MESOSCALE EXPERIMENTS HELP TO EVALUATE IN-SITU BURNING OF OIL SPILLS[1]

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ABSTRACT: *Burning of spilled oil has distinct advantages over other cleanup 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 other unburned and residue byproducts. Disadvantages include the dispersal of the combustion products into the air.*

Mesoscale and laboratory experiments have been conducted to measure the burning characteristics of crude oil fires. Measurements on crude oil pool fires from 0.4 m to 17.2 m in effective diameter were made to obtain data on the rate of burning, heat release rate, composition of the combustion products, and downwind dispersion of the products. The smaller experiments were performed in laboratories at the National Institute of Standards and Technology and the Fire Research Institute in Japan; and the larger ones at the U.S. Coast Guard Fire Safety and Test Detachment in Mobile, Alabama. From these experiments, the value for surface regression rate of a burning crude oil spill was found to be 0.055 mm/s.

A major concern for public safety is the content and extent of the smoke plume from the fires. Smoke yield, the fraction of the oil mass burned that is emitted as particulate, was found to be 13 percent. A large-eddy simulation calculation method for smoke plume trajectory and smoke particulate deposition developed by NIST showed that the smoke particulate deposition from a 114 m² burn would occur in striations over a long, slender area 3.2 km wide and 258 km downwind of the burn.

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 other unburned and residue byproducts. Because the oil is converted to gaseous 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 particulates and other products of combustion that may persist for many kilometers from the burn. This 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. In 1985, a joint Minerals Management Service (MMS) and Environment Canada (EC) in-situ burning research program was begun at the National Institute of Standards and Technology (NIST). This research program was designed to study the burning of large crude oil spills on water and, by quantifying the products of combustion and developing methods to predict the downwind smoke particulate deposition, how this burning would affect air quality.

To understand the important features of in-situ burning, both laboratory and mesoscale experiments are necessary. In this research program there is a continuing interaction between findings from measurements on small fire experiments performed in the controlled laboratory environments of NIST and the Fire Research Institute (FRI) in Japan, and large fire experiments at facilities like the U.S. Coast Guard (USCG) Fire Safety and Test Detachment in Mobile, Alabama, where outdoor liquid fuel burns in large pans are possible. Finally, actual burns of spilled oil at sea will be necessary to evaluate the method at the anticipated scale of actual response operations.

Experimental facilities

At NIST, two major facilities were used to perform measurements on crude oil pool fires ranging in diameter from 0.085 m to 0.6 m. The smallest fires, 0.085 m diameter, were conducted in the cone calorimeter to determine the effective heat of combustion for the crude oils and evaluate smoke yield using three different measurement methods. The cone calorimeter, shown in Figure 1, is more formally known as stan-

