Measurement of Large Scale Oil Spill Burns

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ABSTRACT

Research has shown that burning can be an effective means to remove oil from the surface of the water. The combustion characteristics of crude oil have been measured in large laboratory tests using a nominal one meter diameter pool fire. This work reports on progress mid-way through a 2½ year research program. The objective of this research is to develop measurement equipment and calculations that can be used to characterize oil spill burning at operational scale during field trials of the technology. Field scale measurement techniques for fire radiation, smoke yield, particulate sampling, plume trajectory are described. Progress in the calculation of particulate deposition downwind of the burn site is presented.

INTRODUCTION

Response to oil spills includes considerations of oil containment, recovery, disposal and the logistics of delivering adequate response equipment quickly to the spill site. Particularly in remote areas, the use of burning as a oil spill response method is attractive. Burning requires a minimum of equipment, and because the oil is gasified during combustion, the need for physical collection, storage, and transport of recovered product is reduced to the few percent of the original spill volume that remains as residue after burning. The technology of oil spill burning and other response methods have been reviewed recently [1, 2, 3].

The technology of greatest interest is that designed to burn oil in-place. Present work is directed at burning spills under natural confinement such as within ice leads or with artificial confinement within fire-proof collection booms. Using the latter approach, approximately 15,000 gallons of oil from the recent Exxon Valdez spill were confined after nearly two days in the water and burned. The resulting fire lasting approximately 45 minutes consumed all but 300 gallons of residue that remained in the boom [4].

Environment Canada. Arctic and Marine Oil Spill Program Technical Seminar, 13th. June 6-8, 1990, Edmonton, Alberta, Canada, Environment Canada, Ottawa, Ontario, 1-38 pp, 1990.

Burning oil spills in-place normally produces a visible smoke plume containing soot and other combustion products produced in the burning. The smoke plume produced by burning of crude oil spills and the possibility of undesirable combustion products carried in the plume have led to public concerns over the effects of burning large crude oil spills. Lack of knowledge about heat and radiation from large fires has also hampered application of burning to oil spills because of unresolved questions of personnel and equipment safety.

Burning may be thought of as an emerging technology for response to oil spills. The National Institute of Standards and Technology (NIST) is the U.S. National laboratory with the mission to aid industry in the development of new methods to improve productivity. In the area of technology for oil spill response, this includes providing the means to answer public concerns about the consequences of burning to provide a basis for evaluation of its use by industry. Under funding from the Minerals Management Service, U.S. Department of the Interior, with contributions from the United States Coast Guard, U.S. Department of Transportation, and unique technical assistance from the Technology Development and Technical Services Branch of Environment Canada, NIST has carried on a program of oil spill burning research since 1985.

BACKGROUND

In the five year research program, specialized large laboratory scale fire facilities at NIST have been used to investigate the fire dynamics and chemistry of the oil spill burning process. These studies have provided new quantitative information about the crude oil burning process. For example, laboratory measurements [5] have shown that the soot yield, the mass fraction of oil converted to soot during burning, is nominally 10 percent based on tests with Alberta Sweet crude oil. Other technical results about burning rate and combustion products are contained in previous papers [5, 6, 7, 8].

As with any large natural or accidental event that may impact the environment, opportunities to observe and measure the effects of large fires during emergency conditions are rare. Furthermore, permits to conduct large scale experiments that simulate oil spill burns at the appropriate scale and the large amount of funding needed to perform measurements at field scale are difficult to obtain. At best only infrequent opportunities will be available. Anticipating the sparsity of large scale test data, advanced calculations of plume dynamics have been part of the NIST research program since the beginning. These calculations provide a means to extrapolate laboratory measurements of burning conditions and combustion products through predictions of visible plume trajectory and deposition of products downwind of postulated large oil spill burns. Simply, these methods under development in the NIST research program will provide a means to perform hundreds of calculational experiments to add to the available experience from actual field tests. Examples of progress in the development of these calculation methods are contained in previous papers [5, 6, 7, 8].

