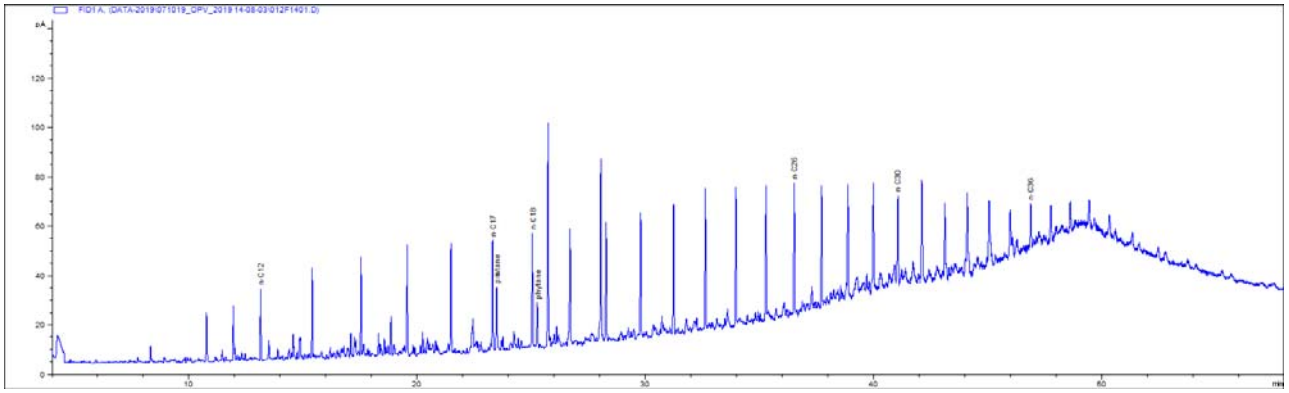

Figure B 25 Oseberg 200 ^{o}C+: ISB residue June 19 in Desmi Pyroboom, left side in boom (2019-5234-S1)

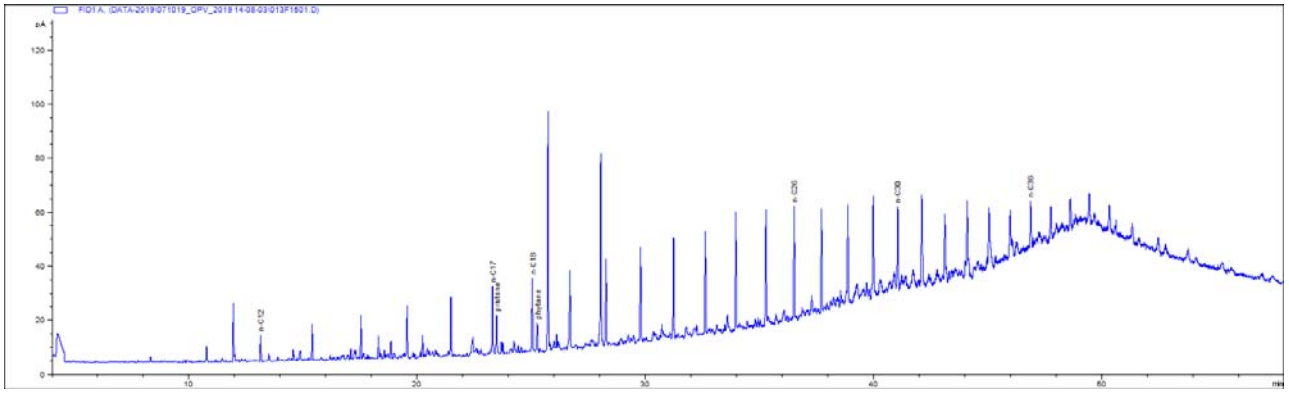

Figure B 26 Oseberg 200 ^{o}C+: ISB residue June 19 in Desmi Pyroboom, in boom apex (2019-5234-S2)

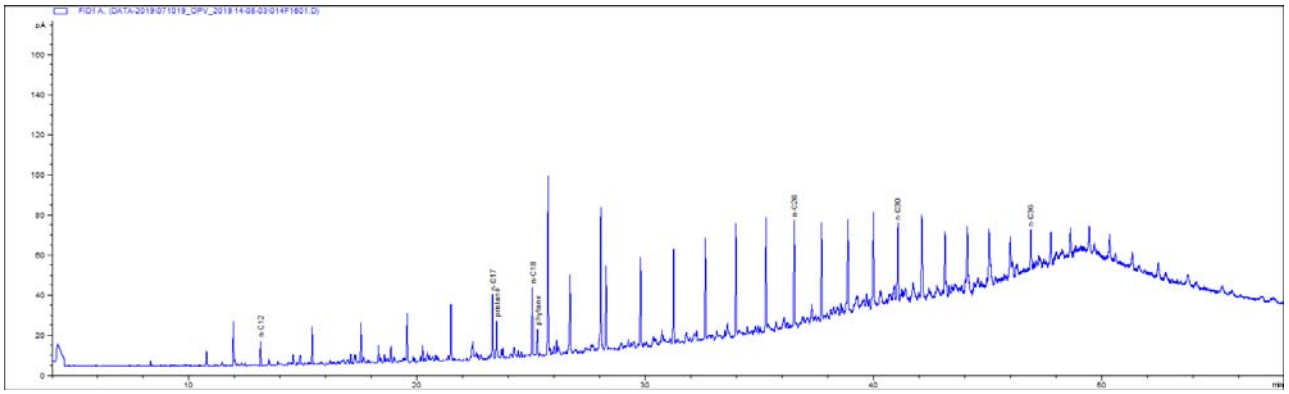

Figure B 27 Oseberg 200 ^{o}C+: ISB residue June 19 in Desmi Pyroboom, right side in boom (2019-5234-S3)

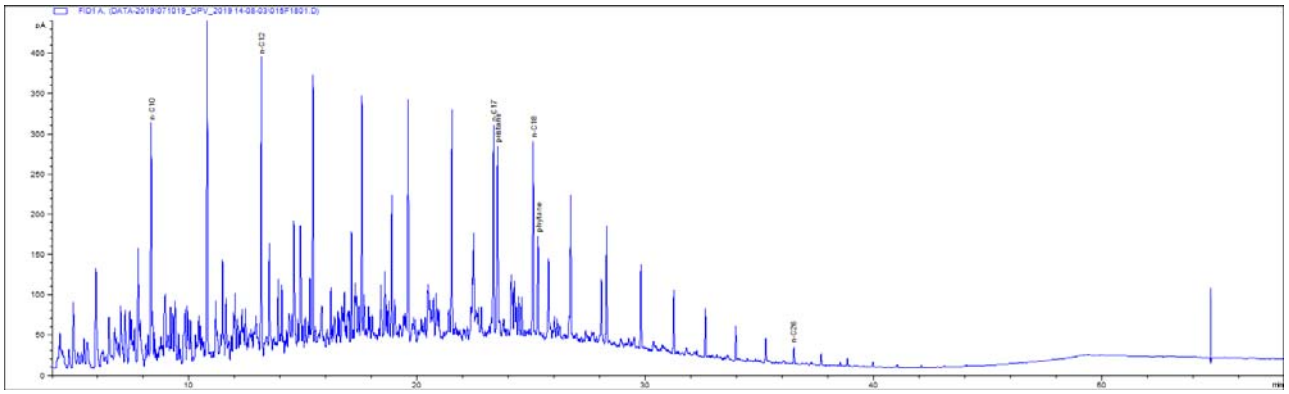

Figure B 28 Marine Gas Oil (MGO): Fresh oil sampled during deployment to sea, June 19, 2019 (2019-5235-S1)