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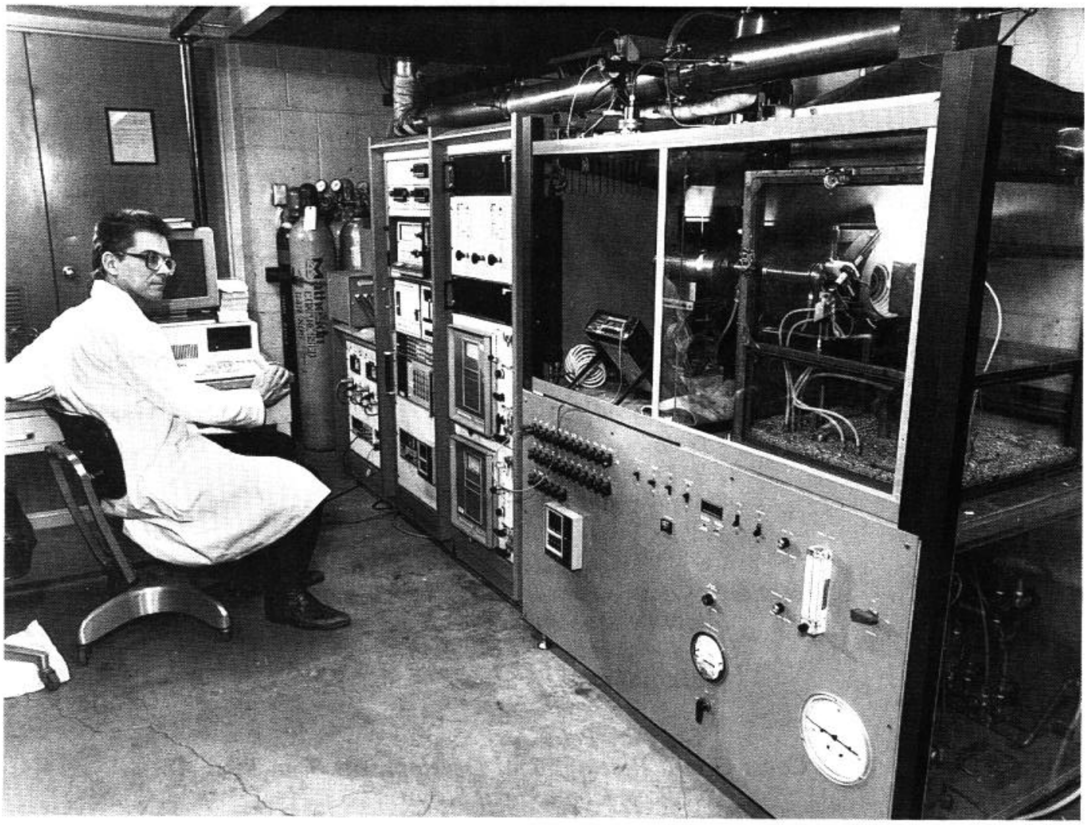

Figure 1. NIST cone calorimeter

dard test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter.[2] The name of the apparatus, cone calorimeter, is derived from the shape of the heater used to irradiate samples. The heater coils are formed along the inner surface of a truncated cone. By imposing additional thermal radiation on a small sample, the sample is made to burn as if it were a small portion of a larger fire. All of the major material flammability characteristics can be evaluated using this laboratory apparatus. These include: rate of heat release, effective heat of combustion, total heat release, ignitibility, mass loss rate, smoke specific extinction area, and yields of various gaseous species and particulates.

A larger calorimeter apparatus capable of accommodating samples up to 0.6 m in diameter was used to provide additional NIST laboratory data on the effect of fire diameter on smoke yield from crude oil fires. This instrumented exhaust hood, shown in Figure 2, has been the workhorse of the laboratory scale studies of crude oil combustion for several years in this research program.[3-9] Samples drawn from the exhaust hood duct were used to quantify the amount of each major combustion product generated per kilogram of crude oil burned, the chemical composition of the smoke including PAH content, the particulate size distribution of both fresh and aged smoke, and the oxygen consumed in the combustion process. Oxygen consumption calorimetry is used to calculate the heat release rate of the fire, which is the primary quantity used to characterize burning intensity. To further characterize the combustion process, additional instrumentation was used to measure radiant heat flux from the flame and the mass loss rate of the burning fuel.

Relatively small, 0.6 m diameter, fires provided a means of measuring fire characteristics under controlled conditions, but are too small to provide an adequate test of measurement equipment being developed for field use. Through the cooperation of the FRI in Tokyo, joint studies of crude oil burning characteristics were conducted. The institute maintains a fire test facility in which crude oil pools up to 3 m in diameter are burned, with all of the combustion products collected in a large hood system. Figure 3 shows a 2 m diameter Murban crude oil fire burning in the 24 m by 24 m by 20 m-high test hall. This facility can accommodate fires that are large enough to evaluate sampling packages designed for mesoscale experiments. The exhaust system for the building was instrumented so that measurements similar to those performed in the NIST facility could be made by using the entire FRI test building as a smoke collection hood.

