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OIL-BURNING TESTS CONDUCTED IN THE PRESENCE OF A HIGH PRESSURE WATERJET BARRIER

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ABSTRACT

A series of burning tests were carried out in a 12m x 15m outdoor basin near Fleet Technology Limited's laboratory in Kanata. The tests were conducted in the presence of a prototype high pressure waterjet barrier that was previously produced by Environment Canada to investigate its effect on the volumetric and mass burn efficiency, and on the opacity of the smoke. It was found that the presence of the waterjet barrier reduced the opacity of the smoke. However, it contributed to the formation of emulsions which reduced the burn efficiency.

INTRODUCTION AND PROJECT OBJECTIVES

Over the past decade, considerable efforts have been expended towards the development of countermeasures that are effective for floating oil slicks.

Waterjets are one method that has been studied to herd and contain the spilled oil. Low pressure waterjets were tested as fireproof oil slick containment devices (Comfort, 1980). Subsequently, a system of high pressure waterjets was developed for oil spill control and a large prototype system was produced (Meikle et al, 1985; Meikle, 1983). This system has been deployed in the field (eg. Laperriere, 1985) and tested in the laboratory. Recently, tests have been done to optimize the mechanical configuration of the high pressure waterjets (eg. operating pressure, angle of incidence, nozzle spacing) for oil spill retention (Phillips et al, 1987).

However, the effect of the waterjet barrier on oil burning efficiency has not been tested. It was hypothesized that the waterjet barrier may also improve the combustion of the oil by providing greater aeration of the flame. Comfort, 1989 has recently conducted a project to improve present understanding of this issue.

The specific objectives of the test program were to:

(a) evaluate the effect of the waterjet barrier on the volumetric and mass oil burn efficiency.

(b) evaluate the effect of the waterjet barrier on the opacity of the smoke plume produced during the burn.

PROJECT SCOPE

Test Setup and Description

Test Facilities Burning tests were conducted in an outdoor basin near Fleet Technology Limited's laboratories in Kanata, Ontario. This basin was 12m x 15m in area and 0.5m deep. See Figures 1 and 2.

A high pressure waterjet system was supplied by Environment Canada for the tests and was operated by a technician from Sanivan Inc. during the project. The waterjet barrier was deployed in a "V" and a circle configuration, as shown in Figures 1 and 2 and Plates 1 and 2. The waterjet barrier is described subsequently.

Test Documentation Each test was documented using colour video photography and 35mm still photographs. Both black and white, and colour photographs were taken.

The following parameters were measured for each test:

(a) Environment Data: Ambient Air temperature
Ambient Water temperature
Ambient Windspeed and direction

(b) Oil Burn Data: Pre-burn weight and volume of the oil
Weight and volume of the residue
Density and reflectance of the smoke plume
Duration of burn
Flame temperature
Moisture content of the residue (for some tests)

The oil used for each test was placed in standard 200 litre (45 gal.) drums to determine the pre-burn weight and volume. For the first test, the weight of the oil was measured using a large balance beam scale and the volume was measured using a linear scale. See Figure 3 for schematic. These measurements were used to determine the pre-burn weight and volume of the oil for subsequent tests.

At the end of each test, the residue was collected using a combination of pails and shovels. With this collection approach, some water was picked up with the oil. The residue was placed in an oil drum and the water was drained through an outlet at the base of the drum. See Figure 3 for schematic.

After the water had been drained, the volume of the residue was measured using a linear scale and the weight was measured using a large balance beam scale.

Measurements were also made to determine the opacity of the smoke plume. The reflectance of the smoke plume was measured using a Pentax Spotmeter V and a Pentax Gray Card (of 18% reflectance). The luminance of both the plume and the card were measured for each test. Typically, the luminance of the smoke plume was measured near the centre of the plume. These data were used to determine the illuminance just before the test was commenced and the reflectance of the plume.

These data were also related to standard smoke densities shown by measuring the reflectance of the grey shades shown in Figure 4.

