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Combustion of Oil on Water: An Experimental Program

MASTER

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16. Abstract The objectives of this program are to : 1) measure the burning rates of several oils; 2) determine whether adding heat improves the combustibility of the oil(s); 3) identify the conditions necessary to ignite fuels known to be difficult to ignite on ocean waters; and 4) evaluate the accuracy of an oil-burning model proposed by Thompson, Dawson, and Goodier (1979). The oils subjected to the test series are commonly transported on the world's major waterways. The tests were conducted in Oklahoma under warm-weather conditions and in Ohio under cold-weather conditions. Observations regarding their weathering and the thickness of oil layer affect upon the combustion of the oils were made. On the average , 90% of the oil samples burned. The surface temperature of the oils stayed relatively constant at 220°C throughout the burns; this is indicative of equilibrium flash evaporation (EFV). When the thickness of the oil layer became less than 3 millimeters (mm) the flames were extinguished.			
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EXECUTIVE SUMMARY

This study was undertaken to determine how well crude and fuel oils burn on water. Our objectives were 1) to measure the burning rates for several oils; 2) to determine whether adding heat improves the oils' combustibility; 3) to identify the conditions necessary to ignite fuels known to be difficult to ignite on ocean waters (e.g., diesel and Bunker C fuel oils); and 4) to evaluate the accuracy of an oil-burning model proposed by Thompson, Dawson, and Goodier (1979). Observations were made about how weathering and the thickness of the oil layer affect the combustion of crude and fuel oils.

We tested a total of nine oils commonly transported on the world's major waterways. Burns were first conducted in Oklahoma under warm-weather conditions ($\sim 30^{\circ}\text{C}$) and later in Ohio under cold-weather conditions ($\sim 0^{\circ}\text{C}$ to 10°C). The oils tested were as follows:

<u>Oil</u>	<u>Oklahoma Site</u>	<u>Ohio Site</u>
Saharan Blend	x	x
Attaka	x	
Es Sider	x	
Labuan	x	x
Ekofisk	x	
Isthmus/Mayan Blend	x	x
North Slope	x	x
Diesel (fuel oil #2)		x
Bunker C (fuel oil #6)		x

Results

On the average, 90% of the oil samples burned. The surface temperature of the oils stayed relatively constant at 220°C throughout the burns, which is indicative of equilibrium flash vaporization (EFV). We observed entrainment (caused by the formation of water vapor) of oil particles near the end of several burns; this mechanism was probably responsible for reducing the volume

of oil left as residual. Our calculations proved, as expected, that combustion ceased when the energy passing the oil/water interface approximated the energy radiated from the flame back to the surface of the oil slick. More specifically, when the thickness of the oil layer became less than 3 millimeters (mm), the flames were extinguished.

Adding heat to the oil pools did not appear to significantly increase burning rates but did enhance the ease with which the oils ignited. Diesel and Bunker C fuel oils did not burn unless gasoline, wood chips, or methanol were added. Once ignition was achieved, 90 to 99% of these oils burned. As predicted by the literature on crude-oil combustion, cooler temperatures caused the burning rate to decline.

Conclusions

Based on our analysis of the experimental data, we arrived at the following major conclusions:

- Crude oils will burn on water if a temperature profile can be established and maintained in the layer of oil.
- Diesel and Bunker C fuel oils will not burn without a primer.
- Combustion can occur for oil layers as thin as 3 mm; apparently, the critical thickness for burning is less than 3 mm.
- Crude oil combusts mainly via the process of equilibrium flash vaporization.
- The distillation model predicted that 35 to 72% of the oil would burn. The actual quantity combusted was 90%. Thus, the distillation model underestimates the degree to which an oil slick will burn.
- Distillation is not a factor in the combustion of crude oils, contrary to reports by Thompson, Dawson, and Goodier (1979). That distillation is not a governing factor is supported by the following observations:
 - a) The surface temperature of the oils remained near 220°C throughout the burns. (Distillation is characterized by a continual increase in temperature.)

- b) According to the Thompson model, to achieve combustion of 90% of a given quantity of crude oil, the surface temperature of the oil must exceed 500°C. In fact, 90% of the crude oil burned at a relatively low surface temperature of 220°C.
- c) The oil residual contained light ends. (Under a distillation scenario, all of the light ends would have burned.)

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CONTENTS

EXECUTIVE SUMMARY	iii
ACKNOWLEDGMENTS	xiii
ABBREVIATIONS	xv
INTRODUCTION	1
CONCLUSIONS	3
THEORY	5
COMBUSTION MODEL BASED ON DISTILLATION CONCEPTS	5
HEAT ENHANCEMENT	7
OIL-BURNING EXPERIMENTS	13
TEST SITES.	13
FACILITIES AND EQUIPMENT	13
EXPERIMENTAL PROCEDURE	21
RESULTS	25
HEAT ADDITION TESTS	35
DISCUSSION.	37
BURNING RATES	37
OIL VOLUME BURNED	39
SURFACE TEMPERATURE DURING BURNS	39
EQUILIBRIUM FLASH VAPORIZATION AND ENTRAINMENT	40
HEAT LOSS TO WATER	43
FUTURE RESEARCH.	51
REFERENCES.	53

APPENDIX A - EQUIPMENT SCHEMATICS	A.1
APPENDIX B - WIND SCREEN	B.1
APPENDIX C - CORRELATION OF BURNING RATE AND FUEL PROPERTIES.	C.1
APPENDIX D - COMPARISON OF WIDE-ANGLE RADIOMETER READINGS AND VIEW FACTORS	D.1

FIGURES

1	Theoretical Burning-Rate Curves	11
2	Burning Rate as a Function of Added Heat Flux	12
3	Physical Layout of Oklahoma Test Facility	14
4	Burning Pit, Pan, and Wind Screen	15
5	Thermocouple Rake	17
6	Fabricated Heating Coils	19
7	Calculation of Pre-Ignition Heat Input	23
8	Example of How Data Were Plotted	26
9	Typical Burning-Rate Curve	27
10	Temperature Readings from Thermocouple Rake No. 2 During Burn of Labuan Crude Oil	29
11	Temperature Profile for Labuan Crude Oil Taken at One Minute into the Burn	31
12	Surface Temperature of Five Oils During Combustion	32
13	Entrainment of Oil Droplets in Burns of Ekofisk and Attaka Crude Oils	33
14	The Effect of Added Heat on Burning Rate	36
15	Temperature Profile in the Water when Fire Started Receding	44
16	Transfer of Energy Into Water	47
A.1	Pan Design and Specifications.	A.2
A.2	Stand for Test Pan	A.3
A.3	Design of Level Recorder/Controller System	A.4
A.4	Differential Pressure Amplifiers	A.5
A.5	Design of In-Pool Radiometers.	A.6
A.6	Mounting Techniques for External Radiometers.	A.8

A.7	Placement of Video Cameras During Testing	A.9
A.8	Power Controller Schematic	A.10
A.9	Design of Lead Attachment for Heating Cable	A.11
B.1	Anemometer Placement During Wind-Screen Testing	B.2
B.2	Reduction of Wind Speed by Wind Screen at Position 1	B.3
B.3	Reduction of Wind Speed by Wind Screen at Position 2	B.4
B.4	Fitted Data Curves for Positions 1 and 2	B.4
C.1	Recession Rate as a Function of G for Various Amounts of Heat Addition	C.3
D.1	Upwind Wide-Angle Radiometer Output as a Function of Flame View Factor	D.3
D.2	Downwind Wide-Angle Radiometer Output as a Function of Flame View Factor	D.4

TABLES

1	Break-Even-Point (BEP) Calculations for Attaka Crude Oil at an Assumed Ambient Temperature of 40°F	7
2	Break-Even Points of World Crude Oils	8
3	Amount of Heat Addition to Oil Pool by Heating Coils	22
4	Average Burning Rate with No Heat Addition	27
5	Amount of Oil Combusted and Length of Burns	28
6	Position of Thermocouples	30
7	Break-Even Points for Seven Crude Oils Tested in Oklahoma	34
8	Predicted Percentage of Oil That Would Combust at 220°C vs Actual Percentage Burned	40
9	Composition of Crude Oils Before and After Combustion	41
10	Data Evaluating Atallah's Relationship	50
C.1	"G" Factor Determination from Specific Gravity and Boiling Temperature.	C.4
C.2	"G" Factors Determined from Burning Rates	C.4

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ABBREVIATIONS

ASTM	- American Society for Testing and Materials
ATC	- Applied Technology Corporation
B	- mass transfer driving force
BCL	- Battelle Columbus Laboratory
B_c	- convective, mass-transfer driving force
BEP	- break-even point
cm	- centimeters
C_p	- heat capacity at constant pressure
d	- specific gravity
D	- pan diameter
d.p.	- differential pressure
F	- shape factor (for radiation)
°F	- degrees Fahrenheit
f	- stoichiometric fuel/oxygen ratio
g	- grams
G	- fraction of energy released from the flame that is radiated back to the oil pool
gpm	- gallons per minute
H_c	- heat of combustion
H_{vap}	- heat of vaporization
h	- heat transfer coefficient
ID	- inside diameter
J	- joule
k	- thermal conductivity
°K	- degrees Kelvin
kW/m^2	- kilowatts per square meter
lb_m	- pounds mass
m	- meters
m''	- mass flux
mm	- millimeters
m/s	- meters per second
mV	- millivolt

OD	- outside diameter
PNL	- Pacific Northwest Laboratory
psi	- pounds per square inch
q, q_{rw}	- heat flux radiant surface heat flux
Q	- overall latent heat of pyrolysis
rms	- root mean square
t	- time
T_a	- ambient temperature
T_b	- boiling temperature of liquid
T_f	- flame temperature
T_w	- surface temperature
USCG	- United States Coast Guard
U	- overall heat transfer coefficient
V	- liquid regression rate (burning rate)
V_∞	- liquid regression rate in turbulent flame zone
X	- API gravity
Y_{O_∞}	- mass fraction of ambient oxygen species

GREEK SYMBOLS

σ	- Stefan-Boltzmann constant
κ	- extinction coefficient such that, as d gets larger, $e^{-\kappa d}$ goes to zero
γ	- radiant fraction of combustion heat release
ψ	- radiant fraction of feedback

INTRODUCTION

Combustion is one option for removing crude oils spilled on water. Under certain conditions, burning an oil slick can be more viable than coagulation techniques, skimming, or the use of dispersants. Combustion reduces the spilled oil to a smaller, more manageable residual consisting of heavy hydrocarbons. The high viscosity of the hydrocarbons makes skimming the residual much easier than skimming the oil originally spilled. By reducing the volume of spilled oil and by increasing the remaining oil's viscosity, combustion also keeps the oil slick from spreading.

