

**Smoke Measurements Using an Advanced Helicopter Transported
Sampling Package with Radio Telemetry**

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ABSTRACT

A second generation smoke sampling package designed to be deployed on a helicopter winch cable has been developed and tested. Improvements in the second generation package include real-time sampling for carbon dioxide with an infrared gas analyzer and volatile organic compounds with a photoionization detector. Package location and altitude are determined via an on-board global satellite positioning system. Real time gas analysis data, position data as well as temperature, relative humidity, barometric pressure, wind speed, and package orientation are recorded with an on board data acquisition system and transmitted to a ground station for real-time display on a laptop computer. The package contains three sampling pumps which can be fitted with a variety of sampling trains and gas collection bags. The package was used to survey volatile organic compounds from an intentional fuel discharge and to collect smoke samples from two 231 m² diesel fuel fires at the U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama. The design of the package, operational experience, and measurements taken during the diesel fuel fires will be presented. The burning rate for diesel fuel on water as indicated by the surface regression rate was found to be 0.079 ± 0.003 mm/s. VOC and carbon dioxide concentrations in the smoke plume were measured. The total VOC concentration in the plume approximately 100 m from the fire was only slightly higher than the background value. The carbon dioxide concentration measured in the plume at the same location was generally 50 to 100 ppm above background.

Environment Canada. Arctic and Marine Oilspill Program (AMOP) Technical Seminar, 18th. Proceedings. Volume 2. June 14-16, 1995, Edmonton, Alberta, Canada, Environment Canada, Ottawa, Ontario, 1053-1074 pp, 1995.

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 infrastructure 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 which can be suspended from tethered helium filled miniblimps and in 1993 developed a first generation smoke sampling package designed to be suspended beneath a helicopter[1-5].

Under the sponsorship of the U.S. Coast Guard, NIST developed an advanced smoke sampling package designed to be suspended beneath a helicopter. The package was designed to assess the ability to rapidly collect data on smoke and/or emissions from mesoscale experiments or spills of opportunity. The advanced package included the features from the first generation package and added real-time carbon dioxide and photoionization detectors, a global satellite positioning system (GPS), and the ability to transmit data to a ground station. The advanced helicopter package was 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 package, the smoke from diesel fuel fires would serve this purpose.

ADVANCED HELICOPTER TRANSPORTED SMOKE SAMPLING PACKAGE

The principal objective of the advanced helicopter smoke sampling package was to provide real-time data on carbon dioxide concentration, volatile organic compounds (VOC), and package position to a ground or sea based station as well as 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.

The package has a flat top and bottom, a rounded front end, and tapers toward the rear. The advanced package is 535 mm high, 205 mm wide, and 1045 mm long, with a stabilizing fin 500 mm high and 720 mm long. Figure 1 is a photograph of the advanced 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 37 kg. 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 advanced package is larger than the first generation package which was 370 mm high, 180 mm wide, and 1000 mm long, with a stabilizing fin 340 mm high and 770 mm long. The total weight of the package was 25 kg.

The features from the first generation sampling package incorporated in the advanced package include 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 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.