The large accidental spill of crude oil from the tanker Exxon Valdez in Prince William Sound, Alaska focused national attention on oil spill response technology. In cooperation with a team of interested parties from industry and government planning has begun for operational tests of burning on an experimental oil spill at sea in 1991. In preparation for these tests, the NIST research program was expanded to develop means to measure the burning characteristic of these large fires. To accomplish this task, work was started to make laboratory methods and equipment used in previous studies at NIST robust enough for use in the field. In some cases, completely new measurement techniques were required because laboratory methods were inappropriate for field use or the measurements, such as plume trajectory, are only appropriate to large scale. This paper details the plans and progress to date in a 2½ year research program to move measurement of oil spill burning characteristics from the laboratory to the field using mid-scale 10 m to 15 m diameter fire tests to prove performance of the measurement equipment.

Mid-Scale Testing

As important to this research program as the eventual field tests, mid-scale tests will be performed to evaluate measurement techniques and provide personnel with the opportunity to gain working experience in the environment around large crude oil fires. As part of the interagency cooperation in this project, mid-scale tests are being planned for the summer of 1990 at the U.S. Coast Guard Fire and Safety Test Detachment located on Sand Island in Mobile Bay Alabama.

At this facility, oil pool fires up to 15 m in diameter can be burned in a tank welded to the deck of a 150 m surplus tanker which is used for fire testing. The tanker is moored in a lagoon of a 50 acre island in Mobile Bay, see Figure 1. As the ship is used routinely for fire testing, utilities and some measurement equipment are available on site.

MEASUREMENT PROGRAM

Fire Heat Release Rate (Burning Rate) History

Heat release rate is the primary burning characteristic of a fire. In the laboratory, oxygen consumption calorimetry [9] has been used to evaluate crude oil fire heat release rates [5, 6, 7,]. Estimations of heat release rate can be made also by multiplying the heat of combustion for a fuel times the mass loss rate. In the laboratory, mass loss rate can be determined easily by weighing the fuel.

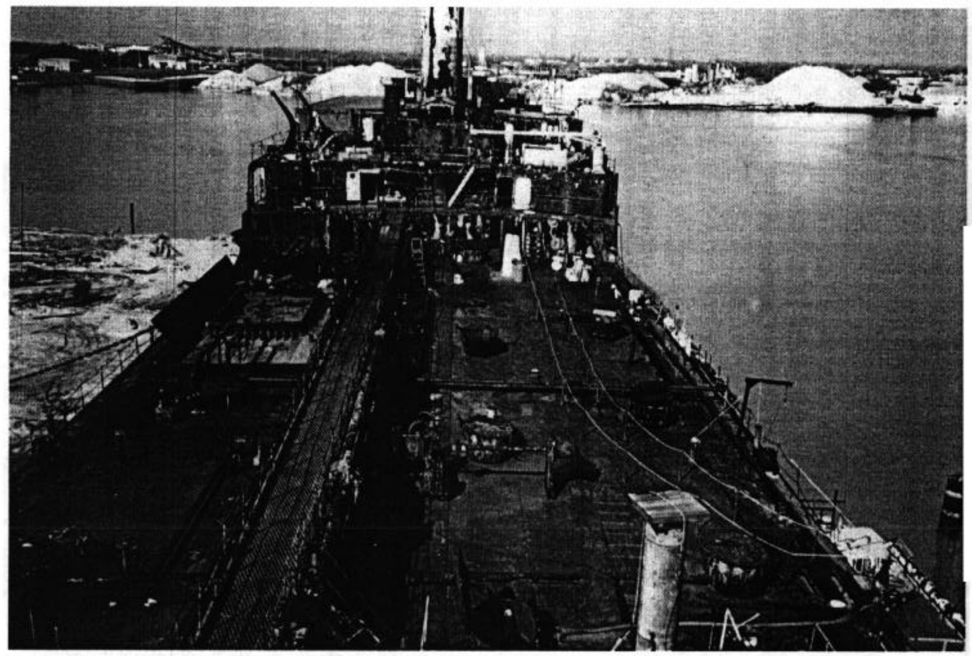

Figure 1 USCG fire test facility Mobile, Alabama.

