

# THE NEWFOUNDLAND OFFSHORE BURN EXPERIMENT—NOBE

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**ABSTRACT:** A group of 25 agencies from Canada and the United States conducted a major offshore burn experiment near Newfoundland, Canada. Two lots of oil, about 50 cubic meters (50 tons) each, were released into a fireproof boom. Each burn lasted over an hour and was monitored for emissions and physical parameters. Over 200 sensors or samplers were employed to yield data on over 2000 parameters or substances. The operation was extensive; more than 20 vessels, 7 aircraft and 230 people were involved in the operation at sea.

The quantitative analytical data show that the emissions from this in-situ oil fire were less than expected. All compounds and parameters measured more than about 150 meters from the fire were below occupational health exposure levels; very little was detected beyond 500 meters. Pollutants were found to be at lower values in the Newfoundland offshore burn than they were in previous pan tests.

Polyaromatic hydrocarbons (PAHs) were found to be lower in the soot than in the starting oil and were consumed by the fire to a large degree. Particulates in the air were measured by several means and found to be of concern only up to 150 meters downwind at sea level. Combustion gases including carbon dioxide, sulphur dioxide, and carbon monoxide did not reach levels of concern. Volatile organic compounds (VOCs) were abundant, however their concentrations were less than emitted from the nonburning spill. Over 50 compounds were quantified, several at levels of concern up to 150 meters downwind. Water under the burns was analyzed; no compounds of concern could be found at the detection level of the methods employed. Toxicity tests performed on this water did not show any adverse effect. The burn residue was analyzed for the same compounds as the air samples. Overall, indications from these burn trials are that 150 meters or farther from the burn source emissions from in-situ burning are lower than health criteria levels.

Ten years of intensive laboratory and tank testing on the in-situ combustion of oil have indicated that the nature and concentrations of atmospheric emissions from in-situ burning of oil offshore will normally be an acceptable tradeoff when weighed against the environmental risks and cleanup costs of nearshore and shoreline contamination.

Analyses conducted to date have shown that the high temperatures reached during efficient in-situ combustion results in relatively complete destruction of the oil.<sup>4</sup> Fire-resistant containment booms developed over the past few years offer the potential, under suitable wind and sea conditions, to maintain oil at a suitable thickness for burning at sea and to contain undesired spreading of the oil and the fire.

Based on the current state of knowledge regarding burning as an oil spill countermeasure, the next logical extension of the technology was the controlled experimental release and burning of oil under realistic, full-scale field conditions. Such an experiment, designed according to rigorous scientific protocols, would allow the identification and quantification of the chemical compounds associated with and generated by the burning of oil on the open ocean. An experiment of this type would also allow the verification of theoretical models that have been developed to predict the content and trajectories of smoke plumes.

This experiment would provide the necessary information for regulatory agencies to consider preapproval for large scale burns under emergency spill conditions (an essential element in making effective use of burning in a field situation). An equally important benefit would involve the development of response protocols that would guide oil industry, spill cooperatives, and government regulatory personnel in the safe and effective application of burning in future spills.

The experiment was designed to meet four primary objectives:

- To obtain measurements of critical burn parameters and to collect and analyze chemical emissions needed for comparison with data

Table 1. Sponsors of NOBE,

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Environment Canada
U.S. Minerals Management Service
Canadian Coast Guard
Marine Spill Response Corporation
United States Coast Guard
American Petroleum Institute
U.S. Environmental Protection Agency
Canadian Association of Petroleum Producers
3M Ceramics Division
Canadian Petroleum Products Institute
Alaska Clean Seas
Amoco Production
PERD—Program for Energy Research and Development
Imperial Oil Limited
Hibernia Development
Exxon Biomedical Services
Canmar/AMOCO Canada

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## 1. In order of funding level

sets and models that are currently based on laboratory and medium scale tests.

- To obtain samples for analysis of the smoke plume, water, and gaseous emissions needed to determine whether the environmental impact of burning is acceptable.
- To conduct a large scale oil burning experiment in realistic open-ocean conditions to demonstrate contained burning as a spill response technique.
- To develop a response protocol that will establish operational strategies for burning and safety procedures under a variety of environmental and operational conditions.

The experiment was marked as a cooperative effort among 25 agencies. Sponsors of the test are listed in Table 1.

## Operational details

The Newfoundland offshore burn experiment took place on the Grand Banks in a 34-km<sup>2</sup> (ca. 10 nautical miles<sup>2</sup>, n mi<sup>2</sup>) area, at coordinates 47° 40' N, 52° W. The location is about 42 km (25 nmi) east of the port of St. John's, Newfoundland. The experiment was conducted on August 12, 1993. The time and place were chosen to minimize ecological damage and interference with the local fishery. Two replicate experiments were conducted in which approximately 50 m<sup>3</sup> (13,200 gal) of oil were discharged in a controlled manner into a boomed area and ignited.

A sophisticated array of state-of-the-art sensing, sampling and data-gathering equipment was deployed from a variety of platforms. The layout of the vessels for the experiment is shown in Figure 1. Sampling near the fire and in the smoke plume was conducted from remote-controlled boats, helicopters, and an ROV (remotely-operated vehicle—submersible) that was deployed beneath the slick. At more distant locations, a tethered blimp, conventional helicopters, fixed-wing aircraft, and a variety of vessels were used. As a contingency measure, a secondary oil containment boom and recovery system was towed behind the fire boom.

The experiment involved the measurement of emissions to the air, levels of oil and related compounds in the water, and operational parameters relevant to in-situ burning. Data were collected and analyzed to generate information on over 2000 parameters.