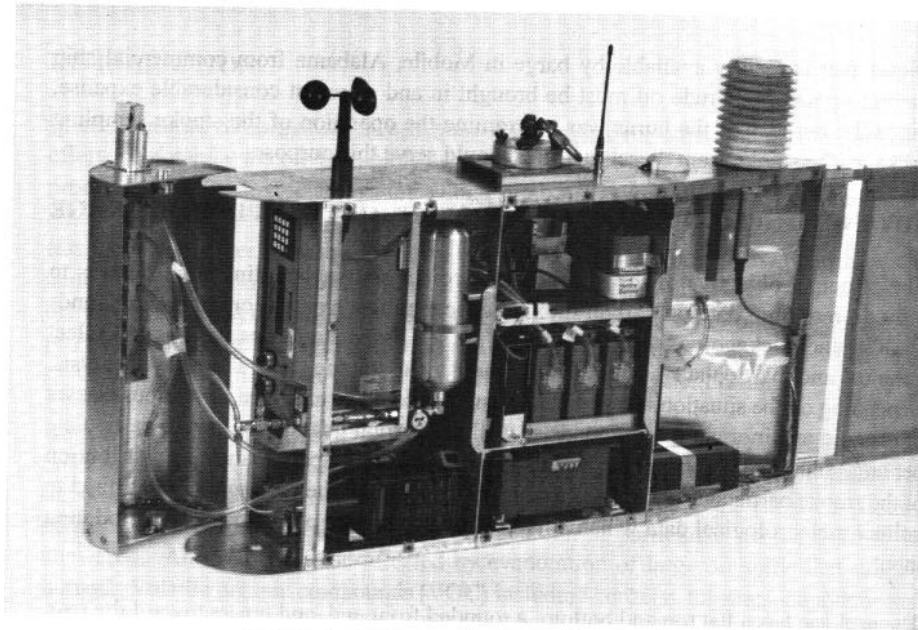


Figure 1. Photograph of sampling package

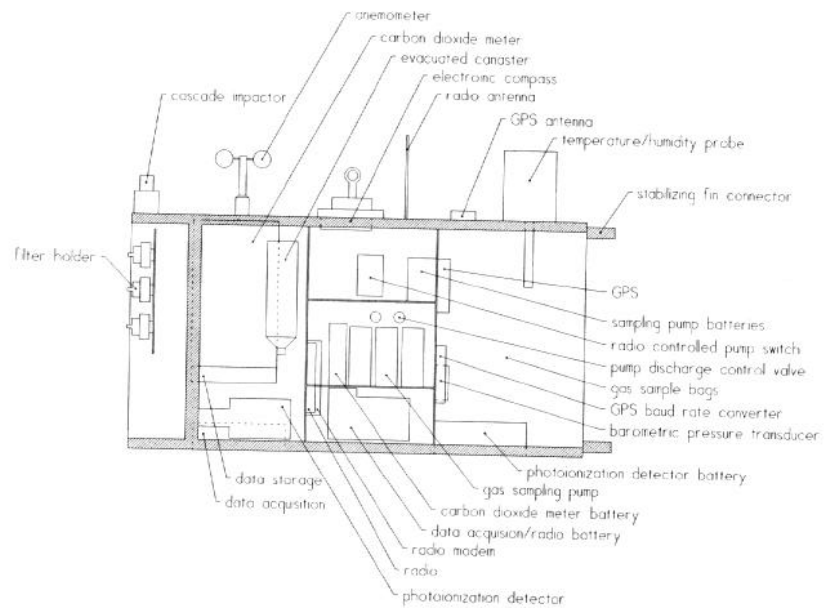


Figure 2. Schematic of sampling package

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.

The weather instruments include a temperature and relative humidity probe, a barometric pressure sensor, an anemometer, and electronic compass. The system can be used to record conditions inside the smoke plume as well as provide an atmospheric profile. 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.

The advanced package incorporates a carbon dioxide meter and photoionization detector not include in the first generation package. The carbon dioxide meter uses the difference of absorption of infrared radiation between a sample of gas to be measured and a sample of gas with the carbon dioxide removed. The response time of the instrument is 1 s and the range is 0-3000 ppm. The photoionization detector uses a 10.6 electron Volt (eV) lamp which detects compounds with an ionization potential less than 10.6 eV. The unit is a standard VOC survey model and is calibrated with isobutylene with an operating concentration range of 0.1 to 2000 ppm isobutylene equivalent. The response time of the photoionization detector is less than 3 s.

An original equipment manufacturer (OEM) model global satellite positioning system is included in the package. The system consist of an external antenna and an enclosed receiver unit without an input keyboard or display. The serial output of the GPS system passes through a baud rate converter to the data acquisition system. The data acquisition system used is programmable and can accept analog input from the weather, carbon dioxide, and photoionization instruments and well as digital input from the GPS system. Data is collected every 10 seconds 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 advanced package includes a radio modem and radio transceiver connected to the data acquisition system. A ground based radio modem and radio transceiver connected

to a laptop computer can be used to contact the data acquisition system in the package and display the data from the weather, carbon dioxide, and photoionization instruments and the GPS in real time. If the radio link is disrupted or lost, the data can be retrieved after the flight from the data storage module.

The advanced package also includes a stainless steel evacuated canister to collect a gas sample for later analysis. The gas sample in the evacuated canister can be analyzed for volatile organic compounds (VOC) which cannot be reliably done with the gas sample from the collection bags.

EXPERIMENTAL CONFIGURATION

Three mesoscale diesel fuel burns to test the smoke sampling package 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 km² 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 3 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 values for the composition of the diesel fuel for burn 1023 are 86.12% carbon, 13.43% hydrogen, and less than 0.5% sulfur by mass. For the 1026 burns the values are 86.56% carbon, 13.84% hydrogen, and less than 0.5% sulfur as determined by a commercial laboratory.

