Reprinted from: Proceedings of 17th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, Vol. I, June 8-10, 1994, Vancourver, British Columbia.

Smoke Measurements Using a Helicopter Transported Sampling Package

William D. Walton, Jay McElroy, William H. Twilley
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce
Gaithersburg, MD 20899

and

Robert R. Hiltabrand
Environmental Safety Branch
Research and Development Center
U.S. Coast Guard
U.S. Department of Transportation
Groton, Connecticut 06340

ABSTRACT

A first generation smoke sampling package designed to be deployed on a helicopter winch cable has been developed. The package contains three sampling pumps which are operated via radio control from the helicopter. The pumps can be fitted with a variety of sampling trains and gas collection bags. The package also contains instruments for measuring and recording temperature, relative humidity, barometric pressure, wind speed, and package orientation. The package was tested using a Coast Guard HH-65A helicopter for aerodynamic stability without a fire and was then used to collect smoke samples from two 231 m^2 diesel fuel fires at the U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama. An improved smoke sampling package designed to be suspended beneath a tethered helium filled miniblimp was also developed and used to collect samples from a 37 m^2 diesel fuel fire. The burning rate for diesel fuel on water as indicated by the surface regression rate was found to be 0.074 ± 0.001 mm/s. Smoke particulate yields ranged from 9 to 14 % of the mass of fuel burned. PAH concentrations on the smoke particulate were measured. The cumulative size distribution of aerodynamic effective diameters for the diesel fuel smoke particulate were found to be similar to those previously measured for crude oil.

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. In situ burning requires

minimal equipment and less labor than other techniques. It can be applied in areas where many other methods cannot due to lack of response infra-structure and/or lack of alternatives. Because the oil is mainly converted to airborne products of combustion by burning, the need for physical collection, storage, and transport of recovered fluids is reduced to the few percent of the original spill volume that remains as residue after burning.

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. Air quality is also affected by evaporation of large oil spills that are not burned. Volatile organic compounds (VOC) including benzene, toluene, and xylene and polycyclic aromatic hydrocarbons (PAH) are found in the air downwind of an evaporating crude oil spill. Laboratory measurements are useful to determine the types of chemical compounds that can be expected from large oil spill burns or the evaporation of the spill. To determine the rate of emissions and the transport of the chemical compounds from a burning or evaporating spill, mesoscale experiments or measurements at spills of opportunity are required. In order to make measurements in the field, light weight portable and rugged smoke sampling packages are required.

BACKGROUND

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[1-4]. It was recognized however, that these smoke sampling packages were not fully optimized and the use of helium filled tethered miniblimps was not practical in all situations.

Under the sponsorship of the U.S. Coast Guard, NIST developed two field deployable smoke sampling packages. One was an improved design to be suspended beneath a tethered helium filled miniblimp and the other a new design to be suspended beneath a helicopter. The packages were designed to rapidly collect data on smoke and/or emissions from mesoscale experiments or spills of opportunity. The packages developed were tested during mesoscale burns of diesel fuel at the U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama. Diesel fuel was selected as fuel for the burns for economic reasons. Diesel fuel is readily available by barge in Mobile, Alabama from commercial ship fueling operators. Crude oil must be brought in and stored at considerable expense. Since the purpose of the burns was to examine the operation of the smoke sampling packages, the smoke from diesel fuel fires would serve this purpose.

MINIBLIMP SAMPLING PACKAGE

NIST has developed and used smoke sampling packages which can be suspended from a tethered helium filled miniblimp. These packages have provided valuable information on the smoke emissions from crude oil fires. The principal advantage of the blimp transported sampling package is its simplicity, low operating cost, and virtually unlimited flight time. The blimp, sampling package, and support equipment can be easily transported. While sampling smoke plumes with blimps appears to be simple, it has taken a great deal of practice over a period of years to determine the most efficient equipment and techniques. The principal disadvantages of using blimps are limited capacity and altitude, obtaining a supply of helium at the site, and that blimps must be operated downwind of the fire in winds less than 10 m/s.

Based on the experience gained in operating blimp transported sampling packages over a number of years, NIST developed a series of design objectives for an improved blimp transported smoke sampling system that could be used to make measurements on spills of opportunity. These objectives were:

1. A minimum weight system which could be transported as luggage on a commercial airline.
2. A system which would not require 110v power to operate, except for analytical instruments used on the ground.
3. A minimum weight sampling package which could accommodate up to 4 sampling pumps and 2 gas collection bags. The sampling pumps should be easy to remove to adjust the total weight of the package.
4. A system which would not rely on rechargeable batteries.
5. Allow operation either from land or a vessel of opportunity.

The basic components of the tethered miniblimp smoke sampling system are the min-blimp, tether line winch, and sample package.

NIST has used a number of conventional shaped blimps with helium capacities from 10 to 42 m^3. The smaller sizes do not have sufficient lift and the larger sizes are difficult to handle. Experience has shown that a capacity of 15 m^3 is optimal in most cases. The package weight which can be properly positioned in the smoke plump depends on the size of the fire, the wind speed and the distance from the fire. For example, with winds of 5 m/s the package must be flown at a height of 150 m at a distance of 200 m from a fire. Higher winds increase the drag on the blimp but reduce the smoke height near the fire. At wind speeds above 10 m/s it is very difficult to control the blimp. An experienced operator can become proficient at selecting an optimal package weight for the conditions.

One of the most difficult flight conditions arises when the winds are near calm. The smoke rises nearly straight up and package altitudes of 500 m or more are necessary to reach the level where the plume reaches neutral buoyancy and begins to spread out. To address this situation, NIST experimented with a round shape blimp which has the

greatest net lift per volume. The round shape worked extremely well in calm winds and could lift a 3 kg package to altitudes of over 600 m. But when tested in a 5 m/s wind the round shape could attain a maximum altitude of less than 20 m with no package. While the round shape has the maximum lift, it also has significant drag. With very little wind speed the drag quickly dominates the lift. The round shape is best in calm winds but the conventional blimp design is best overall choice.

NIST has used 1 commercially made and 3 custom design electric winches. While they greatly reduced the effort to tend a blimp, they require a significant amount of power and are heavy. When operating a 15 m^3 capacity blimp the operator does most of the positioning by hand. As a result, a winch was design for use in spills of opportunity which is hand operated, made of aluminum, with a capacity of over 900 m of line. The winch is strong enough, when anchored, to hold the blimp. It disassembles so it can be transported in a suitcase size container.

The primary constraint on the sample package is weight. The lighter the components, the more samples that can be taken and the higher the blimp can operate. Each of the components was carefully analyzed to determine where weight could be reduced. Light weight aluminum panel construction provided the most efficient design for the package platform. The design is inherently strong and protects the gas sample bags. It can be easily disassembled for transportation. The size was minimized by mounting the sampling pumps on the outside allowing easy access and the ability to place or remove pumps quickly. The greatest weight savings came from operating the pumps with alkaline batteries instead of the normal rechargeable batteries. While somewhat more expensive to operate, it also eliminates the need to maintain rechargeable batteries in a constant state of readiness.

