600281141

USING COHERENT WATER JETS TO CONTROL OIL SPILLS

by

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Contract No. 68-03-2642

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report describes a tool developed at the EPA Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility to control oil slick movement. A high-pressure, coherent water stream was directed vertically into a body of water, causing a surface current that controlled movement of an oil slick. Several tests were performed to determine optimum effectiveness. Results of these tests as well as a theoretical analysis of the currents produced by the water jets are given. This report will be of interest to all those interested in controlling oil spills in inland and coastal waters. Further information may be obtained through the Resource Extraction and Handling Division, Oil and Hazardous Materials Spills Branch, Edison, New Jersey.

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ABSTRACT

The ability of coherent water streams to induce a surface current in a body of water and thus control a floating oil slick was examined in a number of test programs conducted at the U.S. Environmental Protection Agency (EPA) Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT). The objective of the tests was to determine whether coherent water streams could serve as an alternative to fabric booms and water sprays in concentrating, diverting, and containing oil slicks.

The water jets were constructed from standard commercial pipe fittings and supplied with water from off-the-shelf centrifugal water pumps. They were mounted on the main towing bridge, they were built into small floats which were angled across the direction of tow and extended from the bows of a simulated oil skimming catamaran. Currents of up to 6 kt were induced by towing the water jets from the main bridge down the test tank. Regular waves and harbor chop or confused sea conditions were developed by the tank's wave generator.

The tests showed that coherent jets could induce a significant surface current and move an oil slick with little oil entrainment. The non-breaking waves produced by the OHMSETT wave generator did not greatly affect performance except where the jet nozzles were cantilevered off the front of the catamaran and the pitch of the vessel caused significant changes in the height and attitude of the jet outlet. The best position for a fixed water jet of the sizes and at the pressures tested was determined to be vertically directed at the surface of the water with the outlet 0.4 to 1.0 m above the surface. These tests showed that the vertical forced component of a coherent water stream was as useful, if not more so, as the horizontal forced component. The performance of a water jet powered by a 30 kw electric motor/centrifugal pump system exceeded that of an air jet of compressed air (210 kPa) extended 0.6 m below the surface and supplied by a 50 kw gasoline-driven air compressor.

This report was submitted in fulfillment of Contract No. 68-03-2642 by Mason & Hanger-Silas Mason Co., Inc., Leonardo, New Jersey, under the sponsorship of the U.S. Environmental Protection Agency. This report covers the following six test periods: August 28 to September 1, 1978; October 30 to November 11, 1978; May 21 to June 1, 1979; July 2 to July 7, 1979; July 26 to July 27, 1979; and September 10 to September 14, 1979, when the work was completed.

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ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

cm	--centimeter
cm^2	--squared centimeter
e.g.	--for example
EPA	--Environmental Protection Agency
deg	--degrees
fwd	--forward
HC	--harbor chop
ht	--height
i.e.	--that is
ID	--inside diameter
IND	--indeterminant
kg	--kilogram
kPa	--kilopascals
kw	--kilowatts
kts	--knots
m	--meter
mm	--millimeter
no.	--number
Poly	--polypropylene
OHMSETT	--Oil and Hazardous Materials Simulated Environmental Test Tank
press	--pressure
sec	--seconds
thk	--thickness
u/w	--underwater
US	--United States
ZRV	--Zero Relative Velocity

SYMBOLS

10/20	--Descriptor of water jet nozzle orientation. The first number is the angle, in degrees, which the nozzle was tilted from the vertical in toward the centerline of the oil skimmer or catamaran. The second number is the angle, in degrees which the nozzle was tilted from the vertical forward in order to shoot the stream of water "upstream" of the system.
%	--percent

METRIC CONVERSION FACTORS

METRIC TO ENGLISH

To convert from	to	Multiply by
Celsius	degree Fahrenheit	$t_C = (t_F - 32)/1.8$
joule	erg	1.000 E+07
joule	foot-pound-force	7.374 E-01
kilogram	pound-mass (lbm avoir)	2.205 E+00
meter	foot	3.281 E+00
meter	inch	3.937 E+01
$meter^2$	$foot^2$	1.076 E+01
$meter^2$	$inch^2$	1.549 E+03
$meter^3$	gallon (U.S. liquid)	2.642 E+02
$meter^3$	liter	1.000 E+03
meter/second	foot/minute	1.969 E+02
meter/second	knot	1.944 E+00
$meter^2$/second	centistoke	1.000 E+06
$meter^3$/second	$foot^3$/minute	2.119 E+03
$meter^3$/second	gallon (U.S. liquid)/minute	1.587 E+04
newton	pound-force (lbf avoir)	2.248 E-01
watt	horsepower (550 ft lbf/s)	1.341 E-03

ENGLISH TO METRIC

centistoke	$meter^2$/second	1.000 E-06
degree Fahrenheit	Celsius	$t_C = (t_F - 32)/1.8$
erg	joule	1.000 E-07
foot	meter	3.048 E-01
$foot^2$	$meter^2$	9.290 E-02
foot/minute	meter/second	5.080 E-03
$foot^3$/minute	$meter^3$/second	4.719 E-04
foot-pound-force	joule	1.356 E+00
gallon (U.S. liquid)	$meter^3$	3.785 E-03
gallon (U.S. liquid)/minute	$meter^3$/second	6.309 E-05
horsepower (550 ft lbf/s)	watt	7.457 E+02
inch	meter	2.540 E-02
$inch^2$	$meter^2$	6.452 E-04
knot (international)	meter/second	5.144 E-01
liter	$meter^3$	1.000 E-03
pound force (lbf avoir)	newton	4.448 E+00
pound-mass (lbm avoir)	kilogram	4.535 E-01
psi	pascals	6.894 E+03

ACKNOWLEDGMENTS

The work of M.G. Johnson of Mason & Hanger-Silas Mason Co., Inc., in the development of the water jets and during the test programs described in this report contributed a great deal to the success of the U.S. EPA water jet program.

Dr. R.I. Hires, Dr. J.P. Breslin and Mr. D.T. Valentine are gratefully acknowledged for their work in developing the first theoretical analyses of water jets.[5,6,7]

Mr. J.S. Farlow, EPA Project Officer for OHMSETT, is gratefully acknowledged for his technical guidance throughout the test program.

SECTION 1

INTRODUCTION

Two factors that cause the cost of oil spill cleanup to soar are labor and expensive equipment inadequacy or failure. This report describes a method developed by the U.S. Environmental Protection Agency (EPA) that could reduce both of those costs: The use of a downward vertical coherent stream of water delivered from a high pressure source onto the body of water containing the oil spill. The result is a surface current away from the point of impact. The surface current induced can effectively control the movement of the oil slick. The device has been named the water jet.

The air-entraining properties of the water jet are what make it valuable to oil slick control. Once the air begins to bubble up to the surface water is brought with it. When a bubble reaches the surface, the displaced and entrained water dissipates radially outward from the burst bubble, forming a surface current. The entrainment of air and the turbulent nature of a water jet hitting a water surface is familiar to anyone who has washed dishes in a sink and turned up the water pressure to agitate the water and form soap bubbles.