Mesoscale configuration

The mesoscale burns of crude oil were carried out under the direction of NIST at the USCG 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 4 is a photograph of a burn in progress at the fire testing facility.

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 steel plate and the walls were 5-mm steel plate. The tops of the walls were reinforced with steel angle to prevent warping during the burns. The base of the pan was at 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 areas. The inner area of the pan was filled with approximately 0.5 m of water and the crude oil was added on top of the water. An oil spill containment dike approximately 0.5 m high was constructed 4 m from the outer edge of the pan.

Crude oil was fed to the burn pan via an underground pipe. A vertical section of the oil fill pipe penetrated the base of the pan and

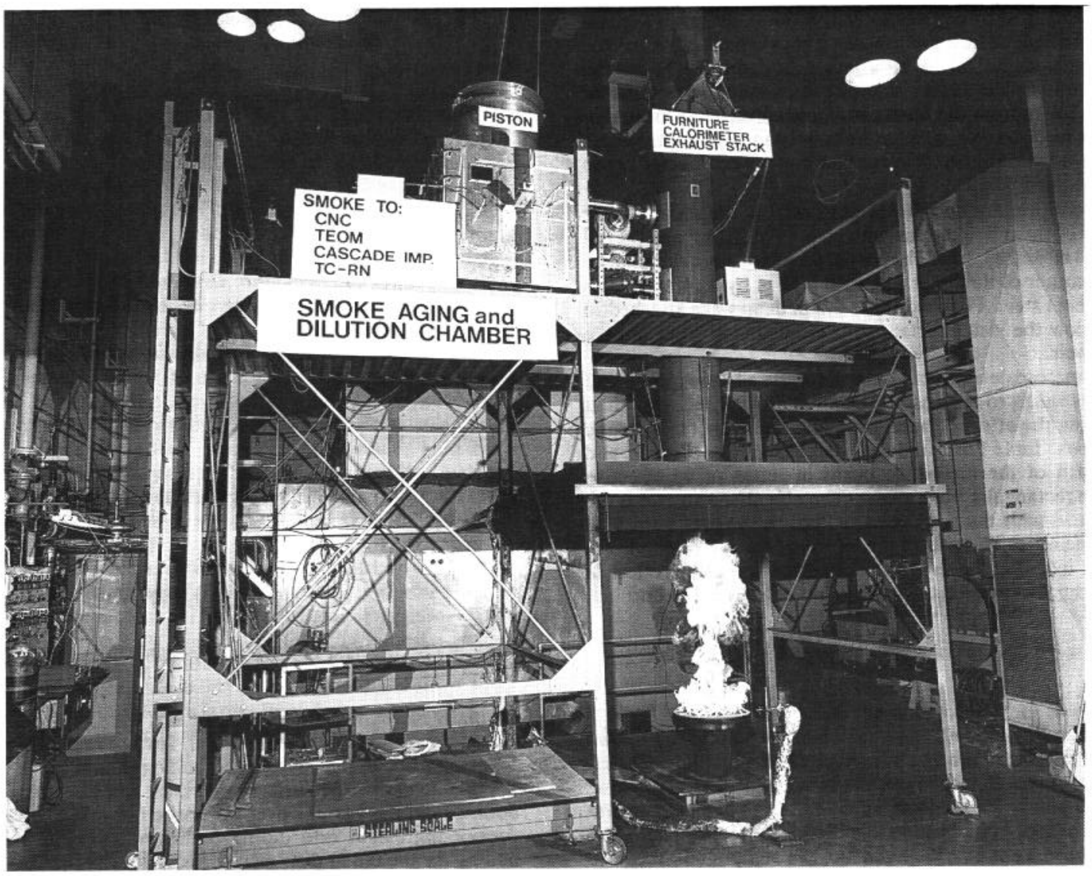

Figure 2. 0.6 meter diameter crude oil fire in NIST large calorimeter

Figure 3. Two meter diameter Murban crude oil fire at Fire Research Institute in Japan