Oil spills, oil-soaked debris, and damaged oil tankers can be burned if appropriate conditions exist regarding the integrity of the vessel, the location of the accident, atmospheric conditions, available manpower, the time elapsed since the accident occurred, and the type of oil spilled (Thompson, Dawson and Goodier 1979).

Statistics show that most oil spills occur under cold-weather, oceanic conditions. Large-scale oil fires on ocean waters can be simulated (burning rate only) by burning a pool of oil that equals or exceeds 1 meter (m) in diameter, according to Blinov and Khudyakov (1961). We combusted oil samples in a 2-m (inside diameter) burning pan. The samples were chosen because they represent a cross section of the oils commonly transported over the world's waterways. Lighter crudes are more common than heavier crudes, because refineries prefer to work with the lighter oils. The selection of representative oil samples was also determined by the availability of certain oils and by funding.

According to Thompson, Dawson and Goodier (1979), it is possible to predict how well crude oils will burn by using specific or API gravity and American Society for Testing and Materials (ASTM) distillation curves for given oils. Thompson, Dawson, and Goodier's model assumes that the combustion of crude oils proceeds via a distillation mechanism, and that the more volatile oil fractions (the light fractions) are combusted before the less volatile, heavier fractions. As the lighter components are burned away, the surface temperature of the oil should rise. (See the following section on theory for

additional details.) In doing our field studies on burning rates for nine crude and fuel oils, we had an opportunity to test the accuracy of this distillation model.

If the distillation model cited above were accurate (meaning that only 35 to 72% of the crude and fuel oils would burn), would adding heat to the oils increase the total volume of oil burned? To answer this question, we devised a theory of heat enhancement (see the following section on theory) and conducted experiments both with and without added heat. During the Oklahoma experiments, each crude oil was burned under three different conditions: 1) without added heat, 2) with the addition of 20.2 kW of energy to the oil via a heating coil, and 3) with the addition of 12.1 kW of energy via a heating coil.

This report discusses the design of the test facility and the results of our experiments. We compared the data we obtained with data on similar combustion experiments whenever possible. Moreover, the discussion on burning-rate data includes a brief literature review. Appendix A provides schematics of the equipment used in the experiment; Appendix B describes the wind screens used both to reduce overall wind speed and to dampen oscillations in wind intensity (replicating the experiments would have been difficult if large fluctuations in wind speed existed); Appendix C shows how to determine "G" factors (the percentage of the total amount of energy released that returns to the oil pool); and Appendix D compares wide-angle radiometer readings and view factors.

CONCLUSIONS

The objectives of this study were to measure burning rates for various oils, to document how added heat affects combustion, to identify a way to ignite diesel and Bunker C fuel oils, and to evaluate the accuracy of the Thompson, Dawson, and Goodier (1979) oil-burning model. Along these lines, we reached the following conclusions:

- Burning rates are a function of the composition of the oil, ambient temperature, and atmospheric conditions. Burning rates declined slightly in colder weather, but all of the oils ignited regardless of the ambient temperature. Whatever its burning rate, an oil can be expected to undergo combustion that is approximately 90% complete, based on an initial oil slick 5 cm thick.
- Adding heat directly to an oil pool before or during a burn enhanced ignition but, at the energy levels at which we worked, did not increase the burning rate significantly.
- Diesel and Bunker C fuel oils will burn if a primer is added to them.
- As expected, the lighter oils ignited more quickly than the heavier oils.
- The distillation model developed by Thompson, Dawson, and Goodier (1979) underestimates the amount of crude oil that will burn by about 18 to 55%.

The main conclusion drawn from our test results is that the combustion of crude oils proceeds via the process of equilibrium flash vaporization, and not via distillation.

More research is needed to substantiate current research and to clarify the direction that future studies on the combustion of crude oils should take. Possibly, microspheres could be used to insulate thin oil slicks from the water surface and thus prevent heat loss from the temperature-profile zone through the oil/water interface. Moreover, solid primers might provide the heat flux needed to sustain combustion.

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THEORY

The following section on theory is divided into two segments. The first segment describes the distillative combustion theory suggested by Thompson, Dawson, and Goodier (1979). The second segment describes the theory behind a heat enhancement process, which we hypothesized might increase burning rates.

COMBUSTION MODEL BASED ON DISTILLATION CONCEPTS

The distillation model proposed by Thompson, Dawson, and Goodier (1979) estimates the net amount of an oil spill that will combust under known temperature conditions. The model calculates the net energy produced from burning each decile or fraction, beginning with the lightest fractions and ending with the heaviest fractions. Thompson, Dawson, and Goodier postulate that at the point where the net energy is zero, a given volume of oil--defined as the break-even point (BEP)--can be combusted. Empirical studies show that 2% of the heat of combustion is radiated back to a pool of oil (Thompson, Dawson, and Goodier 1979; Parker 1974; Burgess et al. 1961; Kanury 1974). The model assumes (Equation 1) that this 2% equals the energy required to raise the temperature of the oil to its boiling point (sensible heat) plus the energy required to vaporize a given fraction of crude oil.

$$(0.02)(H_c) = H_{vap} + C_p (T_b - T_a) \quad (1)$$

Current nomenclature refers to the inverse of the 2% value as the "G" factor (Appendix C).

Values for heat of combustion, heat capacity, and heat of vaporization were calculated from relationships empirically derived by Cragoe (1929). These relationships are presented in Equations (2), (3), and (4).

$$H_c = (19,958 - 2780 d^2 + 1363 d)(2.326) \quad \text{J/g} \quad (2)$$

$$H_v = \frac{1}{d} (110.9 - 0.09 T_b) (2.326) \quad \text{J/g} \quad (3)$$

$$C_p = \frac{1}{\sqrt{d}} [(0.388) + (0.00045 T_b)] (4.187) \quad \text{J/g} - ^\circ\text{K} \quad (4)$$

Relationships are based solely on specific gravity (d) and boiling temperature (T_b in $^\circ\text{F}$). Often, gravities were given as API gravity (x), so we converted them to specific gravity using Equation (5). ASTM distillation curves needed for Equations (2) through (4) were obtained from Oil and Gas Journal (1976) and from Coleman, Shelton and Nichols (1978).

$$d = \frac{141.5}{x + 131.5} \quad (5)$$

Equations (2) through (4) assume a 1-lb_m basis and are based on English units of Btu, lb_m, and $^\circ\text{F}$. (Most ASTM distillation data are also reported in English units.) Standard International (SI) units can be obtained using common conversion factors (e.g., 1.8 Btu/lb_m = 1.0 calorie/gram).

By rearranging Equation (1), we can calculate a net energy term for each specific decile or fraction of a given crude oil sample:

$$\text{Net Energy} = (0.02)(H_c) - H_{\text{vap}} - C_p (T_b - T_a) \quad (6)$$

According to the theory, if the oil fraction's net energy is less than zero, it will not burn. Using these calculations, Thompson, Dawson, and Goodier (1979) determined the percentage of a given crude oil that would burn.

The break-even point (BEP) is defined as the total volume percent of oil that will burn, based on the above calculations. An example of one such calculation is presented in Table 1 for the crude oil, Attaka. The thermodynamic data (H_{vap} , c_p , H_c) may be somewhat imprecise, because the temperature value used in Equations (2) through (4) is simply the average temperature for a particular fraction.

We calculated the BEP for 81 crude oils found around the world, assuming an ambient temperature of 40 $^\circ\text{F}$ (Table 2). The BEP values ranged from 71.7 to 9.9. [Thompson, Dawson, and Goodier (1979) assumed that the heat capacity values were consistently 0.5 Btu/lb_m- $^\circ\text{F}$. We found, using Equation (3), that

TABLE 1. Break-Even Point (BEP) Calculation for Attaka Crude Oil at an Assumed Ambient Temperature of 40°F (a)

Fraction		API Gravity	Average Boiling Temperature, °F	H_c Btu/lb _m	c_p Btu/ lb _m -°F	H_v Btu/lb _m	Net Energy
20	20	57	200	18,851	0.552	123.8	165.0
10	30	50	250	18,723	0.567	113.4	142.0
10	40	45	290	18,621	0.579	105.8	121.9
10	50	42	340	18,555	0.599	98.5	92.9
10	60	38	370	18,462	0.607	93.0	76.0
10	70	36	440	18,412	0.638	84.4	28.8
----- BEP = 71.7 -----				18,334	0.661	76.6	0
10	80	33	500	18,334	0.661	76.6	-14.0
10	90	31	580	18,279	0.681	70.5	-52.3
10	100	25	720	18,100	0.749	51.0	-198.2

(a) Attaka originates in East Kalimantan, Indonesia, and has an average API gravity of 43.2

the heat capacities actually ranged from 0.5 to 0.7 Btu/lb_m-°F. Actual BEP values, thus, are lower than the values calculated in the original work, indicating that the oils are not as amenable to combustion as originally thought.]

HEAT ENHANCEMENT

Thompson, Dawson, and Goodier (1979) suggest that most crude oils will burn if 3% of the total heat of combustion is drawn back into the oil pool. Assuming, as they do, that 2% of the heat of combustion is radiated back to the pool under typical burning conditions, another 1% would have to be added. Promoters such as incendiaries could provide this additional energy (Meikle 1981).

This particular study's heat enhancement theory provides a method for determining the amount of radiant heat needed to achieve a certain burning rate for a specific crude oil. Enhancement data for oils not tested can be interpolated from data on tested oils and from BEP calculations.