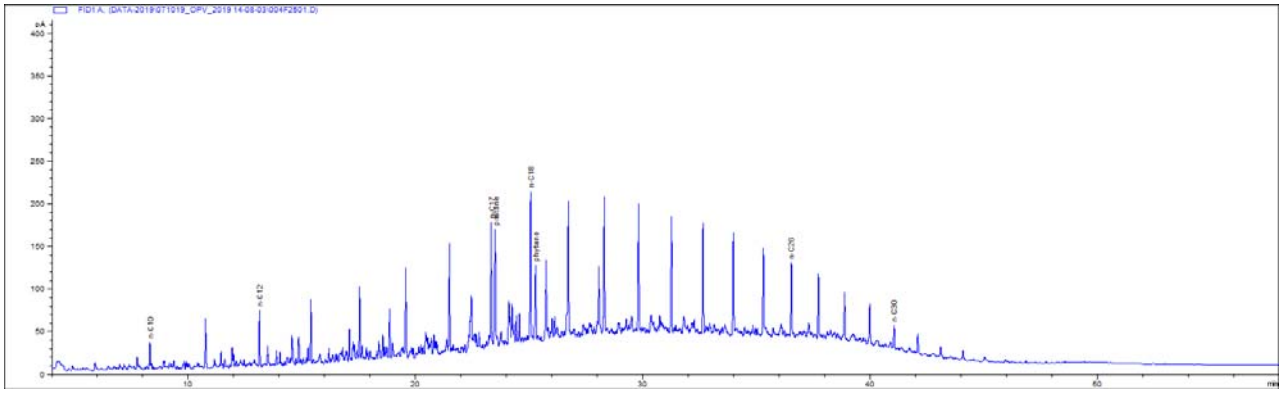

Figure B 29 MGO: ISB residue June 19 in American Fireboom, left side in boom (2019-5235-S2)

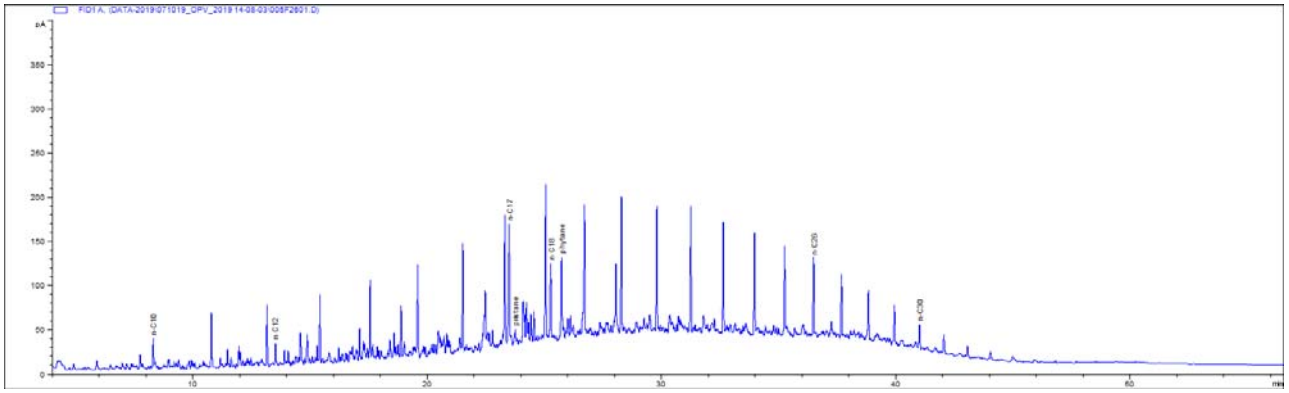

Figure B 30 MGO: ISB residue June 19 in American Fireboom, right side in boom (2019-5235-S3)

C Appendix C Chemical composition of the residues

After OOW 2018 and 2019, all ISB residue samples were analysed for GC screening analysis. In 2018, quantification of SVOC on GC/MS was included for most samples. In 2019, usually one residue sample from each burn was analysed on GC/MS, unless significant differences after GC screening analysis was observed (two samples analysed for Oseberg Pyroboom and IFO180).

From 2018 and 2019, all soot filters were analysed on GC/MS.

Table C 1 *Summary of chemical composition of unburned and burned Grane Blend during Oil on water 2016 (in g/kg/oil). Results from Faksness et al., 2019b.*

SINTEF ID	2016-157	2016-149	2016-150
OOW 2016	Grane fresh	HISB1 OPV 2016	HISB2 OPV 2016
	g/kg	g/kg	g/kg
All SVOC	24,4	3,62	6,05
Decalins	6,62	0,41	0,70
Naphthalenes	11,7	1,16	2,19
2-3 ring PAHs	5,18	1,40	2,34
4-6 ring PAHs	0,87	0,65	0,83
TPH	729	294	368

Table C 2 *Chemical composition of unburned oil and residues from ISB of Oseberg 200^{o}C+ from OOW 2018 (in g analyte/kg oil).*

Test ID	2018-4052-S1	2018-5303-S1	2018-5303-S2	2018-5303-S3	2018-5303-S8
Oseberg 2018	Oseberg 200^{o}C+ (unburned)	On sea in boom	Scraped off boom	Scraped off boom	From net in container
	g/kg	g/kg	g/kg	g/kg	g/kg
Sum SVOC	23,1	3,95	4,08	3,93	3,85
Decalins	5,39	0,29	0,18	0,30	0,33
Naphthalenes	12,6	1,40	1,22	1,39	1,39
2-3 ring PAH	4,30	1,58	1,85	1,57	1,46
4-6 ring PAH	0,77	0,67	0,82	0,67	0,66
TPH	754	390	466	350	347

Table C 3 *Chemical composition of unburned oils and residues from ISB of Oseberg 200°C+ from OOW 2019 (in g analyte/kg oil), both from ISB in American Fireboom and Desmi Pyroboom. Sampling locations in the boom are given.*

Oseberg 2019	2019-5232-S1 Oseberg 200°C+ (unburned)	2019-5232-S3 Fireboom residue apex	2019-5234-S2 Pyroboom residue apex	2019-5234-S1 Pyroboom residue left
	g/kg	g/kg	g/kg	g/kg
Sum SVOC	26,1	5,96	2,65	4,10
Decalins	8,82	1,02	0,23	0,60
Naphthalenes	10,5	1,80	0,57	1,12
2-3 ring PAHs	5,05	2,01	1,11	1,49
4-6 ring PAHs	0,83	0,76	0,52	0,60
TPH	630	401	272	324

Table C 4 *Chemical composition of unburned oil and ISB residue ULSFO from OOW 2018 (in g analyte/kg oil).*

SINTEF ID	2018-3881-S1	2018-5304-S1	2018-5304-S4	2018-5304-S6	2018-5304-S11
ULSFO 2018	ULSFO fresh	On sea in boom	Lumps behind boom on sea	Scraped off boom	Collected on sea of "Utvær"
	g/kg	g/kg	g/kg	g/kg	g/kg
Sum SVOC	19,8	9,99	10,8	11,3	9,69
Decalins	2,34	0,51	0,32	0,74	0,40
Naphthalenes	3,18	0,88	0,76	1,13	0,82
2-3 ring PAH	6,39	3,24	3,53	3,77	3,27
4-6 ring PAH	7,87	5,36	6,20	5,64	5,20
TPH	641	509	246	446	348

Table C 5 *Chemical composition of unburned oil and residue from ISB of IFO 180 and MGO (in g analyte/kg oil) from OOW 2019. Sampling locations in the boom are given.*

IFO and MGO 2019	2019-5233-S1 IFO180 fresh	2019-5233-S2 IFO residue left	2019-5233-S3 IFO residue apex	2019-5235-S1 MGO fresh	2019-5235-S3 MGO residue right
	g/kg	g/kg	g/kg	g/kg	g/kg
Sum SVOC	26,3	6,01	16,6	43,7	16,1
Decalins	1,49	0,06	0,66	20,8	4,49
Naphthalenes	14,0	1,37	7,77	14,8	4,84
2-3 ring PAHs	8,44	3,02	6,08	5,45	5,45
4-6 ring PAHs	1,95	1,41	1,79	0,20	0,77
TPH	456	333	426	888	604

Table C 6 *Estimated amount (in kg) of each component group (Appendix E) in unburned oil (deployed at sea) and in residue from ISB of Oseberg 200°C+ and ULSFO (OOW 2018). The estimates are based on the concentrations given in Table C 2 and Table C 4 and amount residue in Table 3.4. Assume 57% BE for ULSFO.*

OOW 2018	2018-4052 Oseberg 200°C+ kg in release	2018-5303-S8 Oseberg OPV 2018 kg in residue	2018-3881 ULSFO kg in release	2018-5304-S11 ULSFO OPV 2018 kg in residue
Sum SVOC	123	3,9	105	22
Decalins	29	0,3	12	0,9
Naphthalenes	67	1,4	17	1,9
2-3 ring PAHs	23	1,5	34	7,5
4-6 ring PAHs	4,1	0,7	41	12
Amount oil (kg)	5346	1000	5319	2287