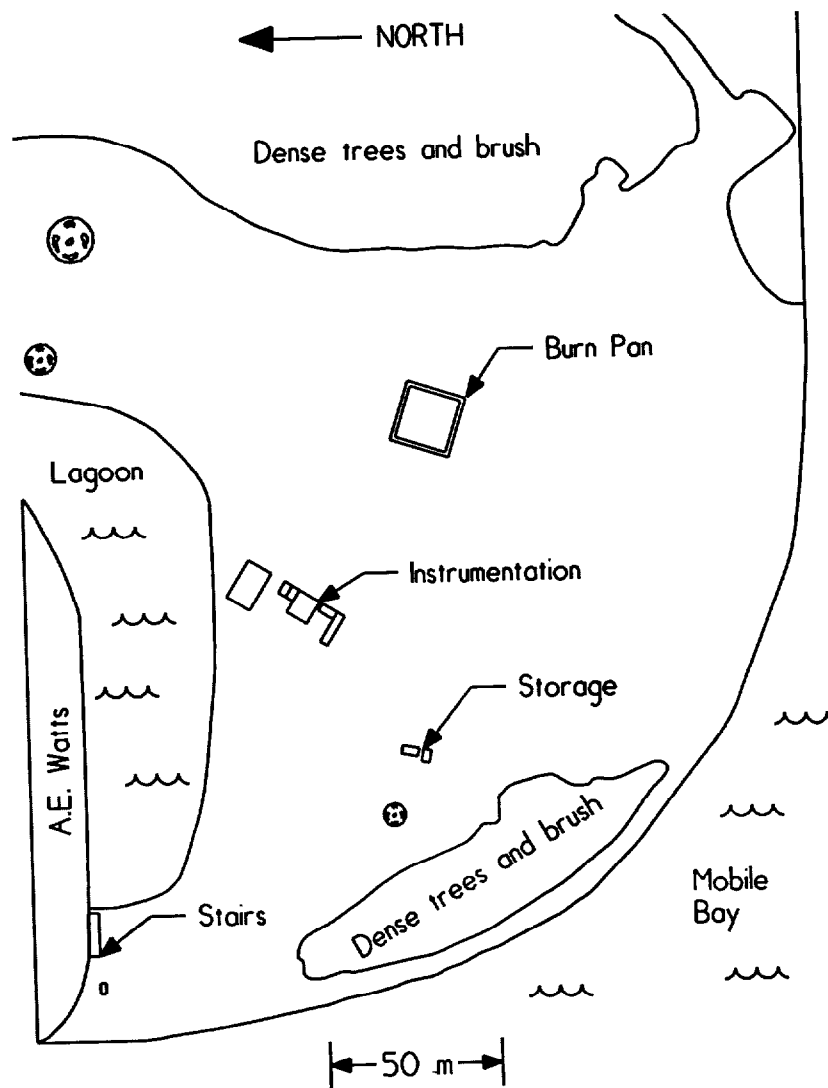


Figure 3. USCG mesoscale burn facility site plan

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 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 m² and a partial pan area of 199 m². The partial pan area was achieved by partitioning a side of the inner pan with a section 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		Effective Burn Diameter		Burn Area/ Full Pan Area (%)	Features
		(m ²)	(ft ²)	(m)	(ft)		
1023	13.1 × 15.2	199	2140	15.9	52.2	86	boom formed one side of burn area
1026a	15.2 × 15.2	231	2490	17.2	56.4	100	
1026b	15.2 × 15.2	231	2490	17.2	56.4	100	

INSTRUMENTATION

Measurements of atmospheric conditions were made with two ground based weather stations. The first ground based station was located 93 m at a bearing of 208° from the southwest corner of the burn pan and 2.1 m above the ground. The second ground based weather station was located 92 m at a bearing 205° 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.

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 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 two in-line flow meters. 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. The fuel was ignited with an extended propane torch and a small quantity of mineral spirits. Video cameras were used to record the burn.

Table 2. Ground meteorological conditions, station 1

Burn No.	Temp. (°C)	Wind Speed (m/s)	Relative Humidity (%)	Barometric Pressure (kPa)	Solar Radiation (kW/m ²)
1023 avg.	27.2 ±0.2	1.7 ±0.2	48 ±2	1012 ±0	0.65
Minimum	26.8	0.4	42	1012	
Maximum	27.7	3.4	52	1012	
1026a avg.	16.5 ±0.6	4.8 ±1.1	57 ±2	1018 ±0	0.52
Minimum	15.3	2.8	53	1018	
Maximum	17.3	8.1	63	1018	
1026b avg.	19.6 ±0.3	4.4 ±1.0	45 ±1	1017 ±0	0.77
Minimum	19.1	2.1	43	1016	
Maximum	20.1	6.7	48	1017	

EXPERIMENTAL CONDITIONS

Tables 2 and 3 give the ground 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. The electronic compass in weather station 1 malfunctioned and wind directions are not available for that station. Also shown in these tables are the maximum

and minimum values measured during the burn and the uncertainty given by one standard deviation. Although the meteorological conditions varied during the burns, the burns were of relatively short duration and the averages are representative of the actual conditions.