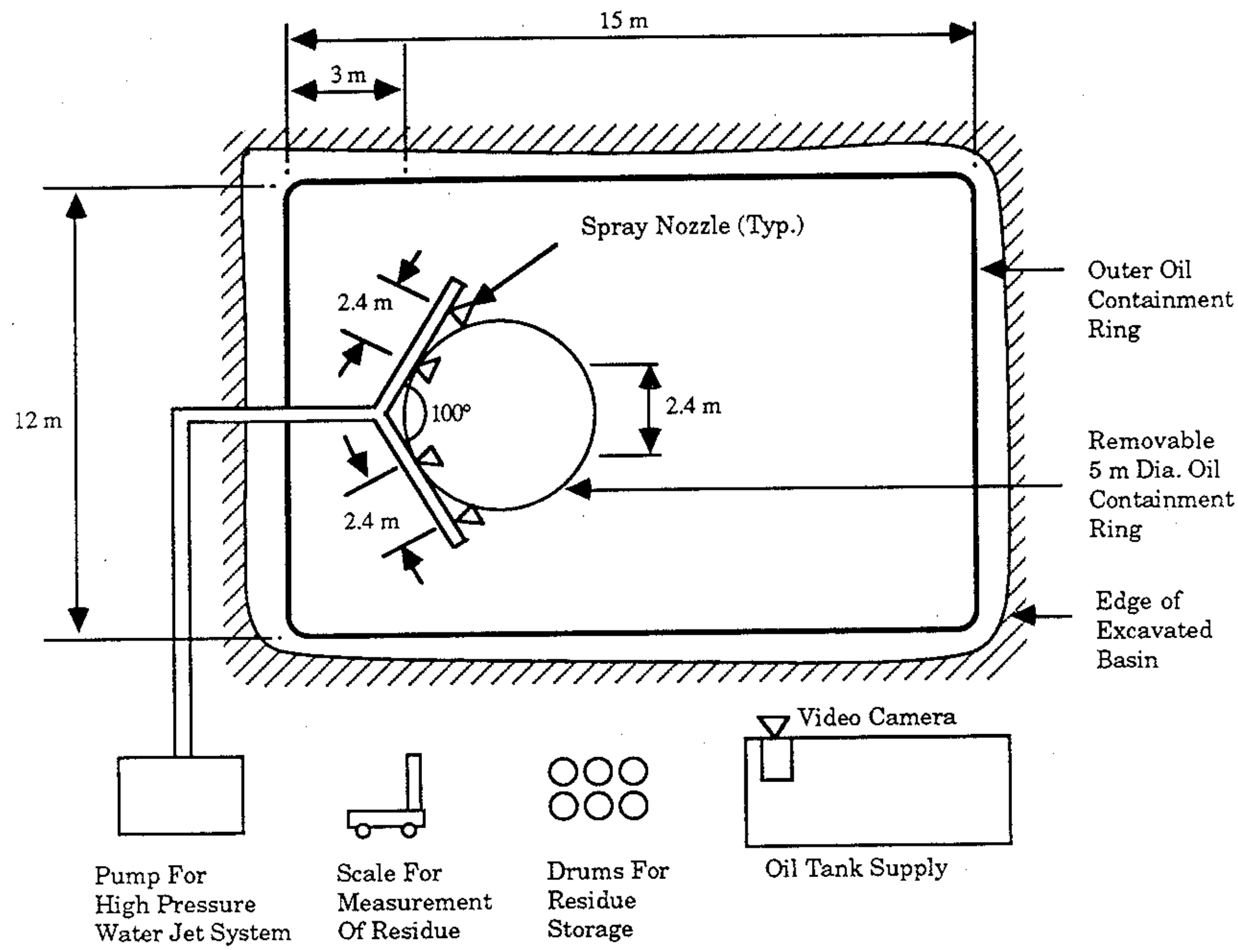


Figure 1a Schematic of Test Setup - Waterjet Barrier Configuration "V"