Table C 7 *Estimated amount (in kg) of each component group (Appendix E) in unburned oil (deployed at sea) and in residue from ISB of Oseberg 200°C+ from OOW 2019. The estimates are based on the concentrations given in Table C 2 and Table C 3 and amount residue in Table 3.4.*

OOW 2019	Oseberg 200°C+ Fireboom kg in release	Oseb Fireboom residue apex kg in residue	Oseberg 200°C+ Pyroboom kg in release	Oseberg Pyroboom residue apex kg in residue	Oseberg Pyroboom ISB residue left kg in residue
Sum SVOC	141	4,2	131	1,2	1,9
Decalins	48	0,7	44	0,1	0,3
Naphthalenes	57	1,3	53	0,3	0,5
2-3 ring PAHs	27	1,4	25	0,5	0,7
4-6 ring PAHs	4,5	0,5	4,2	0,2	0,3
Amount oil (kg)	5389	697	5030	466	466

Table C 8 *Estimated amount (in kg) of each component group (Appendix E) in unburned oil (deployed at sea) and in residue from ISB of IFO180 and MGO from OOW 2019. The estimates are based on the concentrations given in Table C 5 and amount residue in Table 3.4.*

Sample ID	IFO180 fresh kg in release	IFO residue left kg in residue	IFO residue apex kg in residue	MGO fresh kg in release	MGO residue right kg in residue
Sum SVOC	106	8,7	24	222	4,2
Decalins	6,0	0,1	1,0	106	1,2
Naphthalenes	56	2,0	11	75	1,3
2-3 ring PAHs	34	4,4	8,8	28	1,4
4-6 ring PAHs	7,9	2,0	2,6	1,0	0,2
Amount oil (kg)	4031	1449	1449	5083	260

Table C 9 *SVOC components in unburned oil and residue from ISB of Grane Blend during OOW 2016 (in g analyte/kg oil). Results from Faksness et al. (2019b)*

SINTEF ID	2016-157	2016-149	2016-150
Sample ID	Unburned	HISB1 OPV 2016	HISB2 OPV 2016
	g/kg	g/kg	g/kg
Decalin	0,67	0,02	0,03
C1-decalins	1,03	0,04	0,07
C2-decalins	1,24	0,07	0,11
C3-decalins	1,60	0,11	0,19
C4-decalins	2,08	0,17	0,31
Benzo(b)thiophene	ND	ND	ND
Naphthalene	0,75	0,05	0,09
C1-naphthalenes	2,53	0,20	0,36
C2-naphthalenes	3,67	0,34	0,63
C3-naphthalenes	3,00	0,34	0,66
C4-naphthalenes	1,73	0,22	0,44
Biphenyl	0,20	0,02	0,03
Acenaphthylene	0,03	0,01	0,03
Acenaphthene	0,02	ND	ND
Dibenzofuran	0,03	ND	0,01
Fluorene	0,11	0,02	0,04
C1-fluorenes	0,32	0,05	0,10
C2-fluorenes	0,47	0,10	0,19
C3-fluorenes	0,36	0,09	0,17
Phenanthrene	0,24	0,06	0,11
Anthracene	0,26	0,07	ND
C1-phenanthrenes/anthracenes	0,61	0,16	0,29
C2-phenanthrenes/anthracenes	0,74	0,22	0,38
C3-phenanthrenes/anthracenes	0,50	0,18	0,29
C4-phenanthrenes/anthracenes	0,38	0,16	0,24
Dibenzothiophene	0,07	0,01	0,03
C1-dibenzothiophenes	0,12	0,03	0,05
C2-dibenzothiophenes	0,31	0,09	0,15
C3-dibenzothiophenes	0,25	0,08	0,14
C4-dibenzothiophenes	0,14	0,05	0,08
Fluoranthene	0,01	0,01	0,02
Pyrene	0,02	0,02	0,03
C1-fluoranthenes/pyrenes	0,15	0,07	0,11
C2-fluoranthenes/pyrenes	0,05	0,03	0,05
C3-fluoranthenes/pyrenes	0,21	0,11	0,16
Benz(a)anthracene	0,01	0,01	0,01
Chrysene	0,02	0,01	0,02
C1-chrysenes	0,10	0,07	0,09
C2-chrysenes	0,12	0,09	0,11
C3-chrysenes	0,10	0,08	0,09
C4-chrysenes	0,05	0,05	0,06

SINTEF ID	2016-157	2016-149	2016-150
Sample ID	Unburned	HISB1 OPV 2016	HISB2 OPV 2016
	g/kg	g/kg	g/kg
Benzo(b)fluoranthene	0,01	0,01	0,01
Benzo(k)fluoranthene	ND	ND	ND
Benzo(e)pyrene	0,01	0,01	0,02
Benzo(a)pyrene	ND	0,01	0,01
Perylene	0,01	0,01	0,01
Indeno(1,2,3-c,d)pyrene	ND	0,01	0,01
Dibenz(a,h)anthracene	ND	ND	0,01
Benzo(g,h,i)perylene	ND	0,01	0,01
30 ab hopane	0,18	0,15	0,17
28 TAS (20S-triaromatic steroid)	0,09	0,07	0,08
Sum all compounds	24,4	3,62	6,05
Decalins	6,62	0,41	0,70
Naphthalenes	11,7	1,16	2,19
2-3 ring PAHs	5,18	1,40	2,34
4-6 ring PAHs	0,87	0,65	0,83

Table C 10 *SVOC components in unburned oil and residue from ISB of Oseberg 200°C+ during OOW 2018 (in g analyte/kg oil)*

Oseberg OOW 2018	2018-4052-S1 Oseberg 200°C+ (unburned)	2018-5303-S1 On sea in boom	2018-5303-S2 Scraped off boom	2018-5303-S3 Scraped off boom	2018-5303-S8 From net in container
	g/kg oil	g/kg oil	g/kg oil	g/kg oil	g/kg oil
Decalin	0,40	0,02	0,01	0,01	0,02
C1-decalins	0,89	0,04	0,02	0,03	0,04
C2-decalins	1,14	0,05	0,03	0,05	0,06
C3-decalins	1,71	0,11	0,06	0,10	0,11
C4-decalins	1,26	0,08	0,08	0,10	0,11
Benzo(b)thiophene	ND	ND	ND	ND	ND
Naphthalene	0,77	0,05	0,06	0,05	0,05
C1-naphthalenes	3,08	0,23	0,16	0,22	0,24
C2-naphthalenes	4,02	0,40	0,32	0,39	0,41
C3-naphthalenes	3,14	0,42	0,39	0,42	0,42
C4-naphthalenes	1,63	0,30	0,29	0,30	0,27
Biphenyl	0,27	0,02	0,02	0,02	0,02
Acenaphthylene	0,02	0,02	0,04	0,02	0,02
Acenaphthene	0,02	ND	ND	ND	ND
Dibenzofuran	0,07	0,01	0,01	0,01	0,01
Fluorene	0,13	0,02	0,03	0,03	0,02
C1-fluorenes	0,32	0,07	0,07	0,07	0,07
C2-fluorenes	0,39	0,12	0,13	0,12	0,11
C3-fluorenes	0,31	0,11	0,13	0,11	0,11
Phenanthrene	0,26	0,09	0,11	0,09	0,09