The basic package consists of an aluminum box with overall dimensions 305 by 311 by 127 mm and weighs 0.6 kg. It is designed to be disassembled into the six component sides so it can be transported in a compact fashion. The package can accommodate up to four battery operated sampling pumps although three were used for these burns. The pumps can be operated continuously or set to stop after a specified period of time. The platform contains two plug in modules to allow for turning on and off of two of the pumps by radio control. Normally the radio control is not used as it adds 200 grams to the package. Figure 1 is a photograph of the sample package with the front cover removed and figure 2 is a schematic drawing of the package identifying the principal components. The total weight of the package in this configuration is 3.4 kg. Normally the package is located 60 m below the blimp so the blimp can be kept above the plume with the package in the smoke. The tether line from the blimp is connected to the top of the package and the line to the ground is connected to the bottom allowing the package to orient itself into the wind.

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 at 4 L/min are connected

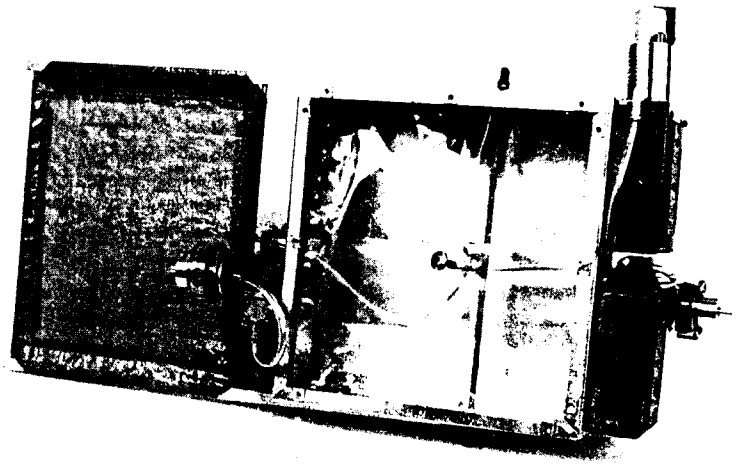

Figure 1. Photograph of miniblimp transported smoke sampling package

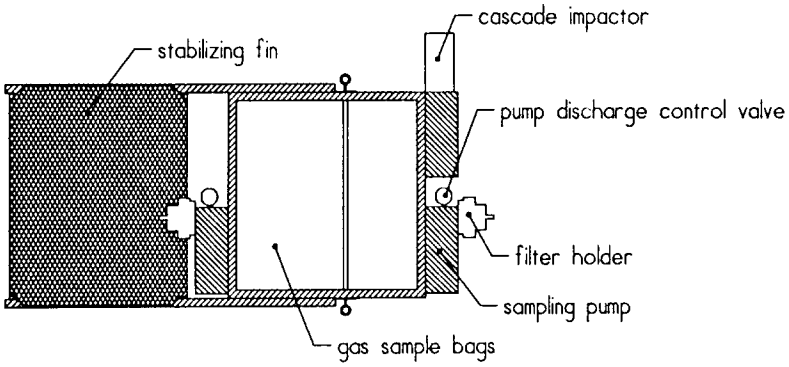

Figure 2. Schematic of miniblimp transported smoke sampling package

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 can then be analyzed for PAH concentration in the smoke. Other types of filters can be used in place of the smoke particulate filters to permit analysis of the smoke for other chemical components.

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 fill 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 test time. The gas collected in the sample bags is typically analyzed with a gas chromatograph.

HELICOPTER TRANSPORTED SMOKE SAMPLING PACKAGE

Although a helicopter transported package requires the availability of a helicopter, its weight is not as critical as with a blimp package, it can be quickly deployed, operated in higher winds, and at a higher altitude than the blimp package. In near calm winds a helicopter transported package has the potential to sample the smoke at the altitude where the smoke reaches neutral buoyancy and spreads out.

The principal objective of the helicopter smoke sampling package was to collect gaseous and particulate samples from the smoke plume for laboratory analysis. Depending on the situation, the particulate samples could be analyzed for various classes of organic and inorganic compounds as well as the total quantity of smoke particulate per unit volume of gas sampled. Further, using a cascade impactor, the size distribution of the smoke particulate could be determined. In addition, the package was designed to collect meteorological data which could be used as smoke plume trajectory modeling input.

In the first stage of development a prototype package was constructed that was 530 mm high, 200 mm wide, and 810 mm long and weighed 18 kg. A light weight fin the same size as the package was attached to the rear of the package to provide aerodynamic stability. While the prototype did not contain sampling apparatus, it did have a strobe light operated by a radio controlled switch and a remote transmitting weather station normally used on a tethered blimp. The radio controlled switch and strobe light were used to test the feasibility of turning sampling pumps off and on from the helicopter. The weather station was used to test the feasibility of operating weather instruments as part of the package and to examine the future use of radio transmitted data from a sampling package.

The package was tested beneath a U.S Coast Guard HH-65A helicopter from the Coast Guard Aviation Training Center in Mobile, Alabama without a fire. During that test it was learned that the package could be easily deployed through the door of

the helicopter on the winch cable. A forward speed of about 10 m/s would prevent the package from spinning during deployment and retrieval. The package was tested with cable lengths of 30 and 60 m and was found to be stable. There was occasionally a slight fluttering of the package with 60 m of cable, no forward helicopter motion, and near calm winds. The package was also tested with the helicopter in forward motion and it appeared that the package would be completely stable when operated with at least light winds.

Both the radio controlled switch which operated in the 72 Mhz model airplane control band and the radio transmitted weather station on 403.5 Mhz operated with no problems and did not appear to interfere with the radios or avionics on the helicopter. The radio controlled switch was operated from within the helicopter and the weather station transmitted to a receiver located on the ground. The weather station transmitted up to a range of a few hundred meters with less than one-half watt power output and a less than optimal antenna. This would indicate that, as expected, a several watt transmitter with optimal antenna could transmit data to and from a package over distances of several thousand meters. The use of weather instruments in the package demonstrated the feasibility of obtaining weather profiles with the same package used for sampling. Although there may be slight interference from the down wash, these profiles would generally be accurate enough to be used in predicting the downwind smoke movement. They would be far superior to ground level weather data which might only be available at a permanent or temporary weather station some distance from a burn site.

Based on the test flight it was determined that the prototype design performed well and development should continue. One of the drawbacks of the prototype was its size did not permit easy transport on a commercial airline flight as luggage. The final package design is the same shape as the prototype but slightly smaller to simplify shipping and handling. The package has a flat top and bottom, a rounded front end, and tapers toward the rear. It is 370 mm high, 180 mm wide, and 1000 mm long. The stabilizing fin is 340 mm high and 770 mm long. Figure 3 is a photograph of the sample package with the front cover removed and figure 4 is a schematic drawing of the package identifying the principal components. The total weight of the package in this configuration is 25 kg. Figure 5 shows the package suspended below a U.S. Coast Guard HH-65A helicopter. Quick connect fasteners are used on one side of the package to allow easy access to the interior. In addition, the entire front of the package which contains the smoke particulate filters can be quickly removed. The package has been designed to separate into three pieces and the fin, each of which can fit into an inexpensive but rugged suitcase size shipping container.

