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Smoke Measurements Using a Tethered Miniblimp at the Newfoundland Offshore Oil Burn Experiment

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ABSTRACT

Smoke measurements were taken during the 1993 Newfoundland Offshore Oil Burn Experiment using a helium filled miniblimp tethered to a vessel operated approximately 300 m downwind of the fire. The smoke sampling package suspended from the miniblimp consisted of sampling pumps which drew smoke through either a cascade impactor or filter and discharged gas samples into collection bags. The smoke yield and smoke particle size distribution were found to be similar to previous measurements made for crude oil. The smoke yields of 14.8 to 15.5 % of the mass of the fuel burned were measured and 83 % of the particulate mass was below 9.8 μm in diameter as measured with a cascade impactor. Measurements of temperature, wind speed, and wind direction taken before and after the burns from the ocean surface to an altitude of 300 m using the tethered miniblimp and a radio telemetry weather station are reported.

INTRODUCTION

In situ burning of spilled oil has distinct advantages over other countermeasures. It offers the potential to convert rapidly large quantities of oil into its primary combustion products, carbon dioxide and water, with a small percentage of smoke particulate and other unburned and residue byproducts. Burning oil spills produces a visible smoke plume containing smoke particulate and other products of combustion which may persist over many kilometers downwind from the burn. This fact gives rise to public health concerns, related to the chemical content of the smoke plume and the downwind deposition of particulate, which need to be answered. Laboratory

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measurements are useful to determine the types of chemical compounds that can be expected from large oil spill burns. To determine the rate of emissions and the transport of the chemical compounds from a burning spill, large scale experiments are required.

A large scale burn experiment was conducted under the direction of Environment Canada off the coast of Newfoundland, Canada near St. John's on August 12, 1993. This experiment known as NOBE (Newfoundland Offshore Burn Experiment) included the sponsorship and participation by more than 25 Canadian and U.S. government agencies and industries. It consisted of two separate burns of crude oil in a towed fire resistant boom. An initial quantity of oil was discharged from a supply vessel through a floating hose into the U shaped towed fire boom. The oil was ignited by dispensing a burning flammable gel from a tank suspended beneath a helicopter. Burning oil was continually added to the boom until the desired total quantity was reached and the fire was allowed to burn out. A large number of samples and measurements were taken during the burns from both vessels and aircraft.

At the request of Environment Canada and under the sponsorship of the Minerals Management Service, U.S. Department of Interior, NIST collected samples from the smoke plume using a smoke sampling package suspended from a tethered helium filled miniblimp. NIST determined smoke yield and smoke particulate size distribution from these samples immediately following the burns then forwarded the smoke particulate samples to Environment Canada for analysis for polycyclic aromatic hydrocarbons (PAH) as part of the cooperative research to maximize the benefit from these large scale experiments.

Before the first burn and after the second burn NIST measured atmospheric conditions from sea level to approximately 300 m in elevation using an airborne weather station attached to the tethered helium filled miniblimp.

ATMOSPHERIC METEOROLOGICAL PROFILE

Measurements of atmospheric conditions were made with an airborne weather station. The airborne weather station was connected to a helium filled miniblimp which was operated from a Canadian Coast Guard Vessel. Airborne atmospheric measurements were made before the first burn and after the second burn so as not to interfere with other airborne measurements made during the fires. The airborne weather station consisted of a thermistor to measure temperature, a cup anemometer to measure wind speed, an electronic compass to measure wind direction, and a pressure transducer to measure barometric pressure. Data from the airborne weather station were transmitted every 20 s via radio to a computerized data collection system on the tending vessel. The position at which the atmospheric measurements were made was determined from a portable global positioning system (GPS) located on the tending vessel.