A water jet can be constructed of common pipe and fittings using any of the many commercially available pumps to supply the water. Properly assembled and positioned, it can operate with minimal supervision and provide rugged installation to oil spill recovery work. Workboats and shipping may pass within a few feet of a float with a water jet without damaging the oil slick control system. In contrast, a fabric boom could be torn or sunk if a vessel were to sail into it. In all of the six test programs conducted by the EPA Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) (Appendix A), the only problems encountered were improperly assembled hoses that parted because of the pressure, the water pump losing prime after being shut down after a test, and an object being lodged in the nozzle of the water jet (e.g., a small rock that was in the hose that supplied the jet). All problems were corrected within minutes.

The technique of using streams and sprays of pressurized water to control oil slicks has been known for sometime. Reports on the use of fire hose streams to control oil slicks have been published by the U.S. government.[1,2] From a literature and patent search and from statements of experienced oil spill cleanup contractors and oil spill recovery equipment manufacturers, it was found that the horizontal velocity component of the water streams is used to create a surface current and move oil, while the vertical component is generally overlooked or directly declared to have no value.[2] The valuable vertical component of the coherent water jet is what this report is primarily concerned with.

A feasibility test to examine the usefulness of water jets as a substitute for a fabric transition piece between converging booms and a skimmer was conducted simultaneously with these tests and appears under a different cover.[3]

SECTION 2

EXPLANATION AND BASIC USES OF WATER JETS TO CONTROL OIL SLICKS

INTRODUCTION

The development of the water jet began as a method to increase the accuracy of testing oil spill control and recovery devices at OHMSETT. Primary to the operations at the OHMSETT facility is the ability to control oil slicks on the water's surface after they have been deployed from the oil distribution system so that the oil slick effectively enters the device being tested. The oil must be laid down on the water at a sufficient distance from the device to allow the oil to recover from the shock of being deployed from a moving source (the main bridge) onto the stationary water surface. Deploying the oil from the "upstream" side of the bridge is sufficient for the oil to form a fairly uniform layer before it contacts the test apparatus intake. However, the time between deployment and contact with the test device allows the oil to spread laterally. This spreading of the oil can cause some of the oil slick to pass around the test device's intake. Such a loss of oil must be estimated from visual observations and thus can be very subjective. These inexact observations can result in test data that show more than 100% throughput efficiency for an oil skimmer.

Several methods have been tried to control the width of an oil slick to conform to a device's intake dimensions. The use of rigid oil containment plates worked well at speeds to six knots in calm water and regular waves. However, when a harbor chop wave condition was encountered, the plates were subjected to side forces large enough to destroy their structural integrity. The use of a pair of flexible oil containment booms was somewhat more successful in harbor chop conditions, but even at low speeds in calm water the turbulence caused by the floatation members and attachment mechanisms of the booms could adversely affect the performance of the device being tested. Another method was the use of floating ropes to guide the oil to the test device. Braided rope and urethane foam-covered rope worked very well in calm water and waves at speeds to six knots (regular stranded rope tended to skid sideways on the water's surface in the direction that the strands were wound). However, with both the booms and the ropes insufficient tension could result in the fabric or rope buckling and folding and causing turbulence, while too much tension caused the rope or fabric to bridge the wave troughs and allow oil to escape beneath it.

The use of fire hoses to push oil to or away from objects or to clear areas ahead of an advancing skimmer has been used for years at OHMSETT and led to the concept of using water jets for guiding oil. Fire hose streams directed at the water surface, move oil primarily by two mechanisms. The first is a current formed by the impact of the high velocity water droplets from the fire hose stream transmitting their energy to the upper surface of the pool (horizontal component of water stream). A fire hose stream nearly parallel to the water's surface creates the highest velocity surface currents and a stream directed vertically into the pool produces minimum surface current by this mechanism. Such surface currents produced by fire hose streams cease almost immediately (within about ten seconds) if the fire hose stream is removed from the point of impact. The second major mechanism, and most important for this report was the surface current produced by rising bubbles of air which are entrained in the water column by the impact of the fire hose stream on the pool surface (vertical component of water stream). Air will be entrained to a minimum depth with a fire hose stream directed nearly parallel to the pool surface while air will be entrained to a maximum depth with the stream directed vertically into the water. Such a surface current will continue to be produced after the fire hose stream is removed due to the many small bubbles which were driven into the water column and rise very slowly. The resulting low velocity, enduring current can control an oil slick for a while after the water jet has moved on. The length of time the current exists depends upon the amount of air entrained and the depth to which it was driven. The tests at OHMSETT indicate that a strong jet can produce a current which can endure for more than 60 seconds.

There are two primary phenomena which contribute to the success of a water jet (Figure 1). The first (Phase I) is the current initiated by the the outward splatter of the water stream when it contacts the body of water. This action is instrumental in preventing oil from being hit by the water jet and subsequently entrained into the water column. A moving jet creates a slight elevation in water level directly in front of the impact point. The outward splatter and slight surface elevation combine to create a mechanism which parts an oil slick directly forward of the impact point of a moving water jet. The second phenomenon (Phase II) is produced by the air which is entrained in the water by the jet (Figure 2). A current is produced by the rising bubbles, which displace water from on top of them and draw water with them as they travel to the surface. When they reach the surface, they push the last layer of water out of the way and then burst. The water following the bubble continues to the surface and dissipates radially. The larger bubbles rise first and fastest and produce a strong initial current. The smaller bubbles rise slowly and maintain the surface current even after the water jet has been removed from the area. A turbulent interaction between jet and water body is important to produce a large number of small bubbles in order to maintain the oil slick in a desired location (Figure 3). A stationary water jet will develop a "crater wall" surrounding the impact point due to the bubbles trying to rise directly up into the jet (Figures 4 and 5).

A third oil moving mechanism is produced only by a moving water jet, or a jet in a current. This is a wave train of rolling, breaking waves not unlike those produced by a vertical solid staff towed through a body of water. These waves give an initial push to the oil by rolling it to the side of the path of the water jet. Each water jet produces two of these waves. The first is developed as a bow wave originating at the point of impact. The second is developed at the point where the water surface rises up behind the jet directly aft of the impact depression (Figure 6). It has been observed that some oil entrainment results from the turbulence produced by these waves but it is not much since these waves seldom exceed 2 cm in height. Besides, the rising bubbles aid in bringing any entrained oil to the surface quickly.

The work presented in this chapter shows the ability of water jets to effectively move an oil slick in all wave conditions at high speeds without significantly entraining oil. Although originally intended to prove the feasibility of using water jets to control oil slicks for testing, the project was expanded to investigate the use of water jets to