In the field, there are no direct measurements for fire heat release rate. In a previous large scale oil burn test, [4] the average fuel consumption rate has been estimated by dividing the total mass of fuel consumed by the burning time. In that burn, 15,000 gallons of North Slope crude oil were consumed during 45 minutes of vigorous burning. The average fuel consumption rate during the vigorous burning was 330 gallons per minute. Thus, even in field burns the average burning rate is easily obtained if the amount of fuel consumed is known; and this average may be all that is needed when the fire is nominally constant in burning rate.

When the burning rate is not constant, more than an average rate is needed to characterize the combustion. It is possible that a technique can be developed for field use that uses measurements of surface thermal radiation, smoke plume trajectory, and burning area to calculate instantaneous fire heat release rate. Such a method will be developed and evaluated in mid-scale testing by correlating measurements of several fire diameters. Use of these correlations at field scale will be an extrapolation of the data beyond that correlated but within the same order of magnitude as the mid-scale tests.

Laboratory measurements of crude oil burning in pools up to 1.2 m in diameter have shown two distinct regions of burning, see Figure 2. After ignition there is a quiescent burning period with slightly decreasing heat release rate reflecting preferential depletion of high vapor pressure components from the fuel. The surface temperature of the burning oil maintains a temperature in the range of 250 to 350 °C. The hot oil below the burning surface eventually comes in contact with the water on which the oil is floating. In small scale tests with thick initial oil layers, the water boils, releasing vapor bubbles that burst at the surface and eject oil droplets into the flame. The increased flux of fuel causes the flame to flare up increasing the rate of heat release until extinction. In laboratory tests, Figure 2, the enhancement in burning rate by water boiling can be more than a factor of two. In large burns within booms being towed through the water [4] and large hydrocarbon pool fire tests conducted in Japan [10] enhanced burning due to water sublayer boiling has not been seen. There are two completely different mechanisms that could account for these observations.

In the case of oil burning while being moved over the water within a fire resistant confinement boom, ambient temperature water is continually being supplied below the oil layer. Thus, depending on the tow speed and current, the residence time for the burning oil over a given water mass may be insufficient to induce boiling. Figure 3 shows a schematic diagram of a laboratory apparatus built to measure oil burning characteristics under conditions simulating field conditions in which a contained burning oil mass is being moved on the water surface. For convenience, in this simulation the confined burning oil is kept stationary; and the water is flowed beneath it at selected speeds. Testing with this apparatus will provide insight into the effect of moving water layers on oil burning rate and residue remaining at flame extinction.

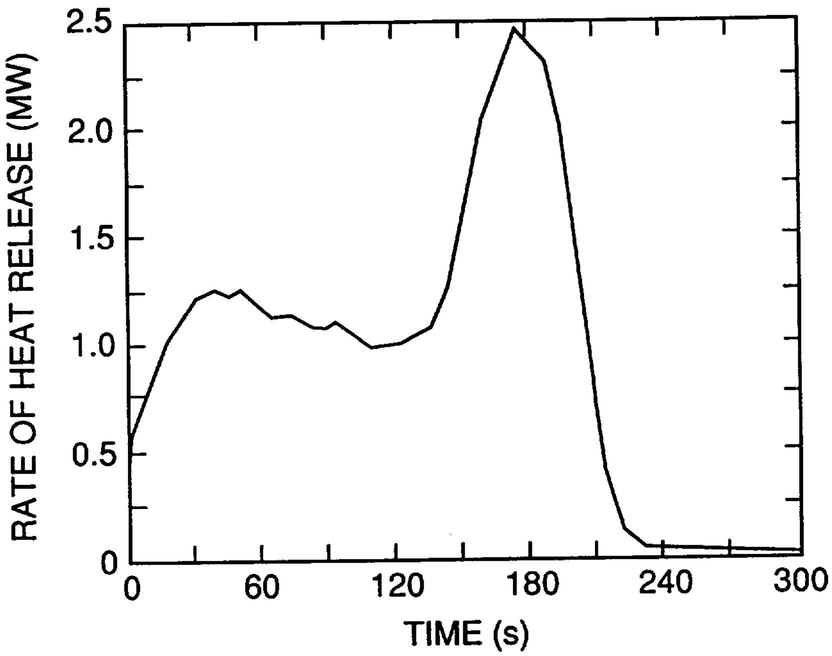

Figure 2 Measured heat release rate for 1.2 m diameter Alberta Sweet crude oil fire.