The vessel procession was led by the CCG vessel *Sir Wilfred Grenfell* (hereafter referred to as the *Grenfell*) that served as the supply and oil discharge vessel. The fire boom was towed directly behind the *Grenfell* by two Boston whalers with 150-ft tow lines. Two 14-ft remote-controlled boats, and a 36-ft sea truck serving as a platform for the tethered blimp, were approximately 50, 100, and 150 m, respectively, behind the apex of the fire boom. The secondary containment boom was towed by two 46-ft vessels 100 m behind the sea truck, that is, 250 m behind the fire boom.

A number of other vessels were stationed farther from the main

procession. These included several Boston whalers from which routine sampling was conducted and other vessels that served as platforms from which the remote-controlled boats and helicopters and the ROV were operated. The command vessel was the CCG vessel *Ann Harvey*. Two vessels were chartered to accommodate scientific observers and visitors. They were also used as platforms for some of the documentation and air measurement. Several smaller boats were used for other sampling purposes and for controlling the remote sampling boats and a remote underwater vessel.

The oil was released into a fire-resistant boomed area and burned within it. Air emissions were monitored downwind using two remote-controlled boats, a research vessel, and an airplane. The plume itself was sampled by two remote-controlled helicopters, a blimp, and an airplane. Water samples were collected from the remote-controlled sampling boats, and air and water temperatures measured from the same vessels. The fire-resistant boom was equipped with thermocouples to monitor temperatures directly impacting it and those in the water directly underneath the fire. A submersible was deployed under the burning slick to monitor temperatures and take video footage. A small boat monitored and measured surface material that escaped and took samples of the residue after the burn.

The oil was released from a supply-type ship through a skimmer so that if there were some problem, the flow could be reversed and the oil recovered. A 700 ft section of boom was used. The planned oil release in each spill was 50 m<sup>3</sup> or about 10,000 Imperial gallons (about 13,000 U.S. gallons). This is about the lower limit of a typical boom capacity. Once sufficient oil was in the boom to sustain combustion, it was ignited using a Helitorch.

The fire-resistant boom used was a commercial version along with some experimental sections. The middle sections near the burn were equipped with a number of thermocouples to measure the temperature on the boom. The boom was towed by a major vessel and the opening was maintained by two vessels towing outward at an angle of approximately 45 degrees. Tow vessels were equipped with current meters to ensure that they would be able to maintain a forward speed of about 0.5 knots. One helicopter was used to ignite the slick and to put out flares to guide the procession into the wind. Another helicopter was used to provide still and video footage for documentation.

## Operational results

The overall results of the burn experiment are summarized in Table 2. Burn 1 started after ignition with a Helitorch. Reports from the helicopters and both airplanes indicated that the smoke plume bifurcated about 2 km downwind. One portion of the smoke plume turned southeast and one turned east after rising about 2 km. Pumping during burn 1 had to be stopped several times because the fire had spread back to the discharge point. The average discharge and burn rate for burn 1 was 915 L/min. The fire-resistant boom was inspected after the first burn. Some signs of abrasion were observed in the Nextel ceramic fabric above the waterline between the flotation logs. At these locations, some small gaps in the fabric occurred approximately 10 to 20 cm from the vertical stainless steel stiffeners. Nevertheless, the boom was fit for another burn.

The crews refitted the equipment for the second burn, which began

Table 2. Burn summary

## Burn 1

Oil volume discharged—48.3 m<sup>3</sup>  
 Burn and pump time—1.5 hours  
 Residue in fireproof boom—0.2 m<sup>3</sup> (max.)  
 Residue in backup boom—0.2 m<sup>3</sup> (max.)  
 Efficiency—> 99 percent

## Burn 2

Oil volume discharged—28.9 m<sup>3</sup>  
 Burn and pump time—1.3 hours  
 Residue in fireproof boom—0.05 m<sup>3</sup> (max.)  
 Residue in backup boom—0.2 m<sup>3</sup> (max.)  
 Efficiency—> 99 percent

