Reprinted from: Proceedings of 12th Joint Panel Meeting of the UJNR Panel on Fire Research and Safety, Oct. 27 - Nov. 2, 1992, Produced by: Building Research Institute, Tsukuba, Ibaraki and Fire Research Institute, Mitaka, Tokyo, 1994.

LARGE FIRES: BURNING OF OIL SPILLS

David D. Evans
William D. Walton
Kathy A. Notarianni
Howard R. Baum
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce
Gaithersburg, MD 20899

and

Hiroshi Koseki
Fire Research Institute
Mitaka, Tokyo 106, Japan

ABSTRACT

In 1991 a series of 14 mesoscale fire experiments were performed to measure the burning characteristics of crude oil on salt water. These oil burns in a pan ranged in size from 6 m square to 15 m square. Results of the measurements for burning rate and smoke emissions are compared to those from previous smaller scale burns conducted both in the U.S. and in Japan. The burning rate as indicated by the regression rate of the oil surface was found to be 0.055 $\pm$ 0.01 mm/s for pan fires with effective diameters greater than 7 m. Smoke particulate yields from fires greater than 2 m in diameter were found to be approximately 0.13 of the oil burned on a mass basis. Predictions of smoke plume trajectory and particulate deposition at ground level from the Large Eddy Simulation (LES) model developed as part of this research effort were found to be different from those predicted by the EPA approved SCREEN model. LES is a steady-state three-dimensional calculation of smoke plume trajectory and smoke particulate deposition based on a mixed finite difference and Lagrangian particle tracking method.

1. 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 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 particulate and other products of combustion which may persist for many kilometers 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. 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 how this burning would affect air quality by quantifying the products of combustion and developing methods to predict the downwind smoke particulate deposition.

To understand the important features of in-situ burning it is necessary to perform both laboratory and mesoscale experiments. Finally, actual burns of spilled oil at sea will be necessary to evaluate the method at the anticipated scale of actual response operations. 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 USCG Fire Safety and Test Detachment in Mobile, Alabama where outdoor liquid fuel burns in large pans are possible.

2. BURNING RATE

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 greater 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, 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 1 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 the boiling causes a much smaller increase of approximately 30 percent. This may be a function of the oil type, initial oil and water thickness, and other parameters in addition to scale. The average burning rate as indicated by the regression rate of the oil surface was found to be 0.055 $\pm$ 0.01 mm/s for pan fires with effective diameters greater than 7 m. This value is useful in estimating the amount of crude oil consumed by burning spills of known area.

3. SMOKE YIELD

To understand the environmental effects of in-situ burning of oil spills the 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; 1) the flux method, 2) the carbon balance method, and 3) 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 the 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 the Murban crude oil.

Smoke yield measurements based on the carbon balance methods for the three order of magnitude range of pan fire diameters studied are shown in figure 2. For the mesoscale burns an estimation of the uncertainty of the smoke yield is shown as error bars in figure 2. From figure 2 it can be seen that smoke yield is dependent on scale. The yield is lower for smaller diameter fires and appears to reach a plateau of 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, the estimate the total smoke particulate production from large oil spill burns would be 13 percent of the total mass of oil burned.

4. PARTICLE SIZE DISTRIBUTION

Particulate size is an important health consideration and also impacts the dynamics of smoke settling. Particles having an aerodynamic effective diameter less than 10 μm are considered respirable [1] 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 size distribution. Smoke particles are an agglomeration of individual spherules. Figure 3 shows a tunneling electron micrograph of smoke particulate emitted from a 1 m diameter crude oil fire. The spherules that make up the structure of the smoke particulate are relatively uniform in size with an average diameter of 0.06 μm. Measurements of smoke particles from 3 m diameter crude oil fires have shown a mixture of spherule diameters in two groupings of 0.15 and 0.06 μm [2].

There is no means to directly translate the observed irregular shape of smoke particles 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 (1 g/cm^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 six stages. Each stage has a cutpoint diameter which 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 larger particles do move to the next stage. The cut point diameter is a function of the flow rate through the instrument and decreases with increasing flow rate.

Figure 4 shown the cumulative size distribution of smoke particulate from a 2.0 m diameter Murban crude oil fire conducted at FRI in Japan and a 12.0 m effective diameter Louisiana crude oil mesoscale fire conducted at USCGFS&TD in Mobile, Alabama. A comparison of the results from the two fires shows that there is a greater number of smaller particles in the 2.0 m diameter fires than in the 12.0 m diameter fires. For the 2.0 m diameter fires 71% of the particles have an aerodynamic effective diameter of 0.52 μm or less while for the 12.0 m diameter fires 13% have an effective diameter of 0.39 μm or less. For the 2.0 m diameter fires 1% of the particles have an effective diameter of 9.8 μm or greater while for the 12.0 m diameter fires 16 % have a diameter of 7.8 μm or greater. As most of the smoke mass produced by both fires was in the size range smaller than 10μm, it would be respirable.

5. MODELING THE SMOKE PLUME TRAJECTORY

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 particulate. 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 simulation 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 U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama.