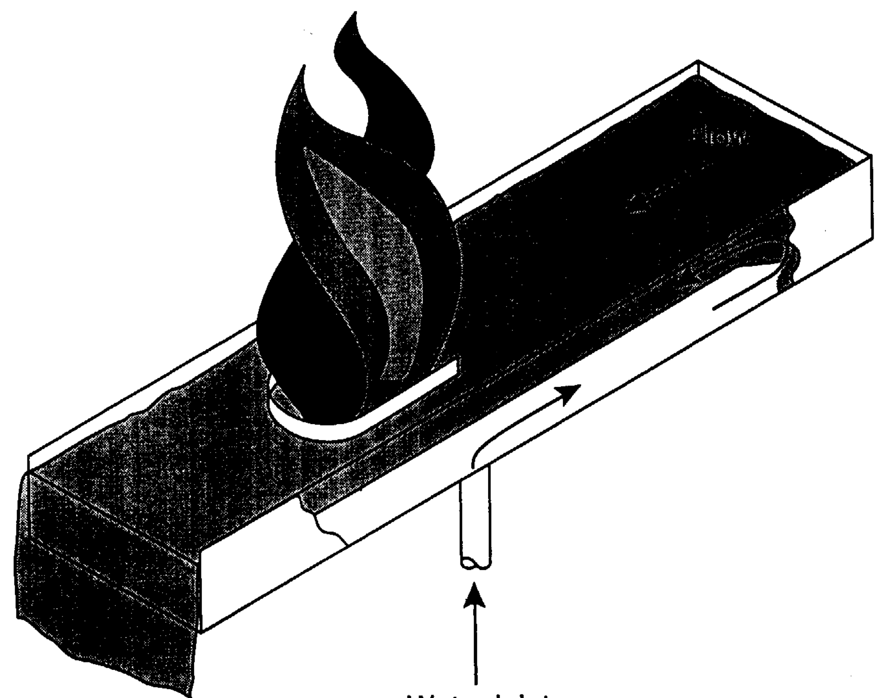

Figure 3 Schematic of boom simulation oil burning apparatus.

Maintaining a flow of cool water beneath the burning oil is only one factor in determining the conditions under which water sublayer boiling will occur during large scale burns in booms being towed through the water. Experiments in Japan at the Fire Research Institute have shown that there is an effect of scale as well. In their work for larger fires in which the fuel layer surface regression rate (or burning rate per unit area) was greater than that measured in smaller laboratory tests, no water sublayer boiling was seen. We postulate that in the larger pool fire tests conducted in Japan, up to 3 m in diameter, the onset of water sublayer boiling occurs when the burning oil layer is very thin. The onset of boiling for the larger scale fires may occur only for very thin layers representing the small depth that heat penetrates into the unburned fuel by thermal conduction from the hot surface because of increased fuel surface regression rate. The stirring of the shallow oil layer by boiling produces a sufficient temperature decrease to quench the burning. Therefore, in a large pool fire with increased burning rate per unit area as compared with small scale tests, the onset of water sublayer boiling produces flame extinction and not vigorous burning.

In field tests, both the large area and motion over the water of the burning oil will provide conditions unfavorable for water sublayer boiling. Mid-scale testing to be performed in this research program will provide greater insight into this effect.