Three pumps which can operate at flow rates up to 4 L/min are used to collect the samples. The intakes of two pumps 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 can then be analyzed for PAH concentration in the smoke. Other types of filters can be used in place of the smoke particulate filters to permit analysis of the smoke for other chemical components. One of the pumps can

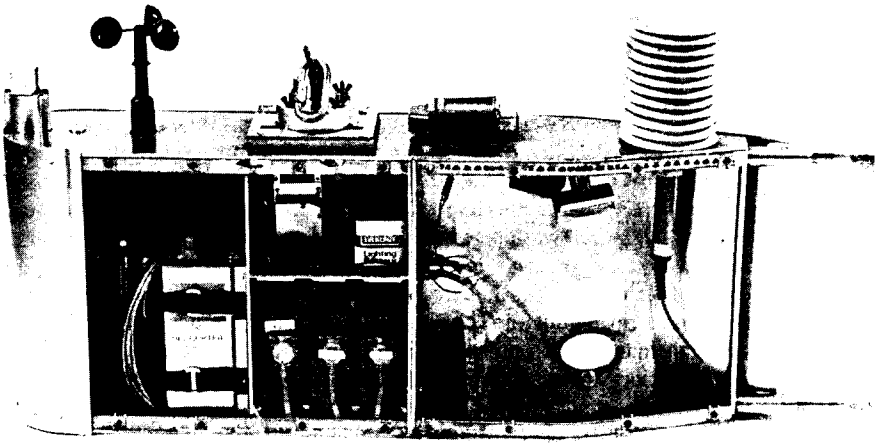

Figure 3. Photograph of helicopter transported smoke sampling package

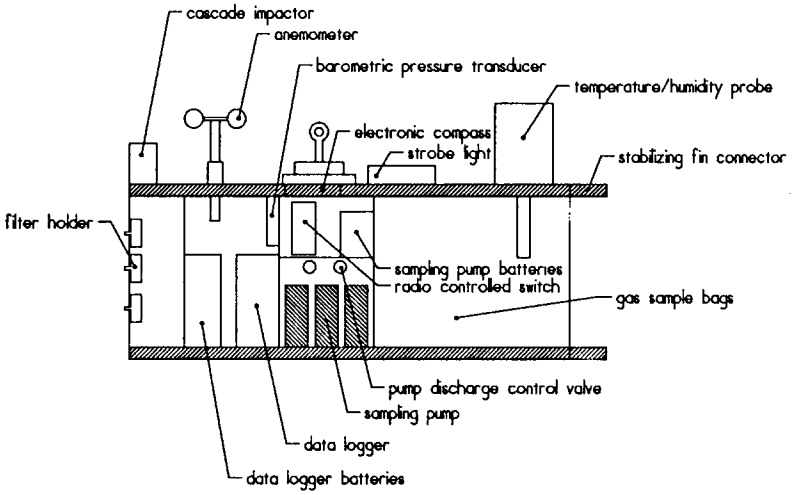

Figure 4. Schematic of Helicopter transported smoke sampling package

Figure 5. Smoke sampling package suspended beneath a U.S. Coast Guard helicopter

be connect to either a sampling filter or, as for the test burns, an 8 stage cascade impactor which segregates smoke particulate from 0 to 10 μm in effective aerodynamic diameter. The substrates for use in the impactor are weighed on a precision balance before and after the fire to determine the particle size distribution. The two pumps with filters have a valve on the discharge which proportions part of the discharge to a tedlar gas sample bag 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 overfilling 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 test time. The gas collected in the sample bags is typically analyzed with a gas chromatograph.

The batteries for the pumps have been modified so that all three pumps can be operated from a single switched battery power supply. This eliminates the need to maintain rechargeable batteries in a constant state of readiness to respond to a spill of opportunity. The power supply can be switched either by a radio controlled switch in the helicopter or by a switch on the unit. A strobe light on top of the unit wired in parallel with the pumps providing a visual indication of when the pumps are operating.

The weather instruments include a temperature and relative humidity probe, a barometric pressure sensor, an anemometer, and electronic compass. Data from the weather instruments is collected every 10 seconds on a data acquisition system and stored in a solid state digital storage module for later computer retrieval. The system acquires data during the entire flight without operator intervention. The system can be used to record conditions inside the smoke plume as well as provide an atmospheric profile. From the barometric pressure the relative height of the package above the initial starting point can be determined. The electronic compass determines the orientation of the package and thus the direction of the wind if the helicopter is stationary or the helicopter's direction if it is moving.

EXPERIMENTAL CONFIGURATION

Three mesoscale diesel fuel burns to test the smoke sampling packages were carried out under the direction of NIST at the United States Coast Guard Fire and Safety Test Detachment facility on Little Sand Island in Mobile Bay, Alabama. Little Sand Island is approximately 0.2 km^2 in size and includes three decommissioned ships docked in a lagoon. The ships and facilities on the island have been used for a wide variety of full-scale marine fire tests. Figure 6 is a plan view of the portion of the island used for the mesoscale burns.

The burns were conducted in a nominal 15 m square steel burn pan constructed specifically for oil spill burning. The burn pan was 0.61 m deep and was constructed with two perimeter walls approximately 1.2 m apart forming an inner and outer area of the pan. The inside dimensions of the inner area of the pan were 15.2 m by 15.2 m. The two perimeter walls were connected with baffles and the space between the walls, which formed the outer area of the pan, was filled with bay water during the burns. The base of the pan was 6 mm thick steel plate and the walls were 5 mm thick steel plate. The tops of the walls were reinforced with steel angle to prevent warping during the burns. The base of the pan was located on ground level and was reinforced with steel beams on steel footers under the pan. Water fill pipes were connected to both the inner and outer areas of the pan. Water was pumped directly from Mobile Bay into both the inner and outer areas of the pan. The inner area of the pan was filled with approximately 0.5 m of water and the diesel fuel was added on top of the water. A sand fuel spill containment dike approximately 0.5 m high was constructed around the perimeter of the pan 4 m from the outer edge.