TABLE 2. Break-Even Points of World Crude Oils

Crude Oil	Origin	Break-Even Point (BEP)
1) Attaka	East Kalimantan, Indonesia	71.7
2) Poleng	Java, Indonesia	63.0
3) Sepinggan	East Kalimantan, Indonesia	57.3
4) Melahin	East Kalimantan, Indonesia	56.7
5) Brass River	Nigeria	54.8
6) Hassi Messaoud	Algeria	53.3
7) Labuan light (Samarang)	Malaysia, Sabah	51.7
8) Seria light	Brunei	51.4
9) Tembungo	Malaysia, Sabah	50.9
10) Qua Iboe	Nigeria	48.3
11) Beryl	United Kingdom	47.4
12) Bonny light	Nigeria	47.0
13) Murban	Abu Dhabi	46.6
14) Zakum	Abu Dhabi	46.6
15) Brega	Libya	46.4
16) Montrose	United Kingdom	46.0
17) Kerindingan	East Kalimantan, Indonesia	45.6
18) El Bunduq	Abu Dhabi	45.2
19) Arjuna	Java, Indonesia	44.5
20) Umm Shaif	Abu Dhabi	44.2
21) Arzew Blend	Algeria	43.8
22) Escravos	Nigeria	43.6
23) Arabian light (Berri)	Saudi Arabia	43.1
24) Kirkuk	Iraq	43.1
25) Qatar marine	Qatar	43.1
26) Mubarek	Sharjak, U.A.E.	42.7
27) Stratfjord	Norway	42.4
28) Zarzaitine	Algeria	42.0
29) Walio Export Mix	Indonesia, West Irian	41.7
30) Pennington	Nigeria	41.3
31) Ekofisk	Norway	41.2

TABLE 2. (contd)

Crude Oil	Origin	Break-Even Point (BEP)
32) Forties	United Kingdom	41.0
33) Qatar land (Dukhan)	Qatar	40.4
34) Darius	Iran	40.2
35) Hout	Neutral Zone	39.8
36) Ninian	United Kingdom	38.7
37) Iranian light	Iran	37.3
38) Thistle	United Kingdom	37.0
39) Piper	United Kingdom	36.9
40) Iranian heavy	Iran	36.4
41) Reforma (Cactus) Isthmus	Mexico	36.4
42) Romashkinskaya	U.S.S.R.	36.4
43) Sassan	Iran	36.3
44) Arabian light	Saudi Arabia	36.2
45) Forcados blend	Nigeria	35.8
46) Lagomedio	Venezuela	35.4
47) Kuwait crude	Kuwait	35.3
48) Trinidad blend	Trinidad	34.7
49) Fereidoon blend	Iran	34.4
50) Arabian Medium	Saudi Arabia	34.3
51) Arabian Medium (Zuluf)	Saudi Arabia	34.3
52) Zueitina	Libya	34.0
53) Oman	Oman	33.6
54) Anguille	Gahnn	33.1
55) Basrah	Iraq	33.0
56) Ecuador (Oriente)	Ecuador	32.5
57) Gulf of Suez blend	Egypt	32.4
58) Dubai	Dubai	32.1
59) Es Sider	Libya	31.8
60) Handil	East Kalimantan, Indonesia	31.1
61) Bu-Attifel	Libya	30.9
62) Amna (high pour)	Libya	30.6

TABLE 2. (contd)

Crude Oil	Origin	Break-Even Point (BEP)
63) Sarir	Libya	30.6
64) Arabian heavy	Saudi Arabia (Safaniya and Khafi; Neutral Zone)	29.4
65) North Slope	U.S.A.	28.8
66) Cabinda	Cabinda (Angola)	28.4
67) Mandji blend	Gabon	28.4
68) Bonny medium	Nigeria	27.9
69) Strip blend, 27.1° API	Iran	27.9
70) Ratawi	Neutral Zone	27.7
71) Minas (Sumatran light)	Indonesia, Sumatra	25.1
72) Emeraude (Brazzaville)	Congo	23.9
73) Burgan (Wafra)	Neutral Zone	21.6
74) Cyrus	Iran	19.6
75) Gamba	Gabon	19.3
76) Tarakan (Pamusian)	East Kalimantan, Indonesia	17.9
77) Eocene	Neutral Zone	17.7
78) Taching	China	16.0
79) Bachequero, 16.8° API (Bachequero heavy)	Venezuela	15.9
80) Jatibarang	Java, Indonesia	14.1
81) Duri	Indonesia	9.9

Our studies on heat enhancement had two major objectives:

1. to generate a heat enhancement model applicable to all crude oils
2. to produce a model versatile enough to determine how combustion is affected by measured doses of additional heat. That is, the model should indicate that "X" amount of heat flux is needed to achieve "Y" amount of combustion.

The heat enhancement theory suggests that the greater the addition of heat to an oil, the higher the burning rate of that oil (Figure 1). Under Case A, no heat has been added to the oil pool, and the oil sustains

FIGURE 1. Theoretical Burning-Rate Curves

combustion by itself. Under Case B, some finite heat flux has been added, causing a higher burning rate and longer total burning time. More oil will burn in Case B than in Case A. Case C reflects an even higher heat flux applied to the oil sample's surface, where a higher burning rate is induced and a greater percentage of oil is burned. This procedure can be repeated at higher heat-flux intervals until power limitations prevent additional heat input or until unrealistic scenarios take form (e.g., as when so much heat is added that the water underneath the oil begins to boil).

By plotting the kinds of data generated in Figure 1, the relationship between promoters (or heat flux) and burning rate can be discerned (Figure 2). In turn, the resulting curve can be used as a tool for interpolating how oils in adjacent BEP ranges will react. The curves essentially provide heat-flux data for a continuum of burning rates and are not specific to the experimental points. Herein lies the value of the heat enhancement model: a few data points will reveal information about many different oils.

FIGURE 2. Burning Rate as a Function of Added Heat Flux

OIL-BURNING EXPERIMENTS

This chapter briefly describes the burning-rate experiments conducted for this study, including the equipment used and the logistics of the test sites. More detailed information on equipment and experimental setup can be found in Appendix A.

TEST SITES

The two-year experimental program was conducted at test sites in Oklahoma and Ohio. The Oklahoma site, located ~2 miles northeast of Newcastle, consisted of 10 acres of flat land (flood riverplain). Wind direction at the site was normally from the south-southeast at 6 meters per second (m/s) or 13 miles per hour. To reduce fluctuations in the wind speed, a wind screen was constructed around the testing area (Appendix B).

The second test site was located in West Jefferson, Ohio, a farming region 15 miles west of Columbus, Ohio. In winter, ambient temperatures at this location were usually near freezing. Although winds generally blow over the region from the south-southwest, conditions at the test site were usually calm. Again, a wind screen was constructed around the testing area to minimize fluctuations in wind speed.

FACILITIES AND EQUIPMENT

The test facilities were equipped to provide data on oil-burning rates, radiative heat flux, and the effects of heat enhancement. Figure 3 illustrates the layout of the Oklahoma test facility, including the oil-burning pan, pit, level recorder/controller, radiometers, and video recording devices. The test components were duplicated for the experimental work at the Ohio site, with the exception of a few modifications to improve data acquisition.

Oil samples were burned in a metal pan positioned inside a pit filled with 2840 l (750 gal) of cooling water. The pit was a cylindrical, galvanized steel tank, 2.95 m in diameter and 55.9 cm deep (Figure 4). To minimize the occurrence of temperature gradients within the burning pan's water supply, an underwater pump recirculated water under the oil at a rate of 18.9 liters per minute (5 gpm) during all test burns.

FIGURE 3. Physical Layout of Oklahoma Test Facility

Oil Burning Pan

Drawing on work by Yumoto (1971) and Blinov and Khudyakov (1961), Hall (1972) suggests that a pool of oil must be at least 1 to 2 m in diameter to model the kind of turbulent burning rate that occurs when oil spills burn. According to their work, a 2-m-diameter pan should minimize any wall effects that might influence the burning rate. The oil pan used for this experimental program was 2 m in diameter (Figure 4), and was supported in the pit by a stand made from angle iron (design specifications given in Appendix A).

Level Recorder/Controller

The level recorder/controller had two functions: it maintained a constant oil level in the test pan and provided data on oil-burning rates. A constant oil-surface level was important when measuring surface conditions (heat fluxes, temperature), because the in-pool instrumentation was fixed in position and

FIGURE 4. Burning Pit, Pan, and Wind Screen

could not adjust to changes in the surface level. Control of the oil level in the pan was maintained by using a solenoid valve and a temperature switch. Essentially, the system replaced oil with water at a rate equivalent to the rate the oil was combusted (see Appendix A for details).

Thermocouple Rakes

Two sets of thermocouple rakes were used to measure in-pool temperature profiles in the oil-water column during the combustion experiments. Seventeen thermocouples were positioned on each rake (Figure 5). The rakes were designed by Battelle Columbus Laboratories (BCL) and fabricated by Medtherm Industries, Huntsville, Alabama. All thermocouples were type-K and had an operating temperature range of -56 to 983°C.

Radiometers

In-pool radiometers were used to determine the heat flux radiated from the flame to the oil pool. These instruments were also designed by BCL and fabricated by Medtherm Industries. Design specifications for the in-pool radiometers are shown in Appendix A.

External radiometers provided data on radiant heat release from the fires. Two wide-angle and two narrow-angle radiometers were used during the experimental burns in Oklahoma. At the Ohio test site, however, only one wide-angle and one narrow-angle radiometer were used. All of the external radiometers had a range of 3.16 to 158 kW/m² (1,000 to 50,000 Btu/hr-ft²). The radiometers were equipped with calcium fluoride windows to ensure that only radiant heat fluxes were measured.

Data Recorders

All data generated were transmitted directly into a data logger in the form of volt or millivolt signals. During a typical combustion experiment, 45 to 47 channels of data were scanned every 4 sec. The channels used for both sets of experiments are described as follows:

FIGURE 5. Thermocouple Rake

<u>Channel Number</u>	<u>Description of Data</u>	<u>Full-Scale Signal to Data Logger</u>
0	Wind Speed	4 Volts
1	Wind Direction	4 Volts
2	In-Pool Radiometer No. 1	40 Millivolts
3	In-Pool Radiometer No. 2	40 Millivolts
4	In-Pool Radiometer No. 3	40 Millivolts
5	In-Pool Radiometer No. 4	40 Millivolts
6	Liquid Level	4 Volts
7	Wide-Angle Radiometer No. 1	40 Millivolts
8	Wide-Angle Radiometer No. 2	40 Millivolts
9	Narrow-Angle Radiometer No. 1	40 Millivolts
10	Narrow-Angle Radiometer No. 2	40 Millivolts
11	Voltage Input to Heating Coil	5 Volts
12	(Not used due to wiring difficulties)	---
13	Reference Thermocouple	°F
14-30	Thermocouple Rake No. 1 (17 Thermocouples)	40 Millivolts
31-48	Thermocouple Rake No. 2 (17 Thermocouples)	40 Millivolts
39	(Not used due to wiring difficulties)	---

For both series of experiments, data were transferred from the data logger to computer tapes. These tapes were then taken to a computer center, where the data were converted to the desired units. The results were then stored on another tape and printed copies were obtained.

