# *The Effect of Diameter on the Burning of Crude Oil Pool Fires*

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**Abstract**

In order to understand the combustion characteristics of crude oil pool fires, an experimental study was carried out at the Fire Research Institute (FRI) large scale test facility. The radiative output, burning rate, and the concentrations of CO, $CO_2$, and smoke (above the flame tip) were measured during the burning of Arabian light crude oil, heptane, toluene, and kerosene floating on water. The effect of scale was studied by using steel pans ranging from 0.6 to 3 meters in diameter.

Crude oil burned less rapidly and gave off less thermal radiation compared with heptane, but when water boiling, i.e., boilover, occurred, the burning rate increased by a factor of two or more. The intensity of boilover is related to pan diameter and initial fuel layer thickness.

## Introduction

There is concern in earthquake prone areas that the large volume of crude oil stored near urban areas could contribute to a mass urban fire. The burning of a crude oil storage tank often results in boilover, in which the water layer below the crude oil begins boiling. Boilover can lead to a many-fold enhancement in the burning rate[1-11] and is widely recognized as the most serious safety issue concerning oil storage facilities.

The in situ burning of crude oil is potentially an effective means for cleaning up large oil spills but it's also an environmental issue in regard to the smoke produced. There's also environmental concern about smoke produced from a fire at an oil storage facility. Laboratory scale studies indicate a smoke yield of about 0.1 g of smoke particulate per g of crude oil consumed.[12] The smoke contains 0.5–1.0 mg of polycyclic aromatic hydrocarbons (PAHs) per g of smoke produced.[12] The PAHs are of envi-

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ronmental concern because some PAHs are believed to be carcinogenic.

While there is some data on the burning rate and smoke production of crude oil at small-scale,[8, 12] there is a lack of quantitative information on the effect of scale on boilover intensity and smoke production for pool diameters greater than about 0.5 m. Therefore, to study the scale effect, a joint experimental study between the Center for Fire Research of the National Institute of Standards and Technology of the USA and the Fire Research Institute (FRI) of Japan was performed in the FRI large-scale test facility.

## Experimental

Figure 1 shows a schematic of the experiment setup. Fuels were burned in pans placed at the center of the test facility, which has an open area 24 m × 24 m and under a 20-m high ceiling. Wind effects were small compared to outdoor tests, but still there were some tests during which the fire plume bent as a result of building drafts induced by outside wind. Arabian light crude oil was burned in 0.6-m, 1-m, and 2-m diameter circular pans and in a 2.7-m square pan with an oil-layer thickness typically of 2 cm. Other tests were performed with heptane, toluene, and kerosene. We measured burning rate, external radiation, smoke emission, and concentrations of CO and $CO_2$ above the flame tip. Near the end of the combustion process, water boiling and splashing were observed. The burning rate was measured with a float-type level meter connected to the

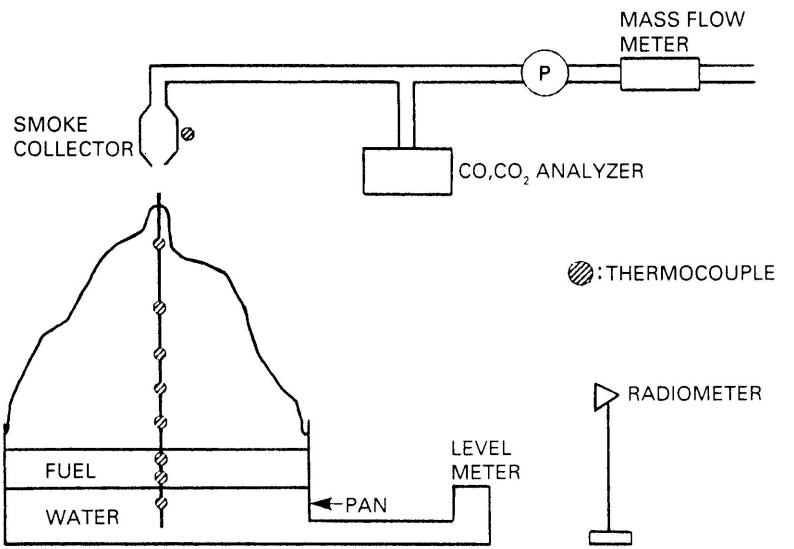


*Figure 1: Schematic diagram of the apparatus.*

pan, so the burning rate was represented as a fuel level regression rate.