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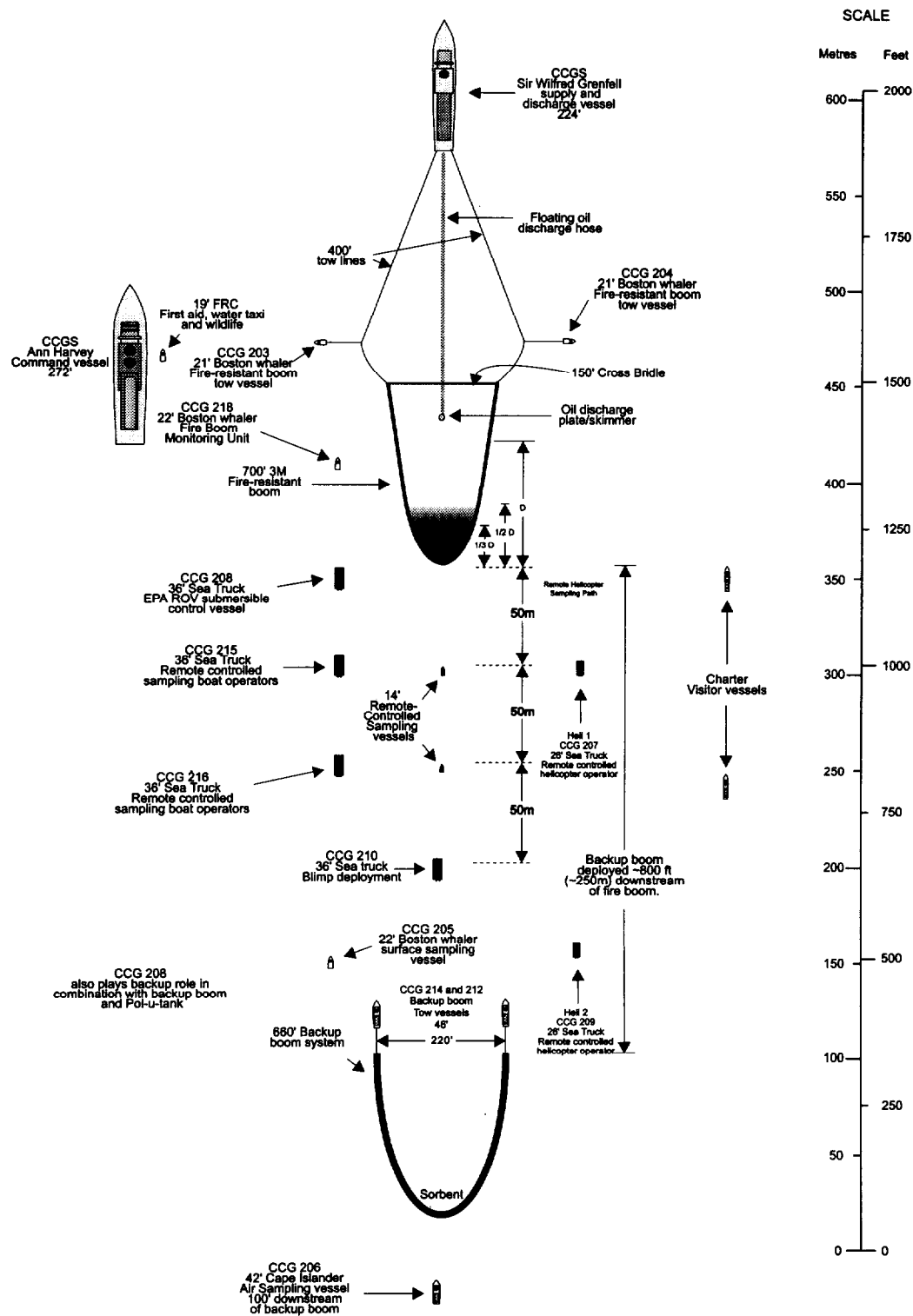


Figure 1. Sea trial layout

in mid-afternoon. The first run of the Helitorch ignited the oil. Some oil was again splashed over, however, like the first burn no sheening whatsoever was observed. The oil outside of the boom burned leaving only small patches of residue which drifted back into the secondary recovery boom. The wind was 8 to 11 km/hr; and this resulted in an approximate 45 degree angle for the plume. This burn was characterized by its classical, regular plume behaviour. The plume did,

however, bifurcate about 2 km downwind, similar to the previous plume.

The pump rate for this burn averaged 610 L/min. Pumping was stopped after 1.3 hours of burn time when some small pieces of the fire-resistant boom were released. The duration had already exceeded planned sampling times and most samplers had already been stopped.

Residue was recovered using sorbents. The highly adhesive and

Table 3. Summary of analytical methods

Sample taken	Sampler	Measurement parameter	Secondary parameters	Additional parameters
Soot at sea level	High-volume sampler Sampling pump, medium volume	Dioxins and dibenzofurans PAHs	Particulates Particulates	PAHs
Soot in smoke	Ram Cascade sampler Sampling pump, low volume blimp, remote-controlled helicopter, research aircraft	Particulates Particle size	PAHs Particulates	Metals
Gases	Summa Canister Sampling pump, low volume CO <sub>2</sub> meter SO <sub>2</sub> meter NO <sub>2</sub> meter CO meter	Volatile organic compounds Volatile organic compounds Carbon dioxide Sulphur dioxide Nitrogen dioxide Carbon monoxide	CO <sub>2</sub>	
Oil		PAHs	Metals	Full analysis
Burn residue		PAHs	Metals	Full analysis
Water under burn		PAHs	Organics	Toxicity

viscous residue clung to adsorbent material very readily. Eight drums of sorbent boom within the secondary recovery boom and adsorbent pom-poms were collected. This contained about 0.5 m<sup>3</sup> of oil or residue.

Following the second burn, the fire-resistant boom was again inspected for damage. In a prototype section (that included some external tension members near the waterline), the stainless steel wire mesh had parted, allowing two meter-long flotation logs to be released. Analysis of the crystalline structure of the wire mesh after the test revealed embrittlement at the location where the flotation logs had been released. To remedy this problem, American Marine Inc., in conjunction with 3M engineers, has incorporated higher-temperature-resistant stainless steel mesh surrounding the flotation logs. American Marine Inc. has also included an internal stainless steel cable within the boom to distribute the tension forces.

## Sampling

Sampling methodologies and target emissions are summarized in Table 3. Detailed methods are described in the literature.<sup>1,2</sup>

## Findings

**Oil and basic operations.** The basic data on the operations and oil pumping were detailed in a previous paper.<sup>3</sup> The speed at which the fire boom and the procession moved was calibrated by using a current meter behind the fire boom. The cables towing the fire boom were monitored using strain gauges. The oil discharge was monitored with a flow meter and electronically recorded. The unique configuration employed proved to be readily operational and highly practical.

