SMOKE PLUME TRAJECTORY FROM IN SITU BURNING OF CRUDE OIL IN ALASKA - FIELD EXPERIMENTS

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ABSTRACT

Several regions in the United States are developing preapproval plans to use *in situ* burning as a possible remediation tool for oil spills. To assess the environmental impact of the smoke plume on human populations, numerical models have been used to predict the concentration of particulate matter downwind of a large fire. In order to assess the accuracy of one of these models, the NIST Large Eddy Simulation model, data from three sets of mesoscale burns have been compared to model simulations run under similar meteorological conditions. The experimental burns are: (1) the Newfoundland Offshore Burn Experiment (NOBE), August 1993, (2) the Alaska Clean Seas Burning of Emulsions, September 1994, and (3) the US Coast Guard/NIST Meso-scale Burn Series, October 1994. The analysis for the first two experiments is complete, and the results are presented. In addition to measurements made far downwind of these burns which were used to evaluate the model, near-field measurements of particulate and CO_2 are presented.

INTRODUCTION

The Alaska Regional Response Team (ARRT) has been working to develop procedures and guidelines to facilitate the decision process regarding *in situ* burning of crude oil. As part of their effort to assess the impact of smoke plumes from *in situ* burning, the ARRT and the Alaska Department of Environmental Conservation (ADEC) established a Cooperative Research and Development Agreement (CRADA) with the National Institute of Standards and Technology (NIST) in 1993. The first part of this project, completed in 1993, involved laboratory-scale experiments to determine the heat release rate and smoke yield from two types of Alaskan crude oils. This information served as input for the Large Eddy Simulation (LES) model of smoke transport, which was used to predict the concentration of combustion products downwind of a series of hypothetical burns for a wide range of weather conditions. In presenting the results of the model, special attention was given to the downwind and lateral extent of ground level particulate concentrations in excess of 150 $\mu g/m^3$ averaged over one hour. Although there is no formal guidance available concerning safe levels of short term particulate emissions from oil fires, 150 $\mu g/m^3$ averaged over 24 hours is the upper level established under air quality control regulations in Alaska[1]. For meteorological conditions typical of the northern and southern coasts of Alaska, the calculations showed that hour-averaged particulate concentrations found at the ground downwind of fires of various strengths would not exceed 150 $\mu g/m^3$ beyond 5 km, nor outside of a strip approximately 1 km wide along the centerline of the plume trajectory. It has been suggested that a factor of safety of 2 be applied to these results to account for the model uncertainties and the lack of field validation for the assumptions inherent in the model. Details of this study are provided in Reference [6].

The intent of the present work is to analyze the results from recent mesoscale burn

[1]Title 18, Alaska Administrative Code, Chapter 50, Citation 20 (AAC 50.020) Ambient Air Quality Standards.

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, 901-913 pp, 1995.

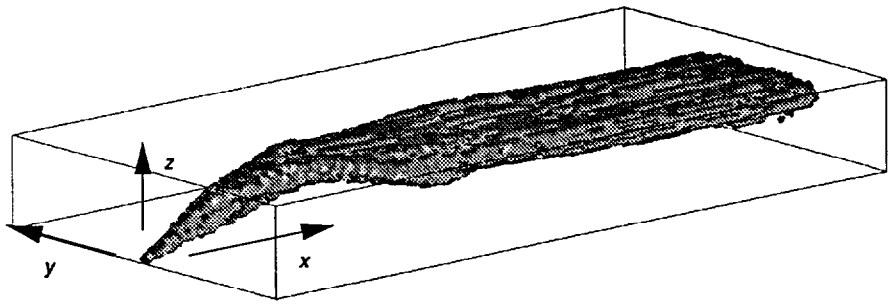

Figure 1: Three dimensional view of a computed smoke plume in the first few kilometers of its development. The height of the viewbox is 1 km, the length 8 km, and the crosswind length 4 km. The wind speed is 6 m/s. The computation is initialized by prescribing the temperature and particulate distribution in the plane spanned by the lateral and vertical coordinates. Then the plume is constructed as the smoke is swept downwind.

experiments, and to compare the results with those predicted by the LES model in order to verify the findings of the theoretical study. The first experiment is the Newfoundland Offshore Burn Experiment (NOBE) conducted by Environment Canada in August 1993. Next, the Burning of Emulsions Experiment conducted by Alaska Clean Seas in September 1994. Finally, a series of mesoscale burns held at the US Coast Guard Fire and Test Detachment, Mobile, Alabama in October 1994. The analysis of this last series is still underway. For each series of burns, the LES model was run for the recorded meteorological and burn conditions, and the results have been compared with data collected in the field. The measurement techniques for the experiments varied, thus each will be described separately.