Figures 5 and 6 illustrate results obtained from a calculation using 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. The 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 5 shows the locations of the particle plume at eleven stations downwind of the fire extending out the first 190 km downwind from the fire. 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 the lateral spreading is enhanced by the interaction of the vorticity in the plume with the ground plane. Finally, the 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 5; even with the enhanced spreading near the ground the plume is a long, slender object.

Figure 6 shows the computed footprint in the ground plane, covering a downwind distance of 258 km, where over ninety 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 which produces highly organized motion near the surface. This plot indicates that the density distribution on 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.

Additional information about the mesoscale oil burning experiments and the complementary laboratory research conducted at NIST and FRI are contained in reference [3]. The next step in the NIST studies is to perform measurements of larger burns in offshore experiments and investigate the burning properties of weathered and emulsified crude oils.

6. ACKNOWLEDGEMENTS

This research was funded jointly by the Minerals Management Service, U.S. Department of the Interior, the American Petroleum Institute, and the U.S. Coast Guard, Department of Transportation. Special technical assistance and cooperation was provided by Merv Fingas of the Technology Development and Technical Services Branch, Environment Canada and the Rod Terpin of the Environmental Protection Agency, Emergency Response Team in Edison, NJ. Some experiments were conducted at the Fire Research Institute in Japan as part of the joint NIST/FRI fire research program.

7. REFERENCES

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

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.D., Walton, W.D., Baum, H.R., Notarianni, K.A., Lawson, J.R., Tang, H.C., Keydel, K.R., Rehm, R.G., Madrzykowski, D., Zile, R.H., Koseki, H., and Tennyson, E.J., 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, En 40-11/5-1992, Environment Canada, Ottawa, Ontario, pp. 593-657, 1992.