**Boom operation.** The 3-M boom withstood the temperatures and strains of the burn with the exception that two flotation logs were lost from one section near, but not in, the apex. This occurred near the end of the burn and did not cause leakage or any particular difficulty. Subsequent examination of the boom revealed that the stainless steel mesh holding the logs had given way. The manufacturer has modified the boom design to incorporate a heavier mesh and several other improvements as a result of this field trial.

**Fire temperature.** Temperatures were recorded at several points on the fire boom. Eight sections were monitored with thermocouples at four locations in the vertical plane. Figure 2 shows a typical output. This shows that the temperatures at the top of the fire boom often reached 1000° C and the temperatures below were substantially lower. Thermocouple probes known to be in the water show no increase in water temperatures.

**Oil analysis.** The physical properties of the oil and residue were analyzed. Table 4 shows the results. The most interesting result is that the residue appears to be a weathered oil with an evaporative loss of about 45 percent by weight. The residue had a density of about 0.95 g/cc and a viscosity of about 100,000 cP.

**Particulates.** Particulates were collected or measured by a number of means. The real-time data collected on Rams (real-time aerosol monitors) are summarized in Table 5 for burns 1 and 2. It shows that particulates were at moderate levels under the plume at the locations sampled by the remote-controlled boats. Particulate levels dropped to

Table 4. Physical analysis of NOBE oil/residue samples

Parameter	Starting crude oil	Residue
Weathering (%)	4%	40–48%
Density	0.8437g/mL (15° C)	0.9365g/mL (15° C)
Viscosity	11 cP (15° C), shear rate 500s <sup>-1</sup> Newtonian viscosity	130500 cP (15° C), shear rate 1s <sup>-1</sup> non-Newtonian viscosity
Pour point	–21° C	34° C
Interfacial tension	21.4 dynes/cm (15° C), air/oil 13.3 dynes/cm (15° C), oil/sea	Not measurable at 15° C Not measurable at 15° C
Asphaltene content	0.7 wt%	2.3 wt%
Wax content	10.1 wt%	13.8 wt%
Flash point	–13° C	>90° C
Water content	0.54 wt%	14.01 wt%
Sulphur content	0.15 wt%	0.40 wt%

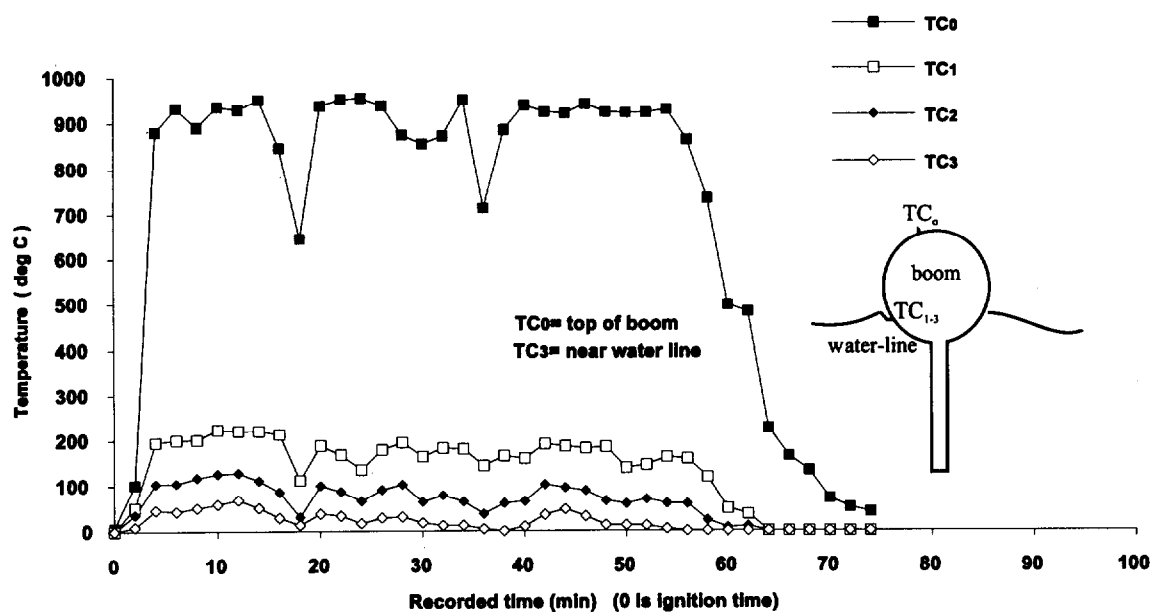


Figure 2. Temperatures at the boom

background levels at the remote sampling station about 1 km downwind. Cascade samplers were used to determine the proportion of the particulate matter in various size ranges. The amount of material below the size of  $10\mu$  was not measurable in this device, however the Rams measured particulates of respirable sizes. This experiment indicates that the amount of particulate material in the respirable range is small at ground level. Data will be available in the future from aircraft measurements for levels of respirable particulates in the air plume itself.

**Polyaromatic hydrocarbons (PAHs).** PAH analysis of particulate material and air itself were performed at several different sample locations and by several different means. Data for burn 1 are summa-

rized in Table 6; those for burn 2 in Table 7. A comparison of the concentration of PAHs in the starting oil, residues, and soot at downwind points has been done and is shown in Figure 3. This comparison shows that the PAHs are largely consumed by the fire. The amounts of PAHs detected at the Newfoundland burn are about the same or less than that detected in previous burn trials.

**Aldehydes and ketones.** Aldehydes and ketones were measured using a specialized technique specific to the general class of carbonyl compounds. Limited amounts of formaldehyde and acetaldehyde were found during the burn and evaporation period prior to the burn. Data indicate that the concentrations are near background levels and actually are higher during the times when the oil is not burning.