THE LES MODEL OF SMOKE PLUME TRAJECTORY

A detailed description of the LES model may be found in References [9], [6] and [1]. The model consists of the conservation equations of mass, momentum and energy which describe the steady-state, convective transport of heated gases and combustion products introduced into the atmosphere by a steadily burning fire and blown by a uniform ambient wind. The fire itself is not modeled, but rather the plume of smoke which emanates from it. The heat release rate and smoke yield of the fuel are required as inputs. The local meteorological conditions which must be provided are the wind speed, the fluctuation in wind direction, and the temperature stratification of the atmosphere. This model differs from most of the atmospheric dispersion models in use today because it is a *deterministic* rather than an *empirical* model; that is, the approach taken is to solve the governing equations of motion directly rather than relying on empirical formulae which approximate the extent of the dispersion. These empirical models typically assume the pollutant of interest to be Gaussian distributed in the plane perpendicular to the direction of the prevailing wind. The parameters defining the distribution are estimated from experiments. Unfortunately, the problem of *in situ* burning of crude oil is inappropriate for these types of models for two reasons: (1) The nature of the "source" is different than what is normally assumed, a smokestack, and (2) the heat release rate of the source is well beyond those considered in industrial process applications and thus outside of the experimental parameter range.

THE NEWFOUNDLAND OFFSHORE BURN EXPERIMENT

The Newfoundland Offshore Burn Experiment (NOBE) provided an enormous amount of data regarding *in situ* burning of oil at sea. The experiment consisted of two burns of crude oil conducted off the coast of St. John's, Newfoundland on August 12, 1993. Most of the sampling of the chemical species produced by the burning was done relatively close to the fire. However Dr. Ron Ferek of the University of Washington's Cloud and Aerosol Research Group led a team of scientists in performing airborne measurements of the smoke plume from the two burns at distances up to 20 km downwind of the fire. Of particular importance to the present study are the LIDAR measurements of the plume cross section, and the real-time monitoring of the CO_2 level in the plume.

LIDAR measurements were performed during the second burn. For this burn, it was reported that 28.9 m^3 of crude oil of density 843.7 kg/m^3 was burned in 1.3 hours [7]. Even though substantial fluctuations in burning rate were observed, for the purposes of modeling the plume it was assumed that the burning rate was constant at 5.2 kg/s. Based on previous work with Louisiana crude [9], the effective heat of combustion of the oil was assumed to be 42,000 kJ/kg, even though a different oil was used for the experiment[2]. The smoke yield for the burn was measured by the team from NIST to be approximately 15% [10], and the fraction of the total heat release lost from the flame as radiation through the dense smoke plume was assumed to be 10% [5]. Thus, the *convective* heat release rate for the model run was about 200 MW and the particulate production rate was 0.78 kg/s. Atmospheric temperature soundings taken from the University of Washington airplane [3] and from the NIST tethered blimp [10] show a temperature inversion from about 100 to 175 m in altitude, accompanied by a shift of roughly 30 to 40 degrees in the direction of the wind. The wind speed at the ground was about 5 to 6 m/s, increasing to about 8 m/s a few hundred meters up.

Figure 2 displays cross sections of the simulated plume at downwind locations which approximately match those taken by the University of Washington airplane (See Fig. 3). The effect of the shift in the wind direction at about 120 m in altitude is obvious in both the simulated and the actual plume cross sections. There is reasonably good qualitative and quantitative[3] agreement between the two for a distance of about 6 km from the fire. Beyond this point the simulation breaks down due to a lofting of the actual plume to a height of about 700 m. A LIDAR measurement (Fig. 4) taken along the plume centerline shows the plume initially rising to a height of about 200 m, leveling off for about 5 km, and then gradually rising to a height of about 600 m after 20 km. The centerline of the simulated plume reached a height of about 250 m, but does not exhibit this gradual rise. It is unclear exactly why it occurs. It has been speculated that this lofting might be due to the heat generated by the absorption of sunlight by the smoke particulate. Another explanation is the presence of local convective cells in the path of the plume. These updrafts occur over small areas and cannot be predicted from the meteorology of the entire region. In any case, this example points out the limitation of any predictive dispersion or meteorological model. Large scale patterns and trends can be predicted, but small scale details cannot.

In addition to LIDAR measurements, the University of Washington airplane made a number of other measurements. Of interest to this study are measurements of CO_2. Plume particulate concentrations may be derived either by quantifying LIDAR cross section data as shown above, or by measuring the excess CO_2 and backing out the particulate concentration based on the smoke yield and the elemental carbon mass fraction of the fuel. Direct measurements of excess CO_2 made while flying the airplane along the centerline of the plume have been used to estimate the concentration of particulate matter. Taking the smoke yield to be 15% (from the NIST tethered blimp)

[2]The heat of combustion is based on laboratory tests of a number of crude oils.

[3]This quantification is based on an analysis of the scattering characteristics of the individual smoke particles. Details of the analysis may be found in Reference [3].