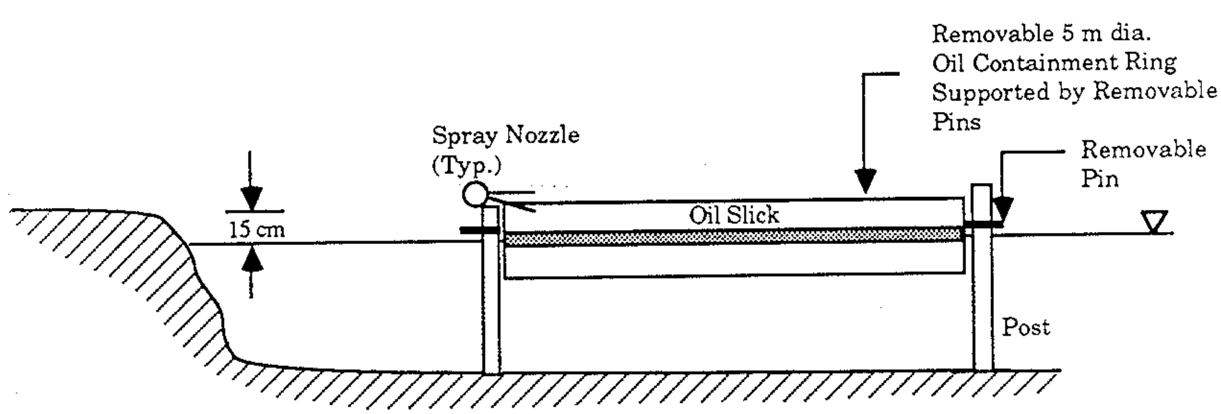


Figure 1b Cross-sectional View: "V" Configuration

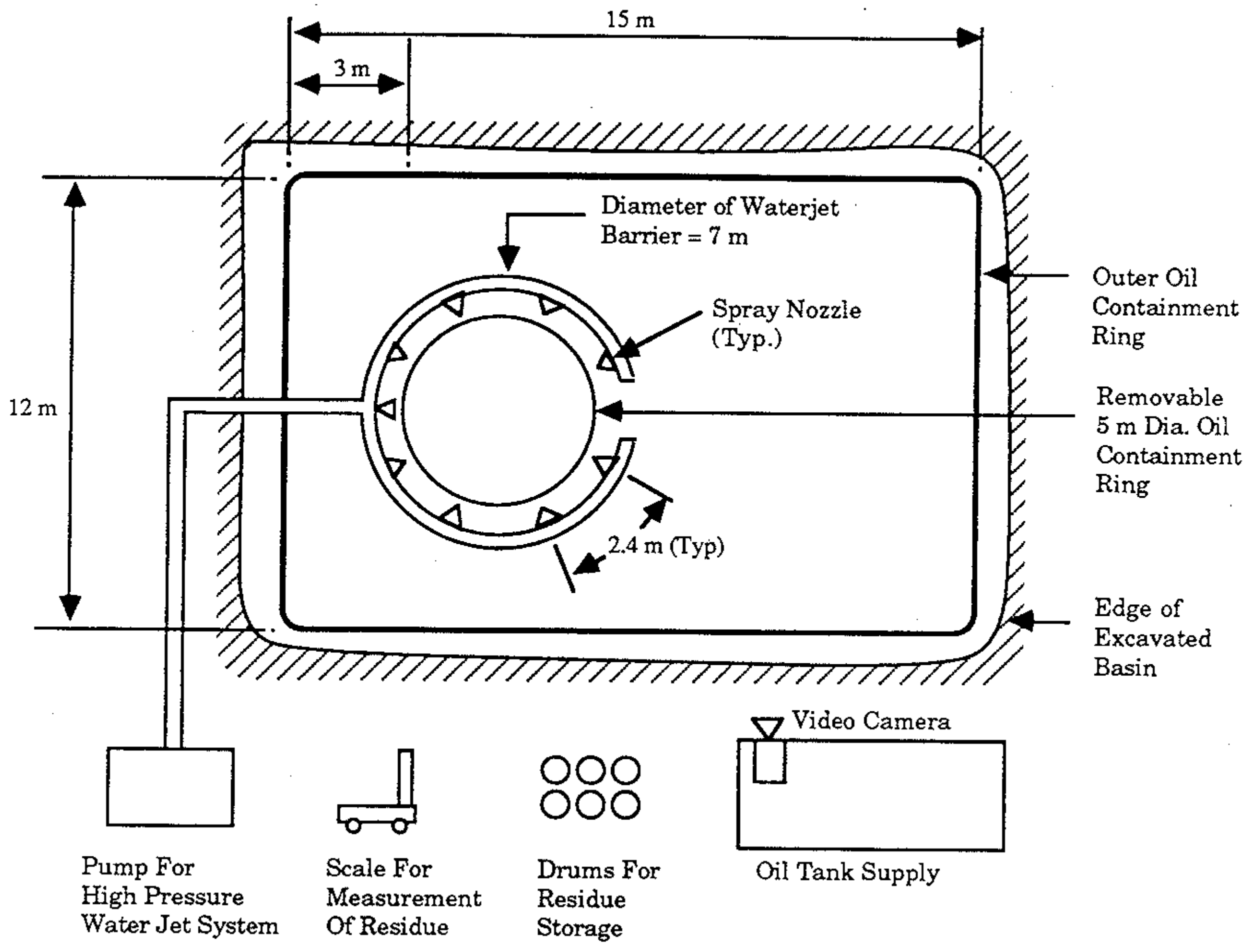
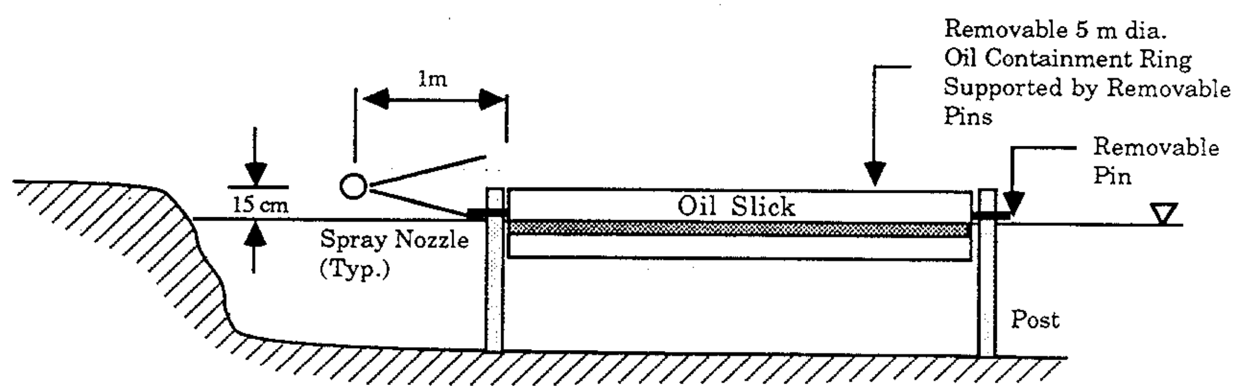


Figure 2a Schematic of Test Setup - Waterjet Barrier Configuration: Circle



Note: Centreline of waterjet kept at same elevation as top of containment ring.