The fuel used for the burns was number 2 diesel fuel obtained from a commercial supplier in Mobile, Alabama. The fuel used for burn 1019 was 86.20% carbon,

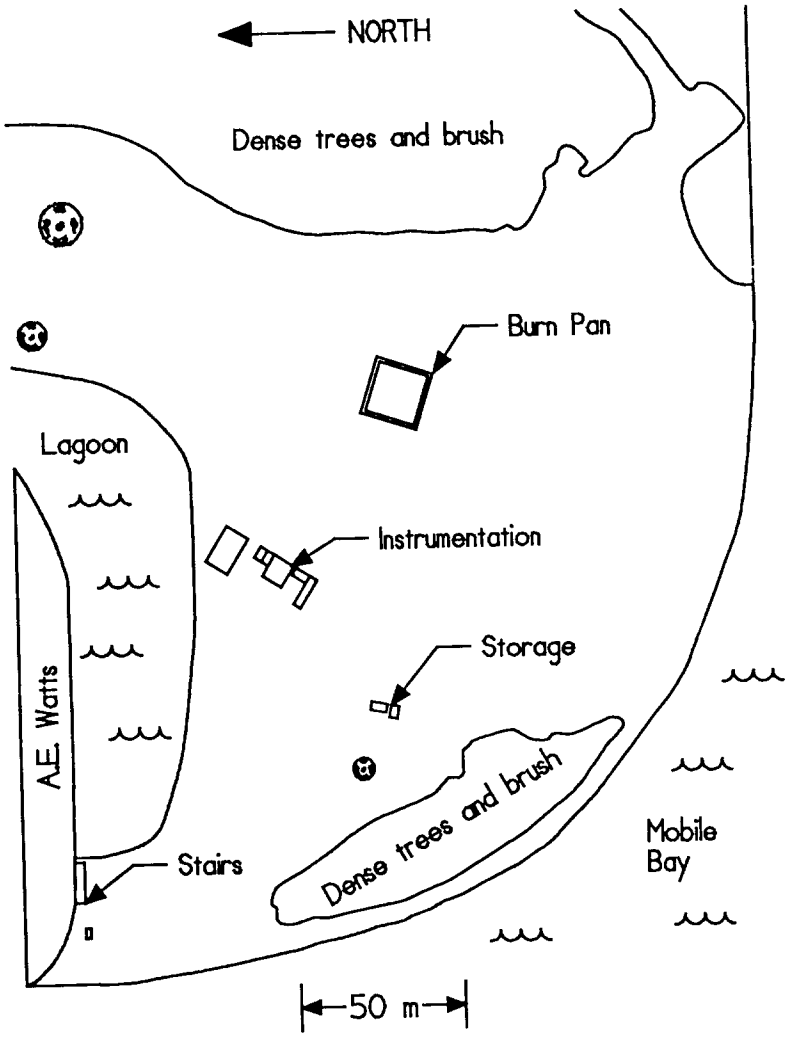

Figure 6. USCG mesoscale burn facility site plan

13.29% hydrogen, and 0.65% sulfur, and for burns 1022a and 1022b was 86.49% carbon, 12.74% hydrogen, and 0.53% sulfur by mass as measured by a commercial testing laboratory.

Diesel fuel was pumped to the burn pan via an underground pipe. A vertical section of the fuel fill pipe penetrated the base of the pan and terminated in a fitting to

disperse the fuel horizontally below the water level. The supply side of the fuel fill pipe terminated approximately 200 m from the burn pan. Gate valves were located in the supply pipe next to the pan, 52 m from the pan and at the supply point. A check valve and a orifice plate flow meter were located in the supply pipe near the pan.

Two different primary burn areas were used in the series. These areas consisted of the full inner pan with an area of 231 m^2 and a partial pan area of 37.2 m^2. The partial pan area was achieved by partitioning a corner of the inner pan with two 6.1 m sections of fire resistant boom.

A total of 3 burns were conducted. Table 1 gives the size and areas for the burns. An effective diameter was calculated for both of the rectangular burn areas. The effective diameter is the diameter of a circle with the same area as the rectangular burn area used.

Table 1. Burn size

Burn No.	Burn Size (m)	Burn Area (m^2)	Burn Area (ft^2)	Effective Burn Diameter (m)	Effective Burn Diameter (ft)	Burn Area/ Full Pan Area (%)	Features
1019	6.10 × 6.10	37.2	400	6.88	22.6	16	boom formed two sides of burn area
1022a	15.2 × 15.2	231	2490	17.2	56.4	100	
1022b	15.2 × 15.2	231	2490	17.2	56.4	100	

INSTRUMENTATION

A manometer and pressure transducer were used to measure the liquid level in the pan. Since the diesel fuel and the water in the pan had different densities, a correction was applied to determine the thickness of the fuel layer during the burn. A tube was connected to the inner pan through a pipe penetrating the inner and outer walls of the pan. The tube ran underground to the instrumentation building and connected to a liquid manometer and a pressure transducer. The output from the pressure transducer was recorded every two seconds on a computerized data acquisition system.

Measurements of atmospheric conditions were made with two ground based and one airborne weather stations. The first ground based station was located 85 m at a bearing of 161° from the southwest corner of the burn pan and 2.1 m above the ground. The second ground based weather station was located 85 m at a bearing 159° from the southeast corner of the burn pan and 2.6 m above the ground. Both ground stations consisted of a thermistor to measure temperature, a propeller on vane anemometer to measure wind direction and speed, and a capacitive relative humidity

sensor. In addition the first weather station had a silicon photodiode pyranometer to measure incident solar radiation. Atmospheric data from the first ground based weather station were recorded every 30 s and from the second station every 32 s with a computerized data acquisition system. The airborne weather station was connected to a helium filled miniblimp which was tethered approximately 50 m from the pan. Airborne weather measurements were made prior to the burns so as not to interfere with flight operations 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 via radio to a ground based computerized data collection system every 20 s.

BURN PROCEDURE

Prior to pumping fuel into the pan, water was pumped into the outer pan so that the water level was nearly to the top of the pan. Water was also pumped into the inner pan so that the water surface level was approximately 110 mm below the top of the pan. The distance from four reference points at the top of each side of the pan to the surface of the water in the inner pan was measured and recorded. A water sample from the inner pan was analyzed for salinity.

The diesel fuel was brought to the site on a barge by a commercial supplier prior to each burn. Fuel was pumped through a flexible hose from the barge through the underground piping system and into the pan. The quantity of fuel delivered from the barge was monitored with an in-line flow meter. For the first burn additional fuel was pumped from the barge to account for the filling of the pipe between the barge and the pan. For the last burn the fuel in the pipe was purged with compressed air. The distance from the surface of the fuel to the fixed reference point at the top of the pan was recorded. The manometer pressure transducer data recording was started and the fuel was ignited with an extended propane torch and a small quantity of mineral spirits. Video cameras were used to record the burn. When the fire was out, the distance from the surface of the water to the fixed reference point at the top of the pan was recorded on the four sides of the pan.

EXPERIMENTAL CONDITIONS

Tables 2 and 3 give the ground and table 4 the airborne meteorological conditions measured during each of the burns. The values in tables 2 and 3 are averages over the time from ignition to extinction. Wind directions are the direction from which the wind originates with 0° being true north. Also shown in these tables are the maximum and minimum values measured during the burn and the uncertainty given by one standard deviation. There is generally good agreement between the two ground stations although there is a consistent difference in the relative humidity and atmospheric pressure. Since the instruments in the weather station given in table 2 were most recently calibrated they are assumed to be accurate. Although the meteorological conditions varied during the burns, the burns were of relatively short duration and the averages are representative of the actual conditions. The airborne

weather data was collected at an elevation of approximately 100 to 150 m. Previous measurements showed the meteorological conditions to be generally uniform above 20 m [3]. The measurements were taken 120 minutes before burn 1019, 30 minutes before burn 1022a, and 35 minutes before burn 1022b. For flight safety reasons, the tethered blimp with the meteorological instruments was not deployed during the burns.