Table 3. Ground meteorological conditions, station 2

Burn No.	Temp. (°C)	Wind Speed (m/s)	Wind Direction (degrees)	Relative Humidity (%)	Barometric Pressure (kPa)
1023 avg.	28.1 ±0.2	1.6 ±0.8	38 ±43	88 ±1	1020 ±1
Minimum	27.7	0.6	303	86	1020
Maximum	29.2	3.8	174	88	1021
1026a avg.	15.4 ±0.6	5.1 ±1.7	358 ±18	80.7 ±2	1024 ±0
Minimum	14.2	1.9	330	78	1024
Maximum	16.6	8.7	50	84	1024
1026b avg.	18.9 ±0.3	4.7 ±1.5	356 ±21	73 ±1	1024 ±0
Minimum	18.2	2.4	323	72	1024
Maximum	19.5	8.0	71	74	1024

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 160 to 220 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 4.

The initial volume of fuel using the barge flow meter and was within 1% of the fuel volume measured with the in-line flow meter. Table 5 gives the volume of fuel and the initial fuel depth. Virtually all of the fuel was consumed by burning.

Table 4. Burn chronology

Burn No.	Effective Burn Dia. (m)	Time to 75% Involvement (s)	Time to Full Involvement (s)	Time to Begin Extinction (s)	Time to 25% Extinction (s)	Time to Extinction (s)
1023	15.6	100	160	1191	1240	1573
1026a	17.2	110	220	990	1025	1600
1026b	17.2	90	160	970	1010	1440

Note: All times from ignition

Table 5. Fuel volume

Burn No.	Diesel Fuel		Fuel Depth	
	(m³)	(gal)	(mm)	(in)
1023	17.1	4509	86	3.4
1026a	17.1	4500	74	2.9
1026b	17.1	4500	74	2.9

The surface regression rate was estimated from the quantity of fuel burned and the time from 75% involvement to 25% extinction. Based on observations, most of the fuel was consumed during that time period. 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[6]. The uncertainty represents one standard deviation for the six measurements made, two each at 0, 25, and 50 kW/m² external radiant heat flux.

Table 6 shows the burning and surface regression rates and the observed burn times. Table 7 gives the same information in customary industrial units. Figure 4 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 and diesel fuel [1-5]. The mean value for the diesel fuel in this series is 0.079 ± 0.003 mm/s. The mean value for the burning rate per unit area is 0.066 ± 0.002 kg/s/m² (7.0 ± 0.3 gal/hr/ft²) and for the heat release rate per unit area is 2540 ± 94 kW/m². The uncertainty represents one standard deviation.

Table 6. Burning rate

Burn No.	Effective Burn Dia. (m)	Burn Time (s)	Burning Rate			Surface Regression Rate (mm/s)
			(kg/s/m ²)	(kW/m ²)	MW	
1023	15.9	1140	0.063	2435	484	0.076
1026a	17.2	915	0.067	2604	602	0.081
1026b	17.2	920	0.067	2590	598	0.080

Table 7. Burning rate (customary units)

Burn No.	Effective Burn Dia. (ft)	Burn Time (s)	Burning Rate (gal/hr/ft ²)	Surface Regression Rate (in/min)
1023	52.2	1140	6.6	0.18
1026a	56.4	915	7.1	0.19
1026b	56.4	920	7.1	0.19