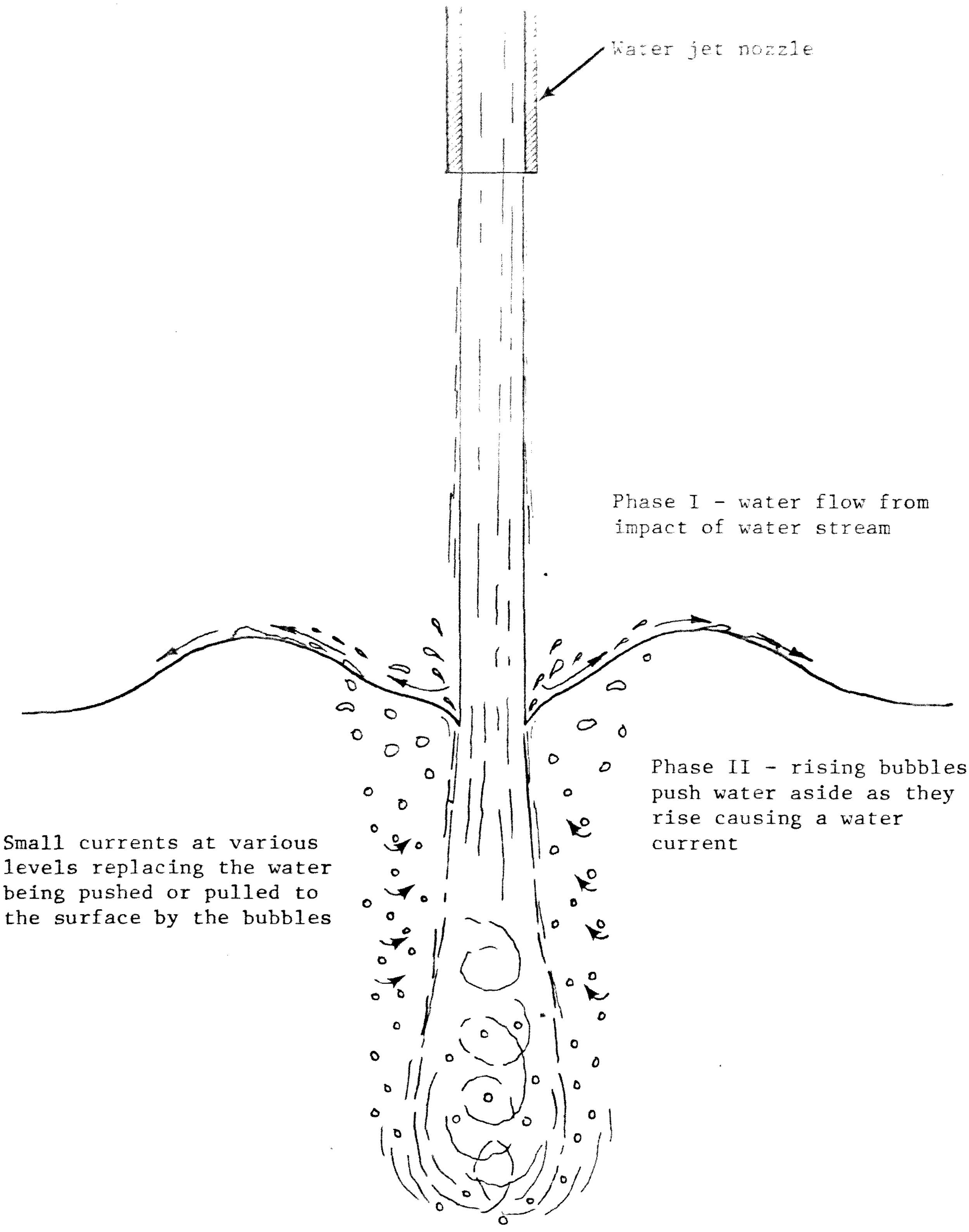
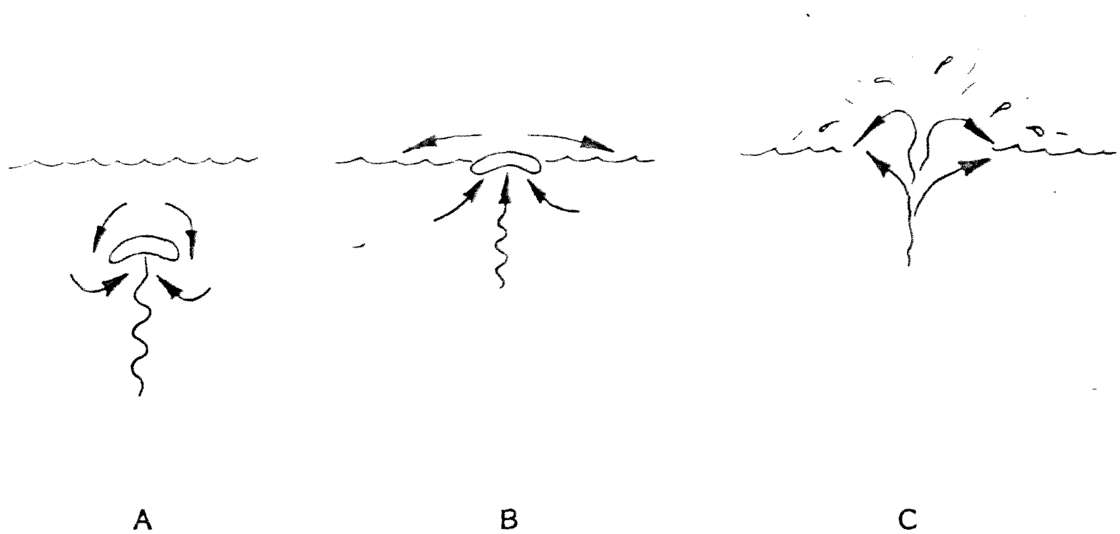


Figure 1. Section view of water jet action.



A. As air bubble rises water is pushed from on top and entrained behind.

B. As bubble reaches the surface the last water layer is pushed radially outward in the surface.

C. As the bubble bursts the water entrained beneath it is carried to the surface and also radially dissipated.

Figure 2. Single air bubble rising to the water's surface.