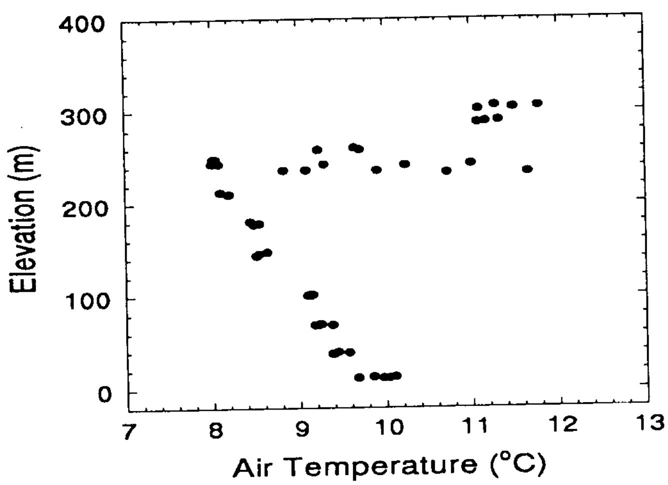

Figure 1. Atmospheric temperature profile before burn 1

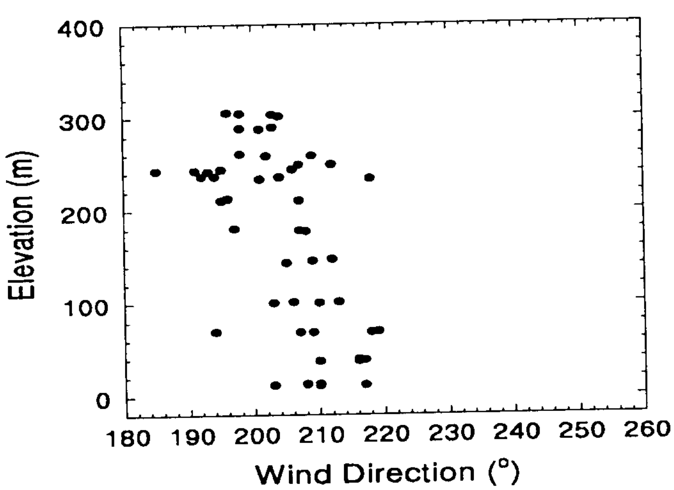

Figure 2. Atmospheric wind direction profile before burn 1

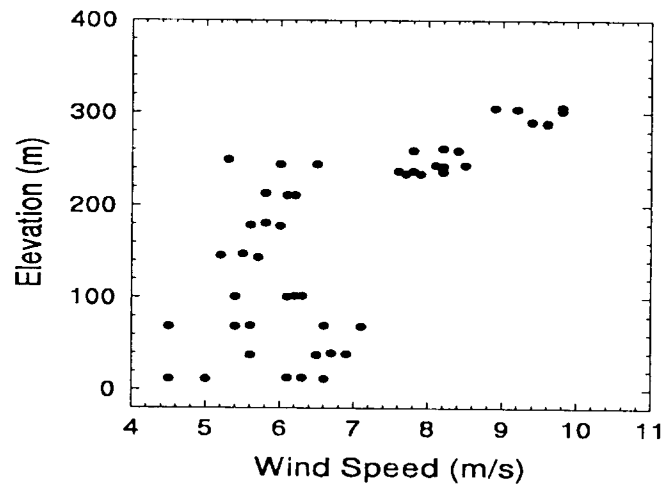

Figure 3. Atmospheric wind speed profile before burn 1

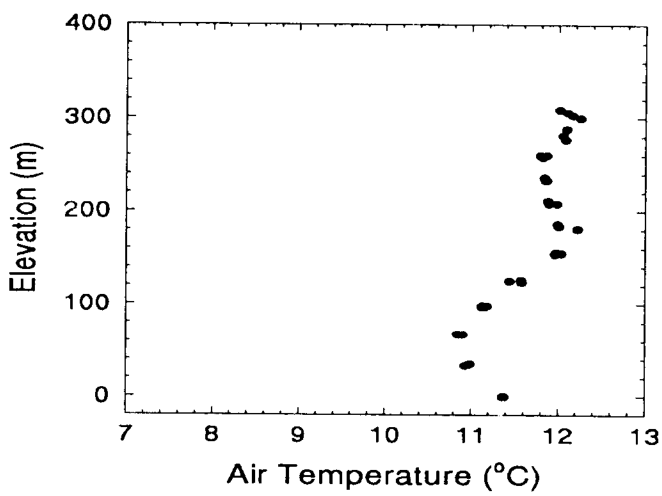

Figure 4. Atmospheric temperature profile after burn 2

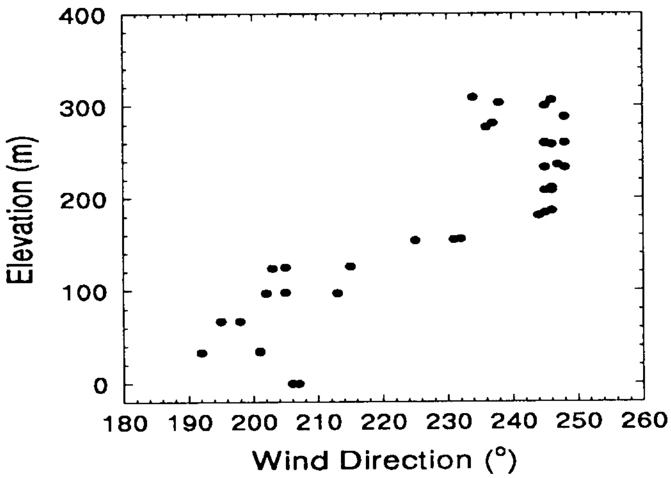

Figure 5. Atmospheric wind direction profile after burn 2

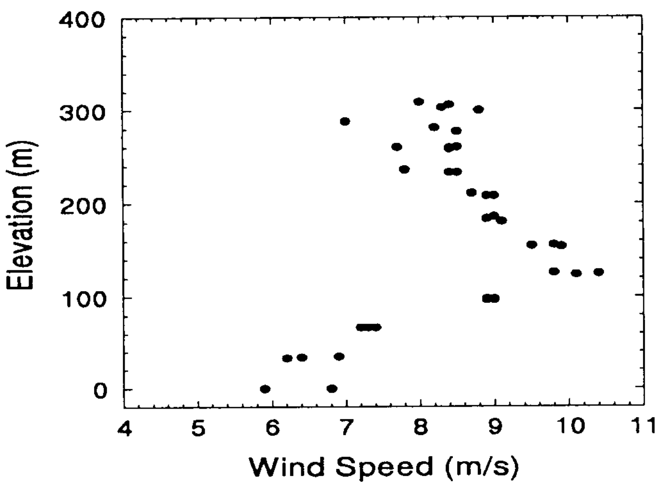

Figure 6. Atmospheric wind speed profile after burn 2

The first atmospheric profile was conducted between 08:12 and 08:35 Newfoundland daylight savings time at approximately 47° 44.10' N, 52° 02.99' W. The second profile was conducted between 15:27 and 15:53 at 47° 40.60' N, 52° 06.17' W. The first burn took place between approximately 10:30 and 12:04 and the second burn between 14:07 and 15:04. Figures 1-3 show the atmospheric profiles before burn 1 and figure 3-6 the profiles after burn 2. Wind directions are the direction from which the wind originates with 0° being true north. The magnetic variation used from chart LC 8014 was 24° 30' W in 1987 with an annual change of 9' E, resulting in a variation for 1993 of 23° 54' W. The temperature discontinuity in figure 1 corresponded with the observation of a small cloud at an elevation of approximately 200 m.