Table 2. Ground meteorological conditions, station 1

Burn No.	Temp. (°C)	Wind Speed (m/s)	Wind Direction (degrees)	Relative Humidity (%)	Barometric Pressure (kPa)	Solar Radiation (kW/m^2)
1019 avg.	27.0 ±0.2	1.6 ±0.3	120 ±21	77 ±1	1010 ±0	0.756 ±0.043
Minimum	26.6	0.7	63	73	1010	0.658
Maximum	27.5	2.4	150	79	1011	0.825
1022a avg.	15.3 ±0.2	5.7 ±1.0	356 ±15	70 ±1	1020 ±0	0.143 ±0.076
Minimum	15.0	3.1	51	68	1020	0.021
Maximum	15.6	8.1	309	73	1020	0.254
1022b avg.	16.2 ±0.2	5.5 ±1.1	359 ±17	68 ±1	1020 ±0	0.128 ±0.087
Minimum	16.0	2.9	46	66	1020	0.024
Maximum	16.5	7.4	326	70	1020	0.329

Table 3. Ground meteorological conditions, station 2

Burn No.	Temp. (°C)	Wind Speed (m/s)	Wind Direction (degrees)	Relative Humidity (%)	Barometric Pressure (kPa)
1019 avg.	27.2 ±0.2	2.9 ±0.3	148 ±3	88 ±1	1020 ±1
Minimum	26.9	2.4	142	86	1020
Maximum	27.6	3.3	154	88	1021
1022a avg.	15.0 ±0.3	4.9 ±0.7	353 ±9	80.7 ±2	1024 ±0
Minimum	14.5	3.6	16	78	1024
Maximum	15.6	6.0	343	84	1024
1022b avg.	16.0 ±0.3	4.3 ±0.2	0 ±11	73 ±1	1024 ±0
Minimum	15.6	4.0	22	72	1024
Maximum	16.4	4.8	346	74	1024

Table 4. Airborne meteorological conditions

Burn No.	Temp. (°C)	Wind Speed (m/s)	Wind Direction (degrees)
1019 avg.	23.4±0.2	8.8±0.5	125±7
Minimum	22.7	7.8	110
Maximum	23.7	10.1	140
1022a avg.	12.3±0.1	9.0±1.0	7±7
Minimum	12.1	6.7	23
Maximum	12.6	10.9	345
1022b avg.	13.2±0.2	9.6±0.8	359±15
Minimum	12.9	8.1	33
Maximum	13.5	11.5	306

BURNING RATE

The burning of the diesel fuel was observed to take place in three phases; 1) spreading, 2) steady burning, and 3) transition to extinction. The spreading phase lasted from 180 to 240 s as flames spread over the surface from the single ignition point on the upwind side of the pan to cover the entire fuel surface. Once the entire fuel surface was covered with flames, the burning continued at a steady rate until the fuel was nearly consumed and the fire began a transition to extinction. This was characterized by areas of the fuel surface with no visible flames. Frequently, there were oscillations in the burning behavior with increased and decreased burning area and transition to and from boiling. The burning area decreased toward the downwind side of the pan until extinction. A brief chronology of the observed burning behavior for each of the burns is given in table 5.

Table 5. Burn chronology

Burn No.	Effective Burn Dia. (m)	Initial Fuel Depth (mm)	Time to 75% Involvement (s)	Time to Full Involvement (s)	Time to Begin Extinction (s)	Time to 25% Extinction (s)	Time to Extinction (s)
1019	6.88	82	210	240	1110	1125	1585
1022a	17.2	57	99	194	789	759	1404
1022b	17.2	57	135	585	585	795	1183

Note: All times from ignition

The initial volume of fuel was estimated using the barge flow meter and was within 2 % of the liquid surface measurements taken before the fuel was added and after the fuel was added. Table 6 gives the initial volume of fuel. Virtually all of the fuel was consumed by burning.

Table 6. Fuel volume

Burn No.	Diesel Fuel (m^3)	Diesel Fuel (gal)
1019	3.0	800
1022a	13.3	3500
1022b	13.3	3500

The burning rate was estimated from the change in the liquid level in the pan as measured by the pressure transducer for burns 1022a and 1022b. The output of the pressure transducer was calibrated in salt water and converted to fuel depth using the specific gravity of the fuel. The specific gravity of the fuel was 0.836 ±0.001 as measured using the mechanical oscillator technique with an accuracy of ±0.001. The salt content of the water in the pan was measured using the sodium ion electrode method with an accuracy of ±0.01 %. The salt concentration was 1.1 % NaCl and specific gravity of the water in the pan was 1.01. The fuel surface regression rate was calculated using a least squares linear fit of the pressure transducer output over the time from full pan involvement to the beginning of extinction.

Table 7. Fuel surface regression rate

Burn No.	Effective Burn Dia. (m)	Surface Regression Rate from Pressure Transducer Measurements (mm/s)	Surface Regression Rate from Liquid Quantity Measurements (mm/s)
1019	6.88		0.086
1022a	17.2	0.073	0.087
1022b	17.2	0.076	0.087

Table 7 gives the fuel surface regression rate determined from the pressure transducer and the measurements of the fuel quantity. The fuel surface regression rate from the liquid quantity was determined by dividing the quantity of fuel consumed by the burn time during which at least 75 % of the fuel surface was burning. The regression rate determined from the fuel quantity measurements burns 1022a and 1022b is 17% higher than the average rate determined from the pressure transducer. Regression rates calculated from the pressure transducer measurements are not dependent on estimating the total burn time. The measurements from the pressure transducer are used to calculate the burning rate. The regression rate for burn 1019 was estimated

from the liquid quantity measurement and the ratio of the average measurements for burns 1022a and 1022b.

The specific mass burning rate (rate of mass loss per unit area) was calculated from the surface regression rate and the density of the fuel. The heat release rate was determined by multiplying the mass loss rate by the effective heat of combustion for the diesel fuel. The heat of combustion for the diesel fuel used in the mesoscale burns was determined in the Cone Calorimeter to be 38600 ± 650 kJ/kg.[5] The uncertainty represents one standard deviation for the six measurements made, two each at 0, 25, and 50 kw/m^2 external radiant heat flux.

Table 8 shows the burning and surface regression rates and the observed burn times. Table 9 gives the same information in engineering units. Figure 7 is a graph of the surface regression rate as a function of the effective burn diameter. Also shown are previous mesoscale measurements for crude oil. The mean value for diesel fuel is 0.074 ± 0.001 mm/s. The mean value for the burning rate per unit area is 0.062 ± 0.001 kg/s/m^2 (6.5 ± 0.1 gal/hr/ft^2) and for the heat release rate per unit area is 2390 ± 40 kW/m^2. The uncertainty represents one standard deviation.