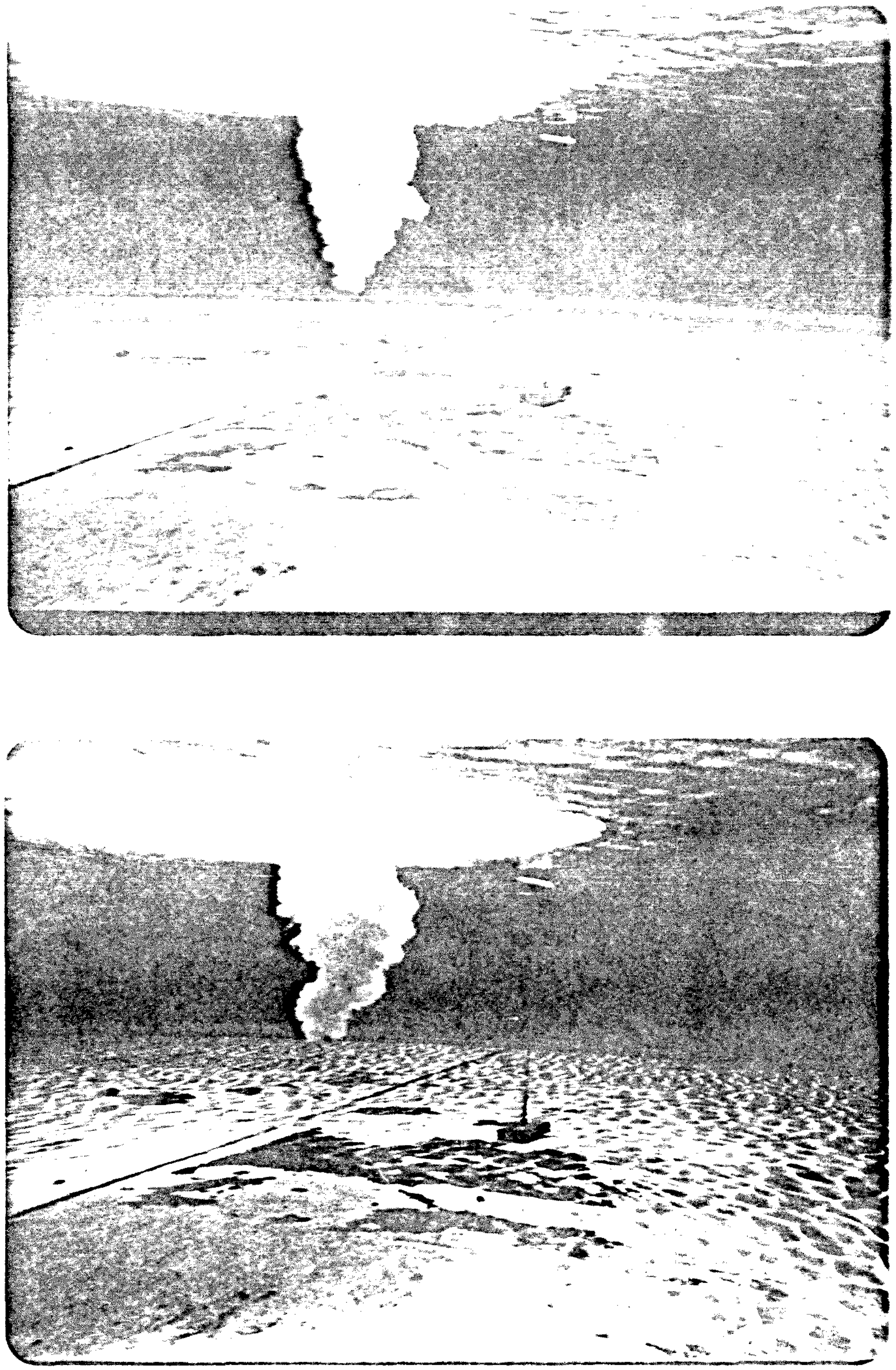


Figure 3. An underwater view of a time lapse sequence of a stationary water jet.

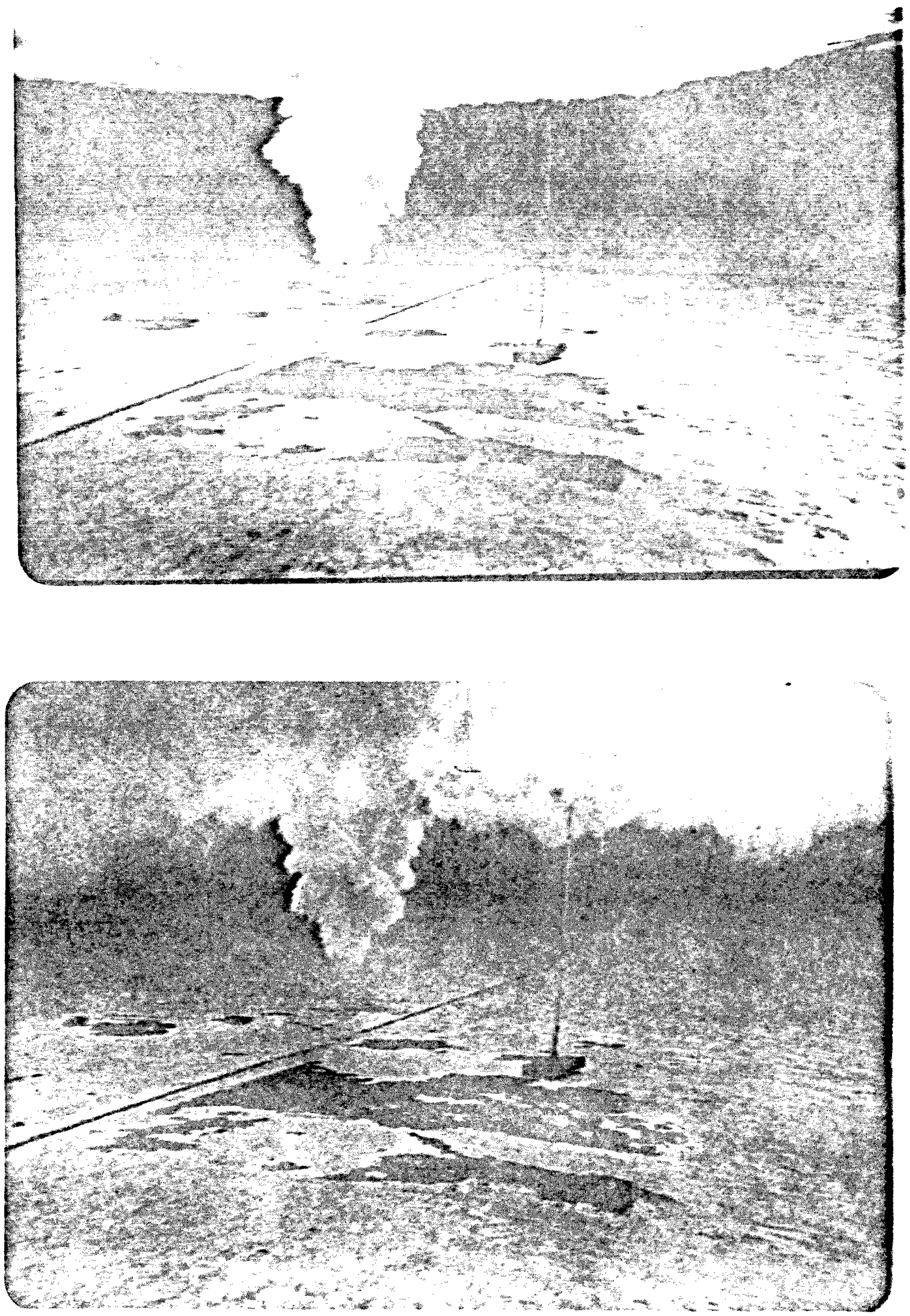


Figure 3. Continued.

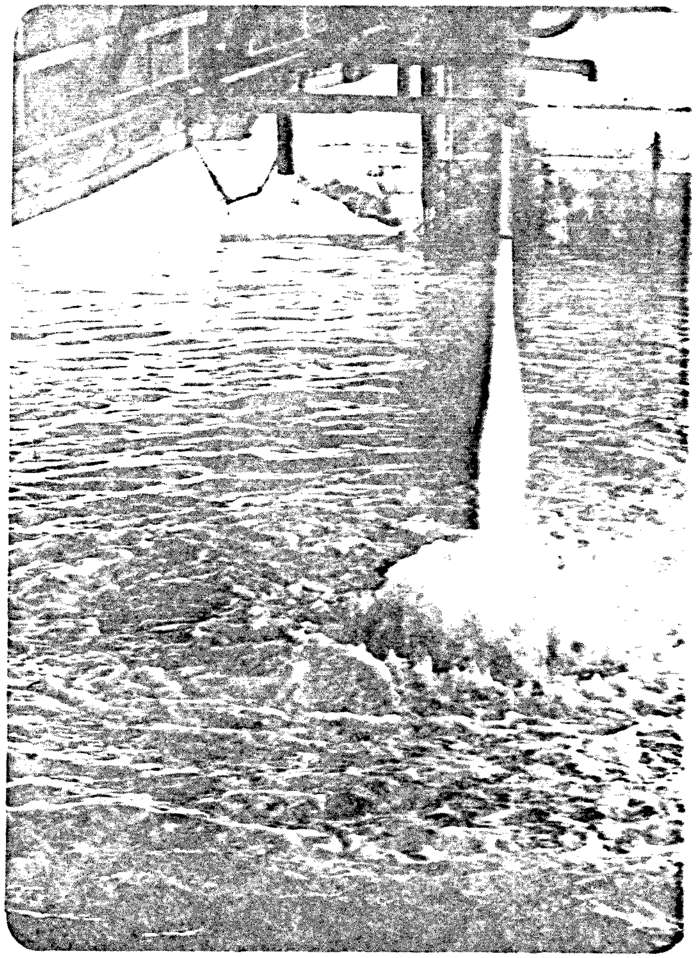


Figure 4. Stationary water jet--side view.