As thin layer boilover occurs, there is a splashing of water outside the pan causing the apparent fuel level regression rate to exceed the burning rate. A correction was made for the splashing water in estimating the fuel level regression rate.

Radiation from the entire flame to the surroundings was estimated based on measurements by three wide-angle thermopile-type radiometers. They were oriented toward the flame axis at a height slightly higher (0.1–0.3 m) than the pan and located at $L/D = 3$ and $L/D = 5$ where $D$ is the pan diameter and $L$ is the radial distance from the pan center to the radiometer.

Smoke, CO, and $CO_2$ were collected above the flame tip. Downstream of the soot collector tube, the gas line was split with one branch going to a flow meter and pump. The second branch (as shown in Figure 1) flowed through a cold trap and flow meter before entering the CO and $CO_2$ analyzers, which are based on nondispersive infrared spectroscopy.

The temperatures inside and near the flame and in the fuel and water were measured using 0.32-mm diameter Chromel-Alumel (K-type) thermocouples fully sheathed with a 1.6-mm diameter stainless steel tube. Two thermocouples were embedded in the fuel and one was in the water. Each thermocouple tip was placed along the centerline of the pan. The outputs of these sensors were recorded on a pen-type recorder and/or on a digital data acquisition system.

## Results and Discussion

*Burning Rate*

Figure 2 shows the time history of burning rate (fuel regression rate) in a 0.6-m pan fire. About two minutes after ignition, the burning rate reaches a plateau. This is maintained until later in the test when the burning rate increased about four-fold as a result of thin layer boilover.

Figure 3 shows the relationship between pre-boilover burning rate and pan diameter, $D$. With a square tank, $D$ was calculated with the equation: $D = (4/\pi)^{1/2} \times W$. Here, $W$ is the length of one side. For reference, small-scale test data[8] and other large-scale test data[9,10,11] are shown. These data, obtained by several investigators, are well correlated with a single curve. For these size pans, the burning rate increased with increasing pan size up to a maximum at about 10-20 m in diameter.

*Radiative Outputs*

Figure 4 shows the time history of radiative outputs at $L/D = 3$ and $L/D = 5$ in the test for which burning rate data is shown in Figure 2. When thin layer boilover occurred, radiative outputs also increased, but with a much smaller relative change than shown for the burning rate in Figure 2.

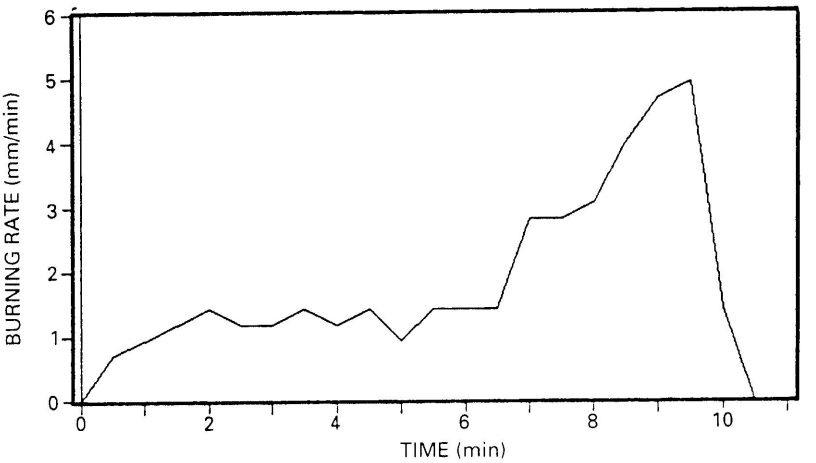


*Figure 2: Time history of the burning rate of crude oil (2 cm layer) in a 0.6 m pan.*