Table 5. Particulate analysis<sub>1</sub>

Analysis	Background (mg/m <sup>3</sup> )	Remote station 1 50 meters (mg/m <sup>3</sup> )	Remote station 2 100 meters (mg/m <sup>3</sup> )	Downwind station 500 meters (mg/m <sup>3</sup> )
<b>Burn 1</b>				
<b>Particulates &gt; 10 microns (Ram)</b>				
Background (1.1) rep 1 (EPA)	0.02 < 0.04 < 4.50			
Background (1.1) rep 2 (EPA)	0.04 < 0.04 < 0.06			
Background (1.1)	0 < 0 < 0			
Preignition (1.2) rep 1				0.02 < 0.07 < 4.44
Preignition (1.2) rep 2				0.0 < 0.26 < 29.1
Preignition (1.2)		0.0 < 0.2 < 3.3	0.0 < 0.01 < 0.9	
Burn (1.6) rep 1		0.6 < 12.0 < 14.9	13.3 < 14.3 < 15.1	0.01 < 0.05 < 3.05
Burn, (1.6) rep 2		0.0 < 9.2 < 96.9	0.0 < 14.0 < 15.7	0.02 < 0.13 < 22.5
Postburn (1.7)	10.5 < 13.4 < 14.5			
<b>Total Particulates (mg/m<sup>3</sup>)</b>				
PS-1	0.0 < 0.12 < 0.23			
<b>Burn 2</b>				
<b>Particulates &lt; 10 microns (Ram)</b>				
Background (2.1)				0.02 < 0.03 < 4.2
Preignition (2.2)		0.0 < 0.9 < 1.6	0.0 < 0.01 < 2.7	0.02 < 0.03 < 1.16
Burn (2.6)		0.0 < 10.3 < 29.9	0.0 < 12.3 < 35.0	0.0 < 0.07 < 14.1
Postburn (2.7)		0		0.02 < 0.12 < 12.69
Post residue period (2.8)				0.02 < 0.04 < 3.43

1. Values given as minimum &lt; average &lt; maximum

Table 6. PAH analysis of air and particulate samples—burn 1,

Analysis (µg/m³)	R/C boat 4 <sub>2</sub>	R/C boat 2 <sub>3</sub>	R/C boat 1 <sub>4</sub>	Downwind station	R/C heli 1	R/C heli 2	Blimp	Convair	Fresh crude oil	Weathered crude oil	Residue
<b>Particulates &lt; 5 µ—Cyclone</b>											
Burn (1.6)	1.58	2.83 & < 1.1	3.78 & < 1.1	3.37 & < 1.0							
Background Aug 07, 93	12.74			2.03							
Trip blank	0.16										
<b>Smoke samples from blimp</b>							0.54				
<b>PUF/background (8:20–8:45)</b>								0.42			
<b>PUF/burn (10:56–11:08)</b>											
Background Aug 07,93								1.36			
Blank, loaded								3.08			
Blank trip								1.24			
								3.1			
<b>Cascade impactor</b>											
Burn (1.6)	< 0.08	0.46	0.36	0.19							
Background Aug 07, 93	0.75			0.59							
Trip blank, Aug 07, 93	0.55										
<b>PS-1 + PUF + XAD</b>											
Burn (1.6)	7.45	11.05	11.34	3.3							
Background Aug 07, 93			6.26	7.99							
Trip blank	3.52			3.67							
Field blank	2.31										
<b>Back + pre-ign + burn (clean air / filter)</b>				< 4.35							
<b>Burn (plume / filter + XAD)</b>					104.28	37.04					
Background Jun 30, 93					< 20						
Trip blank (XAD)					0.43						
Blank static (filter)					ND						
<b>Helicopter blade wipe (µg/g)</b>											
Postburn (1.7)					85.12	80.68					
Blank run (wipe after evaporation flight)					< 22	< 13					
Blank wipes					< 43	< 250					
<b>Oil Samples (µg/g)</b>											
Background, Hugheden (Jul 22, 94)									11833	11383	
Background, St-John's (Aug 02, 94)										11564	
Apex of fireboom, preignition (1.2)										8467	
Between fireboom and row boom, burn (1.6)											4304
Apex of fireboom, post-burn (1.7)											2985
Post residue period (2.8)											2991

1. Values are given as averages, "&" indicates the averages of two sensors.
2. R/C boat 4 in position RS-1 for the first 17 minutes, it is then not used for the remainder of the sampling time.
3. R/C boat 2 in position RS-2 for the first 17 minutes, it then moves into in position RS-1 for the remainder of the burn.
4. R/C boat 1 is sent out to position RS-2 and starts sampling 53 minutes into burn.

**Dioxins and dibenzofurans.** The high-volume samples taken on the remote-controlled boats and on the downwind station were also analyzed for dioxins and dibenzofurans. The values are at background levels. This confirms previous studies that show that dioxins and dibenzofurans are not produced by fires.

**Combustion gases.** Tests were made for a number of gases, but CO and NO<sub>x</sub> are not above the lower detection levels. Sulphur dioxide, SO<sub>2</sub>, is only detected when using an impinger method. Direct-reading instruments do not detect the compound above background levels. This indicates that the SO<sub>2</sub> is in an acid aerosol form since the impinger method also detects this form. Carbon dioxide is measured around the burn and is found in concentrations that are highest at ground level.