Oseberg OOW 2018	2018-4052-S1 Oseberg 200°C+ (unburned) g/kg oil	2018-5303-S1 On sea in boom g/kg oil	2018-5303-S2 Scraped off boom g/kg oil	2018-5303-S3 Scraped off boom g/kg oil	2018-5303-S8 From net in container g/kg oil
Anthracene	0,01	0,01	0,01	0,01	0,01
C1-phenanthrenes/anthracenes	0,59	0,22	0,25	0,21	0,20
C2-phenanthrenes/anthracenes	0,61	0,27	0,30	0,27	0,25
C3-phenanthrenes/anthracenes	0,42	0,22	0,25	0,23	0,21
C4-phenanthrenes/anthracenes	0,27	0,16	0,21	0,14	0,15
Dibenzothiophene	0,05	0,01	0,02	0,01	0,01
C1-dibenzothiophenes	0,15	0,05	0,05	0,05	ND
C2-dibenzothiophenes	0,19	0,08	0,09	0,08	0,07
C3-dibenzothiophenes	0,14	0,07	0,08	0,07	0,06
C4-dibenzothiophenes	0,08	0,04	0,05	0,04	0,04
Fluoranthene	0,01	0,02	0,02	0,02	0,02
Pyrene	0,02	0,02	0,03	0,02	0,02
C1-fluoranthrenes/pyrenes	0,12	0,08	0,10	0,09	0,08
C2-fluoranthenes/pyrenes	0,16	0,11	0,13	0,11	0,10
C3-fluoranthenes/pyrenes	0,15	0,11	0,13	0,10	0,11
Benz(a)anthracene	0,01	0,01	0,01	0,01	0,01
Chrysene	0,02	0,02	0,02	0,02	0,02
C1-chrysenes	0,07	0,06	0,07	0,06	0,06
C2-chrysenes	0,08	0,08	0,10	0,09	0,08
C3-chrysenes	0,06	0,06	0,07	0,06	0,06
C4-chrysenes	0,04	0,04	0,04	0,04	0,04
Benzo(b)fluoranthene	0,01	0,01	0,01	0,01	0,01
Benzo(k)fluoranthene	ND	ND	ND	ND	ND
Benzo(e)pyrene	0,01	0,02	0,02	0,02	0,02
Benzo(a)pyrene	ND	0,01	0,02	0,01	0,01
Perylene	ND	ND	ND	ND	ND
Indeno(1,2,3-c,d)pyrene	ND	0,01	0,01	0,01	0,01
Dibenz(a,h)anthracene	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene	ND	0,01	0,02	0,01	0,01
Sum alle	23,1	3,95	4,08	3,93	3,85
Decalins	5,39	0,29	0,18	0,30	0,33
Naphthalenes	12,6	1,40	1,22	1,39	1,39
2-3 ring PAH	4,30	1,58	1,85	1,57	1,46
4-6 ring PAH	0,77	0,67	0,82	0,67	0,66

ND: Not detected

Table C 11 SVOC components in unburned oil and residue from ISB of Oseberg 200°C+ during OOW 2019 (in g analyte/kg oil)

Oseberg OOW 2019	2019-5232-S1 Oseberg 200°C+ (unburned)	2019-5232-S3 Fireboom residue apex	2019-5234-S1 Pyroboom residue left	2019-5234-S2 Pyroboom residue apex
	g/kg	g/kg	g/kg	g/kg
Decalin	0,72	0,07	0,04	0,01
C1-decalins	1,70	0,18	0,10	0,03
C2-decalins	2,11	0,24	0,14	0,05
C3-decalins	2,53	0,32	0,19	0,07
C4-decalins	1,76	0,22	0,14	0,06
Benzo(b)thiophene	ND	ND	ND	ND
Naphthalene	1,01	0,13	0,08	0,04
C1-naphthalenes	2,89	0,40	0,24	0,10
C2-naphthalenes	2,85	0,49	0,30	0,14
C3-naphthalenes	2,32	0,46	0,29	0,16
C4-naphthalenes	1,44	0,32	0,20	0,12
Biphenyl	0,27	0,04	0,03	0,01
Acenaphthylene	0,02	0,02	0,01	0,01
Acenaphthene	0,02	ND	ND	ND
Dibenzofuran	0,06	0,01	0,01	ND
Fluorene	0,13	0,03	0,02	0,01
C1-fluorenes	0,32	0,08	0,06	0,04
C2-fluorenes	0,45	0,15	0,10	0,07
C3-fluorenes	0,40	0,15	0,11	0,08
Phenanthrene	0,27	0,10	0,07	0,05
Anthracene	0,02	0,01	0,01	0,01
C1-phenanthrenes/anthracenes	0,67	0,26	0,19	0,14
C2-phenanthrenes/anthracenes	0,78	0,35	0,26	0,20
C3-phenanthrenes/anthracenes	0,56	0,29	0,22	0,17
C4-phenanthrenes/anthracenes	0,39	0,21	0,17	0,14
Dibenzothiophene	0,05	0,02	0,01	0,01
C1-dibenzothiophenes	0,10	0,04	0,03	0,02
C2-dibenzothiophenes	0,23	0,09	0,07	0,05
C3-dibenzothiophenes	0,19	0,09	0,07	0,05
C4-dibenzothiophenes	0,11	0,06	0,04	0,04
Fluoranthene	0,01	0,01	0,01	0,01
Pyrene	0,02	0,02	0,02	0,01
C1-fluoranthrenes/pyrenes	0,14	0,09	0,07	0,06
C2-fluoranthenes/pyrenes	0,04	0,03	0,03	0,02
C3-fluoranthenes/pyrenes	0,16	0,13	0,09	0,08
Benz(a)anthracene	0,02	0,02	0,01	0,01
Chrysene	0,02	0,02	0,02	0,02
C1-chrysenes	0,10	0,09	0,07	0,06
C2-chrysenes	0,12	0,11	0,09	0,08
C3-chrysenes	0,09	0,09	0,07	0,06
C4-chrysenes	0,07	0,07	0,05	0,05

Oseberg OOW 2019	2019-5232-S1 Oseberg 200°C+ (unburned)	2019-5232-S3 Fireboom residue apex	2019-5234-S1 Pyroboom residue left	2019-5234-S2 Pyroboom residue apex
	g/kg	g/kg	g/kg	g/kg
Benzo(b)fluoranthene	0,01	0,01	0,01	0,01
Benzo(k)fluoranthene	ND	ND	ND	ND
Benzo(e)pyrene	0,01	0,01	0,01	0,01
Benzo(a)pyrene	0,01	0,01	0,01	0,01
Perylene	ND	ND	ND	ND
Indeno(1,2,3-c,d)pyrene	ND	0,01	0,01	0,01
Dibenz(a,h)anthracene	ND	ND	ND	ND
Benzo(g,h,i)perylene	ND	0,01	0,01	0,01
30 ab hopane	0,22	0,26	0,22	0,18
Sum SVOC	26,1	5,96	4,10	2,65
Decalins	8,82	1,02	0,60	0,23
Naphthalenes	10,5	1,80	1,12	0,57
2-3 ring PAHs	5,05	2,01	1,49	1,11
4-6 ring PAHs	0,83	0,76	0,60	0,52

Table C 12 *SVOC components in unburned oil and residue from ISB of ULSFO during OOW 2018 (in g analyte/kg oil)*

Oseberg OOW 2018	2018-3881-S1 ULSFO fresh	2018-5304-S1 On sea in boom	2018-5304-S4 Lumps behind boom on sea	2018-5304-S6 Scraped off boom	2018-5304-S11 Collected on sea of "Utvær"
	g/kg oil	g/kg oil	g/kg oil	g/kg oil	g/kg oil
Decalin	0,10	0,02	0,01	0,02	0,01
C1-decalins	0,26	0,04	0,03	0,06	0,04
C2-decalins	0,40	0,07	0,04	0,11	0,07
C3-decalins	0,74	0,19	0,11	0,29	0,13
C4-decalins	0,84	0,19	0,13	0,26	0,16
Benzo(b)thiophene	ND	ND	ND	ND	ND
Naphthalene	0,05	0,02	0,02	0,02	0,02
C1-naphthalenes	0,30	0,07	0,05	0,09	0,06
C2-naphthalenes	0,81	0,20	0,16	0,27	0,18
C3-naphthalenes	1,19	0,34	0,29	0,43	0,31
C4-naphthalenes	0,83	0,25	0,25	0,32	0,25
Biphenyl	0,01	ND	ND	ND	ND
Acenaphthylene	ND	0,01	0,01	0,01	0,01
Acenaphthene	0,01	ND	ND	ND	ND
Dibenzofuran	ND	ND	ND	ND	ND
Fluorene	0,03	0,01	0,01	0,01	0,01
C1-fluorenes	0,11	0,04	0,04	0,04	0,03
C2-fluorenes	0,28	0,12	0,11	0,13	0,11
C3-fluorenes	0,30	0,15	0,16	0,17	0,15
Phenanthrene	0,11	0,05	0,05	0,06	0,05