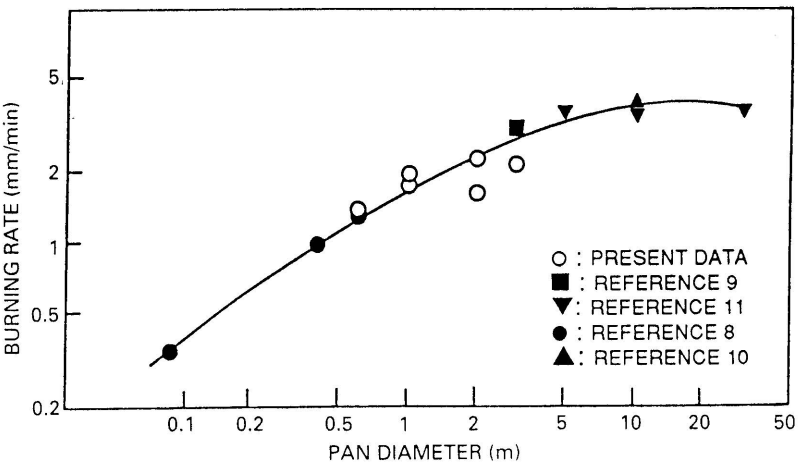


*Figure 3: Relationship between burning rate and tank diameter.*

Figure 5 shows the relationship between radiative output at $L/D$ = 5 and the pan diameter. For reference, some other data[9,10,11] are shown including heptane data. While the burning rate is slightly increasing for pan diameters greater than 2 m, it appears that the irradiance decreases for pan diameters greater than 2 m. This indicates that the

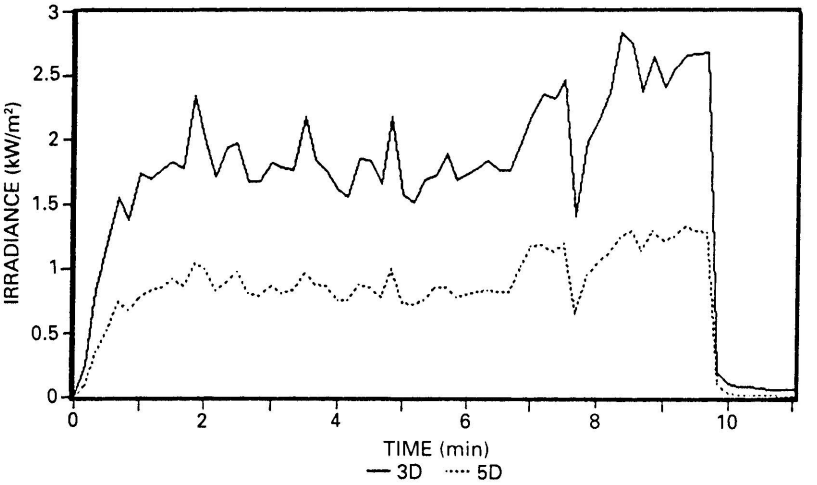


*Figure 4: An example of time history of irradiance at $L/D = 3$ and $L/D = 5$ in the same test of Figure 2.*

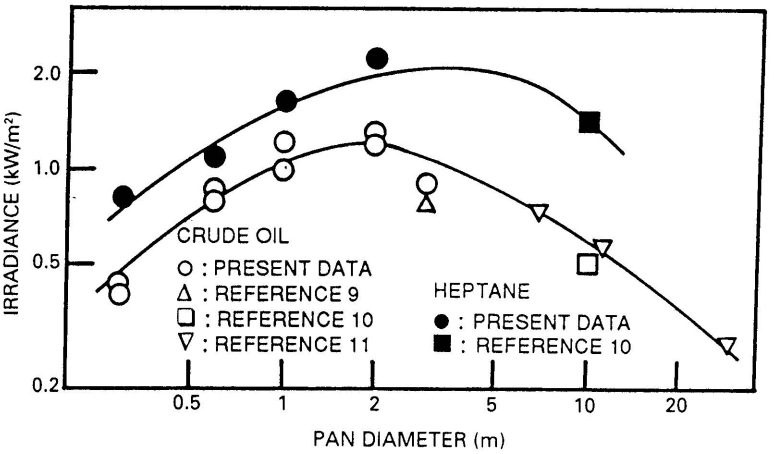


*Figure 5: Relationship between radiative output and tank diameter.*

smoke blockage effect on external radiation is large, but that smoke blockage on internal radiation, which is related to burning rate, is small in crude oil and heptane fires. External radiation from the heptane fire is larger than that of crude oil in any size pan.