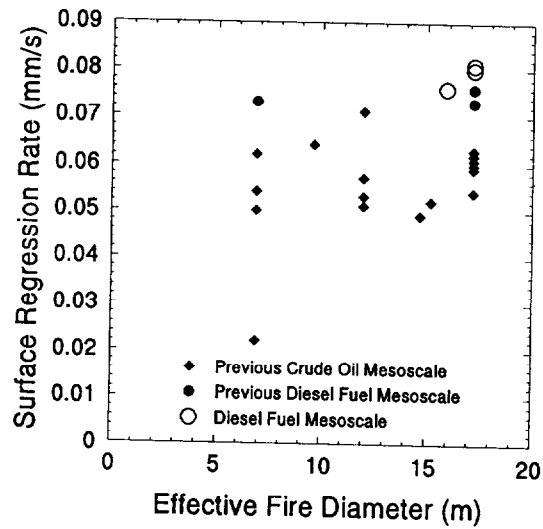


Figure 4. Fuel surface regression rate

SAMPLING MEASUREMENTS

One application for the advanced helicopter sampling package could be to remotely evaluate the level of VOCs or other substances near a spill. Prior to ignition for burn 1023 the helicopter made a pass over the fuel in the pan with the sample package as close to the ground as possible. The pilot found this to be difficult since the pilot could not see the package. Normally the winch cable is lowered for rescues when the helicopter is nearly stationary and the winch operator controls the cable position. Figure 5 shows the helicopter with the package suspended beneath as it approached the pan. Figure 6 shows the flight path of the package as measured by the GPS and figure 7 the elevation over the same time period. Figure 8 shows the reading from the photoionization detector also over the same time period. The spike in the data is most likely caused by the helicopter exhaust as the sampling package was raised after the pass over the pan. Concentrations at ground level around the pan made with the same model photoionization detector ranged as high as 100. The valve on the evacuated canister did not function properly on this pass.

Following the pass of the package over the unburned fuel the fuel was ignited. The burn was conducted with light winds as indicated in table 2 and the plume rose in a short distance to over 400 m which was above the operating ceiling for the helicopter. As a result no smoke sampling measurements could be made for burn 1023.



Figure 5. Sampling package over fuel in pan

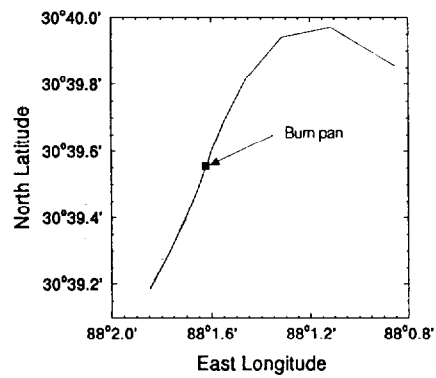


Figure 6. Sample package position prior to burn 1023

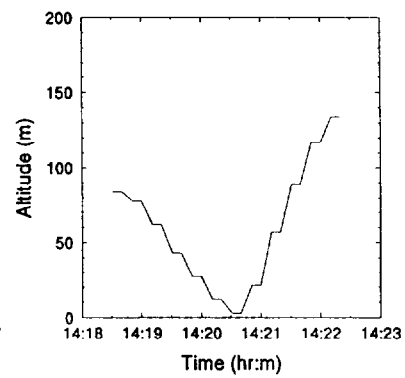


Figure 7. Sample package altitude prior to burn 1023

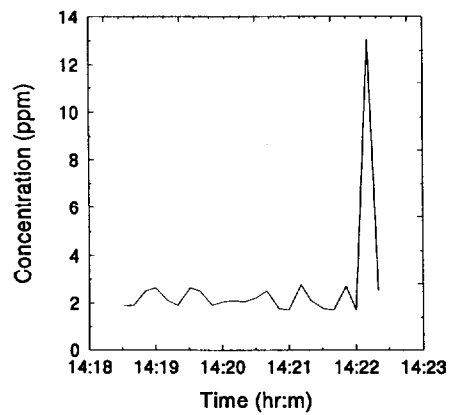


Figure 8. VOC concentration prior to burn 1023

Two additional burns were conducted on a day with higher winds and figure 8 shows the helicopter deploying the package in the smoke plume above one of these burns. Figure 9 shows the package flight path for burn 1026a and figure 10 the altitude during the same time period. Figure 11 shows the photoionization measurement and figure 12 the carbon dioxide measurement during the same time period. Figure 13 shows the package flight path for burn 1026b and figure 14 the altitude during the same time period. Figure 15 shows the photoionization measurement and figure 16 the carbon dioxide measurement during the same time period.