Figure 7. Miniblimp used for smoke sampling during a NOBE burn

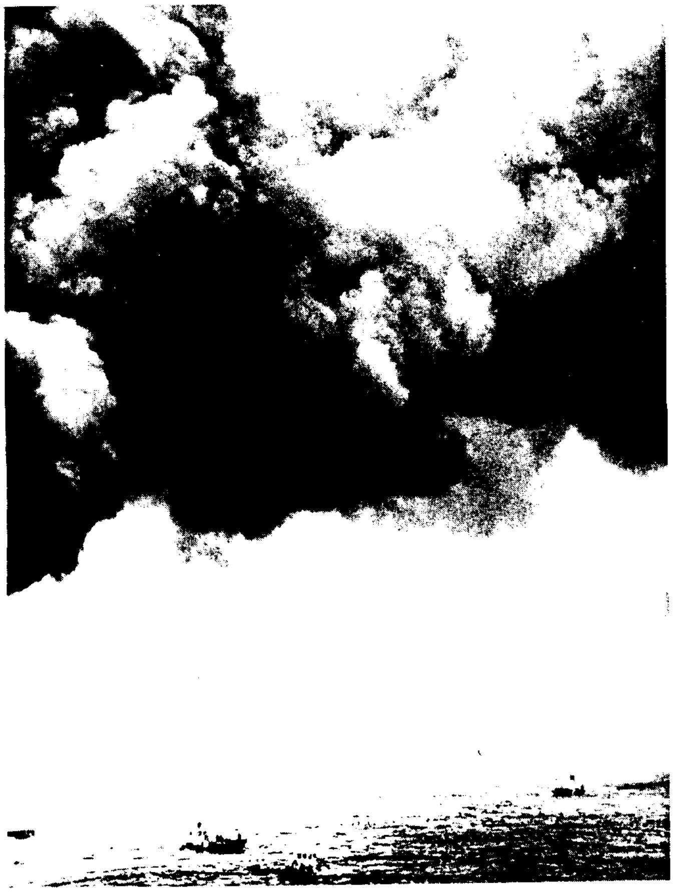

Figure 8. Miniblimp and tending vessel during a NOBE burn

SMOKE SAMPLING MEASUREMENTS

NIST has conducted a number of mesoscale experiments to measure the characteristics of smoke from burning crude oil spills. It has developed several generations of smoke sampling packages with can be suspended from tethered helium filled miniblimps. NIST personnel have also developed considerable expertise in operating these packages.[1-5] During the NOBE burns the miniblimp was operated from a Canadian Coast Guard vessel located downwind of the fire. Figure 7 shows a NOBE burn with the miniblimp located above the plume. Figure 8 shows the miniblimp and the vessel from which it was operated. Figure 9 shows a view of the burn from the position of the miniblimp operating vessel. The twin vortices characteristic of large fires in a crosswind are visible. The smoke sampling package was positioned in one of the vortices.

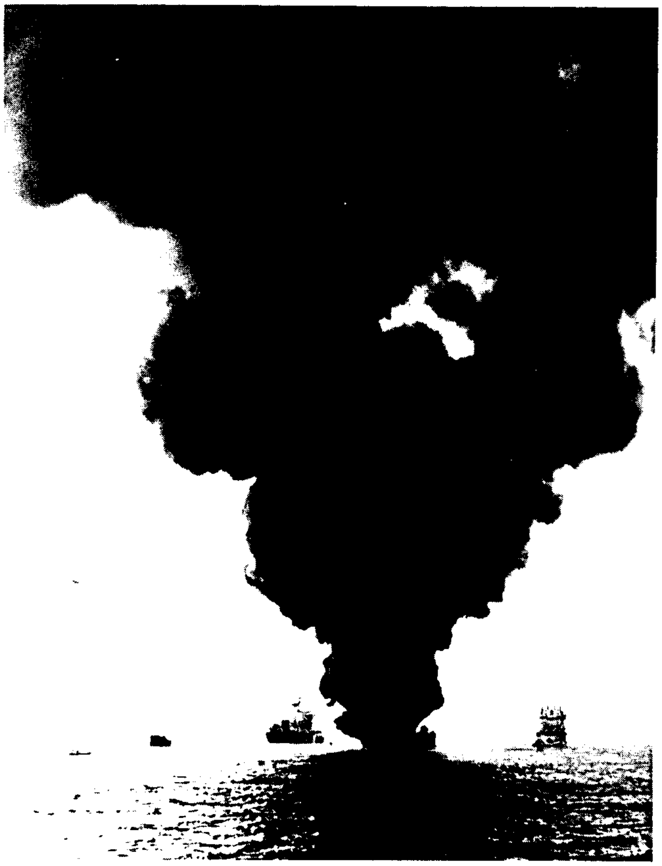

Figure 9. View of NOBE burn from miniblimp tending vessel

The basic package used for the NOBE burns consisted of an aluminum box with overall dimensions 305 by 311 by 127 mm. It is designed to be disassembled into the six component sides so it can be transported in a compact fashion. The package could accommodate up to four battery operated sampling pumps. In this experiment two were used for the first burn and three for the second burn. The total weight of the package as configured for the second burn was 3.4 kg. The package was suspended 30 m below a 5.6 m long 2.3 m diameter miniblimp so the blimp could be kept above the plume with the package in the smoke. The tether line from the blimp was connected to the top of the package and the line to the tending vessel was connected to the bottom allowing the package to orient itself into the wind. A complete description of the package is given in reference [5].