Oseberg OOW 2018	2018-3881-S1 ULSFO fresh g/kg oil	2018-5304-S1 On sea in boom g/kg oil	2018-5304-S4 Lumps behind boom on sea g/kg oil	2018-5304-S6 Scraped off boom g/kg oil	2018-5304-S11 Collected on sea of "Utvær" g/kg oil
Anthracene	0,01	0,01	0,01	0,01	0,01
C1-phenanthrenes/anthracenes	0,52	0,23	0,25	0,28	0,24
C2-phenanthrenes/anthracenes	1,49	0,75	0,77	0,84	0,72
C3-phenanthrenes/anthracenes	1,95	1,04	1,15	1,20	1,04
C4-phenanthrenes/anthracenes	1,25	0,68	0,79	0,83	0,74
Dibenzothiophene	ND	ND	ND	ND	ND
C1-dibenzothiophenes	0,05	0,02	0,02	0,03	0,02
C2-dibenzothiophenes	0,08	0,04	0,04	0,04	0,04
C3-dibenzothiophenes	0,10	0,06	0,06	0,06	0,05
C4-dibenzothiophenes	0,07	0,04	0,05	0,05	0,04
Fluoranthene	0,04	0,02	0,03	0,03	0,03
Pyrene	0,24	0,13	0,16	0,15	0,14
C1-fluoranthrenes/pyrenes	0,96	0,53	0,66	0,62	0,57
C2-fluoranthenes/pyrenes	1,45	0,92	0,99	0,96	0,87
C3-fluoranthenes/pyrenes	1,24	0,85	0,89	0,72	0,76
Benz(a)anthracene	0,14	0,10	0,12	0,11	0,10
Chrysene	0,19	0,13	0,15	0,14	0,13
C1-chrysenes	0,98	0,67	0,80	0,73	0,63
C2-chrysenes	1,14	0,90	1,15	1,00	0,88
C3-chrysenes	0,86	0,60	0,71	0,64	0,58
C4-chrysenes	0,36	0,26	0,29	0,27	0,26
Benzo(b)fluoranthene	0,04	0,03	0,04	0,04	0,03
Benzo(k)fluoranthene	ND	ND	ND	ND	ND
Benzo(e)pyrene	0,10	0,08	0,10	0,09	0,09
Benzo(a)pyrene	0,06	0,05	0,06	0,06	0,05
Perylene	0,03	0,02	0,03	0,02	0,02
Indeno(1,2,3-c,d)pyrene	ND	ND	ND	ND	ND
Dibenz(a,h)anthracene	ND	0,02	ND	ND	ND
Benzo(g,h,i)perylene	0,05	0,05	0,06	0,05	0,05
Sum alle	19,8	9,99	10,8	11,3	9,69
Decalins	2,34	0,51	0,32	0,74	0,40
Naphthalenes	3,18	0,88	0,76	1,13	0,82
2-3 ring PAH	6,39	3,24	3,53	3,77	3,27
4-6 ring PAH	7,87	5,36	6,20	5,64	5,20

ND: Not detected

Table C 13 *SVOC components in unburned oil and residue from ISB of IFO180 and MGO during OOW 2019 (in g analyte/kg oil).*

OOW 2019	2019-5233-S1 IFO180 fresh	2019-5233-S2 IFO residue left	2019-5233-S3 IFO 180 residue apex	2019-5235-S1 MGO fresh	2019-5235-S3 MGO residue right
	g/kg	g/kg	g/kg	g/kg	g/kg
Decalin	0,17	ND	0,06	3,03	0,37
C1-decalins	0,30	0,01	0,12	5,17	0,78
C2-decalins	0,35	0,01	0,15	5,20	1,03
C3-decalins	0,41	0,02	0,18	4,76	1,25
C4-decalins	0,27	0,02	0,14	2,64	1,07
Benzo(b)thiophene	ND	ND	ND	ND	ND
Naphthalene	1,75	0,12	1,20	1,80	0,41
C1-naphthalenes	3,23	0,24	1,88	3,91	1,14
C2-naphthalenes	4,15	0,36	2,07	4,46	1,25
C3-naphthalenes	3,22	0,39	1,71	2,94	1,14
C4-naphthalenes	1,64	0,25	0,91	1,69	0,89
Biphenyl	0,13	0,01	0,06	0,67	0,15
Acenaphthylene	0,05	0,01	0,04	0,01	0,06
Acenaphthene	0,11	0,01	0,06	0,03	0,01
Dibenzofuran	0,04	0,01	0,02	0,10	0,03
Fluorene	0,16	0,03	0,10	0,27	0,13
C1-fluorenes	0,38	0,08	0,24	0,60	0,36
C2-fluorenes	0,63	0,17	0,41	0,77	0,65
C3-fluorenes	0,57	0,18	0,40	0,57	0,67
Phenanthrene	0,47	0,15	0,32	0,30	0,25
Anthracene	0,06	0,03	0,05	0,02	0,03
C1-phenanthrenes/anthracenes	1,30	0,47	0,92	0,63	0,65
C2-phenanthrenes/anthracenes	1,61	0,64	1,19	0,57	0,81
C3-phenanthrenes/anthracenes	1,11	0,47	0,86	0,30	0,61
C4-phenanthrenes/anthracenes	0,62	0,28	0,51	0,20	0,48
Dibenzothiophene	0,07	0,02	0,05	0,04	0,02
C1-dibenzothiophenes	0,17	0,05	0,12	0,10	0,06
C2-dibenzothiophenes	0,38	0,14	0,28	0,14	0,17
C3-dibenzothiophenes	0,37	0,16	0,29	0,10	0,16
C4-dibenzothiophenes	0,21	0,10	0,17	0,04	0,12
Fluoranthene	0,02	0,02	0,02	0,01	0,03
Pyrene	0,09	0,06	0,07	0,02	0,05
C1-fluoranthrenes/pyrenes	0,32	0,20	0,27	0,07	0,16
C2-fluoranthenes/pyrenes	0,08	0,05	0,07	0,02	0,05
C3-fluoranthenes/pyrenes	0,34	0,21	0,30	0,03	0,14
Benz(a)anthracene	0,04	0,04	0,04	ND	0,02
Chrysene	0,05	0,05	0,05	0,01	0,03
C1-chrysenes	0,25	0,19	0,23	0,02	0,07
C2-chrysenes	0,30	0,22	0,28	0,01	0,07
C3-chrysenes	0,23	0,16	0,22	0,01	0,05
C4-chrysenes	0,17	0,11	0,15	ND	0,04

OOW 2019	2019-5233-S1 IFO180 fresh g/kg	2019-5233-S2 IFO residue left g/kg	2019-5233-S3 IFO 180 residue apex g/kg	2019-5235-S1 MGO fresh g/kg	2019-5235-S3 MGO residue right g/kg
Benzo(b)fluoranthene	0,01	0,01	0,01	ND	0,01
Benzo(k)fluoranthene	ND	ND	ND	ND	ND
Benzo(e)pyrene	0,02	0,02	0,02	ND	0,01
Benzo(a)pyrene	0,01	0,02	0,01	ND	0,02
Perylene	0,01	0,01	0,01	ND	ND
Indeno(1,2,3-c,d)pyrene	ND	0,01	ND	ND	0,01
Dibenz(a,h)anthracene	ND	0,01	0,01	ND	ND
Benzo(g,h,i)perylene	0,01	0,01	0,01	ND	0,01
30 ab hopane	0,17	0,13	0,16	0,01	0,08
Sum SVOC	26,3	6,01	16,6	43,7	16,1
Decalins	1,49	0,06	0,66	20,8	4,49
Naphthalenes	14,0	1,37	7,77	14,8	4,84
2-3 ring PAHs	8,44	3,02	6,08	5,45	5,45
4-6 ring PAHs	1,95	1,41	1,79	0,20	0,77

D Appendix D Chemical composition of the soot

No soot filters were collected by SINTEF in 2016. From 2018 and 2019, all soot filters were analysed on GC/MS.