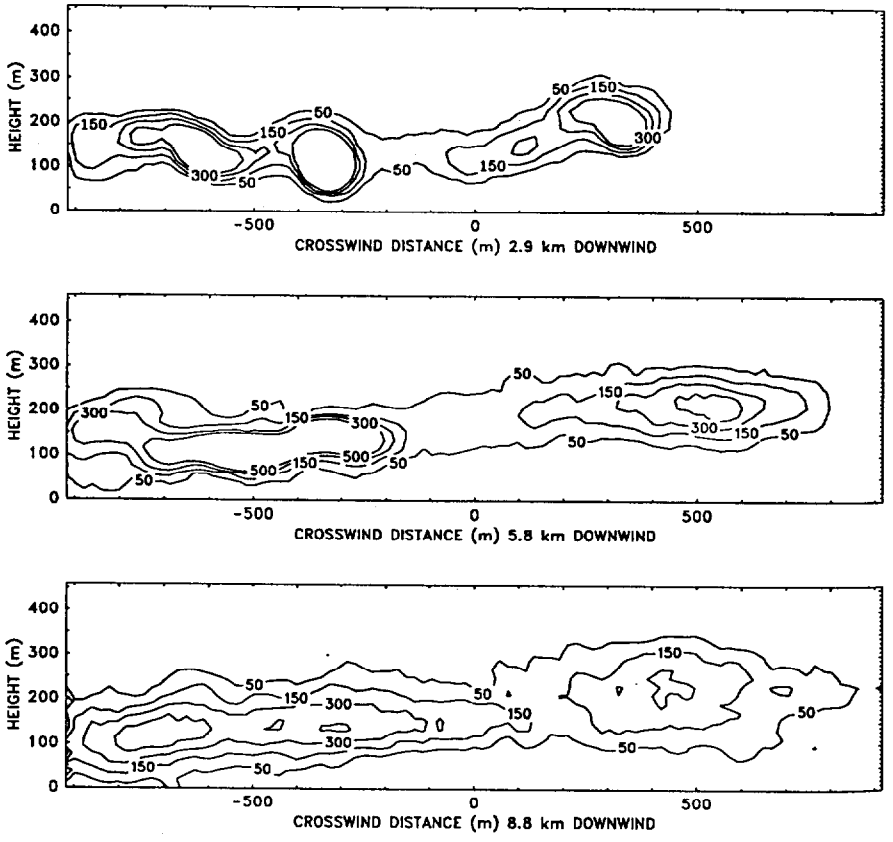

Figure 2: Cross sectional slices of the simulated smoke plume from the second NOBE burn. Shown are particulate concentration contours of 50, 150 and 300 $\mu g/m^3$ at three locations downwind corresponding to where LIDAR measurements were taken. The vertical length scale indicates height above sea level, while the horizontal scale indicates the distance from the assumed plume centerline.