Figure 2 b Cross-sectional View: Circle Configuration

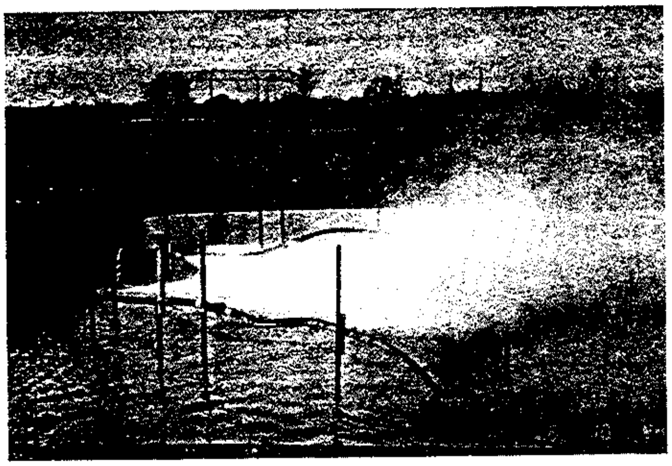


Plate 1

Waterjet Barrier in "V" Configuration

Plate 2

Waterjet Barrier in Circle Configuration

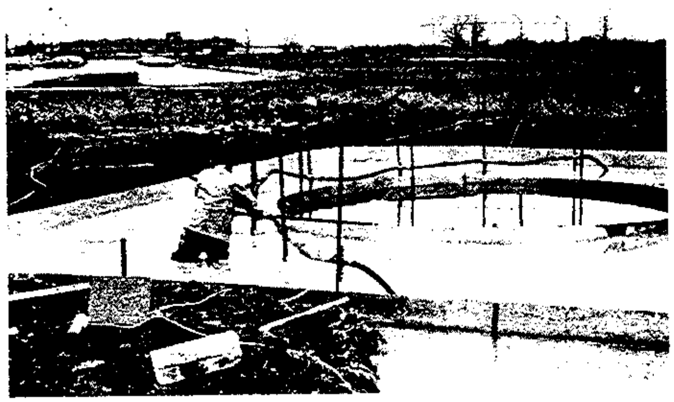


Plate 3

Ignition of Oil Slick

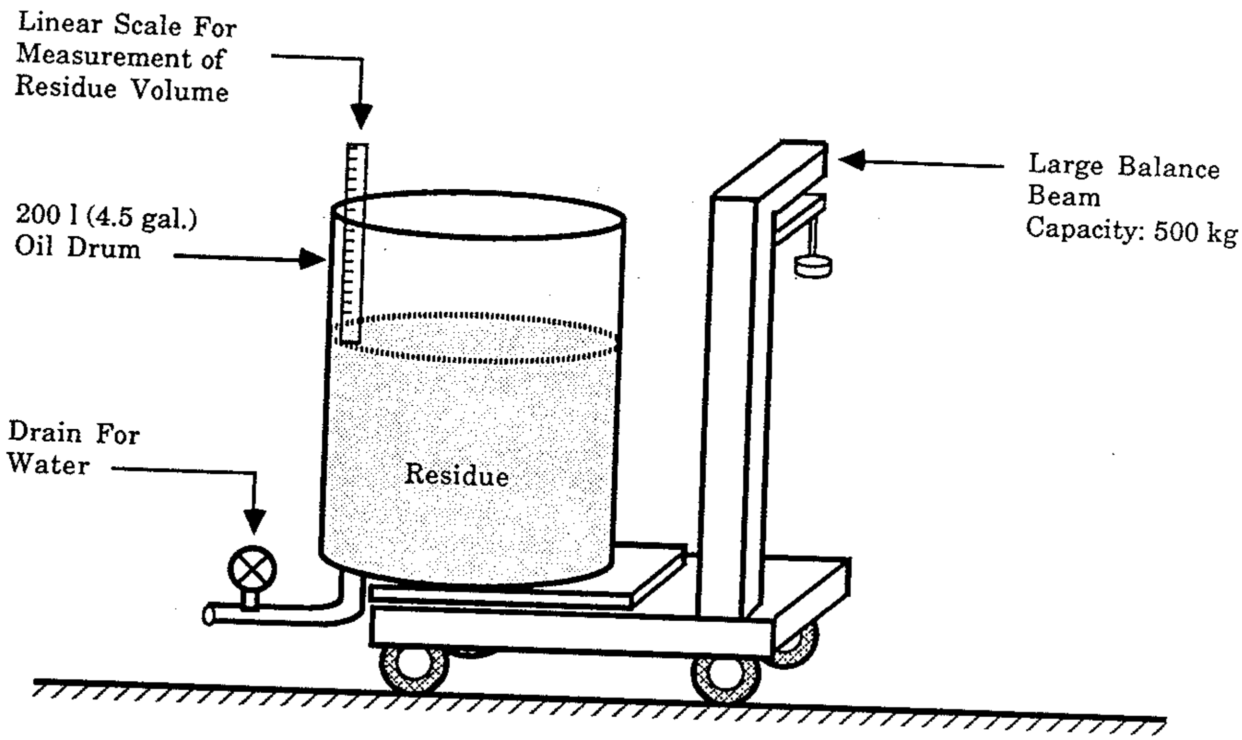


Figure 3 Schematic of Setup For Measurement of Weight and Volume of Residue

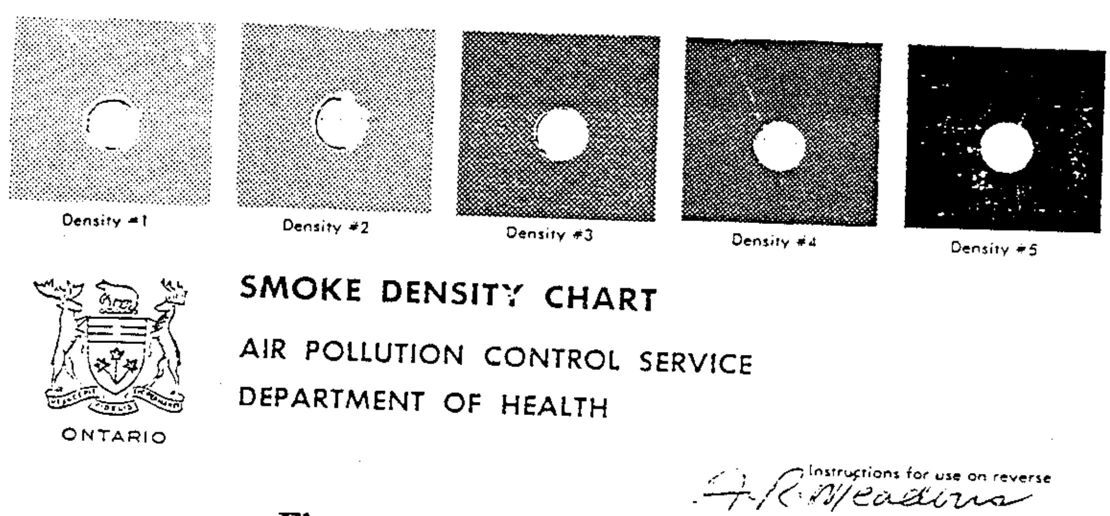


Figure 4 Smoke Density Chart

Waterjet Barrier As outlined in the first section, a large, prototype, high pressure waterjet barrier system has been developed and produced by Environment Canada. This prototype system was used in this project.

The setup of the waterjet barrier selected for these tests was based on the results of previous tests to optimize the performance of the system (Phillips et al, 1987) and on previous operating experience (e.g. Laperriere, 1985).

The table below describes some key setup parameters for the waterjet barrier:

Nozzle:	No. 6530 Spread angle: 65° Aperture: 0.13 in. Vertical angle between jet and water surface: 10°
Operating Pressure:	See following text.
Height of Nozzles:	15-30cm
Spacing of Nozzles:	2.5-3m
Configuration of Waterjet Barriers:	"V" and "circle" as shown in Figures 1 and 2.

It was initially planned to operate the waterjet barrier at the same pressure used during previous laboratory tests (Phillips et al, 1987) and field deployment (e.g. Laperriere, 1985). The range of operating pressures tested in the laboratory by Phillips et al, 1987 was 6.9 to 20.7 mpa (1000 to 3000 psi). During a field deployment at Norman Wells, NWT, Laperrière, 1985 operated the waterjet barrier at 5.9 mpa (850 psi) and 9.0 mpa (1300 psi) in the deflection mode and at 9.7 mpa (1400 psi) in the collection mode.

During our tests, it was found that the operation of the waterjet barrier at pressures in excess of 6.9 mpa (1000 psi) caused a noticeable reduction in the extent of the flame which would have resulted in the eventual extinction of the flame. Furthermore, it was found that the oil became emulsified in the presence of the waterjet.