Table D 1 *Chemical composition of soot from filters sampled in the smoke plume during ISB from drones during OOW 2018. Results are gives in g analyte/kg soot. Amount soot is from gravimetric measurements. No soot particles were sampled from drone 2 (possible that the pump was not turned on).*

OOW 2018	2018-3941 Filter Oseberg drone 1 g/kg	2018-3942 Filter ULSFO drone 1 g/kg	2018-3943 Filter background g/kg
Sum SVOC	2,95	1,48	0,02
Decalins	ND	ND	ND
Naphthalenes	0,16	0,06	0,01
2-3 ring PAH	0,61	0,35	0,01
4-6 ring PAH	2,18	1,06	ND
Amount soot (mg)	0,13	0,32	ND

Table D 2 *Chemical composition of soot from filters sampled in the smoke plume during ISB from drones during OOW 2019. Results are gives in g analyte/kg soot. Amount soot is from gravimetric measurements. Results are corrected for background (average of two filters). Low amount of soot on sample 2019-5396 results in too high concentrations (Sample not included in Figure 3.12).*

SINTEF ID	2019-5363	2019-5391	2019-5393	2019-5394	2019-5392	2019-5395	2019-5396
Filter no.	1	2	5	6	3	7	9
	Drone 1 Oseberg Fireboom g/kg	Drone 2 Oseberg Fireboom g/kg	Drone 1 Oseberg Pyroboom g/kg	Drone 2 Oseberg Pyroboom g/kg	Drone 1 IFO 180 g/kg	Drone 1 MGO g/kg	Drone 2 MGO g/kg
Sum SVOC	0,929	0,344	0,810	0,939	1,273	0,847	10,4
Decalins	0,143	0,123	0,269	0,340	0,405	0,284	4,50
Naphthalenes	0,163	0,142	0,280	0,366	0,429	0,302	4,99
2-3 ring PAHs	0,105	0,023	0,090	0,060	0,114	0,088	0,503
4-6 ring PAHs	0,518	0,057	0,172	0,173	0,324	0,173	0,448
Amount soot (mg)	0,19	0,36	0,24	0,14	0,11	0,18	0,01

Table D 3 *Sampling on sea surface of possible soot/oil fallouts during ISB of Oseberg 200°C+ (with pads) during OOW 2018. The results are normalized to fluoranthene as there was not possible to quantify the amount of soot on the pads. The unburned oil and PM2.5 from DustTrak monitoring from MOB-S included. Sampling locations are shown in Figure 3.1 and given in Table A 2.*

Oseberg OOW 2018	2018-4052-S1 Oseberg 200°C+ (unburned)	2018-5303-S4 Transect 1	2018-5303-S5 Transect 2	2018-5303-S7 Transect 3	2018-5303-S6 Transect 4
Sum SVOC	152	114	161	152	156
Decalins	ND	0,05	0,08	ND	0,07
Naphthalenes	77,5	58,2	82,6	77,5	76,3
2-3 ring PAH	70,6	53,2	75,3	70,6	76,0
4-6 ring PAH	3,50	2,70	2,94	3,50	3,27
PM2.5 (µg/m^3)		6,1	5,5	5,7	3,0

Table D 4 *Sampling on sea surface of possible soot/oil fallouts during ISB of ULSFO (with pads) during OOW 2018. The results are normalized to fluoranthene as there was not possible to quantify the amount of soot on the pads. The unburned oil and PM2.5 from DustTrak monitoring from MOB-S included. Sampling locations are shown in Figure 3.1 . and given in Table A 2.*

ULSFO OOW 2018	2018-3881-S1 ULSFO fresh (unburned)	2018-5304-S9 ULSFO Transec 2	2018-5304-S10 ULSFO Transec 1
Sum SVOC	208	182	953
Decalins	0,07	0,02	36,6
Naphthalenes	96,9	77,4	522
2-3 ring PAH	107	90,4	328
4-6 ring PAH	3,69	14,3	65,8
PM2.5 (µg/m^3)		6,7	9,5

Table D 5 *Estimated amount (in g) of each component group (Appendix E) in total amount soot produced during ISB in 2018 and 2019. The estimates are based on concentrations of soot given in Table D 1 and Table D 2, estimated BC given in Figure 3.14 and amount burned oil in Table 3.4. It is assumed that BC is 100% soot.*

	Oseberg 2018 g in soot	ULSFO 2018 g in soot	Oseb Fireboom g in soot	Oseb Pyroboom g in soot	IFO 180 g in soot	MGO g in soot
Sum SVOC	1282	494	784	518	427	490
Decalins	ND	ND	121	172	136	164
Naphthalenes	70	20	138	179	144	175
2-3 ring PAHs	265	117	89	57	38	51
4-6 ring PAHs	947	354	437	110	109	100
% BC	10	11	18	14	13	12
g BC/kg oil burned	100	110	180	140	130	120
kg oil burned	4346	3032	4692	4564	2582	4823
kg soot produced	435	334	845	639	336	579

Table D 6 *SVOC composition of soot on filters sampled in the smoke plume during ISB during OOW 2018 (in mg analyte/g soot)*

OOW 2018	2018-3941 Filter Oseberg drone 1 mg/g soot	2018-3942 Filter ULSFO drone 1 mg/g soot	2018-3943 Filter background mg/g soot
Decalin	ND	ND	ND
C1-decalins	ND	ND	ND
C2-decalins	ND	ND	ND
C3-decalins	ND	ND	ND
C4-decalins	ND	ND	ND
Benzo(b)thiophene	ND	ND	ND
Naphthalene	0,06	0,02	ND
C1-naphthalenes	0,04	0,02	ND
C2-naphthalenes	0,06	0,03	0,01
C3-naphthalenes	ND	ND	ND
C4-naphthalenes	ND	ND	ND
Biphenyl	0,04	0,01	ND
Acenaphthylene	0,03	0,01	ND
Acenaphthene	ND	ND	ND
Dibenzofuran	0,02	0,01	ND
Fluorene	0,02	0,01	ND
C1-fluorenes	0,01	0,01	ND
C2-fluorenes	ND	ND	ND
C3-fluorenes	ND	ND	ND
Phenanthrene	0,34	0,16	ND
Anthracene	0,07	0,02	ND
C1-phenanthrenes/anthracenes	0,05	0,03	ND
C2-phenanthrenes/anthracenes	ND	0,05	ND
C3-phenanthrenes/anthracenes	ND	0,03	ND
C4-phenanthrenes/anthracenes	ND	0,02	ND
Dibenzothiophene	0,02	ND	ND
C1-dibenzothiophenes	ND	ND	ND
C2-dibenzothiophenes	ND	ND	ND
C3-dibenzothiophenes	ND	ND	ND
C4-dibenzothiophenes	ND	ND	ND
Fluoranthene	0,44	0,23	ND
Pyrene	0,43	0,24	ND
C1-fluoranthrenes/pyrenes	0,08	0,04	ND
C2-fluoranthenes/pyrenes	ND	0,04	ND
C3-fluoranthenes/pyrenes	ND	ND	ND
Benz(a)anthracene	0,13	0,04	ND
Chrysene	0,13	0,05	ND
C1-chrysenes	ND	0,02	ND
C2-chrysenes	ND	0,02	ND
C3-chrysenes	ND	ND	ND
C4-chrysenes	ND	ND	ND

OOW 2018	2018-3941 Filter Oseberg drone 1 mg/g soot	2018-3942 Filter ULSFO drone 1 mg/g soot	2018-3943 Filter background mg/g soot
Benzo(b)fluoranthene	0,16	0,07	ND
Benzo(k)fluoranthene	0,07	0,03	ND
Benzo(e)pyrene	0,13	0,05	ND
Benzo(a)pyrene	0,19	0,07	ND
Perylene	0,05	0,02	ND
Indeno(1,2,3-c,d)pyrene	0,18	0,07	ND
Dibenz(a,h)anthracene	ND	ND	ND
Benzo(g,h,i)perylene	0,19	0,09	ND
Sum alle	2,95	1,48	0,02
Decalins	ND	ND	ND
Naphthalenes	0,16	0,06	0,01
2-3 ring PAH	0,61	0,35	0,01
4-6 ring PAH	2,18	1,06	ND

ND: Not detected

Table D 7 *SVOC composition of soot on filters sampled in the smoke plume during ISB, from OOW 2019 (in mg analyte/g soot). Amount soot is from gravimetric measurements. Results are corrected for background (average of two filters). Low amount of soot on sample 2019-5396 results in too high concentrations (Sample not included in Figure 3.12)*