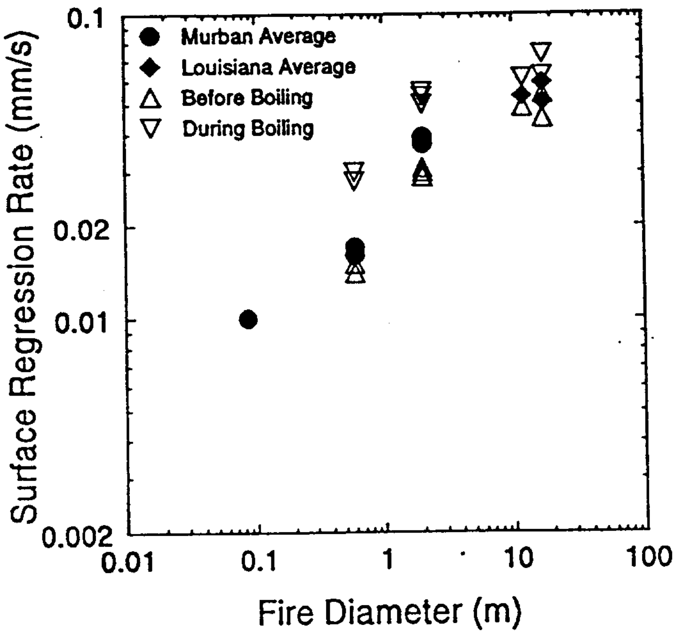

Figure 1. Burning surface regression rate for crude oil fires

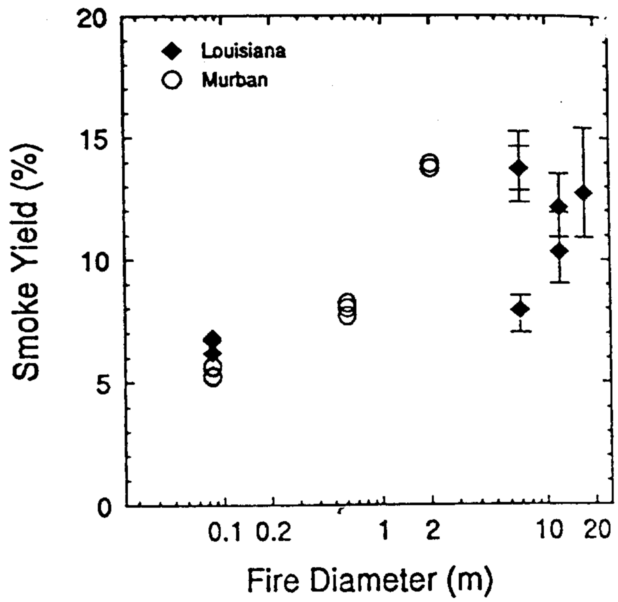

Figure 2. Smoke yield by carbon balance method

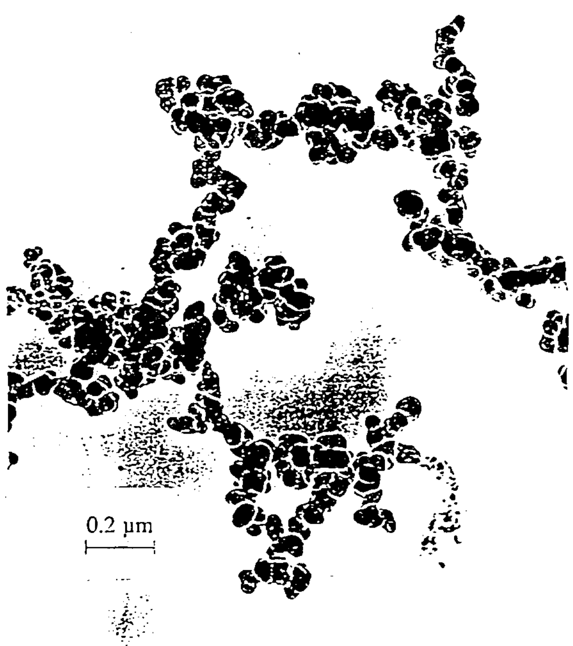

Figure 3. Micrograph of smoke particle

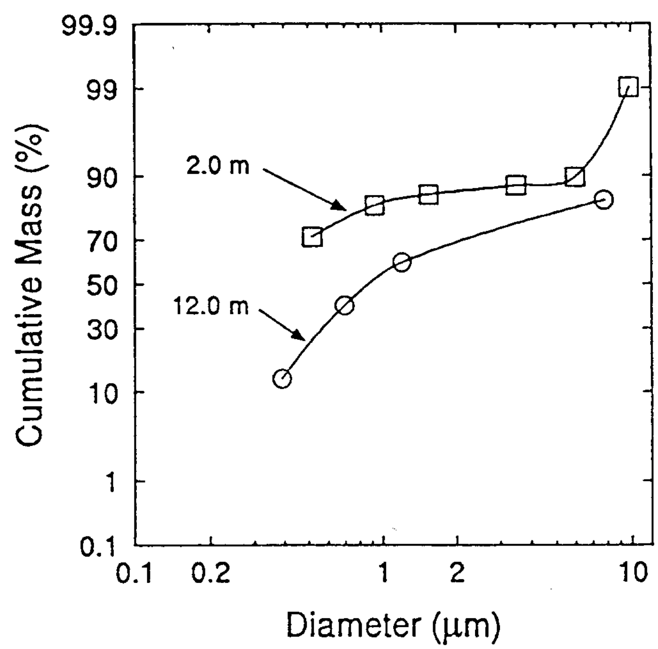

Figure 4. Smoke particle size distribution from crude oil fire

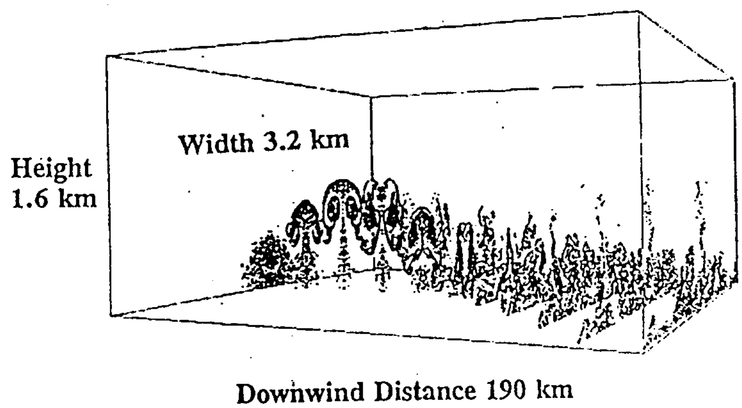

Figure 5. LES prediction of downwind smoke plume

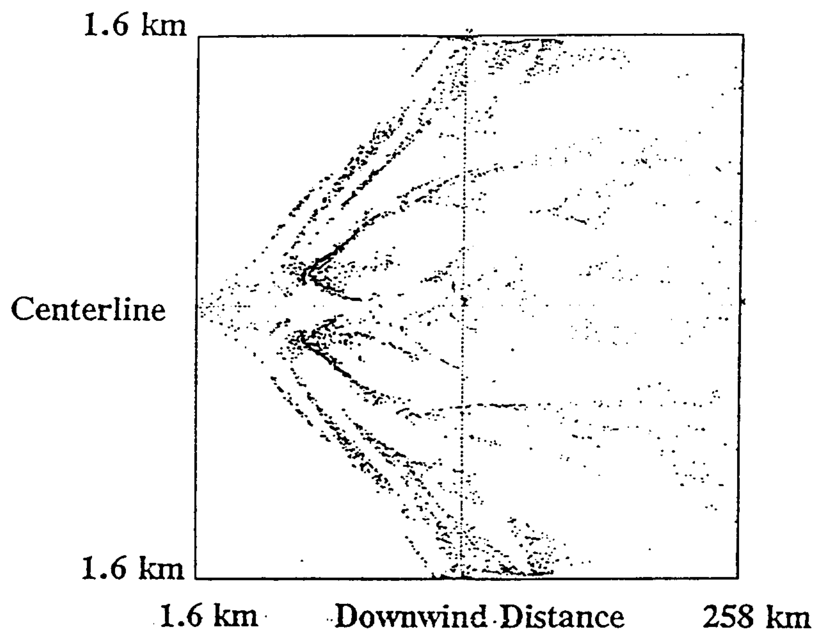

Figure 6. LES prediction of the pattern of downwind particulate deposition