Consequently, it was decided to operate the waterjet barrier at lower pressure for our tests.

The maximum operating pressure for these tests ranged from 0.7 to 6.9mpa (100 to 1000 psi). These tests were conducted by instructing the technician operating the waterjet barrier to maximize the length of the burn. Efforts were made to operate the waterjet barrier at the pressure which provided maximum aeration of the flame. This was judged by the colour of the smoke and efforts were made to keep the smoke as clear as possible. When it was clear that the extent of the flame was being reduced by the jet, the pressure of the waterjet barrier was reduced and the flame was allowed to build. This sequence was repeated until the burn was complete and the flame was extinguished. Efforts were not made to relight the oil after the flame was extinguished.

As will be discussed, the opacity of the smoke was significantly affected by the operation of the waterjet barrier. Special care was taken to operate the waterjet barrier so that the aeration of the flame was maximized, and hence the density of the plume was minimized. Thus, the results of this test program can be expected to overestimate the probable reduction in smoke density that would be achieved in a field deployment.

Oil Properties Table 1 summarizes the available data to describe the properties of the oil used during the tests.

These properties were confirmed by Environment Canada who undertook analyses of oil samples collected during the test program.

TABLE 1
SUMMARY OF OIL PROPERTIES

Published Data by Gaiswinkler Enterprises Limited

Oil Type:	Ontario Light Crude Oil	
Oil Properties:	Specific gravity at 60°F	: 0.816
	A.P.I. gravity at 60°F	: 41.9
	Sulphur percent (by wt)	: 0.18
	Pour point	: 15°F
	Colour	: greenish black
	Carbon residue percent (by wt)	: 1.0
	Saybolt universal viscosity at 100°F	: 39 sec.