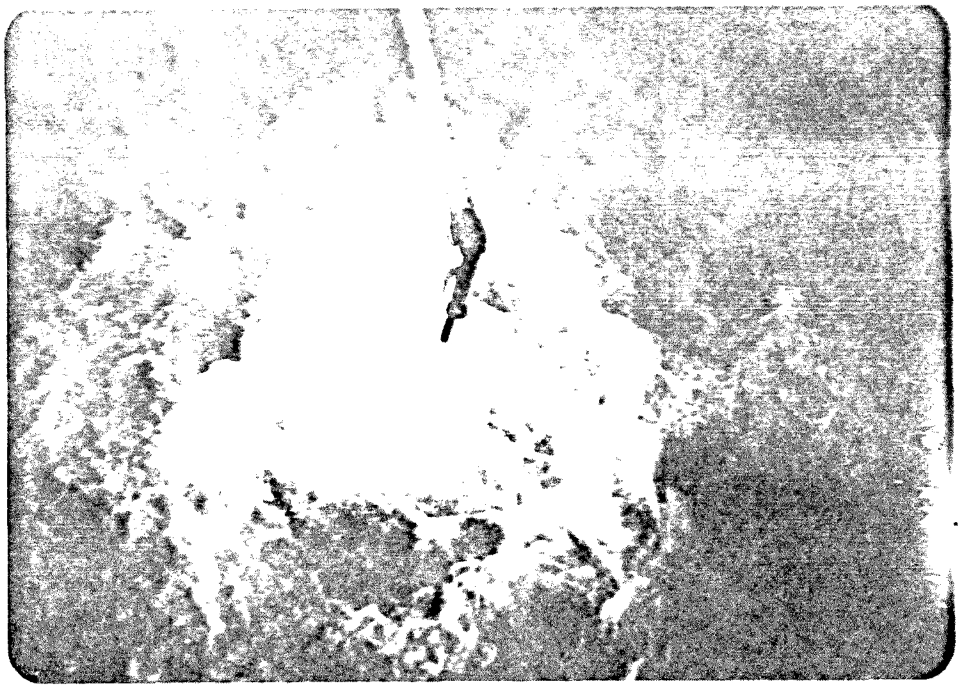


Figure 5. Stationary water jet--top view.

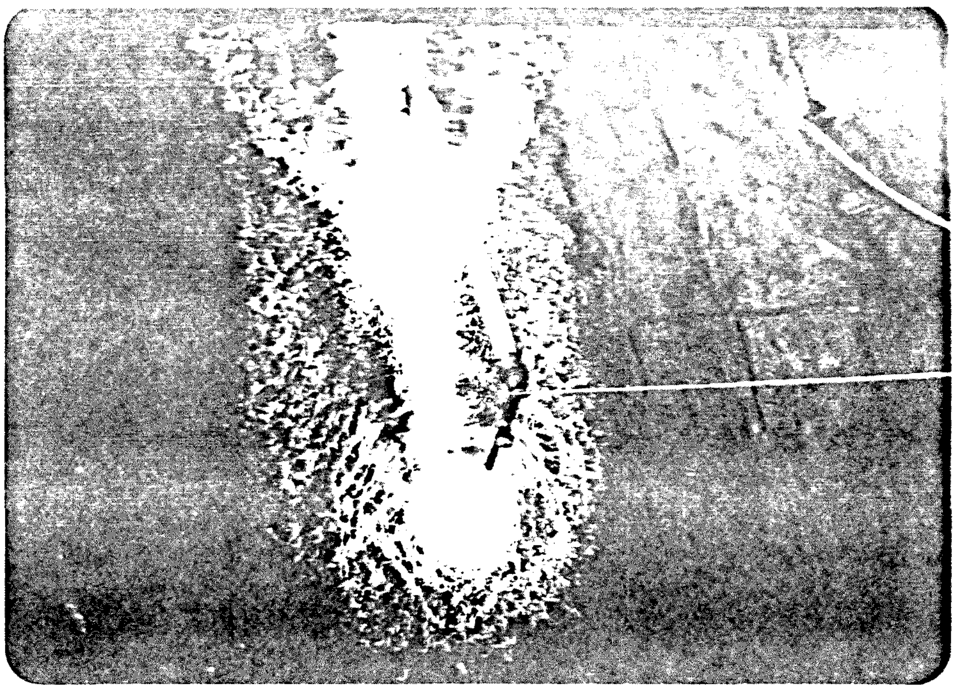


Figure 6. Moving water jet exhibiting characteristic wave train.

converge a wide, thin slick into a narrow, thick one. Problems encountered by trying to use fabric oil boom to converge oil slicks during recovery operations have proved it to be an expensive and low speed operation. If water jets could be substituted for the boom the operation could be simplified and sped up.

CONCLUSIONS

Vertically directed water jets proved capable of moving and restraining an oil slick on the surface of water at speeds up to 6 kt and in wave conditions (up to 1.2 m wave height).

Despite the turbulence produced by a water jet when plunging into the water's surface, a relatively high current and thick oil slick need be present before a substantial amount of oil can penetrate the crater produced by the jet and be entrained beneath the water stream. Very little oil entrainment was noticed even with the thickest slick (5 mm) tested at a tow speed of six knots.

The bow waves produced by the passage of the water jet helped to move the oil initially. Some oil is entrained by the bow waves and wake produced by the jet, but the oil remains near the surface and rises quickly as it is moved with the currents produced by the rising bubbles.

When converging an oil slick, sufficient time must be allowed after the water jet passes an area to enable the surface current to fully develop and to move the oil slick before an oil skimmer can most effectively encounter the thickened slick. This could be anywhere from 3 to 60 seconds depending upon the desired convergence.

Three millimeter thick oil slicks were not moved as easily as 1-mm thin oil slicks.

The best performance of the converging water jet arrangement was obtained using two and three pairs of jets at a high pressure. At six knots a 4.5 m wide, 1.08 mm thick slick was converged to a 0.6 m wide, 8.1 mm thick slick in 10 seconds. These results are most probably not the maximum attainable using three pairs of jets. Since the first pair of jets were positioned wide and forward of the oil slick their full effectiveness was not utilized.

From the single jet tests it was found that the most effective performance occurred at the highest pressures with the largest nozzle at low tow speeds and at a nozzle exit height of 0.4 to 1.0 m above the water's surface.

The water jet system performed well and was free from major breakdowns throughout the test program. However, a slight burr on the inside of a nozzle could cause the water stream to lose coherence and spray more. The penetrating and air entraining power of the jet is thus diminished and subsequently oil slick movement performance decreases. Pipes and nozzles should be checked for imperfections and rocks and other foreign matter should be removed from the hoses before assembly.