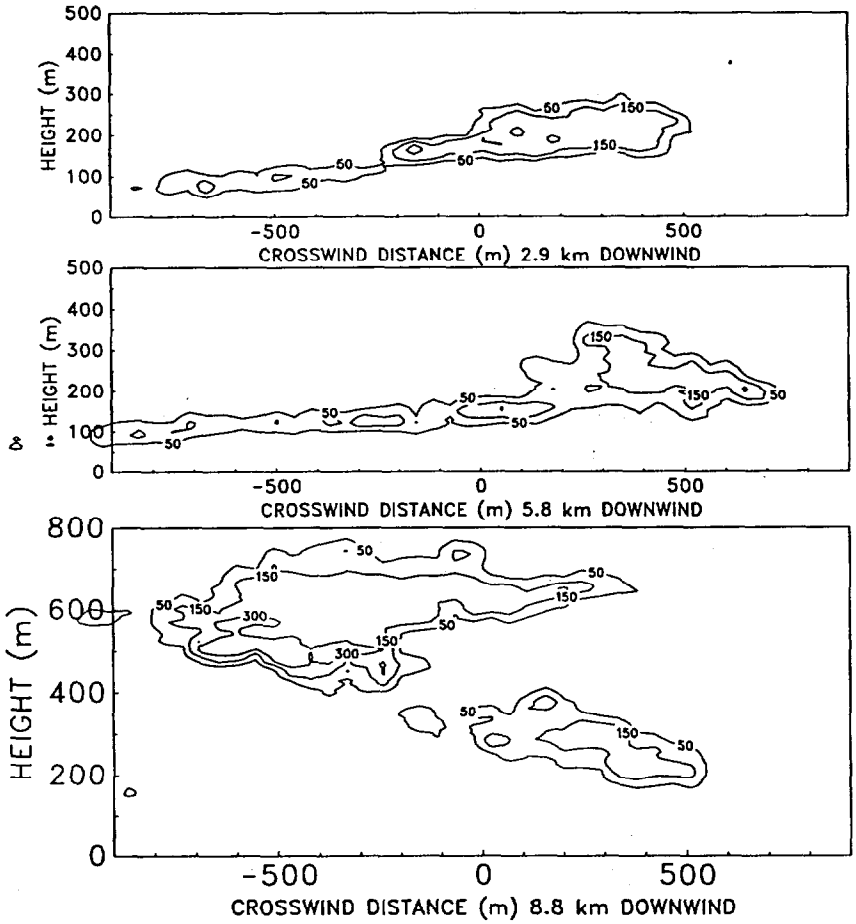

Figure 3: Cross sectional slices of the actual smoke plume from the second NOBE burn, courtesy of the University of Washington Cloud and Aerosol Research Group. Shown are contours of particulate concentration at 50, 150 and 300 $\mu g/m^3$. The crosswind scale indicates relative distances, and the origin was chosen to compare with the simulation.

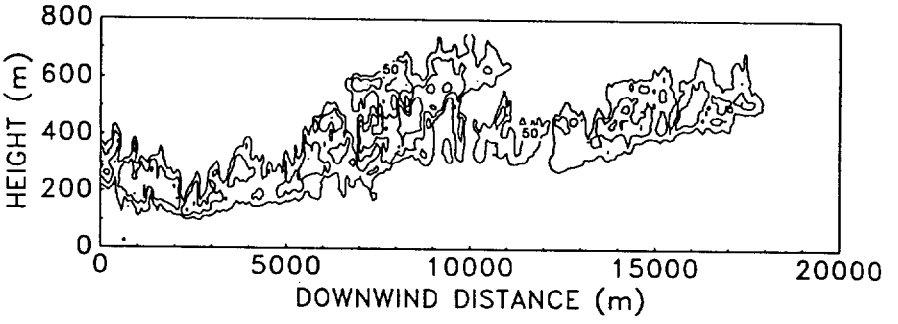

Figure 4: LIDAR measurement of plume centerline of the second burn taken from University of Washington airplane. Note that the horizontal and vertical length scales are very different. In actuality, the plume shown is a long, slender object. Also, the origin of the plot is about 0.9 km from the actual fire.

and the elemental carbon mass fraction of the fuel to be 0.8664 ; it is estimated that 1 ppm excess CO_2 corresponds to a particulate concentration of 103 $\mu g/m^3$. Direct measurements of excess CO_2 from the airplane show volume fractions decreasing to about 1.5 ppm (the equivalent of 150 $\mu g/m^3$ particulate) by about 16 km downwind of the burn. The quantified LIDAR images are consistent with this finding. The model calculation predicts that concentrations in excess of 150 $\mu g/m^3$ extend slightly farther than 20 km downwind. The discrepancy in the two estimates is not surprising, given the enhanced plume dispersion of the experiment due to the unexpected lofting. Also, the comparison is being made based on only one pass of the airplane along the plume centerline, which may not account for the maximum concentration. Indeed, the model predicts, and visual sightings confirm, the existence of counter-rotating vortices which are generated by the fire and which entrain a substantial fraction of the particulate. Thus, it is not necessarily true that the maximum concentration of particulate would be found along the centerline of the plume. *In situ* measurements of the plume cannot account for its complex structure, and thus a better means of measuring particulate concentration would be through the use of integrated techniques, such as the LIDAR measurements discussed above.

ALASKAN CLEAN SEAS EMULSION BURN TEST

In early September 1994, Alaska Clean Seas conducted at their Fire Training Ground in Prudhoe Bay, Alaska, three mesoscale burns to determine the feasibility of burning emulsified oil [2]. At the request of the Alaska office of the US Environmental Protection Agency, the EPA's Emergency Response Team (EPA/ERT) came to Prudhoe Bay with 12 real-time aerosol monitors (RAMs). These instruments use a light scattering technique to measure particulate concentrations[4]. The twelve instruments were set out on three foot tripods, spread out in rows of three or four, at distances ranging from 1 to 5 km from the burn site. The deployment strategy varied from burn to burn, depending on the weather conditions and the terrain over which the plume was expected to loft. The instruments were set to sample every second, and then log the 5 second average. Global positioning instruments recorded the locations of the individual devices.

Table 1 summarizes the three mesoscale emulsion burns. Each burn consisted of burning an oil mixture within the confines of a fire-resistant circular boom which floated in a pit filled with water. The boom diameter was roughly 9 m (30 ft), and

[4]The real-time aerosol monitors (RAMs) were equipped with an air intake separator to eliminate particulate larger than 10 microns in size.