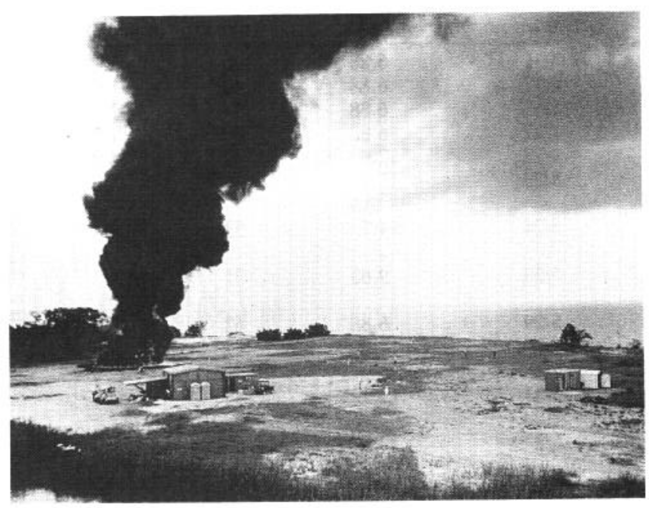

Figure 4. 17.2 meter effective diameter Louisiana crude oil fire at the USCG Safety and Fire Test Detachment mesoscale test facility in Mobile, Alabama

terminated in a flanged fitting located below the water level. A plate was bolted on the flanged fitting with spacers between the plate and the flange. This allowed the oil to be injected horizontally below the surface of the water. The supply side of the oil 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.

Three 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 partial pan areas of 114 m^2 and 37.2 m^2. The partial pan areas were achieved by partitioning a corner of the inner pan with 0.14 m by 0.14 m timbers covered with sheet steel. Plywood skirts 0.3 m deep were attached to the timbers below the water surface to prevent the oil from flowing under the timbers.

A total of 14 mesoscale burns of Louisiana crude oil were conducted: two preliminary burns to test instrumentation and procedures, eight burns to examine the effect of burn area, and four burns to examine special conditions. Table 1 lists initial oil depths, wind conditions, and the size for each of the mesoscale burns in terms of an effective diameter of the rectangular burn areas. (The effective diameter is the diameter of circle with the same area as the rectangular burn area used.) Special features of some of the experiments are listed also in Table 1. These included the use of fire resistant boom, the effect of water spray on smoke emissions, and the effect of oil aging on burning.