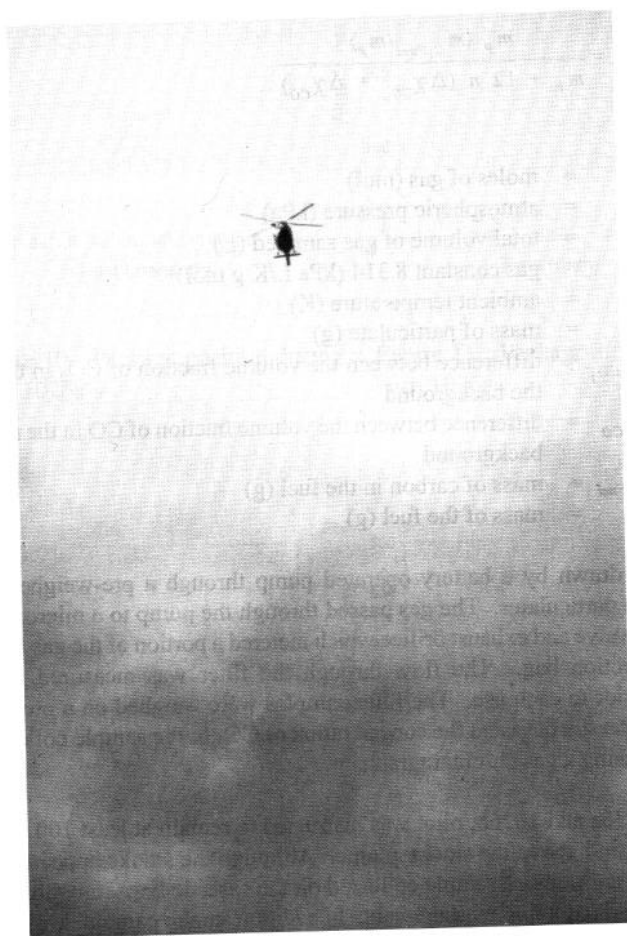


Figure 9. Helicopter transported smoke sampling package over smoke plume

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:

$$Y_s = \frac{m_p}{m_F} \quad (1)$$

In terms of the measured quantities the smoke yield is.

$$Y_s = \frac{m_p (m_{C,Fuel}/m_F)}{m_p + 12 n (\Delta \chi_{CO_2} + \Delta \chi_{CO})} \quad (2)$$

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)
 m_p = mass of particulate (g)
 $\Delta \chi_{CO_2}$ = 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
 $m_{C,Fuel}$ = mass of carbon in the fuel (g)
 m_F = mass of the fuel (g)

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.

For burns 1026a and 1026b, pilot was instructed to remain at least 100 m horizontally from the fire and above the smoke plume. Although the smoke appeared visibly dark there was not an adequate sample collected on the cascade impactor substrates to make a particle size distribution measurement. In addition smoke particulate and gas samples collected with the gas sampling pumps provided samples that were too small to be reliably used to determine smoke yield. From figure 12 for burn 1026a it can be seen

that the carbon dioxide concentration in the plume at the location of the package ranged from ambient to approximately 50 ppm above ambient as the package moved in and out of the smoke. Similarly from figure 16 for burn 1026b the carbon dioxide excess above ambient was approximately 100 ppm. The average concentration measured in the gas sampling bag was approximately 10 ppm for burn 1026a and 20 ppm for burn 1026b.

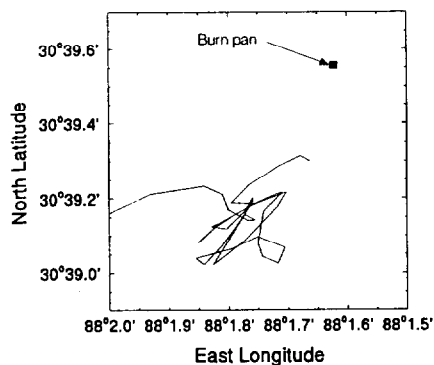


Figure 10. Package position during burn 1026a

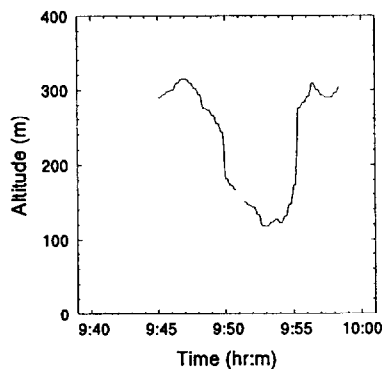


Figure 11. Package altitude during burn 1026a

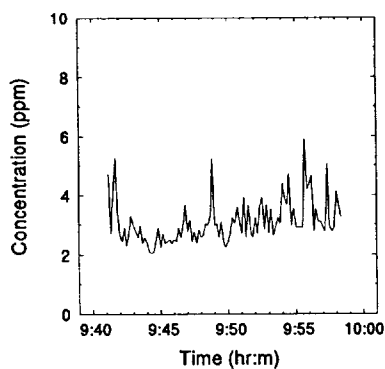


Figure 12. VOC concentration during burn 1026a

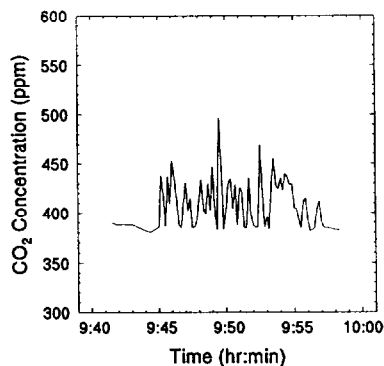


Figure 13. Carbon dioxide concentration during burn 1026a

These values are near limit of accuracy for the gas chromatograph used to measure the carbon dioxide concentration of the gas collected in the gas sampling bag. Similarly the mass of smoke on the sample filters was on the order of 100 μg . These values are an order of magnitude less than the minimum considered necessary to obtain a reliable smoke yield and 2 orders of magnitude than those obtained in the past [1-5].