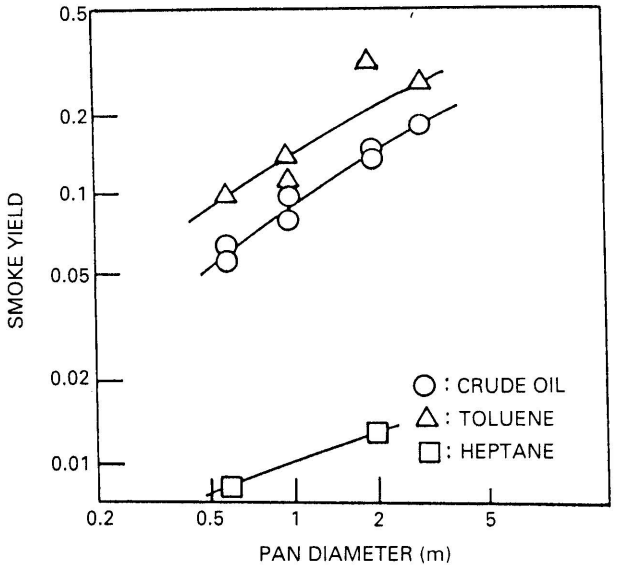


*Figure 6: Relationship between smoke yield and tank diameter.*

*Radiative Fraction*

The radiative fraction[13], $X$, is represented as:

$$X = Q_{rad} / Q_{tot} \quad (1)$$

Here, $Q_{rad}$ is the total radiative power output. Assuming the flame radiation is isotropic, $Q_{rad}$ is simply the flux times the spherical surface area:

$$Q_{rad} = 4\pi L^2 q \quad (2)$$

where $q$ is the irradiance measured by the radiometer at $L/D = 5$. $Q_{tot}$ is the net calorific potential of the flame assuming complete combustion. In steady state burning, $X$ is about 0.3–0.4, but when thin layer boiling occurred it decreased to about 0.2. A possible reason for the decrease in the radiative fraction is a reduction in relative soot production when water boiling occurs.

*Smoke Emission*

Smoke was collected above the flame tip at a height where the average temperature was about 100°C. A useful measure of smoke emission used previously by Mulholland et al.[8] is smoke yield, $\varepsilon$, which is defined

as the mass of smoke aerosol generated per mass of fuel consumed. We calculated the smoke yield, $\varepsilon$, by the carbon balance method:

$$\varepsilon = Y_s \times F_c \tag{3}$$

Here $Y_s$ is the carbon mass in the smoke aerosol, as a fraction of the carbon mass in the total combustion products ($CO_2$, CO, and smoke aerosols), and $F_c$ is the mass fraction of carbon in Arabian crude oil , measured as 0.84 by elemental analysis. Figure 6 shows the relationship between smoke yield, $\varepsilon$, and pan diameter. Mulholland et al.'s data[8] show $\varepsilon$ of the large- scale fire is similar to the small-scale one, but results given here indicate that the larger the pan, the larger the smoke yield. Future testing is needed to verify this difference. We also collected smoke for observation with a transmission electronmicroscope (TEM). TEM photographs indicated the smoke was made up of particles that are agglomerate structures made of spherules with a typical diameter of 60 nm.