Thermal Radiation

Measurements of thermal radiation from the burning oil are used to predict the potential hazard to personnel and equipment operating near the burn site. Thermal radiation measurements can also be used to predict the burning rate of the fuel. Correlations such as the ones developed by Shokri and Beyler [11] and Mudan and Croce [12] may be used to predict the radiative heat flux at a ground level target a given distance from the pool. These correlations are based primarily on gasoline, kerosene, JP-4 and JP-5 fires. Other large scale fire results which include data for crude oil have been reported by Koseki [10, 13]. Previous tests have shown the average surface emissive power of large sooty fires actually decreases with increasing diameter. This is probably a result of substantial radiation blocking by absorption in the thick black smoke carried around the flame by turbulent mixing. As a result, thermal radiation becomes a complex function of pool diameter. It remains to be seen whether this behavior can be quantified well enough to provide a measurement technique for the burning rate.

Thermal radiation to targets at various distances from the crude oil fires will be measured with Gardon type radiant heat flux gauges. These gauges are used routinely in fire safety research studies. The gauges measure the temperature difference between the center of a thin blackened surface and a thermal sink temperature at the edge. The radiant heat flux to the blackened surface is a function of the temperature difference.

Smoke Sampling

The sampling of smoke for chemical and yield analysis is a relatively easy task in the laboratory. This process consists of using an appropriate filter media such as PTFE with an 0.8 μm pore size for collecting the smoke particulates, a pump for drawing the smoke into the filter, and a constant flow rate controller. The mass of soot is determined by weighing the filter, and the filtered material is analyzed. In the laboratory, the equipment used for sampling can be of any reasonable size and weight, and is usually conveniently located on a test bench near the experiment. However, in the field with large fires, where the appropriate sample point in a smoke cloud may be several hundred feet in the air, this task of sampling becomes quite complex. With the need to sample well above ground level, the size and weight of an experimental package becomes critical. The efficiency of this experimental package takes on additional importance since sampling will be done in a constantly varying environment driven by the local weather conditions. Figure 4 shows the sampling system currently being used in this project. The largest part of this system is the sampling pump which is 15.7 cm long, 4.5 cm in diameter, and weighs 0.79 kg. This lightweight pump is identical to that flown as part of experiments on NASA Space Shuttle missions within the last year. The pump is operated from a simple 12 volt DC battery or power supply, and draws a constant flow rate of 10 liters per minute through a clean 47 mm filter. The filter holder is made of aluminum and is 5.5 cm long, 5.5 cm in diameter and weighs 0.16 kg. Clear plastic tubing is used to connect the system components. Filter media taken from this system during field tests will be returned to the laboratory so that PAH's and other important constituents may be measured.

Soot Production (Soot Yield)

Determinations of mass of soot produced per unit mass of fuel consumed has been done in laboratory tests using two methods [5]: stack particle flux sampling and the carbon balance method. Stack particle flux sampling is based on comparison of the mass of particulates collected from a known portion of the total smoke plume flow from the fire to the measured mass loss of the burning fuel during the same period of time. The carbon balance method determines the soot yield based on ratio of soot mass to the total mass of carbon found (soot plus mass of carbon contained in CO_2 and CO gases) in a sample of smoke plume combustion products. Of these two, only the carbon balance method is feasible for application to large fires.

A third method being investigated is isotopic tagging and tracing of particles by mass spectrometry [14]. This method also has the potential to measure soot deposition far downwind of a smoke source and therefore could be appropriate for use in the planned field tests.