The typical traces of CO<sub>2</sub> as found at ground level is shown in Figure 4. As this figure indicates, the CO<sub>2</sub> level rises quickly upon ignition and remains high until the fire is extinguished. Carbon dioxide was also measured in the Summa canisters placed on several of the vessels in the area. The distribution of CO<sub>2</sub> over the test site during burn 2 is shown in Figure 5. This shows that the CO<sub>2</sub> plume moves close to the surface and that the gas has a distinct plume of its own, separate from the smoke plume.

**VOCs.** Over 140 compounds were measured using Summa canisters. Overall cumulative VOC concentrations for burn 1 are summarized in Table 8. The analytes measured are shown in Figure 6. The levels of volatile organic compounds are well above concern levels

Table 7. PAH analysis of air and particulate samples—burn 2<sub>1</sub>

Analysis ( $\mu\text{g}/\text{m}^3$ )	Remote Station 1 R/C boat 1	Remote Station 2 R/C boat 2	Downwind station	R/C Heli 1	R/C Heli 2	Blimp	Convair	Fresh crude oil	Weathered crude oil	Residue
Particulates < 5 $\mu$ —cyclone										
Burn (2.6)	2.12 & < 1.0	9.77 & < 1.0	4.21 & < 0.8							
Smoke samples from blimp						1.85				
PUF / burn (14:13–14:24)							1.02			
PUF / postburn (15:28–16:23)							2.43			
PUF / postresidue (16:27–16:38)							0.78			
Cascade impactor										
Burn (2.6)		0.35	0.29							
PS-1 + PUF + XAD										
Burn (2.6)	12.35	11.22	4.11							
Burn (clean air / filter)				< 8.3						
Burn (plume / filter + XAD)				128.18	59					
Blank static (filter)				< 20						
Helicopter blade wipe ( $\mu\text{g}/\text{g}$ )										
Postburn (2.7)				220.72	65.7					
Oil samples ( $\mu\text{g}/\text{g}$ )										
Background, Hugheden (Jul 22, 94)								11833	11383	
Background, St-John's (Aug 02, 94)									11564	
Between fireboom and row boom										2917
Apex of fireboom, post-burn (2.7)										3468
Postresidue (2.8)										2991

1. Values are given as averages; "&" indicates the averages of two sensors

within 150 meters of the fire; however, the levels of these compounds are even greater from an evaporating slick that is not burning.

**Metals.** Crude oil contains several metals in the ppm range. The analysis from the Newfoundland tests is not complete, but in previous tank tests, metals could not be detected on soot particles.

**Water-borne compounds.** Water from under the burns was sampled and analyzed for a number of compounds. Detailed data are presented in a previous paper.<sup>1</sup> No compounds above background levels were detected in the water once the oil was on the water, during the burn or after the burn.

### Overall findings

The Newfoundland burn and the previous tank test burns have revealed several facts about the fate, behaviour, and quantity of the basic emissions from burning.

**Gases.** Combustion gases are diffusely distributed by the dynamics of burning and do not have spatial relationship to the plume. A good model is to view gas dispersal as following a toroidal-like pattern around the burn. This pattern is deformed by increasing wind veloc-

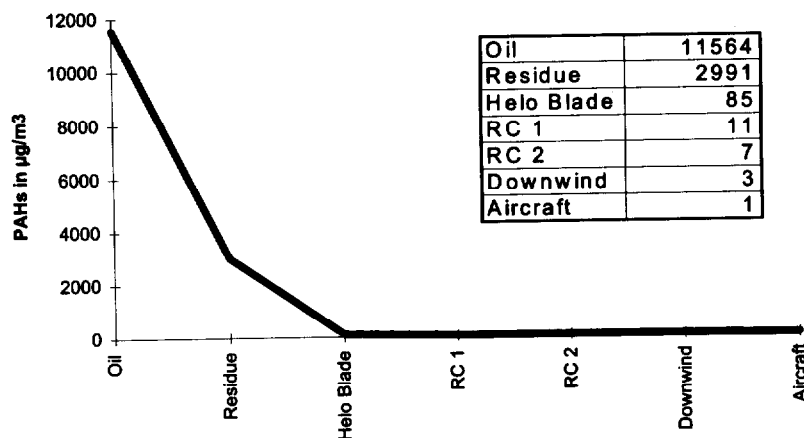


Figure 3. Concentration of PAHs in the starting oil, residues, and soot at downwind points