Table 8. Burning rate

Burn No.	Effective Burn Dia. (m)	Burn Time (s)	Burning Rate (kg/s/m^2)	Burning Rate (kW/m^2)	MW	Surface Regression Rate (mm/s)
1019	6.88	915	0.061	2360	87	0.073
1022a	17.2	660	0.061	2370	550	0.073
1022b	17.2	660	0.063	2440	560	0.076

Table 9. Burning rate (customary units)

Burn No.	Effective Burn Dia. (ft)	Burn Time (s)	Initial Fuel Thickness (in)	Burning Rate (gal/hr/ft^2)	Surface Regression Rate (in/min)
1019	22.6	915	3.2	6.4	0.17
1022a	56.4	660	2.3	6.5	0.17
1022b	56.4	660	2.3	6.7	0.18

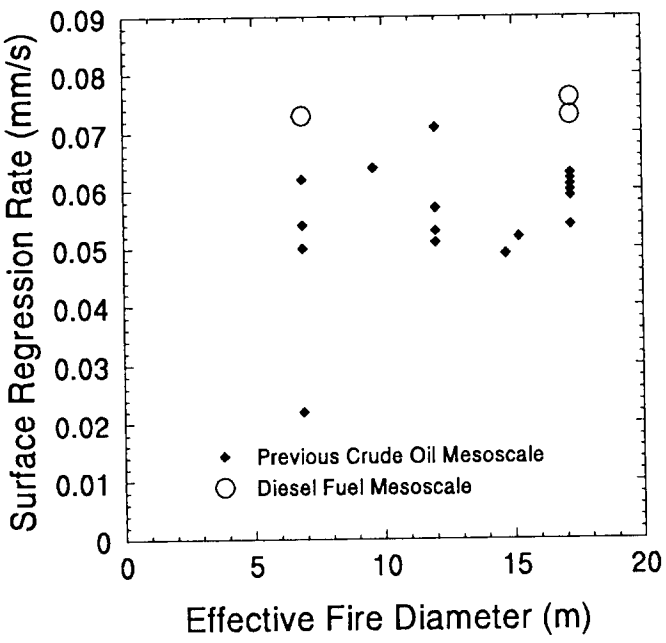

Figure 7. Fuel surface regression rate

SMOKE SAMPLING MEASUREMENTS

Table 10 gives a list of the airborne samples taken. One of the smoke yield sampling pumps failed to operate during burn 1022a. For burn 1019 the sampling pumps were started on the ground the package was then deployed while suspended approximately 60 m below a 5.6 m long 2.3 m diameter tethered helium filled miniblimp. The miniblimp was positioned downwind from the fire with the sampling package centered in the smoke plume. For burns 1022a and 1022b the sampling package was suspended approximately 60 m below a Coast Guard HH-65A helicopter on the winch cable. The package was lowered from the helicopter, the sampling pumps started with the radio controlled switch, and the package positioned in smoke plume downwind of the fire. Figure 8 shows the sampling package below the tethered miniblimp and figure 9 the package below the helicopter during a mesoscale burn.

An analysis of the video of the two burns with the helicopter transported package showed a tendency for the pilot to slowly move down the side of the plume towards the fire to stay out of the puffing of the smoke. As a result the package was moved closer to the ground and closer to the fire than desired. During burn 1022b the package entered the intermittent flame region of the plume and damage was sustained to the plastic stabilizing fin. The maximum temperature measured at the package during burn 1022a was 32 °C and the minimum relative humidity was 23 %. The maximum temperature measured at the package during burn 1022b was 42 °C and the minimum relative humidity was 12 % although a higher temperature would have been required to damage the stabilizing fin. Unfortunately different pilots were used for burns 1022a and 1022b and the experience gained from the first burn was not conveyed to the pilot for the second. The experience from these two burns will allow for better pilot pre-flight briefings in the future. The video of the burns shows the top of the plume becomes nearly level a few hundred meters from the fire and the pilots should be instructed to stay in that area even if the package is intermittently above the smoke.

Table 10. Airborne Samples

Burn No.	Sample No.	Sample Type	Start Time[1] (s)	Total Time (s)	Range (m)	Altitude (m)
1019	1	Smoke yield	-540	1114	60	60-90
	2	Smoke yield	-540	1114	60	60-90
	3	Impactor	-540	1114	60	60-90
1022a	1	Smoke yield	312	1050	30	45-60
	3	Impactor	312	490	30	45-60
1022b	1	Smoke yield	228	660	15-30	15-30
	2	Smoke yield	228	660	15-30	15-30
	3	Impactor	228	660	15-30	15-30

[1] - Time from ignition

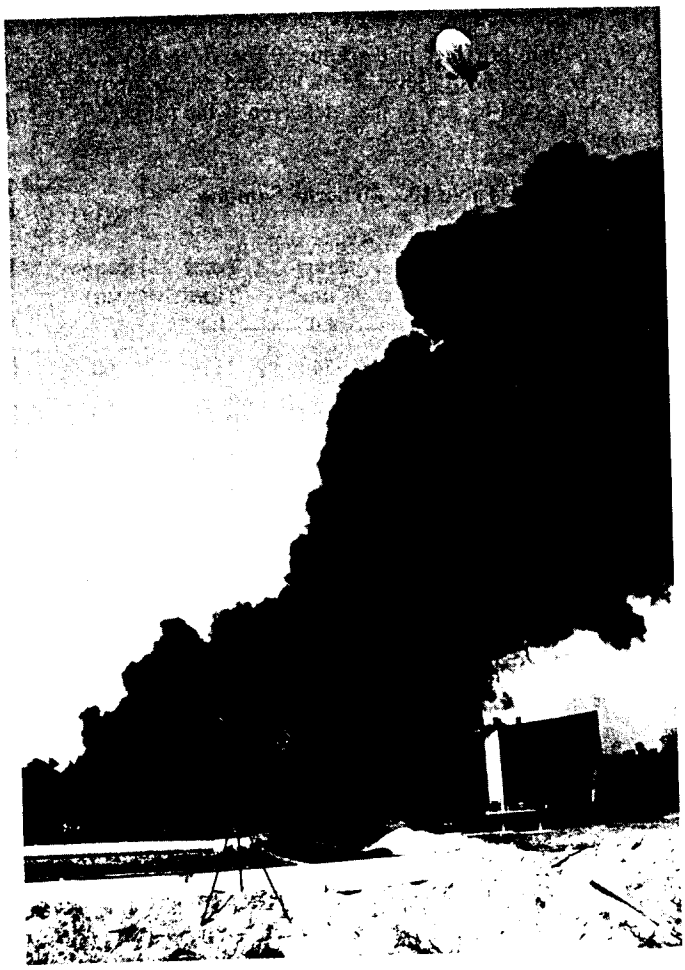

Figure 8. Miniblimp transported smoke sampling package

Figure 9. Helicopter transported smoke sampling package

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:

$$Y_S = \frac{m_P}{m_F} \tag{1}$$

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

$$m_{C,Smoke} = m_{C,Fuel} \tag{2}$$

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 occur in the smoke plume up to the point where the sample is take 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:

$$Y_S = \frac{m_P}{m_{C,Smoke}} \frac{m_{C,Fuel}}{m_F} \tag{3}$$

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 mesoscale burns, the concentration of CO in the gas samples were 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:

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

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. From the elemental analysis of the diesel fuel, this value is 0.8620 for burn 1019 and 0.8649 for burns 1022a and 1022b.