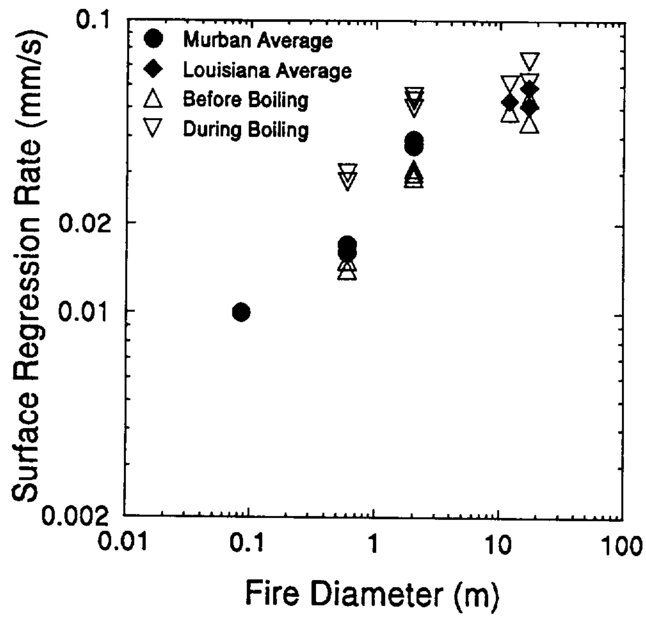

Figure 5. Burning surface regression rate for crude oil fires

Results

The study of crude oil combustion on water is complicated by two factors. One is that the oil is being burned in a layer floating on water. The other is that crude oil is a blend of many hydrocarbons with a wide range of boiling points, the majority of which are at higher temperatures than the boiling point of water. Distillation measurements of the Louisiana crude oil show that 90 percent of the compounds in the oil have boiling points above 100° C. During burning the surface of the crude oil maintains a temperature of around 300° C. As the fuel is consumed and the fuel layer becomes thin, heat transferred through the fuel to the water below can result in boiling of the water. The boiling effect has been observed in laboratory-scale as well as field-scale burns. Boiling of the water below the fuel agitates the fuel layer with both fuel and water droplets being sprayed into the flame, substantially increasing the burning rate of the fire, as indicated by the measured oil surface regression rate. Surface regression rates are thus reported prior to and during the boiling phase.

Figure 5 shows the surface regression rates before boiling, during boiling, and the average over the entire burn. It can be seen that the surface regression rate during boiling was double the rate before boiling for the 0.6 m diameter burns and nearly double for the 2.0 m diameter burns. For the larger burns conducted as part of the mesoscale experiments, boiling causes a much smaller increase—approximately 30 percent. In addition to scale, this may be a function of oil type, initial oil and water thicknesses, and other parameters. The average burning rate as indicated by the regression rate of the oil surface was found to be 0.055 ± 0.01 mm/s for pan fires with effective diameters greater than 7 m. This value is slightly greater than 0.046

Table 1. Mesoscale experiments

Burn no.	Effective burn diameter (m)	Initial oil depth (mm)	Wind speed (m/s)	Percent consumed	Residue burns	Features
4/16	6.88	90	1.5	93		
4/17	6.88	43	1.9	94		
5/16	6.88	34	2.1	75		
5/17	6.88	60	1.7	92		
5/22	12.0	32	4.0	96		water spray
5/23	15.2	18	5.0	90		boom attached two ends, free to move
5/24	14.7	33	2.4	98		boom attached two ends, free to move
5/28	9.63	31	1.2	93		boom attached two ends, restricted to square area
5/29	6.88	62	5.0	91		oil aging
5/30	12.0	51	3.9	99	1st—1318 s 2nd—NR	
5/31	17.2	49	0.8	99	1st—1054 s 2nd—460 s	
6/3	12.0	63	1.0	99	1st—769 s 2nd—304 s 3rd—401 s	
6/4	12.0	61	2.1	96		
6/5	17.2	62	2.1	99	456 s	

NR = not recorded

mm/s (0.11 inch/min.) published for the burning rate of oil slicks 13 mm or greater in thickness.[1]

Table 1 lists the percentage of the initial oil pool that was consumed in the mesoscale burns. In all but one case, more than 90 percent was burned. In some of the tests, residual oil from the initial burn was gathered and reignited. In all of the multiple-burn cases 99 percent of the oil was consumed by burning. Although it can not be simulated by burning a stagnant oil pool in a pan, the gathering and reignition of the oil may be more representative of the expected results when oil is burned in a boom moving through the water. In the case of the burning oil within a moving boom, thin layers of oil that may have extinguished near the leading edge of the burn area, will be carried toward the apex of the boom where this oil will be reignited as it combines with the burning thicker portion of the oil in the apex of the boom.

To understand the environmental effects of in-situ burning of oil spills, smoke production must be quantified. The quantity of smoke produced from a fire may be expressed as a smoke yield, which is defined as the mass of smoke particulate produced from burning a unit mass of fuel. Three independent measurement methods have been used to determine the smoke yield in the laboratory: the flux method, the carbon balance method, and the light extinction method. Of these three methods only the carbon balance method is suitable for field measurements.