The sampling pumps can operate at flow rates up to 4 L/min. One of the pumps operating at 2 L/min was connected to an 8 stage cascade impactor which segregates smoke particulate from 0 to 10 μm. The substrates for use in the impactors are weighed on a precision balance before and after the fire to determine the particle size distribution. The intakes of the other two pumps operating a 4 L/min are connected to 37 mm smoke particulate sampling filters. The particulate sampling filters are weighed with a precision balance before and after the smoke sample is taken to determine the total mass of smoke particulate collected. The filters were analyzed by Environment Canada for PAH concentration in the smoke.

The two pumps with filters have a control valve on the discharge which proportions part of the discharge to a tedlar gas sample bag with a filled capacity of 2 liters and the rest to the atmosphere. This permits the pumps to be operated at the maximum flow rate and collect the maximum particulate sample while not over-filling the gas sample bag. Before using the system, the total pump flow is measured with a bubble flowmeter. The proportioned valve is adjusted and the discharge to the sample bag measured so that the gas sample bag will be filled during the expected sampling time. The gas collected in the sample bags is analyzed for CO_2 content with a portable gas chromatograph.

Table 1 gives a list of the airborne samples taken. The sample pumps were started with the miniblimp at sea level after the burn had become established. The blimp was then raised to position the smoke sampling package in the plume. Although the test plan called for the blimp to be operated 150 m from the boom, laser range finder measurements during burn 1 showed that the position as directed by the test safety officer was typically from 200 to 400 m. During burn 2 the distance was increased to considerably more than 400 m because of concerns by the safety officer that the boom might fail. Due to the motion of the vessel and the long separation distance, accurate range finder measurements could not be obtained during burn 2.

Table 1. Airborne Samples

Burn No.	Sample No.	Sample Type	Start Time[1] (s)	Total Time (s)	Range (m)	Altitude (m)
1	1	Smoke yield	300	3338	200-400	150
	2	Smoke yield	300	3338	200-400	150
2	1	Smoke yield	180	3877	400+	150
	2	Smoke yield	180	3877	400+	150
	3	Impactor	180	3877	400+	150

[1] - time from ignition

SMOKE YIELD MEASUREMENTS

The smoke production from a fire may be expressed in terms of a smoke yield Y_S which is defined as the mass of smoke particulate m_P produced from burning a fuel mass m_F, as:

$$Y_S = \frac{m_P}{m_F} \quad (1)$$

The mass of carbon in the fuel that is consumed by burning is equal to the mass of carbon in the smoke plume.

$$m_{C,Smoke} = m_{C,Fuel} \quad (2)$$

Three assumptions are made in the analysis. The first is that the smoke particulate is predominately carbon. The second assumption is that samples are collected over a suitable time period to average out natural fluctuations in the fire and plume. The third assumption is that no preferential separation of smoke particulate and combustion gases occurs in the smoke plume up to the point where the sample is taken. In all field measurements the smoke yield measurement is made close to the source where the smoke and gaseous combustion products move in a well formed smoke plume. Combining equations (1) and (2) and taking into account the three assumptions above yields:

$$Y_S = \frac{m_P}{m_{C,Smoke}} \frac{m_{C,Fuel}}{m_F} \quad (3)$$

To evaluate the above ratio, a known volume of smoke is drawn though a filter and the gaseous portion collected in a sample bag. The mass of carbon in the smoke is equal to the mass of carbon in the smoke particulate plus the mass of carbon in the CO_2 and CO in the smoke. In the NOBE burns, the concentration of CO in the gas samples was negligible. The smoke particulate mass is determined by weighing the filter. The mass of the carbon in the gas is the grams of carbon per mole of CO_2 (and CO) times the moles of gas sample times the difference in the volume fraction of CO_2 (and CO) in the sample and the background. The volume fraction of CO_2 in the sample and the background were determined using a gas chromatograph. The mass of carbon in the smoke is:

$$m_{C,Smoke} = m_P + 12\frac{g}{mole}n(\chi^S_{CO_2}-\chi^B_{CO_2}) + 12\frac{g}{mole}n(\chi^S_{CO}-\chi^B_{CO}) \quad (4)$$

The moles of gas in the smoke sample were calculated using the ideal gas law.

$$n = \frac{PV}{RT} \tag{5}$$

where:
n = moles of gas (mol)
P = atmospheric pressure (kPa)
V = total volume of gas sampled (L)
R = gas constant 8.314 (kPa L/K g mol)
T = ambient temperature (K)

The ratio $m_{C,Fuel}/m_F$ is evaluated by determining the elemental carbon mass fraction in the fuel. An elemental analysis of the NOBE oil was conducted by a commercial laboratory. On a mass basis the NOBE oil was 86.64 % carbon, 13.83 % hydrogen, and 0.28 % sulfur.