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 11. The smoke yields are shown in figure 10 along with measurements from previous crude oil burns[4]. The smoke yield measured for the diesel fuel fires was in the same range as that previously measured for crude oil. Due to the helicopter operating closer to the fire than intended smoke yield data was obtained at two different distances from the same size fire. It appears that the smoke yield for the same size fire is lower near the flaming region where the reactions are still taking place and is higher in the region where the combustion is complete. The average yield for the 17.2 m effective diameter fires was 13.0 % approximately 30 m from the fire and 9.7 ± 0.3 % approximately 20 m from the fire. For the 6.88 m effective diameter fire the average smoke yield was 13.5 ± 0.2 % approximately 60 m from the fire.

Table 11. Smoke yield

Burn No.	Effective Burn Dia. (m)	Sample	Start Time[1] (s)	Total Time (s)	Smoke Yield (%)
1119	6.88	1	-540	1114	13.4
		2	-540	1114	13.7
1022a	17.2	1	312	777	13.0
1022b	17.2	1	228	687	9.5
		2	228	687	9.4

[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 particulate aerodynamic size distribution.

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 largest diameter particle which will not pass to the next stage but in practice some

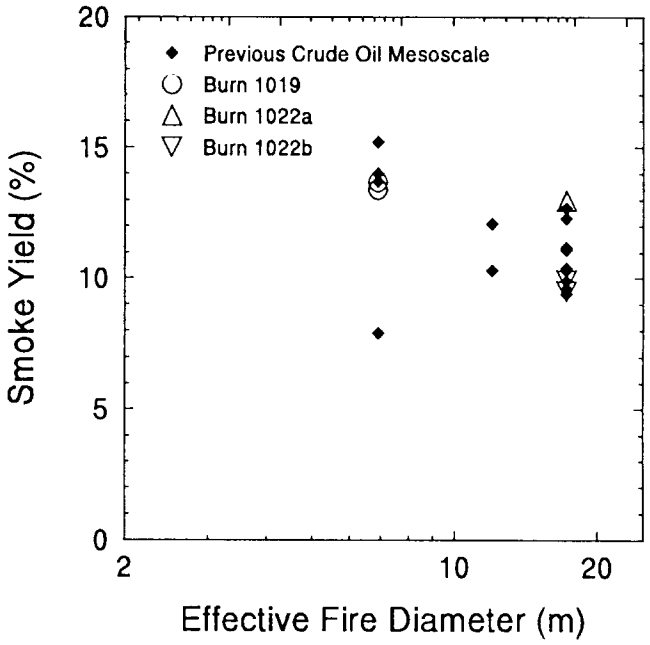

Figure 10. Smoke Yield

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 12 shows the cutpoint diameters for each of the stages in the instrument and the back-up filter [7].

Table 12. 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 the three mesoscale diesel fuel fires as well as a previous 17.2 m effective diameter mesoscale crude oil fire.[4] The size distribution for the diesel fuel sample collected with the

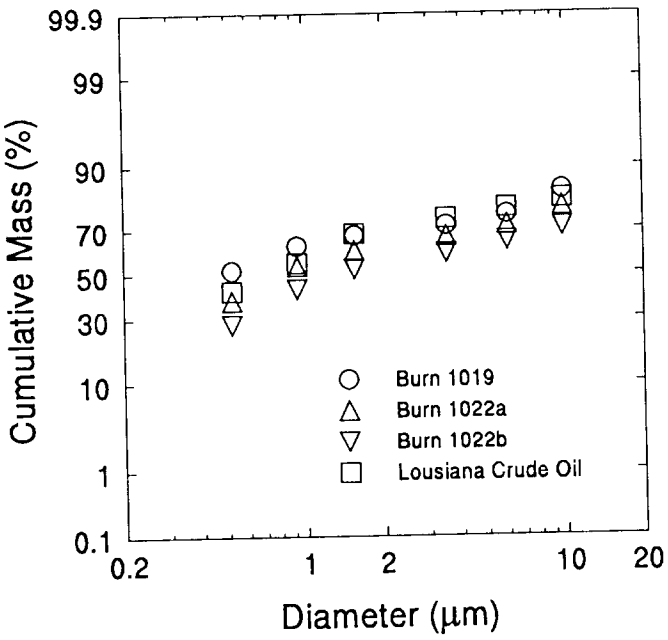

Figure 11. Smoke particulate cumulative size distribution

miniblimp transported package is similar to the distribution for the previous crude oil burn. The size distribution for the samples collected with the helicopter transported package indicate a slightly higher concentration of larger particles closer to the fire although there were not sufficient measurements to clearly establish this trend. The cumulative mass of particulate below 9.8 μm in diameter as measured by the cascade impactor was 84% for burn 1019, 79 % for burn 1022a, and 71 % for burn 1022b.

PAH ANALYSIS

The filter samples used for the smoke yield measurements were also subjected to PAH (Polycyclic Aromatic Hydrocarbon) analysis by the Organic Analytical Research Division at NIST[8]. The filter samples were cut in half and placed in 50 mL centrifuge tubes, spiked with a solution containing known amounts of perdeuterated PAHs and extracted by ultrasonication for 5 minutes with 20 mL dichloromethane (DCM). The extracts were concentrated under N_2 to approximately 5 mL and filtered

through pre-cleaned 0.2 μm syringe filters. The extracts were further concentrated under N_2 to 0.3 mL, pipetted onto pre-extracted aminopropyl-derivated silica cartridges and eluted with 20 mL of a 2% solution of DCM in hexane. The elutates were again concentrated under N_2 to ≤ 100 μL prior to analysis by gas chromatograph with mass spectrometric detection (GC-MS). Standard Reference Material 1491 (Aromatic Hydrocarbons in Hexane/Toluene) was fortified with known amounts of perdeuterated PAHs and processed through the identical proced[illegible] as the samples. Response factors generated by running this standard corrected for differences in the recoveries and detector responses between the analytes and the perdeuterated standards.

The PAHs were detected by mass spectrometry (MS) interfaced with a gas chromatograph(GC). The GC-MS was tuned daily prior to beginning analyses of the samples. From 1 to 2 μL volumes of the prepared extracts and standard were injected onto a 1.5 m retention gap connected to the analytical column used to quantify the PAH. Each extract was analyzed once. The 5% phenylmethyl substituted polysiloxane gas chromatograph column (DB-5ms, 60 m, 0.25 mm, 0.25 μm phase) was used at a head pressure at 40 psi helium (linear velocity of 300 mm/s) with a temperature program beginning with a 1 min hold at 100 °C followed by a rapid ramp (60 °C/min) to 150 °C, then a gradual increase (2 °C/min) to 325 °C. The PAHs present in the sample extracts were quantified by peak area comparisons with perdeuterated PAHs spiked into samples prior to extraction. Response/recovery factors corrected for differences in the recoveries and detector responses between the analytes and the standard.