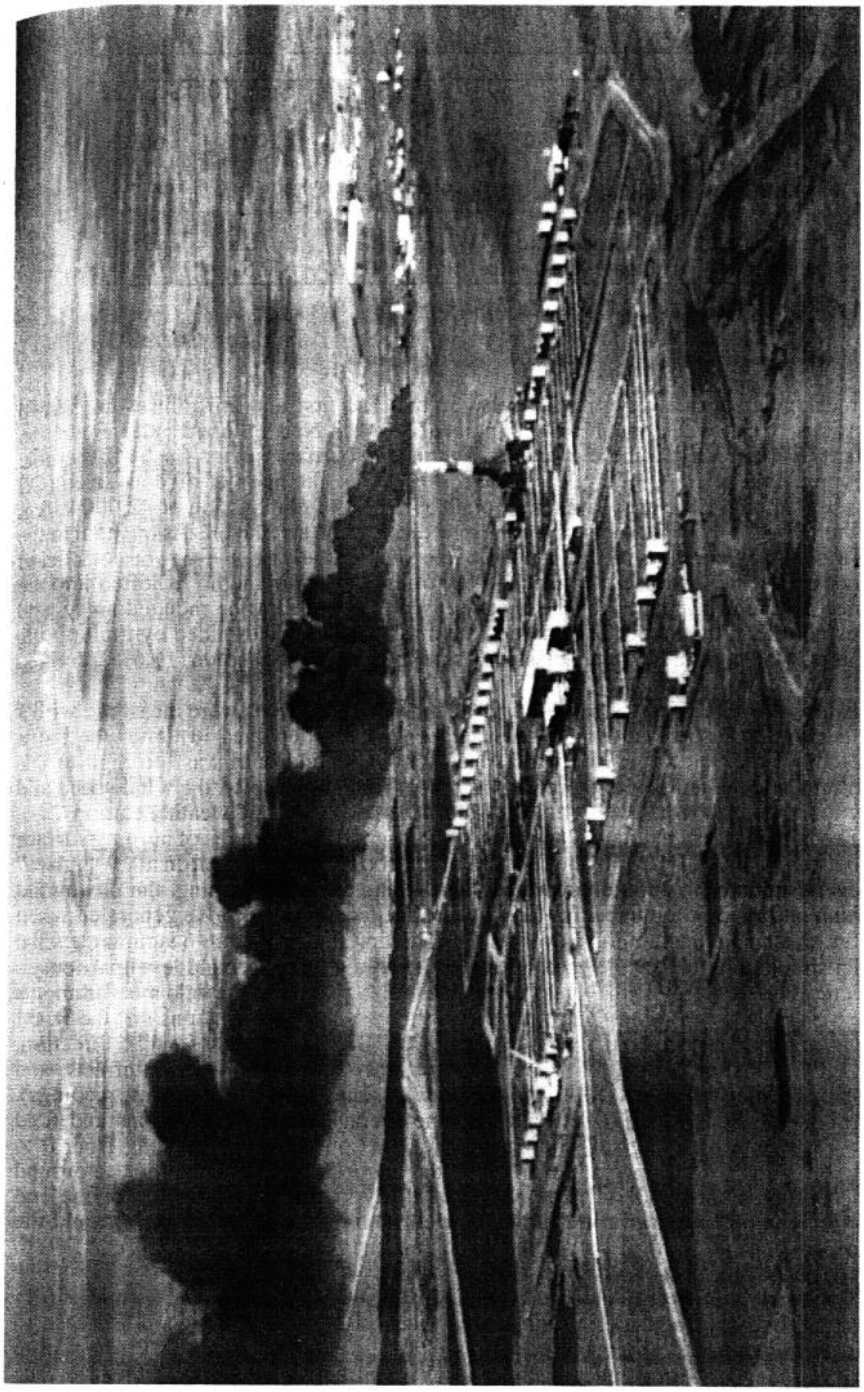

Figure 5: Aerial view of the second ACS burn (pure ANS crude), Prudhoe Bay, Alaska, September 1994.

	Burn 1	Burn 2	Burn 3
Date	Sept. 8	Sept. 10	Sept. 11
Volume of Emulsion (m^3)	7.7	12.2	16.6
Percent Oil	50%	100%	60%
Oil Mass (kg)	3768	10827	6545
Oil Removal Efficiency	97.3%	98.4%	96.7%
Burn Time (minutes)	47	40	45
Estimated Heat Release Rate (MW)	55	186	98
Estimated Particulate Mass Flux (kg/s)	0.15	0.51	0.27

Table 1: Summary of the ACS Meso-Scale Emulsion Burns.

the rectangular pit was roughly 20 m by 30 m. The first and third burns consumed emulsions of salt water and 17.4% evaporated Alaskan North Slope crude. Emulsion breakers were applied to these mixtures. The second burn consumed fresh ANS crude. To compute the average heat release rate for the burns, the mass of oil consumed (Oil Mass x Removal Efficiency) was multiplied by a heat of combustion of 42,000 kJ/kg, and then divided by the number of seconds needed to consume the oil. As an input to the LES model, an estimate is made that 90% of the total heat release rate may be considered the *convective* heat release rate, that is, 90% of the heat from the fire is lofted into the plume. The remaining 10% of the heat released is assumed to be radiated away, and serves no role in the model. The particulate mass flux was determined by multiplying the mass of oil consumed by the measured smoke yield of ANS crude (11.6%), divided by the burn time.