Combining equations (3) and (4) yields the expression for smoke yield in terms of the measured quantities.

$$Y_S = \frac{m_P \, (m_{C,Fuel}/m_F)}{m_P + 12 \, n \, (\Delta\chi_{CO_2} + \Delta\chi_{CO})} \tag{6}$$

where: $\Delta\chi_{CO_2}$ = difference between the volume fraction of CO_2 in the sample and the background
$\Delta\chi_{CO}$ = difference between the volume fraction of CO in the sample and the background

Smoke was drawn by a battery operated pump through a pre-weighed filter which collected the particulates. The gas passed through the pump to a micrometer adjusted flow control valve and exhaust orifice which metered a portion of the gas flow to a 2 liter sample collection bag. The flow through the filter was measured with a bubble flowmeter prior to each use. The filter samples were weighed on a precision balance before and after the burn and the concentration of CO_2 in the sample collection bag was determined using a gas chromatograph.

Smoke yields are given in table 2. The smoke yields are shown in figure 10 along with measurements from previous crude oil burns[4]. In order to present the smoke yield as a function of diameter an approximate effective diameter was calculated for the NOBE burns. This used the preliminary values from Environment Canada of 48.3 m^3 of oil and a burn time of 90 minutes for burn 1 and 28.9 m^3 of oil and a burn time of 80 minutes for burn 2. The area was calculated by dividing the volume by the burn time then dividing by the regression rate previously measured in mesoscale Louisiana oil burns of 0.062 mm/s.[4] Although the burn area was not constant during the NOBE burns and the regression rate is unknown for the oil used, an approximate area is useful to compare the data. The smoke yield measured for the

NOBE burns was in the same range as that previously measured for crude oil. The average yield for the first burn 15.4 ± 0.2 % normally 300 m from the fire and 14.9 ± 0.1 % for the second burn greater than 400 m from the fire. Where the uncertainty represents one standard deviation.

Table 2. Smoke yield

Burn No.	Effective Burn Dia. (m)	Sample	Start Time[1] (s)	Total Time (s)	Smoke Yield (%)
1	13.5	1	300	3338	15.5
		2	300	3338	15.2
2	11.1	1	180	3877	15.0
		2	180	3877	14.8

[1] - time from ignition

PARTICLE SIZE DISTRIBUTION

Particulate size is an important health consideration and also impacts the dynamics of smoke settling. Particulates having an aerodynamic effective diameter less than 10 μm are considered respirable [6] and may be drawn into the lungs with normal breathing. In general small particle sizes have the greatest resistance to settling and can be expected to be carried much further from the burn site than larger particles. In addition to the overall particulate yield from the crude oil fires, it is therefore important to have some knowledge about the aerodynamic size distribution of the particulate.

There are no means to directly translate the observed irregular shape of smoke particles [2] into aerodynamic effective diameters. The aerodynamic effective diameter of a particle is defined as the diameter of a smooth spherical particle with a unit density of 1000 kg/m^3 that has the same settling velocity in air. Therefore, the aerodynamic effective diameter of a particle depends on the size, shape and density of the particle. Cascade impactors measure particle size distribution by the amount of particulate deposited on a series of plates. The particulate laden air is drawn through the cascade impactor which consists of a series of stages each having a nozzle and plate. Aerodynamic forces determine the size ranges that will be deposited on the plate in each stage and the sizes that will pass through to other stages downstream. The fraction of the total deposition collected by each stage of the device determines the distribution of the aerodynamic effective diameter of the particles. The small and light weight commercial impactors used in this study contained 8 stages. For cases where a small quantity of particulate is expected, some of the stages may be removed. Each stage of the impactor is characterized by its cutpoint diameter. The cutpoint diameter is the aerodynamic effective diameter that is collected with 50 percent efficiency. Ideally the cutpoint diameter represents the