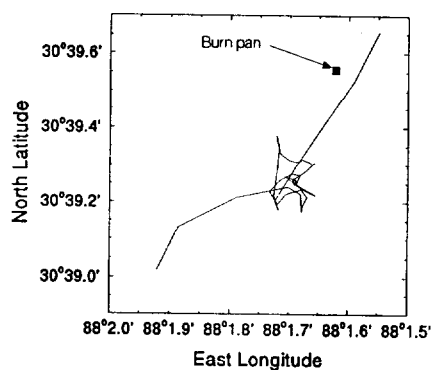


Figure 14. Package position during burn 1026b

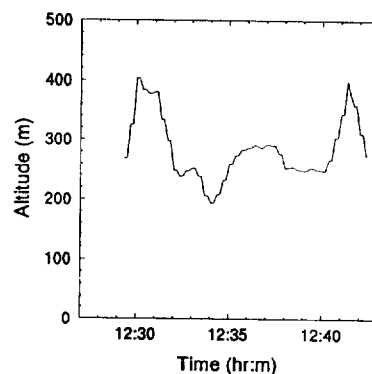


Figure 15. Package altitude during burn 1026b

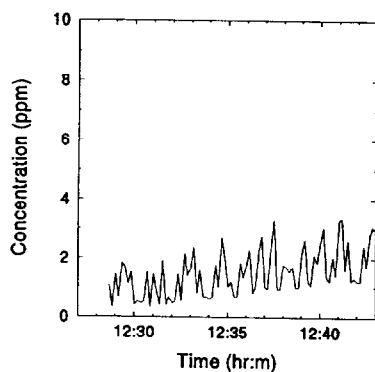


Figure 16. VOC concentration during burn 1026b

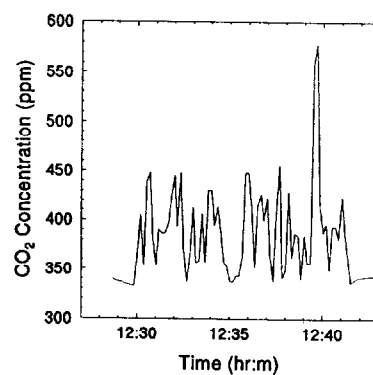


Figure 17. Carbon dioxide concentration during burn 1026b

Table 8. VOC Concentrations (ppbC)

	1026a background	1026a burn	1026b background	1026b burn
Ethene/Acetylene	3.5	1.6	6.1	8.1
Ethane	7.2	1.9	4.8	16.0
Propene	6.1	3.9	5.2	4.1
Propane	6.5	6.1	4.2	10.7
Isobutane	2.9	1.8	0.7	9.1
Isobutane/1-butene	2.4	8.9	6.1	8.2
n-Butane	15.7	9.4	7.7	18.4
Trans-2-butene	0.2	0.1	0.2	0.1
Cis-2-butene	0.5	0.1	0.2	0.5
3-methyl-1-Butene	0.2	0	4.0	0
Isopentane	18.7	52.7	2.2	26.3
1-Pentene	1.2	0.7	1.4	0
2-methyl-1-butene	1.1	0	0	0
n-Pentane	12.9	3.3	0	8.0
Isoprene	0.5	0.5	0	0.8
Trans-2-pentene	1.8	0	0	0
Cis-2-pentene	0.9	0	0	0
2-methyl-2-Butene	2.3	0	0	0
3-methyl-1-Pentene	0.2	0	3.2	0
4-methyl-1-Pentene	0.2	0	0	0
Cyclopentane	1.4	0	0	0
2-Methylpentane	5.9	0	0.7	4.4
3-Methylpentane	4.2	2.4	0.2	5.8
n-Hexane	7.5	3.1	0.1	91.2
Cis-3-hexene	0	0	0	0
Methylcyclopentane	1.6	0.6	0.2	5.0
2,4-dimethylpentane	0	0	0.2	0
1,1,1-Trichlorohexane	0.5	0	0	0
Benzene	5.4	5.8	3.5	9.7
Cyclohexane	0	2.4	0	5.2
2,3-Dimethylpentane	0	0	0	0
Pentanal	11.0	12.2	14.2	5.0
Trichloroethylene	0.3	0	0	0
2,2,4-trime-pentane	0.4	0	0	0
Heptane	3.0	2.5	0.1	4.5
Methylcyclohexane	1.5	1.0	1.0	0
Toluene	7.6	17.4	0.3	37.6
Hexanal	5.2	4.5	56.0	4.7
n-Octane	1.2	2.4	0	2.4
Ethylbenzene	0.9	7.8	0	3.9
m-Xylene	1.9	14.2	0	11.72
p-Xylene	0.7	8.3	0	5.4
2-heptanone	1.2	1.6	6.3	2.0
3-heptanone	0	0	6.8	1.1
Styrene	1.2	0	0	1.1
Heptanal	3.5	3.0	60.0	2.4
o-Xylene	1.3	9.1	0	5.9
Isopropylbenzene	0.3	0	0	0
Benzaldehyde	5.7	1.7	6.8	2.4
α -Pinene	3.6	3.8	0	2.9
n-Propylbenzene	0.4	1.8	0	1.4
1-ethyl-3-Methylbenzene	1.0	3.8	0	2.8
1-ethyl-4-Methylbenzene	0.4	2.1	0	1.7
1-ethyl-2-Methylbenzene	0.6	0	0	0
Octanal	2.1	1.2	59.5	3.3
Limonene	0.8	0	0	1.7
1,3-Diethylbenzene	0.4	0	0	0
n-Butylbenzene	0	0	0	0
Cyclooctane	0	0	0	0
Nonanal	2.0	2.9	31.4	3.8
Undecane	0.7	15.0	0	7.0
Decanal	1.3	2.0	6.2	2.5
Dodecane	0.7	4.0	0	3.2
Total (non-methane)	172.3	228.7	299.5	352.0