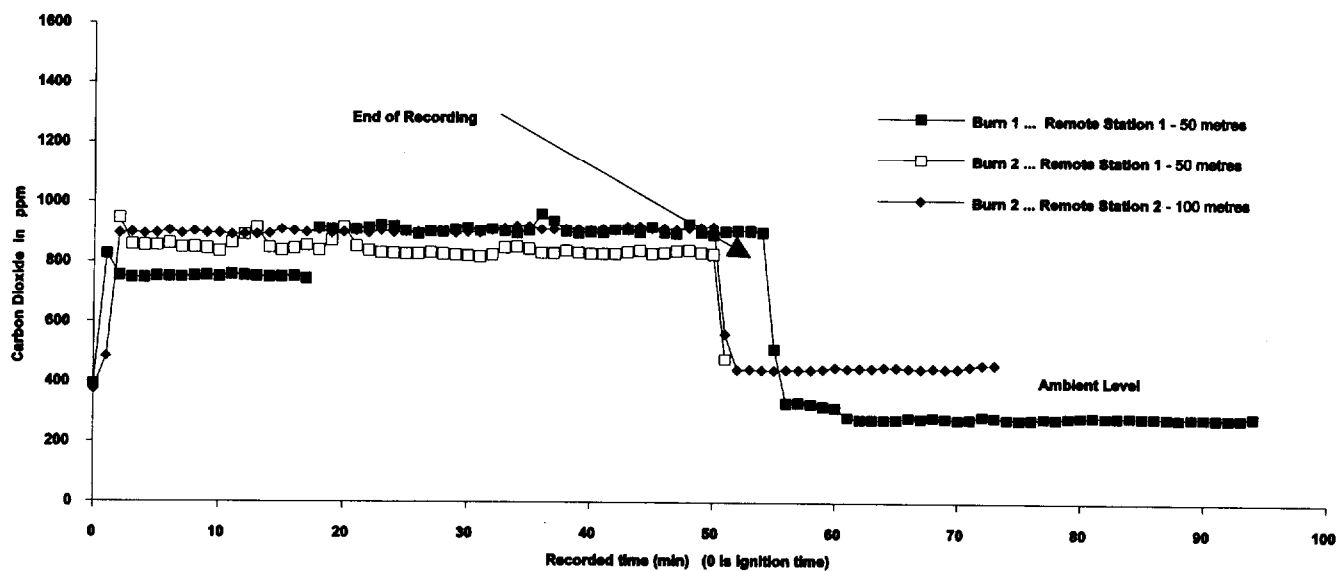


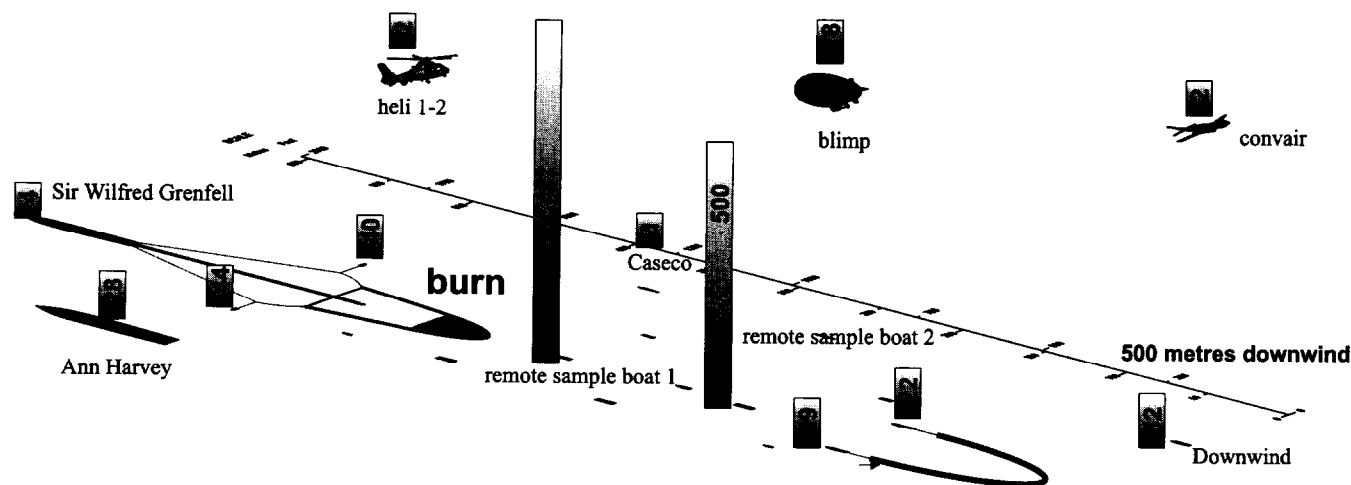
Figure 4. Carbon dioxide measurements

Table 8. VOC analysis of air samples—burn #1,

Analysis total VOC ( $\mu\text{g}/\text{m}^3$ )	R/C boats			Downwind station	Remote heli-1	Remote heli-2	Convair	Sir Wilfred Grenfell	Ann Harvey	CCG boats			
	1	2	4							203	204	212	214
<i>Summa canister</i>													
Background (1.1)					325	271	80 & 609						
Preignition (1.2)		971 & 1543	3675 & 960	48 & 198	254			239	111	3348	140	582	135 232
Burn (1.6)	1143	368	296	721									
R/C Heli 1, in front of smoke plume					283			68	97	488	67	108	407 75
R/C Heli 1, under smoke plume					2083								
R/C Heli 2, under plume (20 m high)						405							
R/C Heli 2, under plume (40 m high)						267							
Convair, above cloud layer							676						
Convair, 1 mi DW at 300 m							759						
Convair, 3 mi DW							577						
Convair, 20 mi DW							232						