Atmospheric temperatures, wind speeds and wind directions were measured with a weather station suspended from a small tethered blimp, deployed just after the burns were completed. However, the wind speed for the second burn was too high to use the blimp, and the temperature profile was taken from a helicopter, the wind speed and direction estimated from the flight log of the airplane and ground weather stations.

The first burn lasted about 47 minutes, during which time the area of burning surface varied from practically zero to the full area of the boom plus spillover. In all, 9 "pulses" of several minutes in duration occurred. Due to the unsteady burning, the downwind instruments detected a number of "hits" due to the fact that the smoke generated when the fire was small was not lofted very high. The first plot of Figure 6 summarizes the model simulation of Burn 1, showing the model prediction of ground level particulate concentration versus the actual measurements made in the field. The field measurements were averaged over the time of the burn. Neither the model predictions nor the RAM data is uniform in space or in time, due in part to random fluctuations in wind direction, convective cells which are not accounted for in the model, small terrain effects, and unsteady burning of the fuel (See Fig. 7 for a typical time history of particulate readings). Nevertheless, the agreement between the time-averaged model predictions and field measurements are quite good, showing particulate concentrations ranging from 0 to 80 $\mu g/m^3$ along the narrow path over which the plume is lofted. In addition to ground level instruments, a small airplane was hired to fly in the vicinity of the plume and record plume positions at various times, as well as to photograph the burn site and the plume. According to flight track data, the plume top rose to a height of about 550 to 600 m, in good agreement with model predictions.

The second burn was conducted for two reasons. First, it provided a control with which to compare the two emulsion burns. Second, it served as a good test case to compare to the numerical model since the smoke yield and heat release rate from a large pool fire of unweathered, unemulsified oil are relatively well known from previous laboratory and mesoscale experiments [6], [9]. The second plot of Figure 6 summarizes the model prediction versus field measurements for Burn 2. Of particular interest in

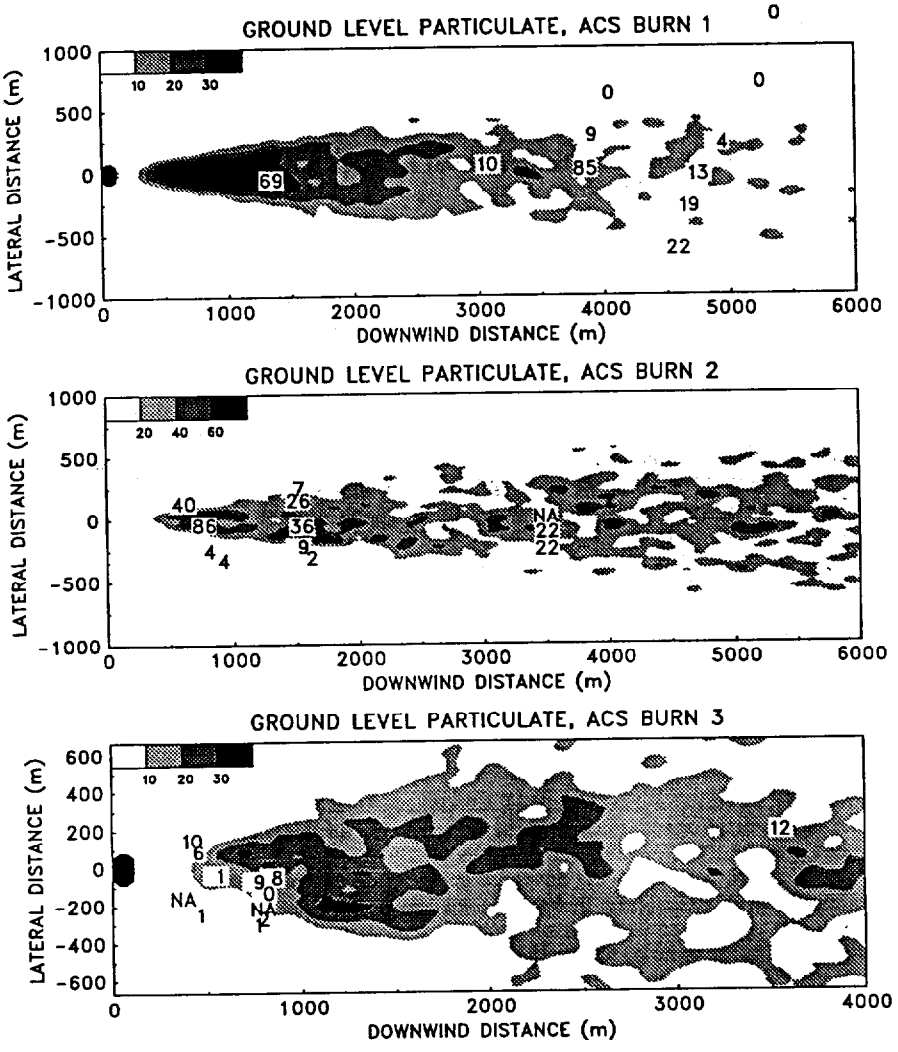

Figure 6: Predicted ground level particulate concentrations from the LES model (shaded contours) along with actual time-averaged RAM data for the three ACS Emulsion Burns. All concentrations are given in units of $\mu g/m^3$.