RECOMMENDATIONS

Given the problems encountered with the other methods of controlling an oil slick for test purposes at OHMSETT, it is recommended that water jets be used until a better method is found.

Prior to employing a water jet system to move oil on water the system should be examined for burrs on the insides of the nozzles and foreign objects (e.g., small rocks) in the piping. Any flow disturbance decreases the jet efficiency.

Methods to increase air entrainment by the jets should be investigated. Increasing the cohesiveness of the water stream via nozzle design, air injection into the nozzle before the outlet, or screening over the exit of the nozzle are a few ideas which warrant investigation.

TEST DESCRIPTION

Equipment Arrangement

The equipment set up for the first test series (slick convergence) consisted of three pairs of nozzles mounted on the main bridge so as to direct a stream of water straight down into the water for maximum air entrainment (Figure 7). The nozzles were 20 cm long, 1.6 cm ID bronze pipe nipples cut and trimmed to present a clean, squared exit for minimum water stream spread.

The first pair of nozzles (No. 1 and 2) were placed on either side of the 4.5 m distribution manifold each 0.75 m outboard and 0.75 m upstream from the distribution manifold. The purpose of the upstream placement was to ensure a minimum of entrainment of the Circo 4X light oil used throughout the entire test series. Since this was the first of a series of tests, it was not known that the jets could have been positioned closer to the slick without causing severe entrainment. The light oil was chosen due to its low viscosity which allows it to spread faster than any other oil used in the standardized test procedures of OHMSETT (Appendix B).

The second pair of nozzles (No. 3 and 4) were placed 3.6 m north (downstream) of the first pair and 4.5 m apart. A third pair of nozzles (No. 5 and 6) were deployed from the north side (downstream) side of the main bridge 4.5 m apart and 3.8 m downstream from the second pair of jets. All jet nozzle exits were positioned 1.8 m above the water surface.

Markers were trailed in the water at 15 and 30 m from the oil distribution point for reference locations (Figure 8). At 15 m a length of small diameter conduit with streamers tied every 0.3 m was suspended above the water's surface to serve as a slick width reference device. At 30 m two floats, 4.5 m apart, were trailed from the auxiliary bridge. A Polaroid camera mounted on the auxiliary bridge recorded the slick width at both marker locations.

Water to the jets and oil for the slick were delivered by standard OHMSETT equipment. The pump used to supply water to the jets was the main bridge fire pump. This pump is capable of delivering 111 m^3/hr at 700 kPa. A maximum pressure of 420 kPa could be obtained with all six jets in operations. The oil distribution system used

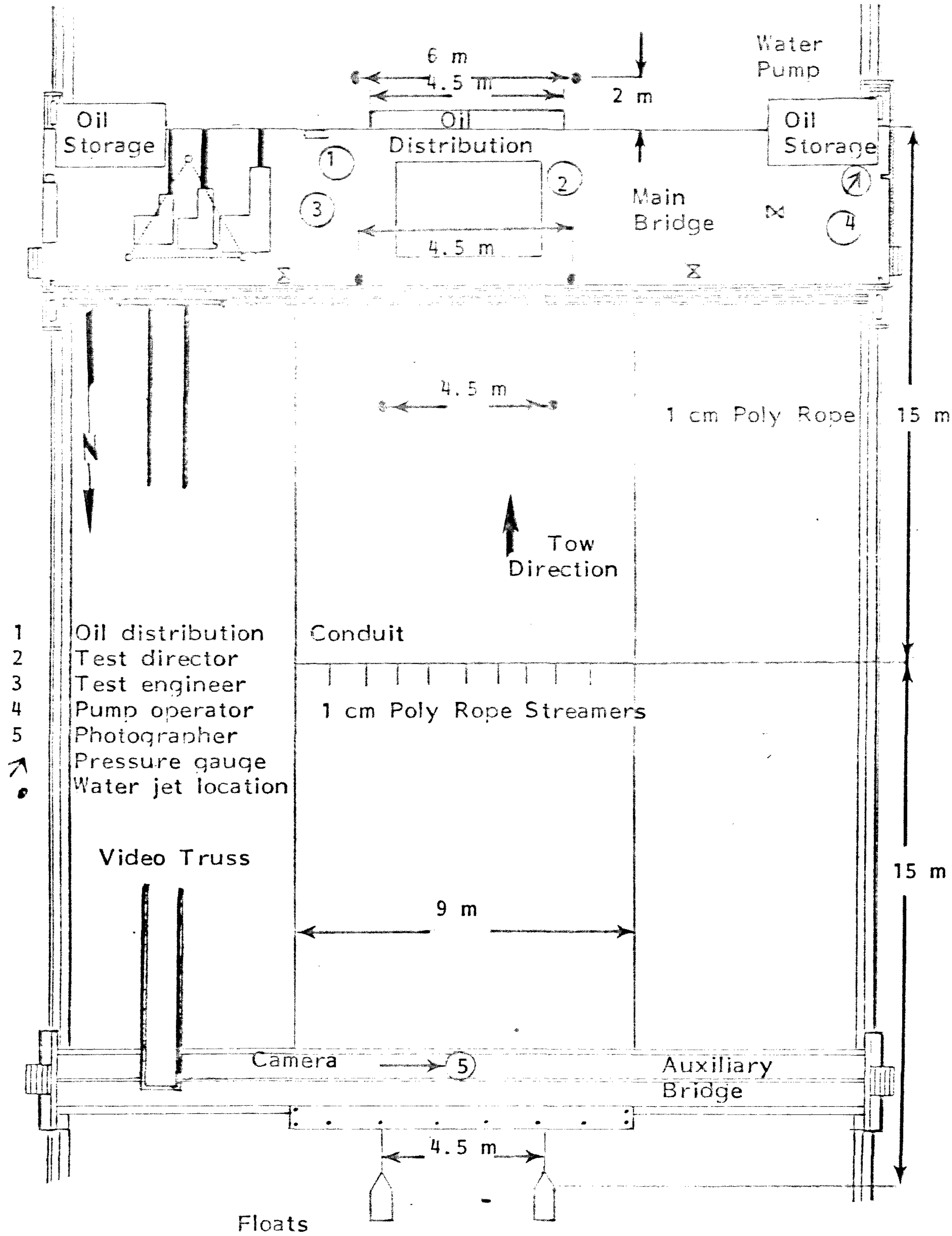


Figure 7. Test set up for oil slick convergence tests.