1. Values given as averages; "&amp;" indicates the averages of two sensors



Figure 5. Distribution of CO<sub>2</sub> over the test site during burn 2

Propene	2-Ethyl-1-Butene	1-Octene
Propane	trans-3-Methyl-2-Pentene	Octane
Freon 22 (Chlorodifluoromethane)	cis-2-Hexene	trans-1,2-Dimethylcyclohexane
Freon 12 (Dichlorodifluoromethane)	cis-3-Methyl-2-Pentene	trans-2-Octene
Propyne	2,2-Dimethylpentane	Tetrachloroethene
Chloromethane	1,2-Dichloroethane	cis-1,4/trans-1,3-Dimethylcyclohexane
Isobutane (2-Methylpropane)	Methylcyclopentane	cis-2-Octene
Freon 114 (1,2-Dichlorotetrafluoroethane)	2,4-Dimethylpentane	cis-1,2-Dimethylcyclohexane
Vinylchloride (Chloroethene)	1,1,1-Trichloroethane	Chlorobenzene
1-Butene/2-Methylpropene	2,2,3-Trimethylbutane	Ethylbenzene
1,3-Butadiene	1-Methylcyclopentene	m/p-Xylene
Butane	Benzene	Bromoform
trans-2-Butene	Carbon tetrachloride	1,4-Dichlorobutane
2,2-Dimethylpropane	Cyclohexane	Styrene
Bromomethane	2-Methylhexane	1,1,2,2-Tetrachloroethane
1-Butyne	2,3-Dimethylpentane	o-Xylene
cis-2-Butene	Cyclohexene	1-Nonene
Chloroethane	3-Methylhexane	Nonane
2-Methylbutane	Dibromomethane	iso-Propylbenzene
Freon 11 (Trichlorofluoromethane)	1,2-Dichloropropane	3,6-Dimethyloctane
1-Pentene	Bromodichloromethane	n-Propylbenzene
2-Methyl-1-Butene	Trichloroethene	3-Ethyltoluene
Pentane	1-Heptene	4-Ethyltoluene
Isoprene (2-Methyl-1,3-Butadiene)	2,2,4-Trimethylpentane	1,3,5-Trimethylbenzene
Ethylbromide	trans-3-Heptene	2-Ethyltoluene
trans-2-Pentene	cis-3-Heptene	1-Decene
1,1-Dichloroethene	Heptane	trans-Butylbenzene
cis-2-Pentene	trans-2-Heptene	1,2,4-Trimethylbenzene
Dichloromethane	cis-2-Heptene	Decane
2-Methyl-2-Butene	cis-1,3-Dichloropropene	1,3-Dichlorobenzene
Freon 113 (1,1,2-Trichlorotrifluoroethane)	2,2-Dimethylhexane	1,4-Dichlorobenzene
2,2-Dimethylbutane	Methylcyclohexane	iso-Butylbenzene
Cyclopentene	2,5-Dimethylhexane	sec-Butylbenzene
trans-1,2-Dichloroethene	2,4-Dimethylhexane	1,2,3-Trimethylbenzene
4-Methyl-1-Pentene	trans-1,3-Dichloropropene	p-Cymene
3-Methyl-1-Pentene	1,1,2-Trichloroethane	1,2-Dichlorobenzene
1,1-Dichloroethane	Bromotrichloromethane	Indane
Cyclopentane	2,3,4-Trimethylpentane	1,3-Diethylbenzene
2,3-Dimethylbutane	Toluene	1,4-Diethylbenzene
trans-4-Methyl-2-Pentene	2-Methylheptane	n-Butylbenzene
2-Methylpentane	4-Methylheptane	1,2-Diethylbenzene
cis-4-Methyl-2-Pentene	1-Methylcyclohexene	Undecane
3-Methylpentane	Dibromochloromethane	1,2,4-Trichlorobenzene
1-Hexene/2-Methyl-1-Pentene	3-Methylheptane	Naphthalene
cis-1,2-Dichloroethene	cis-1,3-Dimethylcyclohexane	Dodecane
Hexane	trans-1,4-Dimethylcyclohexane	Hexachlorbutadiene
Chloroform	EDB (1,2-Dibromoethane)	Hexylbenzene
trans-2-Hexene	2,2,5-Trimethylhexane	

Figure 6. VOC analytes

ities. Generally gas concentrations downwind are very low. Gas concentrations, especially in low winds can be as high around the fire as downwind. Further research work is required to define the movement and distribution of gases resulting from in-situ oil fires.

**Particulate matter/soot.** Particulate matter at ground level is only a matter of concern (greater than occupational health criteria values) very close to the fire and under the plume. The concentration of particulates in the smoke plume may not be a concern past about 500 meters. Data from the aircraft have not been fully analyzed at time of writing. The level of respirable particulates, those with a size less than  $10\mu$ , is poorly understood and requires further research.

**Water quality.** The levels of compounds in the water of the test tanks or under the water at sea have been found to be low and very nearly that of background levels. The aquatic toxicity of the water under a burn is too low to be measured using currently available toxicity tests.

**Organic compounds.** No exotic or highly toxic compounds are generated as a result of the combustion process. Organic macromolecules are in lesser concentration in the smoke and downwind than they are in the oil itself. Volatile organic compounds are released in large concentration by fires, but in lesser concentrations than in an evaporating slick that is not burning.

**Residue.** The residue is generally lighter than water. Density appears to relate to efficiency. If a burn is highly efficient ( $>99.9\%$ ), then the residue may be neutrally buoyant. The residue resembles high-weathered oil, measurements showed this to be about 40 to 50 percent weathered (% weight loss). The residue contains a lower amount of PAHs than the starting oil, although a slightly elevated amount of multiringed PAHs are present. Further research might clarify the processes responsible for producing residue.

**PAHs.** Additional polyaromatic hydrocarbons are not produced by in-situ oil fires. Oils contain significant quantities of PAHs. These are largely destroyed in combustion. The PAH concentrations in the smoke, both in the plume and the particulate precipitation at ground level, are much less than the starting oil. This also includes the concentration of multiringed PAHs that are often created in other combustion processes such as low-temperature incinerators and diesel engines. This finding is very different from that noted in earlier laboratory experiments. It is suspected that reprecipitation of large soot particles

occurs in large-scale tests but does not occur in laboratory tests. These large soot particles are conducive to the accumulation of large multiringed PAHs; and the burn residue does show a slight increase in the concentration of multiringed PAHs. However, when considering the mass balance of the burn, most of the five- and six-ringed PAHs are destroyed by the fire.

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