Smoke yield measurements for two crude oils, Murban and Louisiana, using all three measurement methods were performed in the laboratory to assess the accuracy of the carbon balance method relative to the other two methods. It was shown that the largest variation between the three methods of measuring smoke yield was 6 percent for well-controlled and repeatable 0.085 m diameter laboratory fires. Measurement of smoke yield from larger fires show greater variation, which is attributed to the difficulty of reproducing large fires. The measurements also showed that the smoke yield from Louisiana crude oil is approximately 20 percent greater than that from Murban crude oil.

Smoke yield measurements based on the carbon balance methods for the three order-of-magnitude ranges of pan-fire diameters studied are shown in Figure 6. For the mesoscale burns an estimation of the uncertainty of the smoke yield is shown as error bars in Figure 6. It can be seen that smoke yield is dependent on scale. The yield is lower for smaller diameter fires and appears to be approximately 13 percent for fires with diameters above 2 m. In small diameter fires the air, which is entrained around the fire perimeter, more readily mixes with the fuel resulting in more complete combustion and a lower smoke yield. Using results from this study, an estimate of total smoke particulate production from large oil spill burns would be 13 percent of the total mass of oil burned.

A principal concern in the decision to use in-situ burning as an oil spill mitigation technique is the anticipated trajectory of the smoke plume and the settling out of particulates. A smoke plume trajectory model has been developed to include the capability to describe the rising thermally dominated portion of the smoke plume as well as the descent of the cool, negatively buoyant smoke. A simplified description of the mean thermal stratification of the atmosphere is also included. The wind in the undisturbed atmosphere is assumed to be uniform on average, but the small scale random eddy motion induced by the natural turbulence in the atmosphere is represented by an effective "eddy viscosity." A computer code based on an existing enclosure fire stimulation program has been developed to implement the model. The resulting code, called LES for large eddy simulation, can be readily generalized to include realistic time-averaged ambient temperature and wind profiles in the atmosphere. The full plume trajectory as well as the particulate deposition footprint on the ground have been calculated for one of the mesoscale tests conducted at the USCG Fire and Safety Test Detachment in Mobile, Alabama.