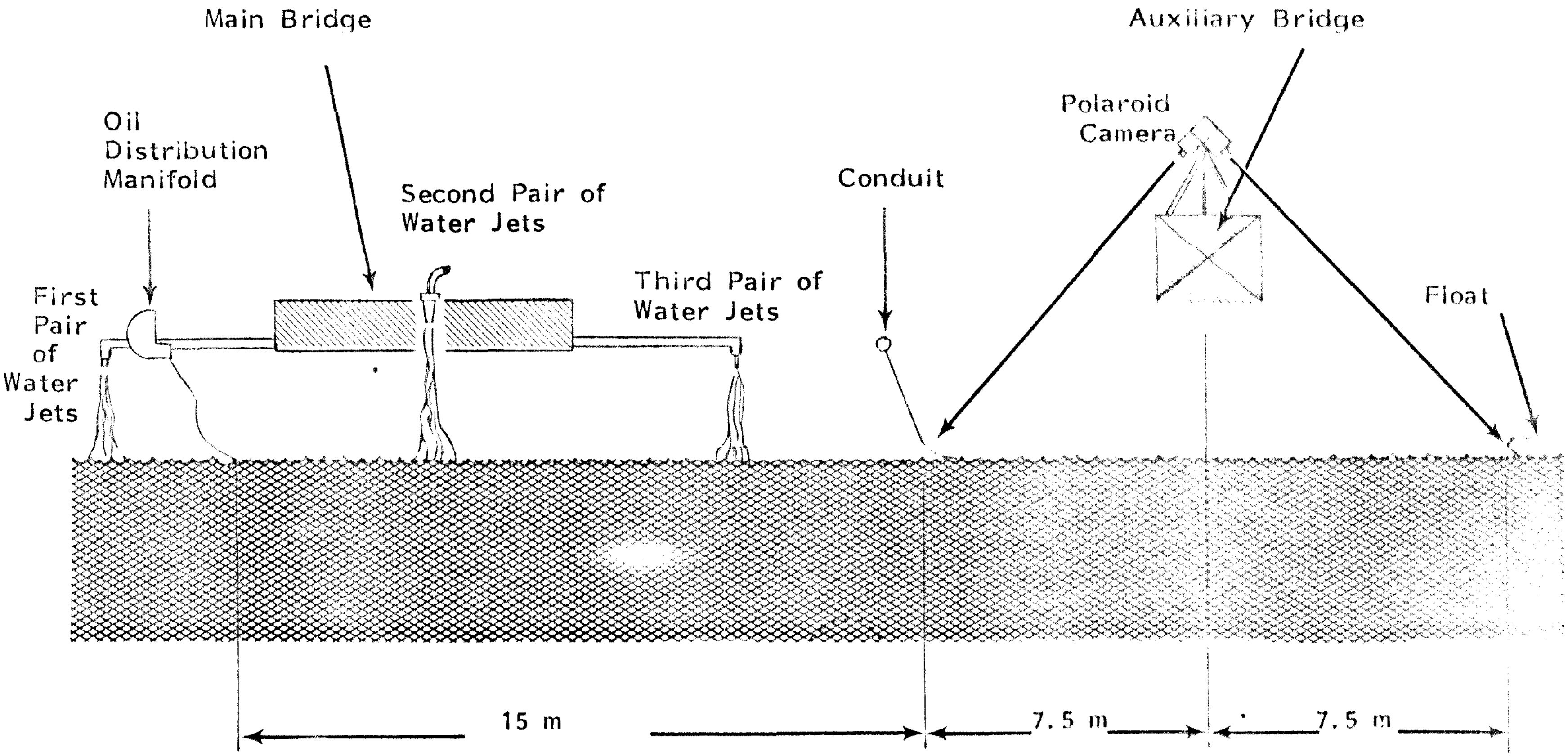


Figure 8. Section view of convergence test set up.

was a 4.5 m wide, three section manifold with splashplate and laydown membrane utilized in many of the tests conducted at OHMSETT to date.

The second series of tests used one nozzle mounted in the center of the north side of the main bridge to split an oil slick (Figures 9 and 10). This test was designed to eliminate confusion caused by interferences to slick movement such as wind and opposing currents generated by other water jets. The same water pump was used as in the previous tests. With only one nozzle being used 560 kPa of pressure could be developed. Both 2.1 cm and 2.7 cm diameter nozzles were tested to compare the relative effect on oil slick movement. The nozzle height was fixed at 0.8 m above the water's surface. Two small wooden beams were assembled at right angles to each other to form a sighting tool (Figure 11) to monitor the oil slick movement. The lower piece was held against a rail which ran the length of the main bridge while the operator sighted oversights on the upper piece at the edge of the oil slick. The location of this inside edge of the parted slick was thus tracked.

The test arrangement for the third series of tests was like that of the second series but added the ability to change the height of the nozzle from the water's surface. A 2.1 cm ID nozzle was used for these water jet tests and also for one test using compressed air released beneath the water's surface.

TEST PROCEDURES

The tests were so arranged as to determine the effects that various parameters have upon oil slick movement. The independent variables consisted of tow speed, wave condition, number of water jets, water jet pressure, nozzle size and height above the water, and oil slick thickness. The dependent variable was oil slick movement.

The tests conducted for the convergence tests were run according to the test matrix (Table 1). Basically the tests consisted of the following:

1. Control tests in which a 4.5 m wide slick of 1, 2, and 3 mm was deployed at 2, 4, and 6 knots to check the actual spread of the oil without water jets.

2. Tests with 2, 4, and 6 water jet nozzles used at different tow speeds and pressures on oil slicks of different thicknesses.

Preparations for a test run consisted of setting the oil flow to the rate needed for a particular slick thickness at the test speed, placing in operation the desired number of nozzles and adjusting valves to obtain the desired water pressure. The bridge was then brought up to speed and oil distribution begun. When the slick reached the 15 m marker the first picture was taken. The bridge speed was maintained while the photographer swiveled the camera for a shot of the slick at the 30 m marker. After the second photo was taken, the oil distribution was stopped, the fire pump was secured, and the bridge was brought to a stop. The skimmer booms were lowered to skim the oil back to the north end of the tank. The photographs taken during a test were examined and data recorded during the time the oil was skimmed.

The nature of the second and third test series necessitated that other matrices (Tables 2 and 3) and test procedures be developed. It was necessary to continuously