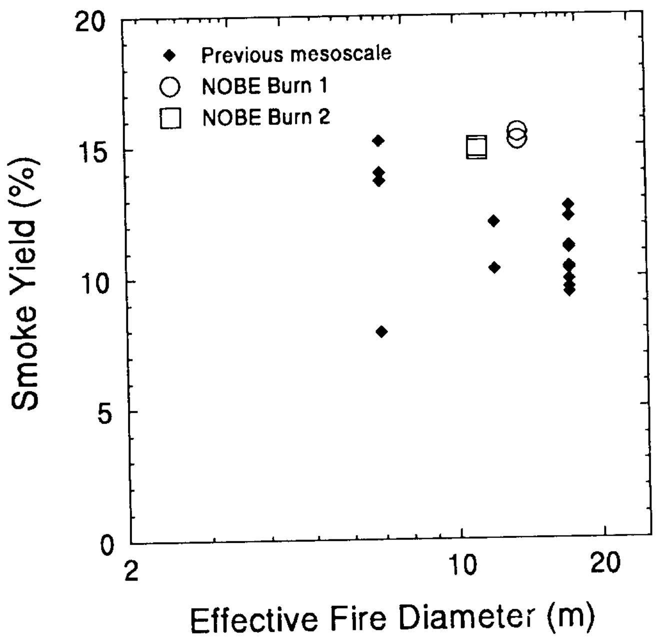

Figure 10. Smoke yield

largest diameter particle which will not pass to the next stage but in practice some larger particles do move to the next stage. The cutpoint diameter is a function of the flow rate through the instrument and decreases with increasing flow rate.

For all burns, the impactor was operated at a flow rate of 2.0 L/min with 8 stages and a back-up filter. Table 3 shows the cutpoint diameters for each of the stages in the instrument and the back-up filter [7].

Table 3. Cascade impactor stage cutpoint size diameters

Stage 1 (μm)	Stage 2 (μm)	Stage 3 (μm)	Stage 4 (μm)	Stage 5 (μm)	Stage 6 (μm)	Stage 7 (μm)	Stage 8 (μm)	Back-up Filter
21.3	14.8	9.8	6.0	3.5	1.55	0.93	0.52	0

Figure 11 shows the cumulative size distribution of smoke particulate from NOBE burn 2 as well as a previous 17.2 m effective diameter mesoscale Louisiana crude oil

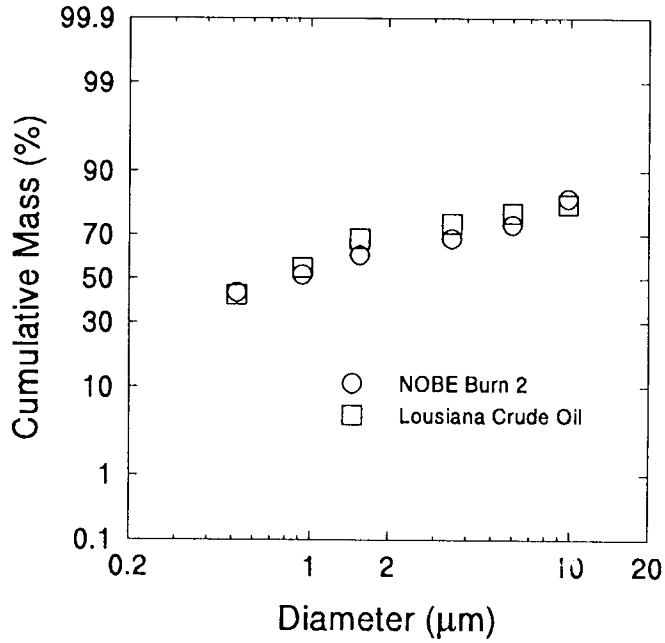

Figure 11. Smoke particulate cumulative size distribution

fire.[4] The size distribution for the Nobe sample is similar to the distribution for the previous crude oil burn. The cumulative mass of particulate below 9.8 µm in diameter as measured by the cascade impactor was 83 % for NOBE burn 2.

CONCLUSIONS

The values for smoke yield measured for NOBE burns, 15.4 ± 0.2 % for burn 1 and 14.9 ± 0.1 % for burn 2 on a mass basis, were within the range of values previously measured for crude oil.

The size distributions of aerodynamic effective diameters for the smoke particulate were nearly identical for the second NOBE burn and the previous Louisiana crude oil burn. For the second NOBE burn 83 % of the particulate mass was below 9.8 µm in diameter as measured with a cascade impactor.