During the initial series of experiments, three two-pen strip recorders also were used to monitor important parameters during the course of the burns. The recorders monitored the activity of the in-pool radiometers and external radiometers and measured the oil pool level (amount of oil combusted) versus time. During the second series of experiments, only the pool level versus time was plotted by a strip recorder. Other parameters could be visually checked during the burn from a scanning terminal, eliminating the need for additional strip-chart recorders.

Video Recorders

All of the combustion experiments were filmed with a color video camera. (Information on time of day and test identification numbers were overlayed on the tape.) Slides and prints of some tests were also taken.

Heat Enhancement Equipment

For the heat enhancement experiments, tests were run at various levels of heat input to determine if burning rates would increase when energy was added to a fire. To supply heat flux, 76.25 m (250 ft) of heating cable was bent around an angle-iron support frame (Figure 6). The wiring was designed to fit over the in-pool radiometers and the thermocouple rakes and not interfere with their operation. When operating at full power, the heater required 480 volts and 42 amperes of electricity, delivering an electrical input of 20.2 kW. To keep the voltage supplied to the coils from interfering with signals from the in-pool instrumentation, the power was initially cycled off and on every 2 min. Later, when it was found that the voltage caused little error in the signals, the power was left on for the duration of the burns.

FIGURE 6. Fabricated Heating Coils

Our laboratory tests indicated that the energy added by heating coils tends to migrate to the surface. Although coils are not an ideal system for adding heat, the quantities of energy they release can be monitored.

EXPERIMENTAL PROCEDURE

The crude oil samples for the Oklahoma experiments--four barrels each of Attaka, Labuan, Saharan Blend, Ekofisk, Isthmus/Mayan Blend, Es Sider, and North Slope--were obtained from commercial oil companies. The oils' composition was verified through tests by an independent laboratory.

Each experiment used 157 l (41.5 gal) of crude oil. (The volume was measured in a calibrated barrel specifically designed for this purpose.) When poured into the 2-m-diameter burning pan, the oil formed a slick 5 cm deep.

Three tests were run on each oil in Oklahoma. The first sample was burned without heat addition. The second and third samples were heated before and during the burns by heating coils delivering approximately 12 and 20 kW of energy, respectively. To minimize weathering, the oils were ignited within 30 min after being placed in the pan.

The total amount of heat added to the oils before and during the burns is reported in Table 3. In general, half of the oils were preheated by the 20.2 kW-powered coils to a surface temperature of 205°F (96.3°C), and the others were raised by the 12.1 kW-powered coils to 155°F (68.5°C). The amount of heat added prior to ignition was assumed to be equal to the heat gained by the oil layer. The amount of heat gained by the oil can be determined using Equation (7). Because the heat capacity (C_p) and the temperature (ΔT) varied with depth, the oil layer was arbitrarily divided into sublayers and averaged values of C_p and ΔT were determined for each sublayer. The amount of heat gained by each sublayer was then calculated using Equation (7). The total heat gained by the oil layer is, therefore, the sum of the values from each sublayer.

$$q = mC_p \Delta T \quad (7)$$

Figure 7 shows how heat input before ignition was calculated. The temperature change (ΔT) within the oil sublayers is the final temperature reached by the sublayer minus the initial ambient temperature (which had been measured before ignition). The initial ambient temperature was about 34°C. Heat

TABLE 3. Amount of Heat Addition to Oil Pool by Heating Coils

Crude Oil	Added Heat, 10^3 kJ			
	Before Burn ^(a)	During Burn ^(b)	Total Energy	Hypothetical Heat Flux kW/m ²
Attaka	11.92	6.17	18.09	6.06
Attaka	4.61	5.82	10.43	3.46
Labuán	13.86	9.77	23.63	8.13
Labuan	2.73	6.06	9.79	3.10
Saharan Blend	16.92	6.17	23.09	5.48
Saharan Blend	4.91	6.51	11.42	4.25
Ekofisk	12.19	9.77	21.96	7.32
Ekofisk	4.79	6.51	11.30	4.55
Es Sider	7.74	10.04	17.74	4.74
Es Sider	4.89	7.61	12.50	4.40
Isthmus/Mayan	14.00	6.17	20.17	8.25
Isthmus/Mayan	4.87	7.61	12.48	3.66
North Slope	7.26	6.17	13.43	4.96
North Slope	4.33	7.61	12.44	4.10

(a) Calculated from recorded temperature profiles

(b) Calculated as the product of the power of and length of time the heater was in operation

capacity values were approximated by taking the value at the average temperature of the sublayer. The mass of the oil in each layer was determined from the oil density and the burning pan dimensions. The calculations assumed that the oil composition was uniform and that no heat was lost to the water or atmosphere. Figure 7 indicates that very little energy was actually lost at the oil/water interface.

FIGURE 7. Calculation of Pre-Ignition Heat Input

A battery of instruments monitored certain variables during the test burns, among them ambient temperature, barometric pressure, relative humidity, wind speed and direction, fluid levels, temperatures at 34 locations within the burning pan, and the amount of heat radiated from the flames back into the oil pool. In all, 47 channels of data were taken every four seconds, processed through a data logger, and recorded on computer tape.

Residual oil present at the end of the test burns was sampled and analyzed for composition. These results were used later in characterizing crude oil combustion.

To determine if an oil slick's thickness affects combustion, we experimented with burning Labuan crude oil in thicknesses of 50, 20, 10, 5, and 3 mm.

RESULTS

Burning rate data for the oils tested were obtained from the level recorder/controller. Data from the system were in the form of continuously dropping step functions (Figure 8, Part A). This functionality does not represent the continuous rate of combustion known to exist; rather, it reflects the rapid opening and closing of the solenoid system. By smoothing the steps of the curve, we were able to show the actual burning-rate curve (Figure 8, Part B). Smoothing of the curve was accomplished by using a computer routine that took running averages of the step-like data. Using the derivative of the smoothed curve resulted in a plot of burning rate versus time (Figure 8, Part C). Data obtained from the oil-thickness-versus-time curve were used to determine the total amount (percentage) of the crude oil sample actually combusted. Our data show that different oils burn at different rates (Table 4). The fastest burning oil was the Isthmus/Mayan blend (4.9 mm/min), and the slowest was Bunker C fuel oil (2.0 mm/min). The typical test burn produced a burning rate-versus-time curve such as the one in Figure 9. The burning rate quickly reached a steady-state plateau (this represents the average burning rate) and continued to burn at this rate until the extinction point was reached. In most cases, about 90% of the crude oil was burned (Table 5), leaving a residual ~5 mm thick.

Because light crude oils have a high heat of combustion and API gravity, they might be expected to combust at a higher rate than heavy crudes. The experimental data do not support this hypothesis (Table 4). No relationship appears to exist between burning rate and API gravity. API gravity is defined in terms of specific gravity as follows:

$$\text{API gravity} = \frac{141.5}{d} - 131.5$$

d = specific gravity

As expected, burning rates declined slightly in cold weather. The data in Table 4 clearly indicate that burning rates were higher in Oklahoma (warm ambient conditions) than in Ohio (cooler ambient conditions).

A. RAW DATA

B. SMOOTHED DATA

C. BURNING-RATE DATA

FIGURE 8. Example of How Data Were Plotted

TABLE 4. Average Burning Rate with No Heat Addition

Oil, API Gravity	Burning Rate, mm/min	
	Oklahoma Tests	Ohio Tests
Saharan Blend, 44.3	4.2	3.5
Attaka, 43.2	4.2	--
Es Sider 37.0	3.4	--
Labuan, 36.0	3.0	3.0
Ekofisk, 35.8	4.6	--
Isthmus/Mayan Blend, 33.0	4.9	3.2
North Slope, 26.8	4.6	4.1
Diesel (#2 Fuel Oil), 35.0	--	3.6
Bunder C (#6 Fuel Oil), 17.5	--	2.0

-- Not tested

FIGURE 9. Typical Burning-Rate Curve

TABLE 5. Amount of Oil Combusted and Length of Burns(a)

<u>Oil</u>	<u>% Combusted</u>	<u>Length of Burn (min)</u>
Saharan Blend	87	15
Attaka	84	14
Es Sider	94	23
Labuan	89	16
Ekofisk	88	17
Isthmus/Mayan Blend	95	16
North Slope	95	14
Diesel ^(b)	97	17
Bunker C ^(b)	92	34

(a) Data averaged for tests at both sites except for Diesel and Bunker C fuel oils

(b) Primer used to start combustion

The lighter oils ignited more quickly than the heavier oils. The entire surface of the lighter crudes began burning instantaneously at the time of ignition, whereas the surfaces of the heavier crudes (e.g., North Slope, Isthmus/Mayan, and Es Sider) started burning only at the ignition point. Eventually, the flames did spread over the entire surface area of the pool. The spreading sequence was completed in 15 to 30 sec in Oklahoma and in 15 to 45 sec in Ohio. All of the crude oils ignited, whether the ambient temperatures were high or low.

The temperatures in the oil and water were continuously monitored during the tests by the thermocouple rakes (Figure 10). [Data from the last thermocouple (#17) on each rake were not plotted because the temperature at this thermocouple was usually identical to the temperature at thermocouple #16.] The thermocouple position relative to the oil's surface is shown in Table 6. If the thermocouple positions are known, one can plot the temperature profiles at any time. Figure 11, for example, illustrates the temperature profile for Labuan crude oil.

FIGURE 10. Temperature Readings from Thermocouple Rake No. 2 During Burn of Labuan Crude Oil

TABLE 6. Position of Thermocouples

Thermocouple No.	Below Oil Surface		Thermocouple No.	Below Oil Surface	
	(mm)	(in.)		(mm)	(in.)
1	0.79	1/32	10	18.26	23/32
2	2.38	3/32	11	24.61	31/32
3	3.97	5/32	12	30.96	1-7/32
4	5.56	7/32	13	43.66	1-23/32
5	7.14	9/32	14	56.36	2-7/32
6	8.73	11/32	15	69.06	2-23/32
7	10.32	13/32	16	94.46	3-23/32
8	11.91	15/32	17	119.86	4-23/32
9	15.08	19/32			

The surface temperatures of the oils during combustion averaged 220°C (Figure 12). End-point values in Figure 12 are scattered because some oils burned longer than others. Temperatures did vary at the beginning and end of the burns, but this deviation was expected. Depending on how quickly the oil ignites, the level controller will oscillate to different degrees and cause differences in the relative positions of the thermocouples, which in turn causes fluctuations in the thermocouple readings. The lighter oils, the fastest to ignite, normally exhibited the most stable temperatures.