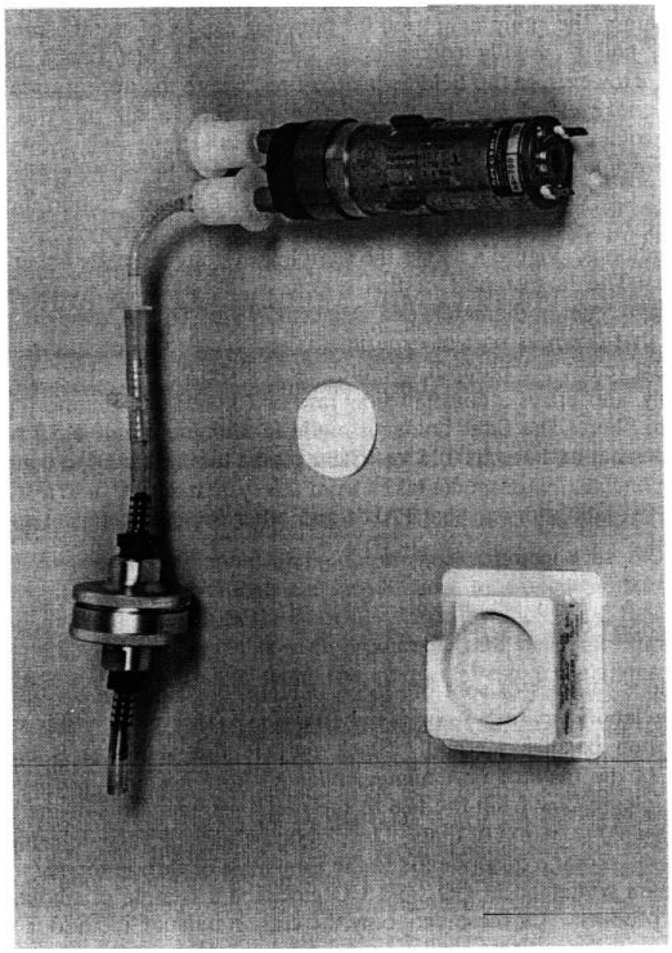

Figure 4 Pump and filter apparatus for smoke sampling.

The isotopic tagging technique involves addition of enriched isotopes of rare-earth elements into the fuel before combustion, and then measuring the perturbations in the natural isotopic ratios in aerosol particles collected downwind. In large scale oil burn tests being planned, particles collected downwind could be identified positively as originating from the oil spill burn and not other sources such as from ship engines. The isotopes used are nontoxic, chemically stable, nonradioactive, and relatively inexpensive, and can be detected with an ultimate sensitivity below 1 part in 10^{15} (mass/mass basis). This rivals or exceeds the sensitivity of the most sensitive inert tracer gases used to study the long-range transport of air masses and represents a more than 40,000-fold reduction in the amount of tracer material needed over previously-used tracer materials.

Since the tracer is added directly to the fuel before burning it is important to know if the tracer is liberated from the fuel during combustion proportionally with the crude oil consumed. Laboratory tests with the 0.6 m diameter pool fire and collection hood and soot sampling instrumentation used in previous studies [5] will be used to evaluate the liberation of the tracer into the combustion products during burning and determine the feasibility of the method for measurement of soot yield from crude oil burns. During these tests soot yield will be determined also by the stack particle flux sampling, a method developed by Mulholland, et al. [15] used in previous testing [5], for comparison with results from the new isotopic method. In these tests only 8 mg of enriched ^{150}Sm will be needed to treat 4 kg of oil needed in the test, a concentration of one part in 500,000. After collection the amount of tracer in the smoke particles will be determined by Inductive-Coupled Plasma Mass Spectrometry (ICP-MS) [14].

Smoke Concentration Measurements by Light Scattering

In order to measure the concentration of smoke in the fire plume rapidly and at many positions a small, light weight light scattering apparatus is being evaluated. The apparatus is shown in Figure 5. It uses a pulsed near-infrared light emitting diode source, a silicon detector, and collimating and filtering optics to sense the light scattered over a forward angle of 45 to 95 degrees by airborne particles passing through a open sensing volume. The airborne particles pass through the sensing chamber as a result of natural air currents. The device can accurately measure concentrations over a range of 0.01 to 100 mg/m^3 with a particle size range up to 10 μm. This instrument measures 10 x 10 x 5 cm and weighs 0.45 kg and is operated by a self-contained rechargeable battery. The meter has an analog output which is connected to a miniature data logger also shown in figure 5 to record measurements during flight. The combined weight of the meter and data logger is 1.05 kg. This meter system will be used at various known locations in the smoke plume with the mid-scale and large scale fire experiments. It is intended for measurement of smoke concentration along the near field plume trajectory.