Figures 7 and 8 illustrate results obtained from a calculation using

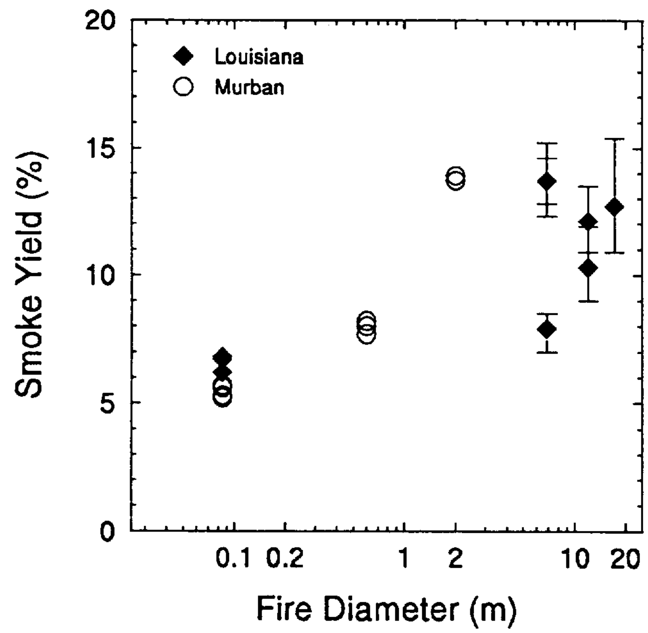

Figure 6. Smoke yield by carbon balance method

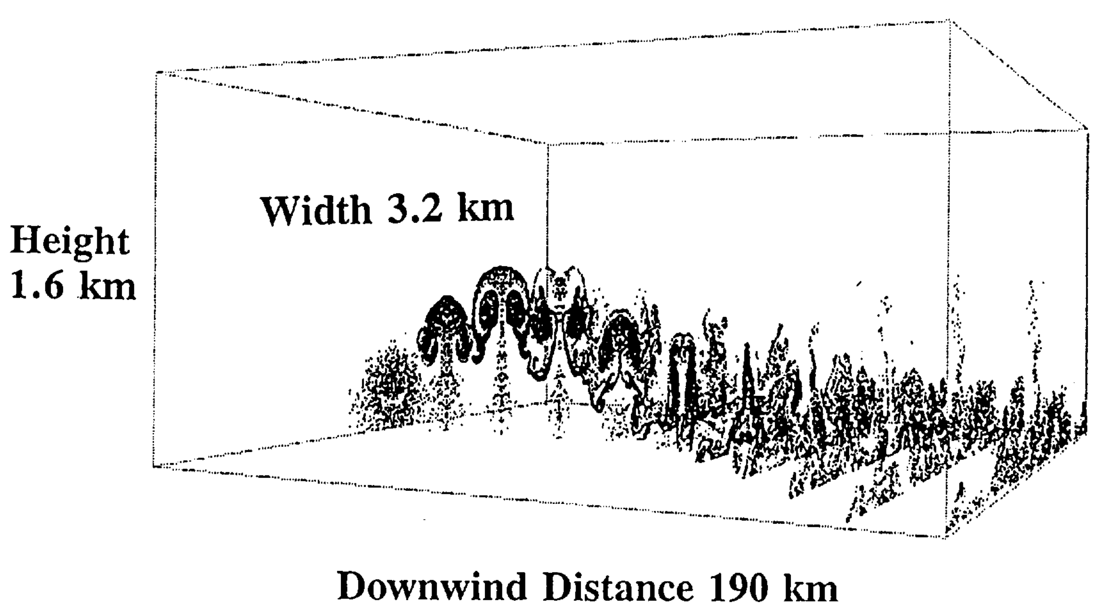

Figure 7. Large eddy simulation prediction of downwind smoke plume

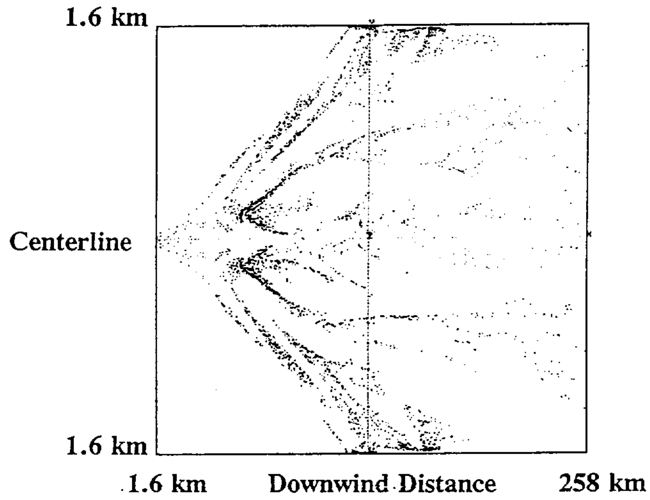

Figure 8. Large eddy simulation prediction of the pattern of downwind particulate deposition

LES to simulate the plume trajectory and downwind smoke particulate deposition from a 114 m^2 mesoscale burn. The burn generated an estimated 0.5 kg/s soot particulate mass flux in a fire whose convective heat release rate is estimated at 110 MW. Wind velocity was measured at 6 m/s. The computational domain represents a volume 1.6 km high, 3.2 km wide, and 258 km in the downwind direction.

Figure 7 shows the locations of the particle plume at 11 stations downwind of the fire extending out the first 190 km. The plume is initially dominated by the large heat input from the fire and the plume rises rapidly to a maximum height of about 0.8 km. The smoke plume gradually separates from the thermal plume, however, once the stabilized height is reached. This is due to a combination of small scale mixing processes and the stratification of the atmosphere. After the separation of the thermal and particle plumes, the negatively buoyant particle plume gradually descends to the ground. Near ground level, lateral spreading is enhanced by the interaction of the vorticity in the plume with the ground plane. Finally, particulate matter within 6.25 m of the ground (the size of one computational cell) is assumed to settle out of the atmosphere and is removed from the computation. The reader is reminded to note the difference in downwind and crosswind scales in Figure 7; even with the enhanced spreading near the ground, the plume is a long, slender object.