Results of Oil Analyses Undertaken by Environment Canada

Density	: 0.8234 g/cc
Viscosity at 60°F	: 5.8 cps

Environmental Conditions Efforts were made to conduct all of the tests in conditions of zero precipitation and low windspeeds.

Table 2 summarizes the environmental conditions for each test.

TABLE 2
SUMMARY OF ENVIRONMENTAL CONDITIONS

Test #	Air Temp. (°C)	Water Temp. (°C)	Ambient Windspeed (m/s)		Precipitation
			Avg.	Peak	
1	3.5	2.3	1.8	2.7	Nil
2	5.0	3.5	2.5	3.0	Nil
3	10.0	8.0	4.0	8.0	Nil
4	11.0	9.0	4.0	6.0	Nil
5	10.0	9.0	4.0	6.0	Nil
6	5.0	5.0	1.7	2.2	Nil
7	6.0	6.0	Nil	Nil	Nil
8	2.0	3.0	2.0	3.1	Nil
9	10.0	4.5	1.3	1.5	Nil
10	6.5	6.0	0.3	0.3	Nil
11	3.0	4.5	3.0	4.3	Nil
12	7.0	6.0	2.7	3.7	Nil

Test Matrix

The following parameters were systematically varied during the test program:

(a) the configuration of the waterjet barrier. Tests were carried out with the waterjet barrier deployed in a "V" and a circle as described earlier. Also, some tests were carried out without the waterjet barrier.

(b) the thickness of the oil slick.

(c) the containment provided to the oil slick. The oil slick was either **"contained"** in a 5m diameter ring or **"uncontained"**.

A total of 12 tests were carried out. The test matrix is summarized in Table 3.

TABLE 3
TEST MATRIX

Test #	Test Date	Mean Thick. of Oil Slick (mm)	Oil Slick Contained In Ring?	Waterjet Barrier Not Operating	Configuration "V"	Configuration Circle
1	Nov. 4	9.9	Yes		√	
2	Nov. 4	19.8	Yes		√	
3	Nov. 6	19.8	Yes	√		
4	Nov. 6	9.9	Yes	√		
5	Nov. 6	9.9	No	√		
6	Nov. 8	9.9	No		√	
7	Nov. 8	19.8	No		√	
8	Nov. 15	9.9	Yes			√
9	Nov. 15	19.8	Yes			√
10	Nov. 15	9.9	Yes			√
11	Nov. 16	9.9	No			√
12	Nov. 16	19.8	No			√

TEST RESULTS

Qualitative Description of the Tests

Test Without the Waterjet Barrier Tests 3, 4 and 5 were done with the waterjet barrier shut off. These tests were done to provide a baseline against which the effects of the waterjet barrier would be measured.

For Tests 3 and 4, the oil was contained in the ring, and hence, the burn was confined to the ring.

Test 5 was an uncontained test. However, the oil was herded by wind action to the end of the tank before it could be ignited. The estimated size of the slick at the time of ignition was $40m^2$ and the mean oil slick thickness was computed to be 5mm. After the oil slick was ignited, the burn was confined to the area initially occupied by the slick.

Each of these burns was very rapid (with a burn duration of 5-6 minutes) and produced a large amount of black, dense smoke. See Plate 4 for a typical burn.

Plate 4

Test #5

Plate 5

Test #2

Plate 6

Test #6

Plate 7

Test #8

Plate 8

Test #11

Plate 9

Test #12

Tests With the Waterjet Barrier in the "V" Configuration The oil was contained in the ring for Tests 1 and 2, while the oil was uncontained for Tests 6 and 7.

For the contained tests, the oil was placed inside the ring and ignited. The waterjet barrier was then activated which pushed the burning oil slick towards the outer edge of the ring. The burning oil slick was estimated to cover about two thirds of the area inside the ring after the waterjets were activated. These burns were of long duration (i.e. 36 and 82 minutes) and the waterjets produced a noticeable reduction in smoke opacity. Plate 5 shows a typical burn.

For the uncontained tests, the oil was placed inside the ring and ignited. The waterjet barrier was then activated and the containment ring was dropped to the bottom of the basin.

For these tests, the burning oil was pushed to the end of the basin by the waterjets. For Test 6, the burn was confined to an estimated area of $40m^2$. The mean oil slick thickness over this area was computed to be 5mm. See Plate 6. For Test 7, the containment ring was obstructed and did not drop cleanly to the bottom. This caused the oil slick to be more dispersed by the action of the waterjet (than was the case for Test 6). However, soon after the ring was dropped, the oil slick was pushed towards the outer ring of the basin and was contained there for the remainder of the burn.