*Concentration of CO and $CO_2$ above the Flame Tip*

CO and $CO_2$ were collected through the same sampling probe along with the smoke just above the flame tip. The concentration of $CO_2$ was about 0.3–0.5%, and that of CO was about 50–500 ppm. Figure 7 shows the time history of the ratio of CO and $CO_2$ concentrations. The ratio increased slightly with time, which may result from a distillation process with the lower vapor pressure component having a higher CO yield. When thin layer boilover occurred, this ratio increased possibly due to

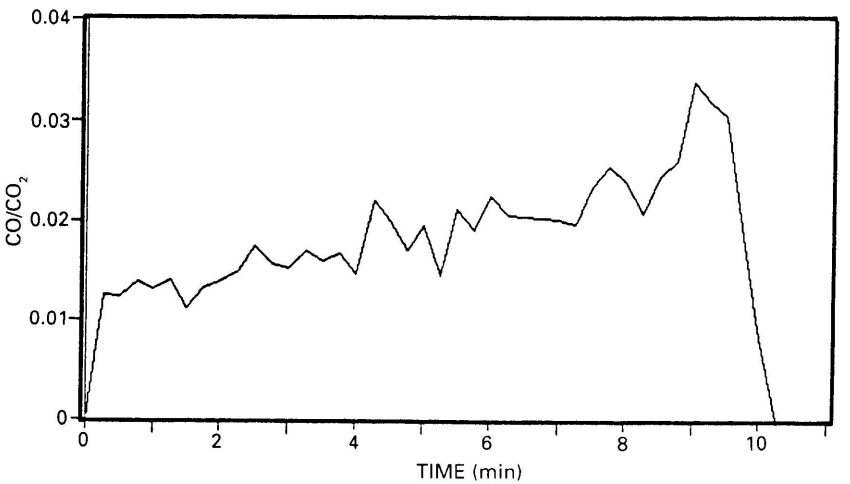


*Figure 7: An example of time history of $CO/CO_2$ above the flame tip in the same test as Figure 2.*

the larger flame present during boilover quenching in the probe. The ratio of $CO/CO_2$ and smoke yield are measures of combustion efficiency.

Figure 8 shows the relationship between the ratio of $CO/CO_2$ and pan diameter. Data are limited, but they indicate that the ratio increased with pan diameter. So combustion efficiency (ratio of conversion of carbon of fuel to $CO_2$) decreased with increasing pan size, shown by an increase in smoke and CO. For a 1-m diameter crude oil pan fire, efficiency was about 90%. Efficiency decreased to 75% for the 2.7 m × 2.7 m pan fire.

*Thin-layer boilover phenomenon*

Water boiling was found to occur near the end of the combustion process, and a considerable amount of oil spilled over the test pan rim. Burning rate and radiative output increased when water boiling occurred. This phenomenon is a kind of boilover, but not as serious as thick- layer boilover. In a series of tests, this thin-layer boilover phenomenon was studied as a first step of a more comprehensive boilover study. We call the phenomenon "thin-layer boilover" to distinguish the boiling effects in our test from the hot zone boilover discussed by Hasegawa,[4] which occurred after several hours burning of crude oil or other heavy oil in pans. Here we focused on the intensity of boilover and on the time required for onset of thin-layer boilover as a function of fuel layer thickness and pan diameter. The magnitude of the boiling effects, $\psi$, was defined as:

$$\psi = V_{bo} / V_{st} \tag{4}$$

$V_{st}$ means the burning rate in steady state condition, and $V_{bo}$ means the maximum burning rate when boiling occurred.