Droplets of oil were ejected from the oil pool into the flame during the tests, perhaps indicating that entrainment was taking place. The photographs in Figure 13 document that droplets formed near the end of several burns of Ekofisk and Attaka (note the small, black flecks in the flame zones). During the experiments, a black layer of oil collected on the soil directly downwind from the burning pan, another indication that entrainment was taking place.

Labuan crude oil slicks ignited whether they were 50, 20, 10, 5, or 3 mm thick. Apparently, the critical thickness for igniting Labuan is less than 3 mm. We were unable to determine how the thickness of the Labuan slick affected burning rate, because the level controller fluctuated a great deal during this set of short-length, experimental burns.

FIGURE 11. Temperature Profile for Labuan Crude Oil Taken at One Minute into the Burn

FIGURE 12. Surface Temperature of Five Oils During Combustion
(Average Temp. = 220°C)

Break-even-point calculations of the distillation model were recalculated to reflect actual temperatures found in Oklahoma. (Actual ambient temperatures ranged from 71 to 95°F, while the model's BEP values assumed a temperature of 40°F.) Higher BEP values resulted from the recalculations (compare Columns 1 and 2 in Table 7), because the higher ambient temperatures reduced the sensible heat term in Equation (1). To further refine BEP values, an independent laboratory analyzed the composition of the crude oils we tested. The laboratory's results were factored into the BEP values found in Column 3 of Table 7. (These BEPs are prone to calculation errors because the lab tested fewer fractions than are reported in the literature. The laboratory-corrected values are, nevertheless, an improvement because they reflect the actual chemical composition of the oils.)

Ekofisk
Crude

Attaka
Crude

FIGURE 13. Entrainment of Oil Droplets in Burns of Ekofisk and Attaka Crude Oils

TABLE 7. Break-Even Points for Seven Crude Oils Tested in Oklahoma

Oil	(1) Hypothetical BEP (T_a assumed to be 4.4°C or 40°F)	(2) Measured BEP (T_a = actual site temp.) ^(a)	(3) Lab-Corrected BEP (T_a = site temp., actual API gravity)	(4) Equation-Corrected BEP (T_a = site temp., actual gravity, "G" factor)	(5) Actual BEP Oklahoma	(6) Actual BEP Ohio
Attaka	71.7	78.2	63.8	52.4	84	--
Labuan	51.7	57.7	48.3	38.0	89	97
Saharan Blend	43.8	49.2	51	38.7	87	87
Ekofisk	41.2	45.1	47.4	33.1	88	--
Isthumus/ Mayan Blend	36.4	40.0	40.5	95	94	
Es Sider	31.4	36.6	43.9	32.3	94	--
North Slope	28.8	33.2	41.1	28.4	95	96

(a) The actual site temperatures encountered in Oklahoma varied because the trials were run on different days and at different times of the day. The ambient temperatures during the various trials were as follows: Attaka 26.1°C (79°F); Labuan 23.9°C (74°F); Saharan Blend 34.1°C (88°F); Ekofisk 21.7°C (71°F); I/M Blend 23.9°C (75°F); Es Sider 35°C (95°F); and North Slope 30.6°C (87°F).

Column 4 in Table 7 compensates for the 2% of the heat of combustion that returns to the oil pool [see Equation (1)]. The actual value was less than 2%, which resulted in the lowest BEP values reported in Table 7. The "G" factors, which were calculated from the experimental data, are listed in Appendix C.

Actual BEP values can be calculated from Equation (8), the results of which are presented in Columns 5 and 6 of Table 7. Note how much higher these actual BEPs are than the calculated values in the previous columns.

$$\text{Actual BEP} = \left[\frac{\text{Original Oil Depth} - \text{Final Oil Depth}}{\text{Original Oil Depth}} \right] (100) \quad (8)$$

HEAT ADDITION TESTS

Our calculations show that adding heat to Attaka, Labuan, Es Sider, Ekofisk, and Saharan Blend crude oils before and during the burns did not greatly affect their burning rates (Figure 14).^(a) The added heat did, however, enhance ignition. The heavy crude oils (e.g., North Slope and Es Sider) normally had slow flame-spreading rates but, when heat was added, their entire surfaces ignited almost immediately.

(a) Malfunctions in the level recorder disqualified burning-rate data for North Slope and Isthmus/Mayan Blend crude oils.

FIGURE 14. The Effect of Added Heat on Burning Rate

DISCUSSION

The major conclusion drawn from our test results is that the combustion of crude oils proceeds via the processes of equilibrium flash vaporization and entrainment, and not via distillation. Most of the following discussion explains the observations and data supporting this conclusion.

BURNING RATES

Burning rates differed depending on the composition of the oils, the ambient temperatures at the site, and atmospheric conditions. Generally, the oils burned faster under warm-weather conditions than under cold-weather conditions (Table 4). However, adding heat directly to the oil before the burns did not appear to enhance the burning rate significantly. (It did enhance ignition.) Ignition took place much faster with energy addition because ignition is a vapor-phase phenomenon, and added sensible heat will increase the rate at which the crude oil volatilizes.

Burning-rate data for a wide variety of substances have been collected over the past twenty years. Initial work by Blinov and Khudyakov in the late fifties, as reviewed by Hottel (1961), indicated that burning rates for most hydrocarbons could be derived from Equation (9), where heat flux equals the sum of the conductive, convective, and radiative components.

$$\frac{q}{\pi D^2/4} = \frac{k_i (T_F - T_B)}{d} + U(T_F - T_B) + \delta F(T_F^4 - T_B^4)(1 - e^{-\kappa D}) \quad (9)$$

Using these assumptions and other simplifications, an expression for burning rate, V , can be derived from Equation (9)

$$V = \left(\frac{\sigma T_F^4}{\rho \Delta H_V} \right) (1 - e^{-\kappa D}) \quad (10)$$

Burgess and his co-workers (1961) noticed that for pools over 1 m in diameter, the liquid regression (i.e., burning) rate, V , becomes constant and is dominated by the radiative term. From this they found that for pure component fuels,

$$V = V_{\infty} (1 - e^{-\kappa D}) \quad (11)$$

where D is the pool diameter and κ is a constant specific to the fuel. Additional work on pure-component, liquid-regression rates was completed by Akita and Yumoto (1971).

Kanury (1974) and deRis, Kanury and Yuen (1973) have developed modeling equations for conducting scaled burning-rate experiments using plastics and other polymer mixtures. Modak (1981) has also done research on modeling pool fires using plastics. Kanury's equation for burning rate is

$$m'' = (h/C_p) \ln (B + 1) \quad (12)$$

where

$$B = [fH_c (1 - \gamma) Y_{\infty} + C_p (T_a - T_w)] [Q(1 - \psi)] \quad (13)$$

This equation can be simplified to

$$m'' \cong \underbrace{\left[q_{rw}'' / [Q \ln (B_c + 1)] \right]}_{\text{radiative term}} + \underbrace{\left[(h/C_p) \ln (B_c + 1) \right]}_{\text{convective term}} \quad (14)$$

where m'' is a mass flux in units of grams per centimeter squared per second. Dividing m'' by the density of the oil readily allows conversion of Equation (14) to V , the burning rate, with units in centimeters per second.

Results and trends in burning-rate data obtained during our work over the last two years, in general, are explained by the previous review of the literature. The constant burning rates observed in the tests can be justified

by Equation (14). If the variations in the convective mass transfer term (B_c) are small, the variations in $\ln(B_c + 1)$ will be even smaller. Thus, the mass flux term (m'') becomes less dependent in the convective component and more dependent on the radiative component. However, the variations in the radiative heat transfer are normally very small (Thompson, Dawson, and Goodier 1979) because the flame tend to block radiation back to the pool (see Enhancement Section). This limitation in back radiation may explain the uniformity in burning rates observed during the experiments.

OIL VOLUME BURNED

Ninety percent of the crude and fuel oils burned, leaving a residual of 10%. These ratios are comparable to data reported by Maybourn (1970), who found that a layer of Kuwait crude 13 mm thick burned down to about the 2-mm level. Twardus (1980) has also reported similar results.

Combustion calculations based on ASTM distillation curves grossly underestimated the percentage of crude oil that would burn. The curves predicted that usually <50% of a crude oil would volatilize and combust at 220°C (Table 8).^(a) In actuality, the amount of crude oil combusted was consistently near 90 wt%. This discrepancy suggests that some mechanism other than distillation took place.

SURFACE TEMPERATURE DURING BURNS

If combustion is a distillation process whereby heavier fractions are successively burned, then all of the crude oil fractions burned should have boiling points less than or equal to the oil's final (or highest) surface temperature, which was ~220°C. Furthermore, the surface temperature of the oil would be expected to increase with time as the lighter, lower boiling-point fractions are volatilized and combusted. Figure 12, a plot of surface temperature versus time, indicates that surface temperature was constant over

(a) According to the distillation model, to achieve combustion of 90 wt% of the crude oils tested, the boiling point of the oils would have to have been 500°C. In reality, 90 wt% of the oils burned at only 220°C.

TABLE 8. Predicted Percentage of Oil That Would Combust at 220°C (Based on ASTM Distillation Curves) vs Actual Percentage Burned

Crude Oil	% Volatilized and Combusted	
	Predicted by ASTM Distillation Curves	Actual Amount Combusted
Attaka	68	85
Labuan	52	89
Saharan Blend	47	87
Es Sider	41	88
Ekofisk	42	95
Isthmus/Mayan Blend	29	94
North Slope	37	95

time. This constant surface temperature implied that the same ratios of light and heavy ends were present in the oil throughout the burns. Composition analysis verifies that the oil residual was composed of both heavy and light ends (Table 9). Thus, the surface temperature and the composition analysis suggest that the oil did not combust in a mode described by distillation.

EQUILIBRIUM FLASH VAPORIZATION AND ENTRAINMENT

Except for Attaka crude oil, the distillation model incorrectly predicted the amounts of crude oil that would burn. (The similarity between actual and calculated break-even points for Attaka is probably a coincidence.) Given the inadequacy of the distillation theory, some other model is needed to explain the events that occur in a pool of crude oil during combustion. Several factors, many based on observation, indicate that equilibrium flash vaporization (EFV) and entrainment are the mechanisms by which crude oils burn. EFV appears to be the primary combustion process and entrainment the secondary one.