SINTEF ID OOW 2019	2019-5363 Oseberg Fireboom Drone 1 mg/g soot	2019-5391 Oseberg Fireboom Drone 2 mg/g soot	2019-5393 Oseberg Pyroboom Drone 1 mg/g soot	2019-5394 Oseberg Pyroboom Drone 2 mg/g soot	2019-5392 IFO 180 Drone 1 mg/g soot	2019-5395 MGO Drone 1 mg/g soot	2019-5396 MGO Drone 2 mg/g soot
Decalin	0,001	0,001	0,003	0,003	0,004	0,003	0,045
C1-decalins	0,004	0,010	0,021	0,028	0,028	0,022	0,378
C2-decalins	0,041	0,035	0,068	0,093	0,109	0,079	1,266
C3-decalins	0,062	0,046	0,100	0,129	0,152	0,100	1,824
C4-decalins	0,035	0,031	0,076	0,087	0,112	0,079	0,991
Benzo(b)thiophene	ND	ND	ND	ND	ND	ND	ND
Naphthalene	0,032	0,026	0,052	0,067	0,081	0,058	0,902
C1-naphthalenes	0,072	0,071	0,133	0,181	0,206	0,143	2,454
C2-naphthalenes	0,043	0,038	0,076	0,099	0,116	0,083	1,408
C3-naphthalenes	0,011	0,006	0,014	0,016	0,021	0,015	0,216
C4-naphthalenes	0,005	0,001	0,005	0,002	0,006	0,003	0,012
Biphenyl	0,009	0,007	0,015	0,019	0,022	0,017	0,263
Acenaphthylene	0,003	ND	0,002	0,001	0,003	0,003	0,013
Acenaphthene	0,001	0,001	0,001	0,002	0,002	0,001	0,016
Dibenzofuran	0,003	0,001	0,003	0,001	0,003	0,003	0,010
Fluorene	0,002	ND	0,002	0,001	0,002	0,003	0,009
C1-fluorenes	0,001	ND	0,001	0,001	0,001	0,001	0,004
C2-fluorenes	0,003	ND	0,004	0,002	0,007	0,001	0,004
C3-fluorenes	ND	ND	ND	ND	ND	ND	ND
Phenanthrene	0,046	0,006	0,039	0,013	0,036	0,038	0,046

SINTEF ID OOW 2019	2019-5363 Oseberg Fireboom Drone 1 mg/g soot	2019-5391 Oseberg Fireboom Drone 2 mg/g soot	2019-5393 Oseberg Pyroboom Drone 1 mg/g soot	2019-5394 Oseberg Pyroboom Drone 2 mg/g soot	2019-5392 IFO 180 Drone 1 mg/g soot	2019-5395 MGO Drone 1 mg/g soot	2019-5396 MGO Drone 2 mg/g soot
Anthracene	0,011	0,001	0,005	0,003	0,008	0,007	0,010
C1-phenanthrenes/anthracenes	0,009	0,001	0,006	0,006	0,008	0,005	0,038
C2-phenanthrenes/anthracenes	ND	ND	ND	ND	ND	ND	ND
C3-phenanthrenes/anthracenes	0,005	0,001	0,003	0,002	0,004	0,001	0,017
C4-phenanthrenes/anthracenes	0,007	0,002	0,005	0,006	0,012	0,005	0,046
Dibenzothiophene	ND	ND	ND	ND	ND	ND	ND
C1-dibenzothiophenes	0,001	ND	ND	ND	ND	ND	ND
C2-dibenzothiophenes	0,002	0,001	0,001	0,001	0,002	0,001	0,011
C3-dibenzothiophenes	0,001	ND	0,002	0,002	0,003	0,001	0,014
C4-dibenzothiophenes	0,001	0,001	0,001	ND	0,001	0,001	0,003
Fluoranthene	0,078	0,010	0,043	0,022	0,053	0,043	0,118
Pyrene	0,070	0,008	0,038	0,016	0,045	0,037	0,046
C1-fluoranthrenes/pyrenes	0,012	0,001	0,005	0,005	0,008	0,005	0,019
C2-fluoranthenes/pyrenes	0,033	0,004	0,012	0,010	0,020	0,012	0,029
C3-fluoranthenes/pyrenes	0,002	ND	ND	0,002	ND	0,001	0,008
Benz(a)anthracene	0,033	0,005	0,006	0,009	0,008	0,006	0,019
Chrysene	0,034	0,003	0,008	0,011	0,021	0,009	0,021
C1-chrysenes	0,004	ND	0,001	0,002	0,003	0,001	0,003
C2-chrysenes	0,001	ND	ND	ND	0,001	ND	ND
C3-chrysenes	ND	ND	ND	ND	ND	ND	ND
C4-chrysenes	ND	ND	ND	ND	ND	ND	ND
Benzo(b)fluoranthene	0,054	0,005	0,013	0,021	0,036	0,013	0,038
Benzo(k)fluoranthene	0,018	0,002	0,004	0,007	0,012	0,004	0,013
Benzo(e)pyrene	0,026	0,003	0,006	0,010	0,018	0,006	0,019
Benzo(a)pyrene	0,039	0,004	0,009	0,015	0,027	0,010	0,030
Perylene	0,009	0,001	0,003	0,004	0,007	0,003	0,017
Indeno(1,2,3-c,d)pyrene	0,048	0,005	0,011	0,019	0,030	0,011	0,036
Dibenz(a,h)anthracene	0,005	ND	0,001	0,002	0,003	0,001	0,002
Benzo(g,h,i)perylene	0,050	0,005	0,013	0,018	0,031	0,012	0,040
Sum SVOC	0,929	0,344	0,810	0,939	1,273	0,847	10,4
Decalins	0,143	0,123	0,269	0,340	0,405	0,284	4,50
Naphthalenes	0,163	0,142	0,280	0,366	0,429	0,302	4,99
2-3 ring PAHs	0,105	0,023	0,090	0,060	0,114	0,088	0,503
4-6 ring PAHs	0,518	0,057	0,172	0,173	0,324	0,173	0,448

Table D 8 *Sampling on sea surface of possible soot/oil fallouts during ISB of Oseberg 200°C+ during OOW 2018 (with pads). The results are normalized to fluoranthene as there was not possible to quantify the amount of soot on the pads. The unburned oil and PM2.5 from DustTrak monitoring from MOB-S included. Sampling locations are shown in Figure 3.1 and given in Table A 2.*

Oseberg OOW 2018	2018-4052-S1 Oseberg 200°C+ (unburned)	2018-5303-S4 Transec 1 - S4	2018-5303-S5 Transec 2 - S5	2018-5303-S7 Transec 3 - S6	2018-5303-S6 Transec 4 - S7
	g/kg oil	g/kg oil	g/kg oil	g/kg oil	g/kg oil
Decalin	2,71	ND	0,01	0,02	0,02
C1-decalins	6,03	ND	0,03	0,05	0,06
C2-decalins	7,76	ND	ND	ND	ND
C3-decalins	11,6	ND	ND	ND	ND
C4-decalins	8,53	ND	ND	ND	ND
Benzo(b)thiophene	ND	ND	ND	ND	ND
Naphthalene	30,1	2,86	2,59	2,66	3,91
C1-naphthalenes	120	7,47	6,52	7,05	9,85
C2-naphthalenes	170	21,3	19,3	21,6	25,7
C3-naphthalenes	133	32,1	20,5	31,2	31,0
C4-naphthalenes	69,0	13,7	9,29	13,7	12,1
Biphenyl	18,9	4,52	2,83	4,49	4,16
Acenaphthylene	1,47	0,34	0,29	0,34	0,41
Acenaphthene	1,08	0,14	0,15	0,17	0,20
Dibenzofuran	5,37	3,16	2,55	3,31	3,58
Fluorene	7,21	2,66	2,00	2,71	2,75
C1-fluorenes	17,9	5,67	3,44	5,36	4,74
C2-fluorenes	21,7	ND	ND	ND	ND
C3-fluorenes	17,0	ND	3,72	5,02	4,74
Phenanthrene	22,5	10,0	7,99	10,0	11,1
Anthracene	0,79	0,27	ND	ND	ND
C1-phenanthrenes/anthracenes	50,0	13,4	9,15	14,1	13,3
C2-phenanthrenes/anthracenes	51,9	12,4	6,85	10,4	10,6
C3-phenanthrenes/anthracenes	36,2	ND	2,42	3,16	3,46
C4-phenanthrenes/anthracenes	22,9	ND	0,53	ND	ND
Dibenzothiophene	4,69	2,46	1,87	2,55	2,65
C1-dibenzothiophenes	12,8	8,89	5,32	8,55	7,98
C2-dibenzothiophenes	16,9	4,89	3,10	4,61	4,39
C3-dibenzothiophenes	11,8	1,76	0,99	1,21	1,21
C4-dibenzothiophenes	7,03	ND	ND	ND	ND
Fluoranthene	1,00	1,00	1,00	1,00	1,00
Pyrene	1,42	0,71	0,56	0,70	0,75
C1-fluoranthrenes/pyrenes	10,8	1,79	0,69	1,12	0,95
C2-fluoranthenes/pyrenes	13,9	ND	ND	ND	ND
C3-fluoranthenes/pyrenes	13,2	ND	ND	ND	ND
Benz(a)anthracene	0,52	ND	0,12	0,20	0,19
Chrysene	1,24	ND	0,07	0,07	0,06
C1-chrysenes	5,62	ND	0,28	0,18	ND
C2-chrysenes	6,70	ND	ND	ND	ND