Table 8. VOC Concentrations (ppbC) (Continued)

	1026a	1026a	1026b	1026b
	background	burn	background	burn
Acetal	26.94	46.75	94.20	17.25
Acetone	29.46	37.34	124.06	29.00
2-propanol	3.59	5.18	8.37	5.50
n-butanol	13.62	18.15	47.77	4.60
2-butanone	4.98	23.84	21.62	6.80
1-butanol	3.22	0	8.96	0
3-pentanone	14.21	0	1.84	0
3-me-pentanal	0	0	11.72	0
Total	96.02	131.26	318.54	63.15

The photoionization detector shows a slight increase in compounds measured in the plume. This is probably a result of a small quantity of uncombusted fuel vapors in the plume.

VOC ANALYSIS

For both of the burns in which the sampling package was deployed, an evacuated stainless steel canister was used to collect gas samples from the smoke plume. The collected was started when the package sampling pumps were turned on and terminated when the sampling pumps were turned off. In addition, two background samples were collected at ground prior to each burn.

The samples were analyzed by a university laboratory under contract to the Coast Guard[7]. The analysis used both cryotrapping and cryofocussing of approximately 500 ml of the 850 ml sample collected in an evacuated stainless steel cylinder. A gas chromatograph with a 100m DB-1 column was used. A known split ration was placed at the exit of the analytical column, allowing for the column effluent to be directed towards both a flame ionization detector (FID) and a mass spectrometric detector (MSD). Identification of compounds with the FID detector was based solely on the repeatability of their characteristic retention times. The analytical procedure used had allowance for the automatic addition, to each sample, of four internal standard compounds which aided in peak recognition. Each chromatogram was examined using a quadropole mass selective detector. Quantification of eluting compounds was performed on the basis of their FID response as calibrated with a NIST prepared n-butane standard. In this way the FID detector was used as a specific carbon detector. Identified peak concentrations are reported in units of ppbC (parts per billion of Carbon).

Table 8 gives the VOC concentrations for the two 1026 burns and backgrounds. The values provided are for single locations and may not be representative of the entire site. The total background values are slightly lower than the plume samples. The plume samples show slightly elevated n-alkanes (butane, pentane, hexane, octane) and BTEX compounds (benzene, toluene, ethylbenzene, and xylenes). These are consistent with

uncombusted fuel. Since the increases are very small it appears that there is very little uncombusted fuel vapor in the plume.

CONCLUSIONS

The advanced helicopter transported smoke sampling package functioned as designed and provided real-time data at the ground station.

Reliable smoke yields could not be obtained for the short duration burns, due to the distance the sampling package was from the fire.

It was difficult to transport the sampling package close to the fuel surface prior to the burn.

The average burning rate for the diesel fuel fires on water was $0.066 \pm 0.002 \text{ kg/s/m}^2$ ($7.0 \pm 0.3 \text{ gal/hr/ft}^2$).

The total VOC concentration in the plume approximately 100 m from the fire was only slightly higher than the background value. The carbon dioxide concentration measured in the plume at the same location was generally 50 to 100 ppm above background.

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