Figure 8 shows the computed footprint in the ground plane, covering a downwind distance of 258 km, where over 90 percent of the particulate matter has settled out of the plume. The particles are distributed in long striations, which are caused by the ground-induced vortex motion that produces highly organized motion near the surface. This plot indicates that the deposition near the ground is far from uniform, so that the average value of 1.5 mg/m^2 over the whole footprint is not a reliable indicator of the local particle deposition. Only a few percent of the ground-level computational cells are actually occupied by particles. Again, the reader should be aware of the difference between the crosswind and downwind length scales when studying this figure.

Acknowledgments

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References

1. Allen, A. A., 1991. In-situ burning of spilled oil. *Spill Technology Newsletter*, v16, n4, pp1–12
2. Babrauskas, V., 1990. The cone calorimeter—a new tool for fire safety engineering. *ASTM Standardization News*, v18, pp32–35
3. Benner, B. A. Jr., N. P. Bryner, S. A. Wise, G. W. Mulholland, R. C. Lao, and M. F. Fingas, 1990. Polycyclic aromatic hydrocarbon emissions from the combustion of crude oil on water. *Environmental Science and Technology*, v24, pp1418–1427
4. Evans, D., H. Baum, B. McCaffrey, G. Mulholland, M. Harkleroad, and W. Manders, 1986. Combustion of oil on water. *Proceedings of the Ninth Arctic Marine Oilspill Program Technical Seminar*. Ministry of Supply and Services Canada, Cat. No. En 40-11/5-1986E. Environment Canada, Edmonton, Alberta, pp301–336
5. Evans, D., H. Baum, G. Mulholland, N. Bryner, and G. Forney, 1989. Smoke plumes from crude oil burns. *Proceedings of the Twelfth Arctic and Marine Oil Spill Program Technical Seminar*. Ministry of Supply and Services Canada, Cat. No. En 40-11/5-1989. Environment Canada, Edmonton, Alberta, pp1–22
6. Evans, D., G. Mulholland, D. Gross, H. Baum, and K. Saito, 1987. Environmental effects of oil spill combustion. *Proceedings of the Tenth Arctic and Marine Oil Spill Program Technical Seminar*. Ministry of Supply and Services Canada, Cat. No. En 40-11/5-1987E. Environment Canada, Edmonton, Alberta, pp91–130
7. Evans, D., G. Mulholland, D. Gross, H. Baum, and K. Saito, 1988. Burning, smoke production, and smoke dispersion from oil spill combustion. *Proceedings of the Eleventh Arctic and Marine Oil Spill Program Technical Seminar*. Ministry of Supply and Services Canada, Cat. No. En 49-11/5-1988 E/F. Environment Canada, Edmonton, Alberta, pp41–87
8. Evans, D., W. Walton, H. Baum, R. Lawson, R. Rehm, R. Harris, A. Ghoniem, and J. Holland, 1990. Measurement of large scale oil spill burns. *Proceedings of the Thirteenth Arctic and Marine Oil Spill Program Technical Seminar*. Ministry of Supply and Services Canada, Cat. No. En 40-11/5-1990. Environment Canada, Edmonton, Alberta, pp1–38
9. Evans, D., W. Walton, H. Baum, G. Mulholland, J. Lawson, H. Koseki, and A. Ghoniem, 1991. Smoke emission from burning crude oil. *Proceedings of the Fourteenth Arctic and Marine Oil Spill Program Technical Seminar*. Ministry of Supply and Services Canada, Cat. No. En 40-11/5-1991. Environment Canada, Edmonton, Alberta, pp421–449