EFV is the combustion of an essentially constant composition vapor over time. The composition of the vapor formed is the same as the composition of the liquid feed, and equilibrium is maintained by continually feeding fresh

TABLE 9. Composition of Crude Oils Before and After Combustion

Crude Oil Test ^(a)	Residual Volume (%)	Volume % of Sample Left at			Crude Oil Test ^(a)	Residual Volume (%)	Volume % of Sample Left at		
		-18° to 93°C	93° to 204°C	204° to 316°C			-18° to 93°C	93° to 204°C	204° to 316°C
Attaka					North Slope				
Initial	--	7.0	35.0	38.5	Initial	--	3.0	23.0	26.5
A	16.0	2.4	18.0	33.0	A	5.4	3.2	19.0	--
B	13.4	2.0	--	25.8	B	10.8	3.2	7.6	22.0
C	8.0	4.0	24.0	--	C	3.6	4.0	17.8	--
Labuan					Es Sider				
Initial	--	1.5	25.0	41.0	Initial	--	4.0	24.0	27.5
A	10.0	2.2	10.2	10.6	A	6.0	4.4	17.0	17.8
B	10.2	3.2	13.6	10.0	B	12.6	--	9.8	23.0
C	12.6	3.2	5.6	59.0	C	1.4	3.2	25.2	13.0
Saharan Blend					Ekofisk				
Initial	--	5.0	28.0	30.0	Initial	--	9.6	25.0	22.4
A	13.0	1.2	42.0	6.0	A	12.2	2.8	27.0	3.8
B	12.6	--	5.6	46.0	B	9.1	1.6	6.4	67.8
C	8.0	3.6	5.0	35.0	C	13.6	7.6	32.0	--
Isthmus/Mayan									
Initial	--	2.5	19.0	36.0					
A	5.0	--	--	--					
B	11.7	5.6	19.6	14.0					
C	6.6	2.0	12.0	38.0					

(a) Test conditions:

A - No heat addition

B - Heat addition through 12.1-kW-powered coil

C - Heat addition through 20.2-kW-powered coil

liquid of constant composition to the vaporization zone at the same rate that vapor is removed. As long as liquid feed is available, the process will continue. The mechanism is normally restricted to systems with minimal mixing or the presence of a very steep temperature profile in the oil, which is in contrast to batch distillation which occurs in a well-mixed system. Characteristically, with EFV the vaporization of the light ends within the entire vapor mixture will depress the dew point of the heavy ends in the liquid fuel, allowing more of the oil to vaporize and burn than would occur with conventional batch distillation.

Experimental results obtained during our tests support the concept of EFV. EFV processes, due to the constant vapor composition burned, are characterized by constant temperatures at the fuel surface with time, unlike batch distillation where the surface temperature of the oil rises with time as heavier components are burned. Figure 12, which plots surface temperature versus time for several of the oil tested, shows that the surface temperature (220°C) of the oil did remain constant during the experiments.

Another set of results supporting EFV is presented in Table 8. By evaluating American Society for Testing and Materials (ASTM) distillation curves, the percentage of the oil sample that could be volatilized at a surface temperature of 220°C was determined. This percentage is equivalent to that expected from batch distillation (Column 1, Table 8). However, with EFV the dew point of the heavy constituents is decreased, allowing a larger percentage of the oil to be burned. The actual percentage of oil burned (Column 2, Table 8) was much higher than that predicted by batch distillation, supporting the EFV mechanism. Some of the actual oil removal may have been caused by entrainment (observed late in burning experiments) which was caused by the formation of water vapor as the slick became thinner.

To further test the EFV concept, samples of oil were taken before and after each experiment to determine the crude oil composition. If EFV were occurring, light fractions would be present in the residuals. Lack of light fractions would tend to support the concept of bulk distillation. Table 9 summarizes the composition analyses. Although the data are scattered, a

significant amount of the light fractions apparently remained in the residuals. This is especially noticeable in the first fractionation zone, from -18 to 93°C.

Finally, EFV requires a fuel layer that remains relatively unmixed over the length of the experiment. For a poorly mixed system a temperature profile should be present in the oil layer whereas in a well-mixed system no temperature profile should be present. Temperature profile data from nearly all experiments supported the EFV concept (unmixed systems) showing very steep temperature profiles. In fact, temperature of the oil 5-10 mm below the oil surface was close to the ambient temperatures (Figure 11).

Figure 13 presents photographic evidence that entrainment occurred during burns of Ekofisk and Attaka. The small, black specks in the photographs are droplets of crude oil being ejected from the oil surface into the flame. Most of the entrainment was probably caused by water vapor, which formed when the burning oil layer became thin enough that the underlying water was heated to its boiling point. The vapor rose from the water beneath the slick, passed through the oil layer and, while moving toward the surface, entrained droplets of oil. Upon being entrained, the oil droplets had to travel only about one centimeter before reaching the flame zone, where temperatures as high as 1000°C were sufficient to combust them.

HEAT LOSS TO WATER

When oil is burned on water, heat loss from the oil to the water is expected to increase as the oil layer becomes thinner. As the critical oil thickness is reached (the thickness at which the flame goes out), a quenching action is exerted by the water. Hall (1972) reports that Atallah defines this critical thickness for the combustion of fuel on water as the thickness at which the heat conducted through the film into the water is equal to that radiated from the flame to the fuel. To verify this theory, we calculated the heat loss to the water from six oils and compared these values to the measured value of the heat radiated from the flame to the fuel.

The heat loss to the water was calculated as heat gained by the water. Temperatures were recorded continuously at various depths in the oil and water

phases. From these measurements, a temperature profile in the water could be determined at any time. Figure 15 illustrates the temperature profile at the time the fire started to recede.

Given that a quasi-steady state has been established, the following equation can be used to describe heat conduction into the water:

$$\lambda \frac{d^2 T}{dy^2} + VC_p \rho \frac{dT}{dy} = 0 \quad (15)$$

where

λ = thermal conductivity

C_p = specific heat

ρ = density

V = speed of regression of the surface at the maximum temperature.

FIGURE 15. Temperature Profile in the Water When Fire Started Receding

The solution to this equation is

$$T - T_0 = Ae^{by} \quad (16)$$

where A and b are constants and T_0 equals ambient temperature. The temperature-profile data at a desired time were fitted to this exponential equation by regression analysis and A and b were calculated. The coefficients of determination (r^2), which indicate the quality of fit achieved by the regression, were usually between 0.7 and 0.9. Values of r^2 near 1.00 indicate a better curve fit than values close to zero.

The amount of heat gained by the water can be calculated at any time by Equation (17)

$$E_w = \rho C_p \Delta T \cdot d \cdot A_s \cdot \frac{1}{1000} \text{ [kJ]} \quad (17)$$

where

ρ = density of water in g/m^3

C_p = heat capacity of water in $\text{kJ/g}^\circ\text{C}$

$\Delta T = T - T_0$, temperature gained in $^\circ\text{C}$

d = depth of water in mm

A_s = surface area of pool in m^2 .

The shaded area in Figure 15 represents $\Delta T \cdot d$ and was calculated as:

$$\Delta T \cdot d = \int_a^{100} T \, dy - T_0 (100 - a) \quad (18)$$

where a = oil/water interface depth in mm = oil thickness in mm.

Substituting the expression for T from Equation (16) into Equation (18) and integrating yields:

$$\Delta T \cdot d = \frac{A}{b} \exp(by) \Big|_a^{100} \quad (19)$$

Therefore, heat gained by unit area of the water is

$$\frac{E_w}{A_s} = \frac{\rho c_p}{1000} \left(\frac{A}{b} \exp (by) \right) \Big|_a^{100} \left[\frac{\text{kJ}}{\text{m}^2} \right] \quad (20)$$

The heat flux to the water can then determined as

$$F_s = \frac{d}{dt} \left(\frac{E_w}{A_s} \right) \left[\frac{\text{kJ}}{\text{m}^2 - \text{sec}} \right] \quad (21)$$

which is the slope of the curve, E_w/A_s , versus time.

To determine if Atallah's relationship is valid, we plotted the net energy passing into the water per unit area versus time for six of the oils (Figure 16). In all cases, there is a gradual to sharp increase in E_w/A_s just before t_1 , the flame receding time, and a gradual decrease in E_w/A_s after t_2 , the flame out time. The slopes were calculated at t_1 and t_2 to determine the heat fluxes. These slopes are summarized in Table 10 and are compared with the heat fluxes measured at the oil surface between t_1 and t_2 . For all six oils, the fluxes at the oil/water interface and oil surface were within 10% of each other during this time period. Since 10% is less than the experimental error, the data verify Atallah's relationship, showing that the heat conducted through the oil into the water was equal to that radiated from the flame to the oil at the critical thickness. The critical thickness calculated for each of the oils averaged 4.5 mm and varied from 1.5 to 8.3 cm.

FIGURE 16. Transfer of Energy Into Water

FIGURE 16. (contd)

FIGURE 16. (contd)

TABLE 10. Data Evaluating Atallah's Relationship

<u>Crude Oil</u>	<u>Oil Thickness</u>	<u>Heat Flux (kJ/m²-sec)</u>			
		<u>Oil/Water Interface</u>		<u>Oil Surface</u>	
		<u>t1</u>	<u>t2</u>	<u>t1</u>	<u>t2</u>
Attaka	8.3 to 7.8	29	23	31 to 50	
Es Sider	2.7 to 4.0	30	10	11 to 17	
Isthmus	2.5	40	0	43 to 46	
Labuan	5.3 to 5.4	27	73	30 to 39	
North Slope	3.5 to 3.7	38	33	29 to 33	
Saharan	4.0	63	40	34 to 45	

FUTURE RESEARCH

Several areas for further study were identified as an outgrowth of the experimental work discussed in this report. More research is needed to substantiate current research and to clarify the direction that future research on the combustion of crude oils should take.

One conclusion reached in the current program is that a crude oil will burn as long as a minimum oil depth exists. Once the temperature profile begins to move into the supporting water layer, combustion apparently ceases. Future research on this aspect of combustion should address the following topics:

1. If thin oil slicks (as normally occur) could be insulated from the supporting water column by a relatively nonconductive medium, would the slicks combust?
2. Ignition and the subsequent establishment of a temperature profile are probably the two most important parameters governing the combustion of crude oils on water. Ignition is often facilitated by liquid primers, but these tend to result in evaporative cooling, and thus fail to provide an adequate heat flux. Solid primers might be more effective.