Oseberg OOW 2018	2018-4052-S1 Oseberg 200°C+ (unburned) g/kg oil	2018-5303-S4 Transec 1 - S4 g/kg oil	2018-5303-S5 Transec 2 - S5 g/kg oil	2018-5303-S7 Transec 3 - S6 g/kg oil	2018-5303-S6 Transec 4 - S7 g/kg oil
C3-chrysenes	4,73	ND	ND	ND	ND
C4-chrysenes	3,48	ND	ND	ND	ND
Benzo(b)fluoranthene	0,71	ND	ND	ND	ND
Benzo(k)fluoranthene	0,18	ND	ND	ND	ND
Benzo(e)pyrene	1,27	ND	ND	ND	ND
Benzo(a)pyrene	0,40	ND	ND	ND	ND
Perylene	0,09	ND	ND	ND	ND
Indeno(1,2,3-c,d)pyrene	ND	ND	ND	ND	ND
Dibenz(a,h)anthracene	ND	ND	ND	ND	ND
Benzo(g,h,i)perylene	0,48	ND	ND	ND	ND
Sum alle	953	152	114	156	161
Decalins	36,6	ND	0,05	0,07	0,08
Naphthalenes	522	77,5	58,2	76,3	82,6
2-3 ring PAH	328	70,6	53,2	76,0	75,3
4-6 ring PAH	65,8	3,50	2,70	3,27	2,94

Table D 9 *Sampling on sea surface of possible soot/oil fallouts during ISB of ULSFO during OOW 2018 (with pads). The results are normalized to fluoranthene as there was not possible to quantify the amount of soot on the pads. The unburned oil and PM2.5 from DustTrak monitoring from MOB-S included. Sampling locations are shown in Figure 3.1 and given in Table A 2.*

ULSFO OOW 2018	2018-3881-S1 ULSFO fresh	2018-5304-S9 Transec 2 - S9	2018-5304-S10 Transec 1 - S10
Decalin	0,19	0,02	0,02
C1-decalins	0,51	0,05	ND
C2-decalins	0,79	ND	ND
C3-decalins	1,44	ND	ND
C4-decalins	1,63	ND	ND
Benzo(b)thiophene	ND	ND	ND
Naphthalene	0,60	3,54	1,72
C1-naphthalenes	3,36	10,6	5,45
C2-naphthalenes	9,47	26,3	18,6
C3-naphthalenes	14,0	28,5	25,5
C4-naphthalenes	9,65	27,9	26,1
Biphenyl	0,14	3,71	2,94
Acenaphthylene	ND	0,46	0,35
Acenaphthene	0,10	0,28	0,25
Dibenzofuran	0,09	4,00	3,06
Fluorene	0,44	3,34	2,58
C1-fluorenes	1,65	6,42	6,09
C2-fluorenes	4,35	14,3	9,41
C3-fluorenes	4,62	5,22	4,10

ULSFO OOW 2018	2018-3881-S1 ULSFO fresh	2018-5304-S9 Transec 2 - S9	2018-5304-S10 Transec 1 - S10
Phenanthrene	2,59	15,2	11,2
Anthracene	0,25	0,36	0,36
C1-phenanthrenes/anthracenes	12,3	17,4	15,7
C2-phenanthrenes/anthracenes	35,2	12,5	12,5
C3-phenanthrenes/anthracenes	46,1	4,22	ND
C4-phenanthrenes/anthracenes	29,5	1,14	ND
Dibenzothiophene	0,12	3,74	2,78
C1-dibenzothiophenes	1,20	8,73	8,02
C2-dibenzothiophenes	1,96	6,36	5,87
C3-dibenzothiophenes	2,48	ND	1,99
C4-dibenzothiophenes	1,72	ND	3,26
Fluoranthene	1,00	1,00	1,00
Pyrene	6,64	0,75	0,80
C1-fluoranthrenes/pyrenes	25,6	1,61	2,14
C2-fluoranthenes/pyrenes	38,6	ND	2,13
C3-fluoranthenes/pyrenes	33,1	ND	1,77
Benz(a)anthracene	3,47	ND	0,19
Chrysene	4,60	0,12	0,34
C1-chrysenes	24,1	0,21	1,27
C2-chrysenes	28,1	ND	2,28
C3-chrysenes	21,1	ND	1,29
C4-chrysenes	8,79	ND	ND
Benzo(b)fluoranthene	1,09	ND	ND
Benzo(k)fluoranthene	ND	ND	ND
Benzo(e)pyrene	2,98	ND	0,39
Benzo(a)pyrene	1,55	ND	0,29
Perylene	0,54	ND	ND
Indeno(1,2,3-c,d)pyrene	ND	ND	ND
Dibenz(a,h)anthracene	ND	ND	ND
Benzo(g,h,i)perylene	1,51	ND	0,40
Sum alle	389	208	182
Decalins	4,56	0,07	0,02
Naphthalenes	37,0	96,9	77,4
2-3 ring PAH	145	107	90,4
4-6 ring PAH	203	3,69	14,3

ND: Not detected

E Appendix E Overview over the components analysed in residues and soot

	Compound	Abb
GC/MS-analyse		
Decalins	Decalin	DE
	C1-decalins	DE1
	C2-decalins	DE2
	C3-decalins	DE3
	C4-decalins	DE4
Naphthalenes	Naphthalene	N
	C1-naphthalenes	N1
	C2-naphthalenes	N2
	C3-naphthalenes	N3
	C4-naphthalenes	N4
2-3 ring PAHs	Benzo(b)thiophene	BT
	Biphenyl	B
	Acenaphthylene	ANY
	Acenaphthene	ANA
	Dibenzofuran	DBF
	Fluorene	F
	C1-fluorenes	F1
	C2-fluorenes	F2
	C3-fluorenes	F3
	Phenanthrene	P
	Anthracene	A
	C1-phenanthrenes/anthracenes	P1
	C2-phenanthrenes/anthracenes	P2
	C3-phenanthrenes/anthracenes	P3
	C4-phenanthrenes/anthracenes	P4
	Dibenzothiophene	D
	C1-dibenzothiophenes	D1
	C2-dibenzothiophenes	D2
	C3-dibenzothiophenes	D3
	C4-dibenzothiophenes	D4
4-6 ring PAHs	Fluoranthene	FL
	Pyrene	PY
	C1-fluoranthrenes/pyrenes	FL1
	C2-fluoranthenes/pyrenes	FL2
	C3-fluoranthenes/pyrenes	FL3
	Benz[*a*]anthracene	BA
	Chrysene	C
	C1-chrysenes	C1
	C2-chrysenes	C2
	C3-chrysenes	C3
	C4-chrysenes	C4
	Benzo[*b*]fluoranthene	BBF
	Benzo[*k*]fluoranthene	BKF
	Benzo[*e*]pyrene	BEP
	Benzo[*a*]pyrene	BAP
	Perylene	PE
	Indeno[*1,2,3-c,d*]pyrene	IN
	Dibenz[*a,h*]anthracene	DBA
	Benzo(g,h,i)perylene	BPE
GC/FID	Screening total hydrokarbon (THC, C10-C36)	