The uncontained burns (i.e. Tests 6 and 7) were very similar to the uncontained burn conducted with the waterjet barrier shut off (i.e. Test 5). The duration of burns 6 and 7 was very short (i.e. 7 and 5 minutes respectively) in comparison to a burn duration of 5 minutes for Test 5. Furthermore, burns 6 and 7 produced a large amount of dense, black smoke, which appeared similar to that produced by burn 5. In general, it appeared that the influence of the waterjets on the burn was minor and that the main effect of the waterjets during these uncontained tests was to herd the oil towards the end of the basin. The edge of the oil slick was relatively distant from the waterjets (i.e. about 10m) and little turbulence was produced by the waterjets on the water surface immediately in front of the slick perimeter.

Tests With the Waterjet Barrier in the Circle Configuration The oil was contained in the ring for Tests 8 to 10, while the oil was uncontained for Tests 11 and 12.

For the contained tests, the oil was placed inside the ring and ignited. The waterjet barrier was then activated which pushed most of the burning oil slick towards the centre of the ring into a circular slick about 3m in diameter. However, some oil remained near the outer edges of the ring as it was not contacted by the waterjets. Eventually, the oil near the edge of the ring was moved to the centre area by the surface currents induced by the waterjets. See Plate 7 for a typical burn.

The flame in the central portion of the ring was aerated by the waterjets and the smoke was light-coloured. The oil which had remained near the edges of the ring burned with a noticeably denser, black smoke.

Emulsions were formed during these tests. There was an especially large amount of residue from Test 8 (i.e. 195% and 220% of the volume and weight of the spilled oil, respectively). Consequently, this test was repeated (as Test 10). However, for Test 10, the maximum operating pressure of the waterjet barrier was reduced to 0.7mpa (100 psi) from 2.1mpa (300 psi) for Test 8. This was found to reduce the residue somewhat. For Test 10, the weight and volume of the residue was 114% and 120% of that of the spilled oil, respectively.

The uncontained tests (i.e. Tests 11 and 12) were conducted by placing the oil in the ring, igniting the oil, activating the waterjet barrier, and then dropping the containment ring to the bottom of the basin. For these tests, some of the oil escaped past the waterjet barrier when the containment ring was dropped. The oil which escaped was contained by the outer ring of the basin. Most of it was eventually moved back inside the circular waterjet barrier by the surface currents produced by the waterjet barrier where it was burned.

Thus, the burn was comprised of oil that was inside the waterjet barrier, which produced smoke that was light-coloured, and oil that was beyond the waterjets, which produced dense, black smoke. See Plates 8 and 9.

Quantitative Test Results

Tables 4, 5 and 6 summarizes the quantitative data that were measured during the test program.

SUMMARY AND CONCLUSIONS

Summary

(i) Burn Efficiency:

(a) The operation of the waterjet barrier significantly increased the weight and volume of the residue (in comparison to tests done without the waterjet barrier). This is summarized below:

Oil Slick Contained in Ring?	Waterjet Barrier Configuration			Residue as a Percentage of the Spilled Oil	
	Not Operating	"V"	Circle	By Volume	By Weight
Yes	✓			11-25	10-22
No	✓			9	9
Yes		✓		16-67	15-61
No		✓		27-42	24-39
Yes			✓	37-195	39-220
No			✓	22-53	24-57

The operation of the waterjet barrier was found to produce turbulence on the water surface and to cause the formation of emulsions. This is believed to be the principal reason for the observed reduction in burn efficiency.

(b) During the tests, care was taken to operate the waterjet barrier to minimize the formation of emulsions as follows:

- The waterjet barrier was operated at relatively low pressures (i.e. a maximum of 0.7 to 6.9mpa over the duration of the tests). These pressures are significantly less than the pressure (of about 14mpa) that previous laboratory tests had shown to provide maximum oil slick retention capability without emulsifying the oil.
- For the tests in which the waterjet barrier was deployed in a circle and the oil slick was contained, the waterjets were set up to avoid direct impingement on the oil. The waterjets were positioned such that they just cleared the top of the containment ring.

TABLE 4
SUMMARY OF OIL BURN DATA

Test #	Maximum Operating Pressure of Waterjet Barrier (mpa)	Burn Duration (min.)	Flame Temperature (°C)
1	6.9 (1000 psi)	36	1290
2	2.8 (400 psi)	82	1260 - 1510
3	Waterjet Barrier Off	6	1350
4	Waterjet Barrier Off	5	1550
5	Waterjet Barrier Off	5	1500
6	4.8 (700 psi)	7	1200
7	6.9 (1000 psi)	5	1400
8	2.1 (300 psi)	10	1400
9	0.7 (100 psi)	28	1590
10	0.7 (100 psi)	12	1500
11	2.1 (300 psi)	30	1400
12	2.1 (300 psi)	34	1400

TABLE 5
SUMMARY OF OIL BURNING EFFICIENCIES

Test	Spilled Oil		Residue Remaining After Burn		Residue as a Percentage of the Spilled Oil		Moisture Content of Residue[4]	
#	Vol. (l)	Wt. (kg)	Vol. (l)	Wt. (kg)	By Volume	By Weight	% by weight	Maximum Variance
1	194	171	130	104	67	61	No data	
2	388	342	61	50	16	15	No data	
3	388	342	43	33	11	10	No data	
4	194	171	48	38	25	22	No data	
5	194	171	17	15	9	9	No data	
6	194	171	82[3]	66[3]	42[3]	39[3]	No data	
7	194	171	52[3]	41[3]	27[3]	24[3]	No data	
8	194	171	379[1]	376[1]	195[1]	220[1]	23	7
9	388	342	142	135	37	39	28	5
10	194	171	222[1]	219[1]	114[1]	128[1]	14	2
11	194	171	103[2]	97[2]	53[2]	57[2]	18	6
12	388	342	84[2]	83.5[2]	22[2]	24[2]	3	1