To burn oil spills thinner than the critical thickness, a way must be found to insulate the oil from the water, and thereby prevent the loss of heat from the oil to the water. Certain materials could be used for this purpose. For example, hollow microspheres, available in various sizes and specific gravities, are possible insulators. Assuming that the surface tension of the oil is not an obstacle, microspheres with a specific gravity of ~ 0.95 could be applied to the slick and allowed to settle between the water and the oil. This insulating layer would eliminate the need to establish a complete temperature profile or minimum depth of oil. Other materials that might provide a similar function could and should be evaluated.

The microspheres might also be designed in such a way that wave action would break them open and force water into their centers. The water intake

would increase the spheres' density and cause them to sink, thus eliminating the need to clean up either the residual or the spheres themselves.

Available research indicates that solid primers and promoters are probably more effective than liquid primers. First, liquid primers tend to spread over the entire surface of the slick, decreasing the amount of primer per unit of surface area. Because the liquid spreads, it is hard to develop a temperature profile in one small segment of the slick. Concentrated primers are more effective in this respect. Second, the heat release per unit area is less for liquid primers, in general, than solid primers. As discussed earlier, during the experimental burns, a small area of the pool ignited, and later the flames spread radially across the rest of the pool. If this is how ignition normally starts, solid primers would be more effective than liquid primers in concentrating heat at the exact point of ignition. Liquid primers tend to evaporate, lowering the amount of energy available to the oil. Solid primers do not hold temperatures down through evaporative cooling. Future research on the utility of insulators, solid primers in combination with insulators, and liquid primers mixed with insulators could greatly enhance the viability of burning oil slicks.

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APPENDIX A

EQUIPMENT SCHEMATICS

APPENDIX A

EQUIPMENT SCHEMATICS

This appendix supplies detailed information on the equipment used in the oil-burning experiments. Schematics are provided to enable the reader to replicate the experiment. This appendix deals only with technical aspects of the equipment; the reader is referred to the main text for an account of the overall test procedure.

OIL-BURNING PAN

The oil-burning pan (Figure A.1) had plug holes for the radiometers and thermocouple rakes. The baffle plate inside the pan buffered the effects of water entering the system from the level-controlling reservoir during the burns. The pan was supported by a stand made of angle iron (Figure A.2).

LEVEL RECORDER/CONTROLLER

The level recorder/controller maintained a constant oil level in the test pan by replacing oil with water as the oil combusted (Figure A.3). The water storage reservoir consisted of a cylindrical steel tank, 3.05 m high and 0.305 m in diameter. A thermocouple in the oil pan monitored the oil's surface temperature up to 205°C (400°F); a solenoid valve was activated if the temperature exceeded 205°C. As the oil burned and its level dropped, the temperature set point was exceeded and the solenoid valve opened, releasing water from the reservoir through a 2-in. pipe into the burning pan. As the oil level rose, it covered the tip of the reference thermocouple, cooling the thermocouple to the set point. This caused the solenoid valve to close and stop the flow of the water into the burning pan. In this manner, a constant surface level in the pan was maintained. This method resulted in minute (less than 1 mm) oscillations of the oil level during the burn.

A differential pressure (d.p.) transmitter was initially used to monitor burning rates during the experiments. The transmitter was replaced early in the Oklahoma experimental program with a pneumatically driven differential

FIGURE A.1. Pan Design and Specifications

pressure amplifier and transducer (Figure A.4). The transducer converted a pneumatic signal into a millivolt signal, and the d.p. amplifier was driven by a line pressure of 3 psi.

THERMOCOUPLE RAKES

A total of 17 chromel-alumel, type-K thermocouples (13 grounded and 4 ungrounded), were positioned on each rake. We had to redesign the rakes to include either grounded or ungrounded thermocouples only, because having both

FIGURE A.2. Stand for Test Pan

types of thermocouples on the same rake resulted in severe ground-loop problems. The center rake (#1) remained in its original position, but the upwind rake (#2) was moved adjacent to in-pool radiometer Number 3. This downwind position provided a better reading than an upwind position because of the position of the flame. All thermocouples had an operating temperature range of -56 to 983°C .

Calibration plots for both sets of rakes were provided by the manufacturer. These plots were used to convert adjusted millivolt signals into temperature values. (To measure the actual millivolt signal, we had to subtract the thermocouple effect at the chromel-alumel and copper lead junctions from

A.4

FIGURE A.3. Design of Level Recorder/Controller System

FIGURE A.4. Differential Pressure Amplifiers

the overall reading. Thus, the actual millivolt signal equaled the measured millivolt signal minus the reference millivolt signal.) Actual millivolt signals were converted to actual temperatures using a curve-fitted, polynomial equation derived from calibration data provided by the manufacturer.

RADIOMETERS

All of the in-pool radiometers had a view window of 150° and were able to absorb a maximum heat flux of $\sim 113.5 \text{ kW/m}^2$ ($10 \text{ Btu/ft}^2\text{-sec}$). The four leads extending from the base of each in-pool radiometer included a nitrogen purge line, two water lines, and a signal lead (Figure A.5). Nitrogen was used to purge the surface of the radiometers, keeping soot and oil from covering the glass windows. Nitrogen pressure to the in-pool radiometers was regulated to 60 psi. Each radiometer required $\sim 0.76 \text{ l/min}$ (0.2 gpm) of water at 100 psi for cooling.

Signals from the instruments were sent, via leads, through the fourth tube leading to the head of the radiometer. All electrical leads were kept sealed with watertight connectors and were coated with an electrical sealant.

At the Oklahoma test site, three external radiometers were placed 7.6 m (25 ft) downwind, and one was placed 4.6 m (15 ft) upwind from the center of the burning pan. The three downwind radiometers consisted of one wide-angle and two narrow-angle radiometers. The wide-angle radiometer was placed at a

FIGURE A.5. Design of In-Pool Radiometers

vertical elevation of 1.8 m (6.0 ft), and the narrow-angle radiometers were set at elevations of 0.92 m (3.0 ft) and 1.8 m (6.0 ft).

Three in-pool radiometers were placed in a north-south plane, parallel to normal southerly winds. A fourth radiometer was placed due west of the center of the pan. These four positions were selected to ensure radiative heat flux measurements that could be extrapolated to other positions within the pan. The thermocouple rakes and the in-pool radiometers were shown earlier in final fabricated and installed form in Figure 4.

Placement of radiometers at the Ohio test site was based on experience gained from the Oklahoma testing. For the Ohio experiments, only two external radiometers were used, one wide angle and one narrow angle. Also, the Oklahoma tests indicated that data from the upwind radiometers were more accurate than data from the downwind radiometers (see the Results Section for details); therefore, both radiometers used during the Ohio field test were placed upwind at a distance of 4.1 m (13.4 ft) and an elevation of 1.8 m (6.0 ft) from the center of the pan.

Figure A.6 illustrates the mounting techniques used for the wide-angle and narrow-angle radiometers. Both nitrogen purges and water cooling were used on the wide- and narrow-angle radiometers. Because operating conditions for external radiometers were not as severe as for in-pool radiometers, lower nitrogen and water pressures were used.

VIDEO RECORDERS

Flame characteristics during the experimental burns were calculated with the aid of two cameras placed at strategic locations (Figure A.7).

HEAT ENHANCEMENT EQUIPMENT

The heat enhancement system consisted of heating cable bent around angle-iron support frame (Figure 6) and a power controller. The system was designed to fit over the in-pool radiometers and the thermocouple rakes and not interfere with their operation. To connect the heating cable to the power controller, the sheathing around the heating cable was cut with an electric grinder. Magnesium insulation between the sheathing and the resistance wire prevented

FIGURE A.6. Mounting Techniques for External Radiometers

FIGURE A.7. Placement of Video Cameras During Testing

any short-circuiting of the cable. Electric sealants were used to prevent the insulation from drawing moisture from the air and shorting-out the cable. The power controller (Figure A.8) functioned by clipping an AC signal. Current and amperage were monitored by digital meters, which were located in the instrument room, as was the actual control to the power supply. The improvised heat dissipator (Figure A.9) was made of a No. 6 copper lead (originating at

FIGURE A.8. Power Controller Schematic

FIGURE A.9. Design of Lead Attachment for Heating Cable

the power supply) connected to a beveled, 1/8-in. copper tube clamped between the lead and the resistance wire. Unfortunately, only two burns could be made before the connection melted and had to be repaired.

APPENDIX B

WIND SCREEN

APPENDIX B

WIND SCREEN

A wind screen was constructed to reduce the wind speed and to lessen fluctuations in the wind speed. Restrictions on wind speed were necessary to ensure consistent data production and to minimize the scatter of data. All current experimental data were taken at wind velocities of less than 4 m/s. Often, experimental tests were postponed when changing wind directions negated the effect of the southerly directed screen.

EFFECT OF WIND SCREEN ON WIND VELOCITY

Two anemometers were used to measure wind speeds both in front of and behind the wind screen to determine its effectiveness. Initially, both anemometers were set side by side to determine the relationship between output signals of the two units. Using two calibrated anemometers and the relationships between millivolt signal and actual wind speed, the effect of the wind screen was determined.

Two orientations were used during wind-screen calibration (Figure B.1). Anemometers were positioned at elevations varying between 1.5 and 1.6 m. The first anemometer was initially placed in front of the screen; the second was placed behind the fence (but in front of the burning pan). Later, the first anemometer was placed in front of the screen and the second behind both the fence and the pan.

Data for the initial orientation of the anemometers are presented in Figure B.2. For any wind speed below 1.8 m/s (3.9 mph), inside wind speed was effectively eliminated by the wind screen. Curve fitting of the data resulted in a function given by the following equation:

$$y = 2.29 \ln x - 1.30; x > 1.76$$

$$y = 0; x \leq 1.76 \quad (B.1)$$

FIGURE B.1. Anemometer Placement During Wind-Screen Testing

The variable "x" represents the external wind speed and "y" represents the inside wind speed (in terms of m/s). Deviation from the curve fit was relatively small, since the coefficient of regression (r^2) was 0.87.

FIGURE B.2. Reduction of Wind Speed by Wind Screen at Position 1

Figure B.3 presents data on the second orientation used. In this case the inside anemometer was placed behind both the screen and the pan. A logarithmic curve fit of the data resulted in Equation (B.2). Variables are the same as those defined and used in Equation (B.1). The coefficient of regression (r^2) was 0.89 which indicates that the curve fit the data closely.

$$y = 1.25 \ln x - 0.71; x > 1.76$$

$$y = 0; x \leq 1.76 \quad (B.2)$$

Figure B.4 plots the results of the two fitted curves. The wind screen was more effective at Position 2 than at Position 1. Complex aerodynamic patterns, caused by the splitting of the wind by the circular screen, appear to explain this phenomenon.