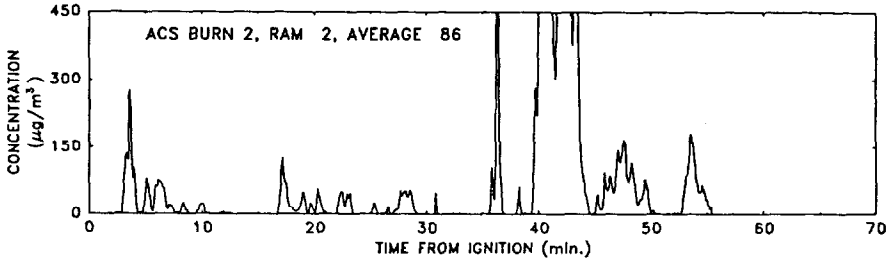

Figure 7: Particulate concentration about 1 km directly downwind of the second ACS burn, as recorded by a real-time aerosol monitor (RAM). The concentrations are given in units of $\mu g/m^3$.

this burn was the presence of a thermal inversion at about 300 m. This inversion layer restricted the plume to a maximum height of about 400 m, and again this altitude was verified by the accompanying flight track recorder from the airplane. The wind variability was less than that recorded for the first or the third burn, yielding a plume which retained its basic shape and structure for about 10 km.

Even though the fuel for the third burn resembled that of the first, the burn was much steadier than the first. This probably was due to a slight modification in the application of the emulsion breaker. In any event, weather conditions on the day of the third burn (September 11) were so foggy that the helicopter, which had been used on previous days to place instruments in the field, was grounded. The wind was from the north, blowing directly over a river bed, but shifting about 10° per hour. Because of the bad terrain and visibility, it was decided to deploy the instruments in the near field, all within a kilometer of the pit except for one which was sent with a monitor further afield. The third plot of Figure 6 summarizes the numerical prediction and field measurements from the third burn.

NEAR-FIELD SMOKE SAMPLING

The accuracy of numerical predictions of far-field particulate concentration and the relation of chemical species such as PAH compounds measured in the smoke to the amount in the original oil both depend directly on the measured smoke yield of the fuel which is burned. For crude oil and other heavy refined fuels, the smoke yield is usually in the range of 10 to 15%, as determined by the carbon balance method which states that the mass of carbon in the fuel consumed is equal to the mass of carbon in the airborne combustion products. Given that the smoke aerosols are predominately carbon, it may be assumed that the carbon consumed by the fire is converted to particulate, CO and CO_2 present in the smoke plume [9]. Of these three, CO is a minor player, thus there ought to be a close correlation between the concentration of CO_2 and smoke particulate in the air if one assumes that the CO_2 and particulate formed by the fire are transported together and undergo turbulent mixing with the air entrained into the smoke plume. However, it has been reported [4] that CO_2 and smoke particulate do not travel together; that the CO_2 forms a separate plume close to the surface, distinct from the smoke plume.

To clarify the situation and verify the assumption made in the carbon balance method of smoke yield determination, near-field sampling of smoke particulate and CO_2 was conducted at the ACS and Mobile burns. A RAM unit and a highly sensitive nondispersive infrared CO_2 analyzer were placed together at various locations within a radius of about 10 meters from the burn pit. Figure 8 shows values of the two quantities during the first ACS burn. The scales of the left and right axes reflect a ratio of 80 $\mu g/m^3$ particulate for every ppm excess CO_2. This same ratio was noted by the University of

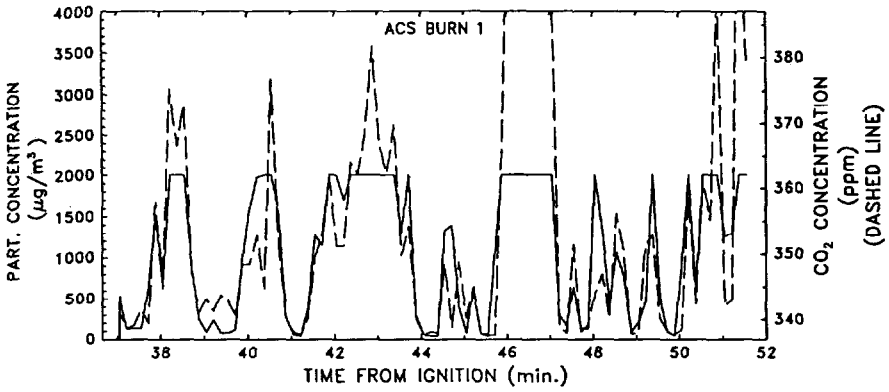

Figure 8: Near-field simultaneous measurements of particulate and CO_2 at the ACS Emulsion Burns. The location of the instruments for this time sequence was about 5 m downwind of the fire, just below the berm of the pit. The scale ratio of the left and right axes is 80 to 1. The flattened peaks of the particulate curve are due to the fact that the RAM has reached its upper range of 2000 $\mu g/m^3$.