To determine the influence of fuel layer thickness on the intensity of

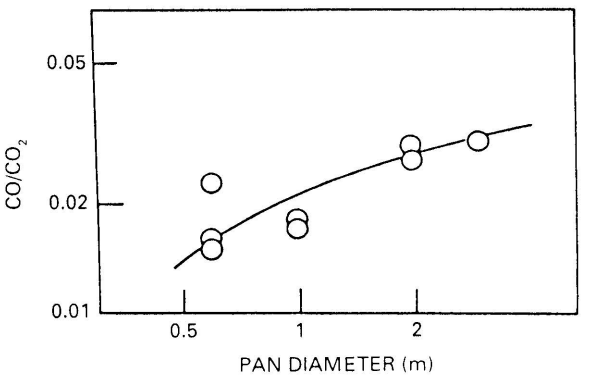


*Figure 8: Relationship between $CO/CO_2$ and tank diameter.*

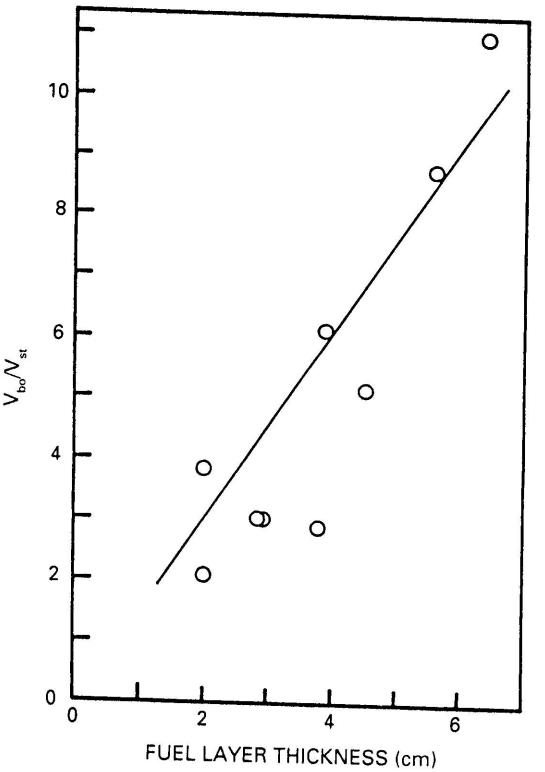


*Figure 9: Relationship between $V_{bo}$ / $V_{st}$ and fuel layer thickness in 0.6 m diameter tank crude oil fire.*

thin-layer boilover, we varied the initial fuel thickness in the 0.6-m crude oil fire. Figure 9 shows the relationship between $\psi$ and the initial fuel thickness. The thicker the fuel layer, the more violent is the thin-layer boilover. Figure 10 shows a roughly linear relationship between time required for thin-layer boilover and fuel layer thickness. This result appears insensitive to pan diameter.

Figure 11 shows the relationship between $\psi$ and pan diameter. According to Evans et al.,[5] fuel thickness is an important factor in regard to boiling effect, so we set fuel thickness at 2 cm for each test in this series. The boiling effect, $\psi$, decreased with increasing pan size. We did not observe a significant boiling effect in the largest test with a $2.7 \times 2.7$ m pan.

According to measurements by Arai et al.,[6] using a 4.8-cm diameter pan, boiling of water under the fuel occurs for fuels with a boiling point temperature higher than that of water. We burned kerosene (bp: 150°–300°C) and toluene (bp: 111°C) in larger pans (pan diameter: 1 m; fuel

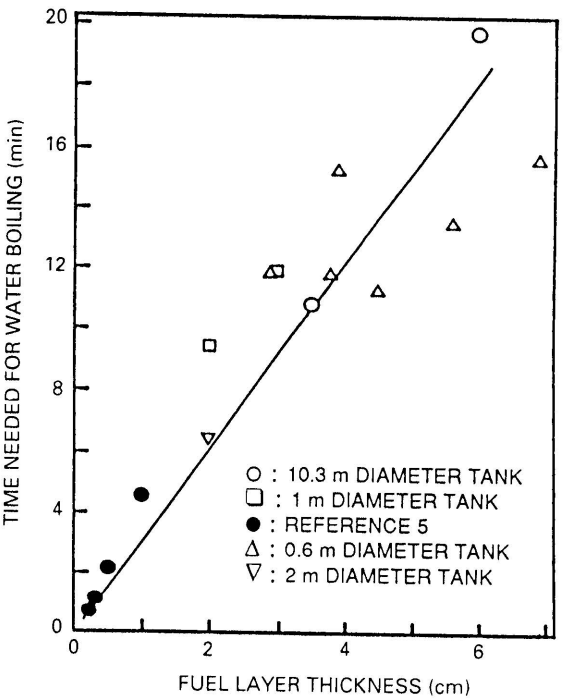


*Figure 10: Relationship between time required for thin-layer boilover to occur and fuel layer thickness in crude oil fire.*