FIGURE B.3. Reduction of Wind Speed by Wind Screen at Position 2

FIGURE B.4. Fitted Data Curves for Positions 1 and 2

Because the wind screen was much more effective than anticipated, tests could be conducted in almost any wind velocity, provided that the wind came from the south. An exception to this rule had to be made if wind speeds exceeded 6.7 m/s, because of turbulence set up by the screen.

Another important variable was wind direction. Because of the orientation of the wind screen, the experimental burns could be conducted only if the winds were from the southeast or southwest. Several testing days were lost when winds blew from the north and east. (Northerly or easterly winds could have bent the flame into the screen or the instrumentation).

APPENDIX C

CORRELATION OF BURNING RATE AND FUEL PROPERTIES

APPENDIX C

CORRELATION OF BURNING RATE AND FUEL PROPERTIES

(Determination of the "G" Factor)

Burgess and Hertzberg (1974) suggest that the burning rate of a variety of fuels from an infinite area (extrapolated from finite-area data) is linearly proportional to the dimensionless group given in Equation (C.1). This proportionality constant has been defined as the "G" factor and is defined as the ratio of heat of combustion, H_c , to sensible heat of vaporization, $H_{vap} + C_p \Delta t$.

$$G = \frac{H_c}{H_{vap} + C_p \Delta t} \quad (C.1)$$

The terms H_c , H_{vap} , and C_p were calculated using the following equations from Cragoe (1929):

$$H_c = (19958 - 3780 d^2 + 1363d) \quad (2.326) \quad [J/g] \quad (C.2)$$

$$H_{vap} = \left(\frac{1}{d}\right) (110.9 - 0.09T_b) \quad (2.326) \quad [J/g] \quad (C.3)$$

$$C_p = \left(\frac{1}{\sqrt{d}}\right) (0.388) + (0.00045T_b) \quad (4.187) \quad [J/g - ^\circ K] \quad (C.4)$$

where

d = specific gravity of the oil

t = boiling temperature of oil ($^\circ F$)

The values of the H_c calculated were compared with the measured values from the field tests and the differences were less than 10%. Therefore, calculated values of H_c were used in calculating G .

Calculated values of G and $1/G$ are given in Table C.1. Specific gravity and boiling temperature values for each oil were obtained from the field tests. The average G and $1/G$ values for the seven oils are 60.9 and 0.0164.

An alternate method of determining the G factor was examined and compared with the results in Table C.1. Burgess et al. (1961) claimed that G is directly proportional to the burning rate, (R). Equation (C.5) describes this relationship.

$$R_{\text{mm/min}} = 0.076 (G) \quad (\text{C.5})$$

A major deviation from Equation (C.5) was observed by Hertzberg (1974) and Spalding (1964) for hydrogen burning data applied to this equation, especially at the high end. Several other authors (Hall 1973; Spalding 1964; Glassman and Hansen 1968; Berl 1964) claim that the liquid fuel density must be included in the recession rate equation, and that the equation must also include the mass ratio of fuel to air at stoichiometric conditions (this term is the Spalding "B" factor). However, the correlations show less scatter without these terms. An excellent correlation is obtained using the relation in Equation (C.6), wherein the coefficient 0.75

$$R_{(\text{mm/min})} = 0.212G^{0.75} \quad (\text{C.6})$$

was discussed in Spalding (1964) and Glassman and Hansen (1968), but not obtained (Putnam 1978).

When we rearrange Equations (C.5) and (C.6), we can calculate G from burning rates measured during the experimental program. These values are presented in Table C.2. Figure C.1 shows the experimental data for burning rate as a function of G . The value of G was computed for each test using the fuel properties and the measured oil-surface temperature. Also shown in Figure C.1 is the suggested relation for pure fuels. Note that the burning rate data obtained for world crude oils indicated that crudes burn like other mixed fuels.

FIGURE C.1. Recession Rate as a Function of G for Various Amounts of Heat Addition

Average values of R and G were also found for the three heat addition cases employed in the present tests. These average quantities were used in Equation (C.6) to obtain the other burning-rate-versus-G plots shown in Figure C.1, which represent the cases of no heat addition, a small heat addition, and a still larger heat addition to the pool. Clearly, the addition of heat tends to make the crude oil burn more like a pure fuel.

TABLE C.1. "G" Factor Determination from Specific Gravity and Boiling Temperature

<u>Crude Oil</u>	<u>Specific Gravity</u>	<u>Boiling Temperature, °C</u>	<u>G</u>	<u>1/G</u>
Labuan	0.860	220	60.4	0.0165
Isthmus	0.886	220	61.0	0.0164
Attaka	0.814	220	59.3	0.0169
Saharan	0.805	220	60.2	0.0166
Es Sider	0.838	220	62.0	0.0161
North Slope	0.897	220	63.4	0.0158
Ekofisk	0.846	220	59.7	0.0167

TABLE C.2. "G" Factors Determined from Burning Rates (No Heat Addition)

Crude Oil	R, min/min	G			1/G		
		Eq. C.1	Eq. C.5	Eq. C.6	Eq. C.1	Eq. C.5	Eq. C.6
Phase 1							
Labuan	3.0	60.5	39.5	34.2	0.016	0.025	0.029
Isthmus	4.9	61.0	64.2	65.4	0.016	0.016	0.015
Attaka	4.2	59.3	55.9	54.5	0.017	0.018	0.018
Saharan	4.2	60.2	55.9	54.4	0.017	0.018	0.018
Es Sider	3.4	62.0	44.5	40.0	0.016	0.022	0.025
North Slope	4.6	63.4	60.8	60.9	0.016	0.016	0.016
Phase 2							
Labuan	3.0	60.5	39.5	34.2	0.016	0.025	0.029
Isthmus	3.2	61.0	42.1	37.3	0.016	0.024	0.027
Saharan	3.5	60.2	46.1	42.0	0.017	0.022	0.024
North Slope	4.1	63.4	53.9	51.9	0.016	0.019	0.019

An explanation of this burning behavior (Figure C.1) is complex because several competing processes occur simultaneously. A partial explanation of the observed data can be obtained by referring to an effective G factor given by Equation (C.7), where

$$G_{\text{eff}} = \left[\frac{H_c}{H_{\text{vap}} + c_p (T_b - T_a) - H_{\text{add}}} \right] \quad (\text{C.7})$$

H_{add} is the amount of explicit heat added to the system by heating coils. However, heat addition also implicitly affects the effective G value through the surface-temperature-dependent term given in Equation (C.7).

On one hand, simple heat addition tends to cause a net deduction from the required total sensible enthalpy and raises the effective value of G , thereby increasing the burning rate. However, heat addition beneath the oil changes the basic nature of the vaporization phenomenon itself; for the fuel studied, it tends to increase the surface temperature and thus the effective total sensible enthalpy. This decreases the burning rate. The presence of a mixing phenomenon can be noted from examination of the temperature histories for different oil depths as a function of time during a burn. For the case of no heat addition, data from the two thermocouple rakes are parallel and temperatures are spread apart. A calm, nonmixing condition is indicated. As a result, one would expect that one layer at a time would be vaporized; this would maintain a constant composition in the vapor and liquid film. However, for many of the runs with the heaters on, one or both of the thermocouple rakes showed long durations, often from near the beginning of the burn to near the end, when several thermocouples near the surface read the same temperature. This indicates a high degree of mixing, resulting in vapor and liquid compositions that vary with time. Thus, the surface temperature and burning rate could possibly change as a function of time.

APPENDIX D

COMPARISON OF WIDE-ANGLE RADIOMETER READINGS AND VIEW FACTORS

APPENDIX D

COMPARISON OF WIDE-ANGLE RADIOMETER READINGS AND VIEW FACTORS

Despite the sharp rises in radiative heat flux that occurred in some instances at the end of burning experiments, a mean radiative flux value was associated with each wide-angle radiometer. Due to the presence of wind at the test site, the flame was tilted at an angle, denoted θ . Therefore, a view factor had to be computed before radiometer data could be compared.

To compute the view factor, the angle of the flame was first determined. This was done using the relation

$$\begin{aligned}\cos\theta &= (U^*)^{-0.5}, & U^* > 1 \\ \theta &= 0 & U^* \leq 1\end{aligned}$$

where the dimensionless velocity, U^* , is given by

$$U^* = U/U_c$$

where U is the wind velocity over the pool (corrected from the measured and wind velocity outside the wind screen) and

$$U_c = (\dot{m}'' g D / \rho_v)^{0.33}$$

The vapor density, ρ_v , was determined from a mean curve for hydrocarbon fuels as a function of the average surface temperature of the fuel. The mass evaporation rate of fuel, $\dot{m}''$, was experimentally determined. Also, to compute the view factor, the flame length had to be determined. Equation (D.1) was used in this case.

$$L/D = 42 \left[\dot{m}'' / (\rho \sqrt{gD}) \right]^{0.061} \quad D.1$$

The flame was assumed to be a skewed cylinder whose diameter was equal to the pool diameter. We calculated view factors for each radiometer based on the flame angle and height for the two positions used during the experimental program.

Figure D.1 shows the radiometer readings as a function of the corresponding view factor for wide-angle, upwind, radiometer No. 1. Figure D.2 shows similar data for downwind radiometer No. 2. Figure D.1 shows that a flame surface radiation of 90 kW/m^2 gives a good fit to the data, with no particular indication of any fuel being consistently high or low. Recently published work on LNG fuel fires on water reported radiation values of 200 kW/m^2 , as compared to values of 120 to 140 kW/m^2 for land spills.

For some tests there was a large burst or increase of radiation near the end of the burn, and flux values were $\sim 200 \text{ kW/m}^2$ for a very short time. These bursts appear to coincide with the start of boiling of the water under the fuel. It is believed that the well-known effect of water or steam in clearing the smoke occurs at this point.

The downwind radiometer data show a much lower value for the heat flux per unit area of the flame. For Saharan, the heat flux is 50 kW/m^2 , and for the other fuels, 25 kW/m^2 . The low fluxes may have been caused by the thick cloud of smoke that formed under the fire plume and shielded the downwind flame region. We also observed that the radiometer coated up rapidly, resulting in a continuing decrease in output with time in many cases. Apparently, Saharan crude oil does not generate as much smoke as the other oils. Its downwind radiation value was a factor of two greater than the other oils.

FIGURE D.1. Upwind Wide-Angle Radiometer Output as a Function of Flame View Factor

FIGURE D.2. Downwind Wide-Angle Radiometer Output as a Function of Flame View Factor

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