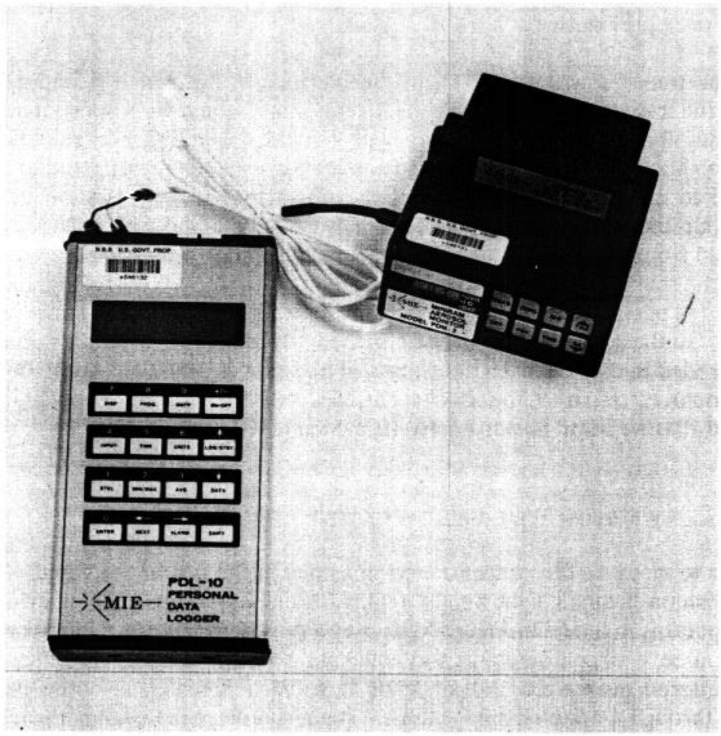

Figure 5 Light scattering apparatus for smoke concentration measurements.

section. Louisiana and North Slope crude oils were used as test materials. The tests were conducted using the ASTM, E662 Smoke Density Chamber (Figure 6) so that the filter samples and the light scattering apparatus results could be evaluated and correlated with standardized optical density (OD) measurements made with the chamber. In addition, reduced data from the tests could be used to compare optical properties of smoke from crude oil with those from other combustibles. All tests were performed without supplemental radiant heating available from electric heating coils in the Smoke Density Chamber. The oils were burned in small crucibles positioned in the chamber at a point where the smoke plume had a clear path to chamber's ceiling. This was done to minimize soot particle deposition on hardware exposed directly to the smoke plume.

Results from the smoke chamber tests showed that smoke concentration measured with the scattering apparatus agreed within 6 percent with concentrations measured by filter collection and weighing, over the range of 55 to 92 mg/m^3. The scattering apparatus as supplied from the manufacturer has a useful measurement range from 0.01 to 100 mg/m^3. By decreasing the sensitivity of the apparatus broader measurement ranges are available. Mid-scale tests together with smoke plume calculations will provide information needed to select the sensitivity range of the scattering apparatus for the field scale tests.

Comparisons of optical density per meter as a function of mass concentration in air of the smoke from the crude oil fires to those of other combustibles are shown in Figure 7. Optical density is a logarithmic measure of light transmittance equal to $\log_{10}(I_0/I)$, where I_0 is the light intensity transmitted without obscuration and I is that for the obscuring sample. The data from both the Louisiana and North Slope crude oils are consistent with the correlation of data generated on a wide range of organic materials tested by King [16] and reported by Seader and Ou [17]. Thus smoke produced from burning crude oil is similar in optical characteristics to other common materials.

INSTRUMENT TRANSPORT AND POSITIONING

In both the mid-scale and field scale crude oil burn tests, measurements are to be made in the smoke plume emitted from the fire. Various means of positioning instruments within the smoke plume have been evaluated. These included: towers, manned aircraft, fixed winged and helicopter remotely piloted aircraft, and balloons or mini-blimps.

In the mid-scale tests, as much instrumentation as possible will be evaluated so that measurement methods of various levels of accuracy and performance may be