Notes:

1. Test 10 was a repetition of test 8. For test 10, the waterjet barrier was operated at a maximum of 100 psi (versus a maximum pressure of 300 psi for test 8).
2. These tests were **uncontained** with the waterjet barrier in a circle configuration. Oil escaped under the waterjet barrier and was contained by the outer ring. Some of the oil which escaped burned outside of the waterjet barrier. The remainder was moved back inside the waterjet barrier by the induced surface currents.
3. These tests were **uncontained** with the waterjet barrier in a "V" configuration. The oil was pushed by the waterjets to the end of the basin where it was contained by the outer ring. The estimated mean thickness of the oil slick at the start of the test was 5mm.
4. These oil analyses were undertaken by Environment Canada.

Table 6
Summary of Smoke Opacity Data

Test #	Luminance of Std. 18% Reflectance Gray Card		Illuminance (Foot-Lamberts)	Luminance of Smoke Plume		Reflectance of Smoke Plume (%)	Smoke Density[2]
	Spotmeter Rdg. (EV)	Luminance (Foot-Lamberts)		Spotmeter Rdg. (EV)	Luminance (Foot-Lamberts)		
1	10.2	46	256	10.5	60	23	4
2	9.0	21	117	8.0	10.5	9	5
3	12.3	210	1170	10.0	42	4	5
4	12.7	270	1500	9.5	30	2	5
5	14.0	670	3720	12.0	165	4	5
6	10.6	64	360	8.6	16.5	5	5
7	12.0	165	920	8.5	16	17	4-5
8	15.2	1450	8060	13.3	420	5	5
9	14.6	1000	5600	14.1-15.5[1]	700-1600	12-29	3-5
10	10.7	66	370	11.5	120	32	3-4
11	11.4	110	610	10-13[1]	41-330	7-54	2-5
12	13.5	460	2560	10.5-14.5[1]	60-900	2-35	3-5

Notes: 1. The smoke plume was alternately light and dark depending on the operation of the waterjet barrier.

2. See Figure 4 for definition of smoke density.

On the other hand, the tests were done on a relatively small scale. For a large burn in the field, the formation of emulsions (produced by the action of the waterjet barrier) is expected to be localized at the perimeter with the result that higher burn efficiencies may be achieved.
Thus, the results of this test program may underestimate the burn efficiencies that would be achieved in a field deployment.

(c) The burn efficiency increases significantly with the slick thickness. For the tests done with a mean slick thickness of 19.8mm, the weight and volume of the residue (expressed as a percentage of that of the spilled oil) was about one quarter of that left from the burns done with a mean slick thickness of 9.9mm.

(d) The weight and volume of the residue was increased when the waterjet barrier was deployed in a circle for the contained tests (in comparison to the "V" configuration). This is believed to reflect increased emulsification of the oil for the circle configuration.

(e) For the uncontained tests, the circle and "V" configurations produced residues that approximately equal in weight and volume. This is believed to reflect the fact that some of the oil escaped past the waterjet barrier in the circle configuration.

(f) The **uncontained** tests were not free from edge effects as the oil was contained by the outer ring of the basin. It is expected that the oil slick would have been more dispersed in a field deployment and that the burn efficiency would be lowered. This would cause these test results to overpredict the burn efficiency that would be achieved in a field deployment.

(ii) Smoke Opacity:

(a) The operation of the waterjet barrier was found to reduce the opacity of the smoke, as summarized below:

Oil Slick Contained in Ring?	Waterjet Barrier Configuration			Reflectance of Smoke Plume (%)	Smoke Density Level**
	Not Operating	"V"	Circle		
Yes	✓			2-4	5
No	✓			4	5
Yes		✓		9-23	4-5
No		✓		5-17	4-5
Yes			✓	5-32	3-5
No			✓	2-54	2-5

**Figure 4 for a definition of the "smoke density level".

(b) The results of this test program are expected to overestimate the probable reduction in smoke opacity that could be achieved by the use of the waterjet barrier in a field deployment as:
- special care was taken to operate the waterjet barrier to maximize the length of burn.
- the tests were done on a relatively small scale which allowed the waterjet barrier to provide relatively good aeration over the whole flame area.

Conclusions

The test program has provided data and observations for a preliminary assessment of the effect of a waterjet barrier on the burn efficiency of a floating oil slick.

The following conclusions are drawn from this test program:

(a) the operation of the waterjet barrier increased the volume and weight of the residue (in comparison to the tests done without the waterjet barrier) as it caused the formation of emulsions.

(b) the operation of the waterjet barrier reduced the opacity of the smoke.

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