Analysis of the filter blank yielded detectable levels of phenanthrene (2.78 ng), 3-methylphenanthrene (2.49 ng), 2-methylphenanthrene (0.69 ng), fluoranthene (0.34 ng), pyrene (0.34 ng), and benz[a]anthracene (0.19 ng). The blank levels were subtracted from those measured in the sample filter extracts prior to normalizing with respect to the masses of soot determined on the filters.

Table 13 gives the PAH concentrations on the smoke particulate for the three diesel fuel burns. The sampling technique used did not necessarily capture the most volatile PAH. There is good agreement between the two samples for burn 1019 and also for the two samples for burn 1022b. The concentrations for burn 1019 where the miniblimp was used are higher than both of the burns where the helicopter was used. Further, the concentrations for burn 1022a are generally higher than those for burn 1022b in which the package was closer to the fire. This would suggest that either the PAHs are still forming in the intermittent flaming region or the collection is affected by the higher temperatures near the fire.

Table 13. PAH Concentrations

PAH Compound	Burn Sample - Concentration (ng/mg)[1]				
	1019-1	1019-2	1022a	1022b-1	1022b-2
phenanthrene	129	147	94.1	29.1	27.4
anthracene	16.9	18.5	13.0	3.09	2.91
3-methylphenanthrene	2.17	1.45	7.37	0.63	<0.1
2-methylphenanthrene	3.19	3.01	9.92	0.94	0.87
2-methylanthracene	0.92	0.92	2.16	0.31	0.25
9- and 4-methylphenanthrene	3.08	3.10	6.01	1.27	1.13
1-methylphenanthrene	2.48	2.45	5.47	0.76	0.74
fluoranthene	120	135	70.1	23.6	21.3
acephenanthrylene	35.4	39.7	21.3	4.80	4.52
pyrene	137	155	82.5	36.3	29.2
benz[a]anthracene	14.6	16.4	8.73	1.46	1.41
triphenylene	3.10	3.64	2.37	0.61	0.57
chrysene	15.3	17.3	9.19	1.81	1.79
benzo[b+j]fluoranthenes	31.7	23.6	10.9	2.19	2.06
benzo[k]fluoranthene	9.27	10.6	4.58	1.07	0.95
benzo[e]pyrene	17.0	19.6	9.43	2.90	2.53
benzo[a]pyrene	29.7	33.7	14.3	3.18	2.94
perylene	5.52	6.36	2.27	0.67	0.63
ideno[1,2,3-cd]pyrene	14.1	16.1	6.60	1.56	1.50
benzo[ghi]perylene	17.9	20.4	8.78	2.70	2.39

[1]Uncertainties estimated at approximately ± 10% of the stated concentrations

CONCLUSIONS

The improved miniblimp transported smoke sampling and the helicopter transported smoke sampling package were both shown to be effective means for collecting smoke samples for in situ burning.

The average burning rate for the diesel fuel fires on water was 0.062 ± 0.001 kg/s/m^2 (6.5 ± 0.1 gal/hr/ft^2).

The values for smoke yield measured for diesel fuel (from 9.4 to 13.7 % on a mass basis) were within the range of values previously measured for crude oil. The values measured closer to the fire and near the combustion region tended to be lower than those measured further away.

The size distributions of aerodynamic effective diameters for the smoke particulate were nearly identical for the diesel fuel burns and the previous crude oil burn. Measurements made using the helicopter transported sampling package closer to the fire showed a slight increase in larger particles. The average value for the three burns was 78 % of the particulate mass was below 9.8 μm in diameter as measured with a cascade impactor.

The concentration of PAH on the smoke particulate tended to be lower closer to the fire.

ACKNOWLEDGEMENTS

This work was funded by the U.S. Coast Guard Research and Development Center, Environmental Safety Branch, under the direction of Commander Shawn Smith.

Dave Beene of the Marine Fire and Safety Research Branch at the Coast Guard Research and Development Center and the Fire and Safety Test Detachment in Mobile under the direction of Chief Warrant Officer Byrd provided outstanding assistance in preparing for and conducting the mesoscale burn experiments.

Appreciation is extended to the U.S. Coast Guard Aviation Training Center in Mobile, Alabama for providing a helicopter and crew which made the testing of the helicopter transported sampling package possible.

REFERENCES

1. Evans, D., Walton, W., Baum, H., Lawson, R., Rehm, R., Harris, R., Ghoniem, A., Holland, J., "Measurement of Large Scale Oil Spill Burns," Proceedings of the Thirteenth Arctic and Marine Oil Spill Program Technical Seminar, June 6-8, 1990, Edmonton, Alberta, Ministry of Supply and Services Canada, Cat. No. En 40-11/5-1990. pp. 1-38, 1990.

2. Evans, D., Walton, W., Baum, H., Mulholland, G., Lawson, J., Koseki, H., Ghoniem, "Smoke Emission from Burning Crude Oil," Proceedings of the Fourteenth Arctic and Marine Oil Spill Program Technical Seminar, June 12-14, 1991, Vancouver, British Columbia, Ministry of Supply and Services Canada, Cat. No. En 40-11/5-1991. pp. 421-449, 1991.

3. Evans, D., Walton, W., Baum, H., Notarianni, K., Lawson, J., Tang, H., Keydel, K., Rehm, R., Madrzykowski, D., Zile, R., Koseki, H., and Tennyson E., "In-Situ Burning of Oil Spills: Mesoscale Experiments," Proceedings of the Fifteenth Arctic and Marine Oil Spill Program Technical Seminar, June 10-12, 1992, Edmonton, Alberta, Ministry of Supply and Services Canada, Cat. No. En 40-11/5-1992. pp. 593-657, 1992.

4. Walton, W., Evans, D., McGratten, K., Baum, H., Twilley, W., Madrzykowski, D., Putorti, A., Rehm, R., Koseki, H., and Tennyson E., "In-Situ Burning of Oil Spills: Mesoscale Experiments and Analysis," Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar, June 7-9, 1993, Calgary, Alberta, Ministry of Supply and Services Canada, pp. 679-734, 1993.

5. Babrauskas, V., The Cone Calorimeter -- A New Tool for Fire Safety Engineering, ASTM Standardization News, Vol 18, pp. 32-35, 1990.

6. Hering, S.V. (editor), Air Sampling Instruments for Evaluation of Atmospheric Contaminates, 7th Edition, American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1989.

7. Marple Personnel Cascade Impactors, Series 290, Instrument Manual, Bulletin No. 290I.M.-3-82, Sierra Instruments, Inc, Carmel Valley, CA.

8. Benner, B., Measurement of Polycyclic Aromatic Hydrocarbons Extracted From Soot Generated by Open Burning of Diesel Fuel, Report of Analysis 835-94-035, NIST, March 1994.