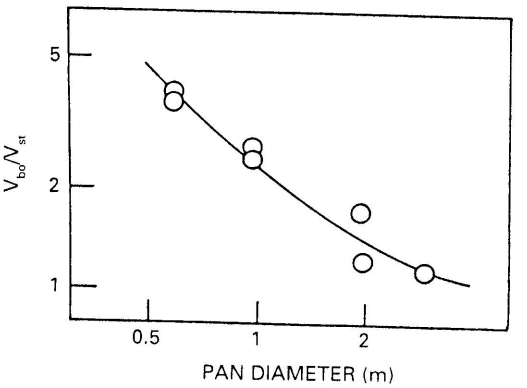


*Figure 11: Relationship between $V_{bo}/V_{st}$ and tank diameter.*

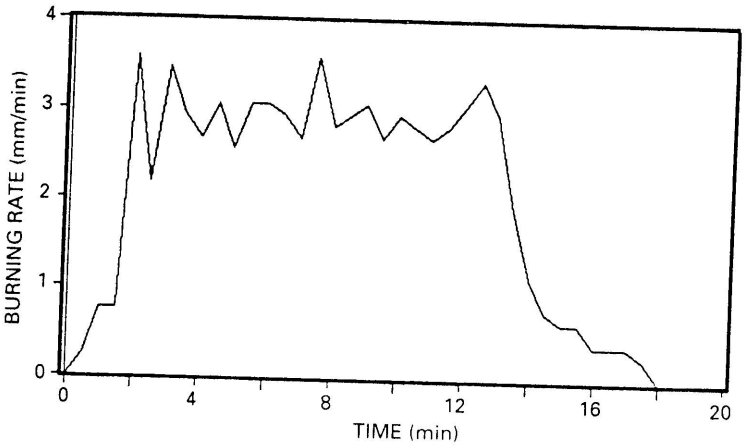


*Figure 12a: Time history of burning rate in kerosene 1-m tank fires (fuel thickness: 4 cm).*

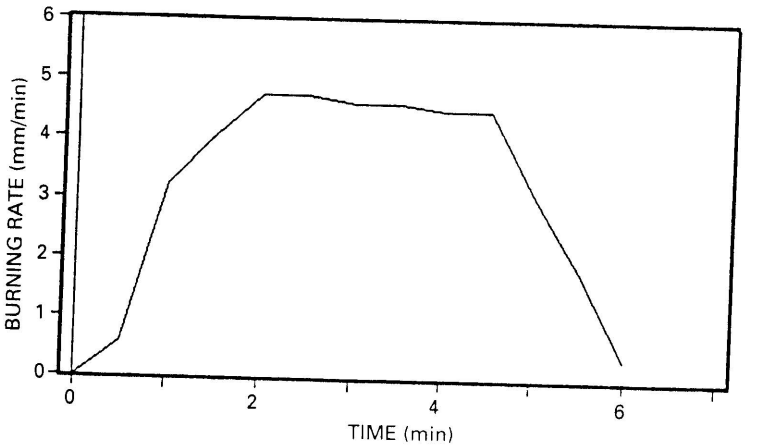


*Figure 12b: Time history of burning rate in toluene 1-m tank fires (fuel thickness: 2 cm).*

thickness: 2 cm and 4 cm, respectively). Figure 12 shows time histories of the burning rates for kerosene and toluene fires. We did not observe intensive boiling phenomenon for these fuels at the end of the burning. This indicates that the cause of the boiling effect is not simply controlled by the boiling temperature of the fuel.

## Conclusions

(1) In steady state burning of liquid fuels, the burning rate and ther-

mal radiation for crude oil fires are less than for heptane fires. The fuel level regression rate for crude oil increases with pan size up to a maximum of about 4 mm/min. at a pan size of 10-20 m in diameter. Thermal radiation increases for increasing pan size up to 2 m, then decreases for larger pans.

(2) Near the end of the burning process, water boiling occurred for crude oil. At the time of this so-called thin-layer boilover, both the burning rate and the radiative output increased. But in the largest pan used, 2.7 m × 2.7 m, no significant boiling effect was observed for a 2-cm initial crude oil layer depth. For a fixed pool diameter, the thin-layer boilover effect and time needed for boiling increased with increasing fuel layer thickness.

(3) It appears that both the smoke yield and the CO yield increase with fire diameter.

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