Washington team at the Newfoundland burn in the plume several kilometers downwind of the fire [3]. This ratio corresponds to a smoke yield of about 11%, based on carbon balance arguments. The smoke yield is consistent with the more rigorous procedure that is usually followed to determine smoke yield, where direct, long time-averaged samples of combustion products are extracted from the core of the smoke plume and analyzed. Figure 9 shows a result of the same experiment conducted at the October, 1994, series of mesoscale burns at the US Coast Guard Fire and Safety Detachment, Mobile, Alabama. Even though crude oil was not burned, but rather diesel fuel, the results are very similar. In fact, the data is plotted with the same scaling ratio as that for the Alaskan burn. As before, the presence of excess CO_2 correlates very closely with both the presence and quantity of particulate recorded throughout the test.

The results from these two experiments, plus the results of the airborne sampling performed by the University of Washington at Newfoundland [3], clearly show when and where CO_2 is detected at ground level near the fire there is also particulate. In fact, the ratio of particulate to CO_2 indicates a smoke yield on the order of 10%. There is no evidence of a CO_2 plume separate from the visually obvious smoke plume as reported in Reference [4]. Furthermore, the ratio of excess CO_2 to particulate was found to be about the same both near the fire and far downwind, indicating that the smoke particulate and CO_2 travel together for large distances from the fire. This finding adds to the validity of the carbon balance method as the appropriate technique for determining smoke yield, which for crude oils and heavy refined fuels is consistently in the range of 10 to 15%.

CONCLUSION

The results of the experiments presented here increase the confidence in the numerical predictions of plume structure, trajectory and composition. The comparison of predicted versus measured particulate concentration is very encouraging, given the uncertainties in the fire and weather characterization. In fact, the model predictions were based on very limited meteorological information – wind speed, wind variation and temperature stratification only. This is important for two reasons. First, local meteorological data for regions of interest is often very limited. Second, if the numerical model is to be used effectively for a wide variety of conditions, it must not depend on

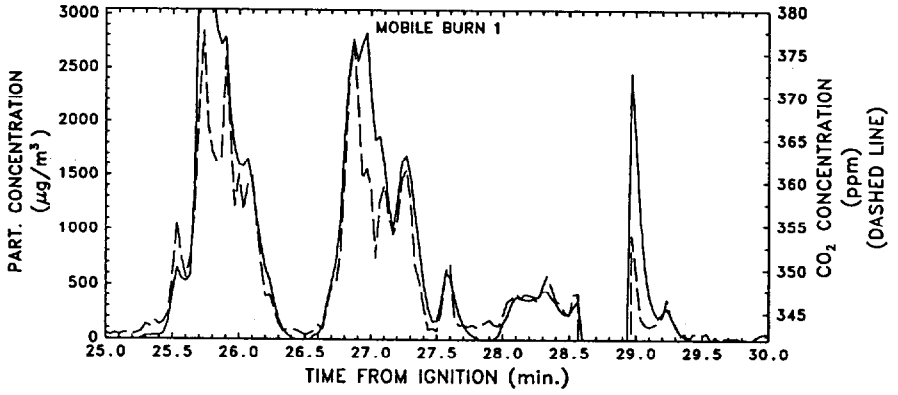

Figure 9: Near-field simultaneous measurements of particulate and CO_2 at the first Mobile Burn. The location of the instruments for this time sequence was about 15 m downwind of the fire. The scale ratio of the left and right axes is 80 to 1.

empirical input parameters tuned for a particular situation.

As far as the field measurement techniques are concerned, these experiments have provided a wealth of information on how to monitor emissions from large burns. Unlike conventional air monitoring where the source, such as a power plant, is expected to generate pollutants over a long period of time, an *in situ* burn will typically last a few hours. High volume samplers are difficult to position and cannot collect enough particulate in that short period of time, hence the need for reliable, portable real-time aerosol monitors. For the purpose of model verification, LIDAR measurements have the most potential because they can capture the overall plume structure rather than sparse point measurements. The drawbacks of this technique are that they are expensive, and that the measurements are difficult to quantify.

Needless to say, all of the tools to track and measure smoke plumes have their advantages and disadvantages. Ultimately, a verified numerical model should provide planners with sufficient information about the impact of the smoke plumes from large open fires.

ACKNOWLEDGEMENTS

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