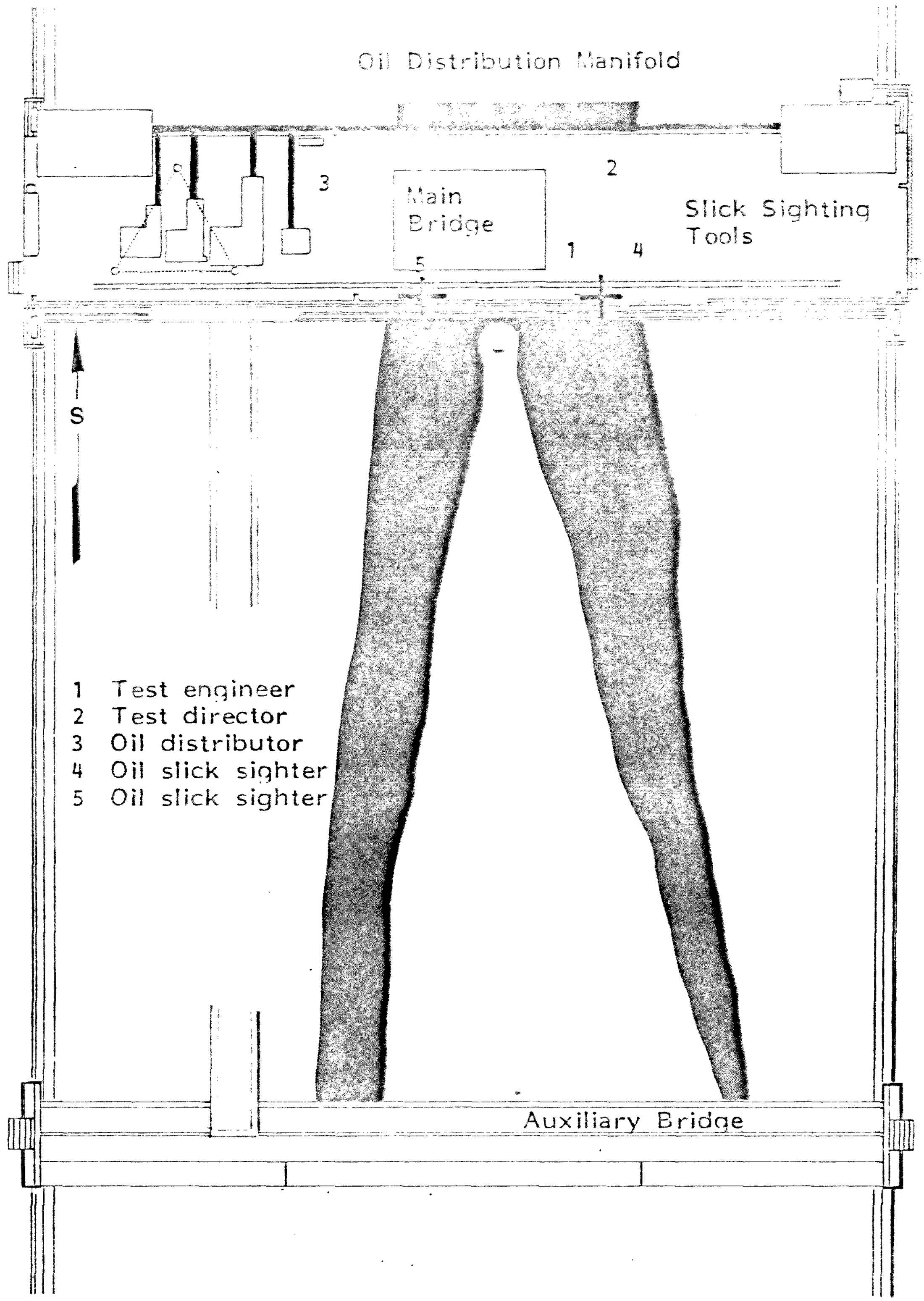


Figure 9. Test set up for single water jet test, slick parting tests.

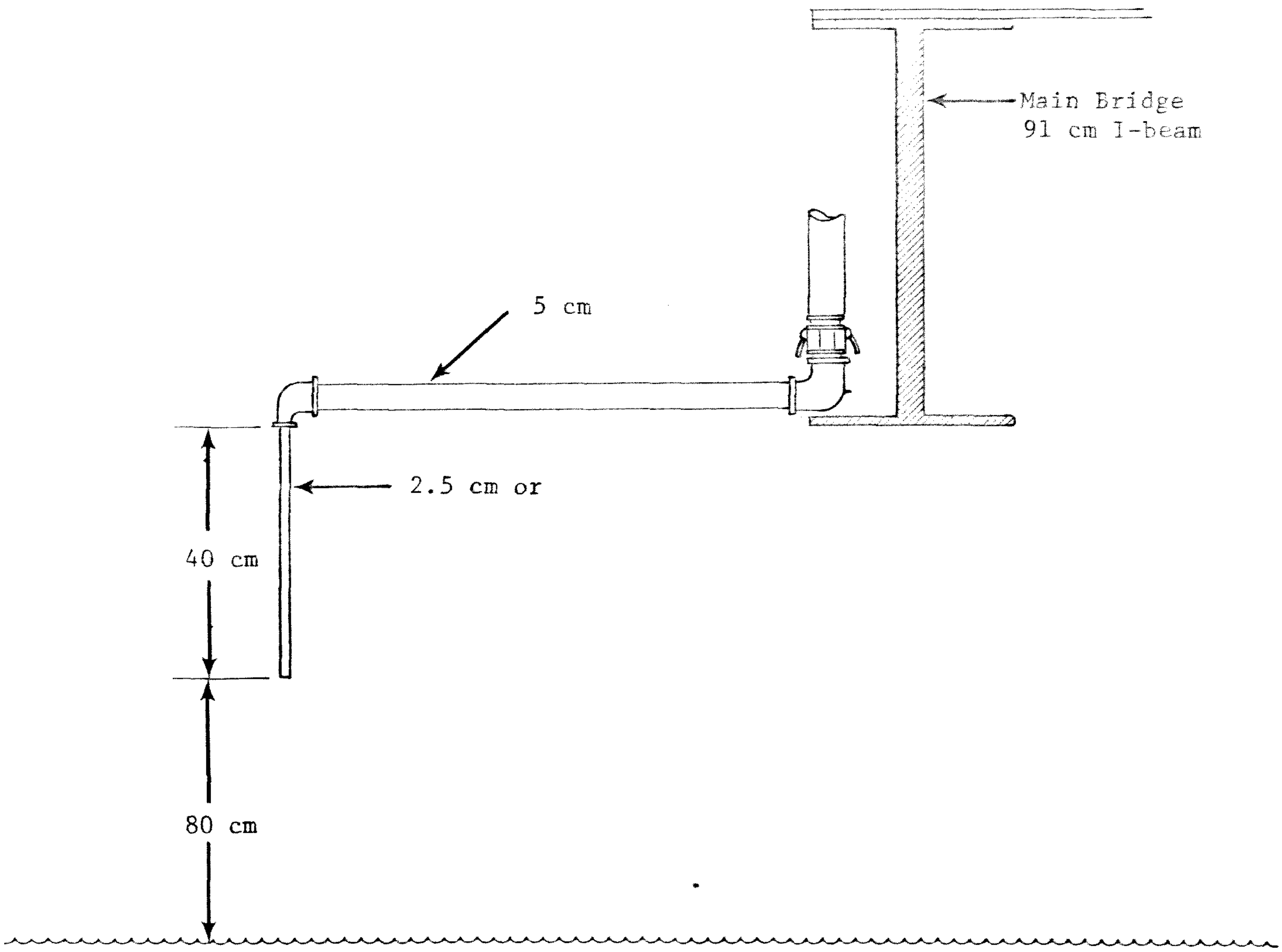


Figure 10. Water jet nozzle mounted on the main bridge.

Figure 11. M.G. Johnson holding an OHMSETT oil slick sighter.

TABLE 1. MATRIX FOR SLICK CONVERGENCE TESTS

Test no.	Tow speed (kts)	Slick thk. (mm)	Number of nozzles	Pressure (kPa)	Wave (mxm)
1	2	1.0	0	0	Calm
2	4	1.0	0	0	Calm
3	6	1.0	0	0	Calm
4	2	2.0	0	0	Calm
5	4	2.0	0	0	Calm
6	6	2.0	0	0	Calm
7	2	3.0	0	0	Calm
8	4	3.0	0	0	Calm
9	6	3.0	0	0	Calm
10	2	1.0	0	0	0.6 m HC
11	4	1.0	0	0	0.6 m HC
12	6	1.0	0	0	0.6 m HC
13	2	2.0	0	0	0.6 m HC
14	4	2.0	0	0	0.6 m HC
15	6	2.0	0	0	0.6 m HC
16	2	3.0	0	0	0.6 m HC
17	4	3.0	0	0	0.6 m HC
18	6	3.0	0	0	0.6 m HC
19	2	1.0	2	70	Calm
20	2	1.0	4	70	Calm
21	2	1.0	6	70	Calm
22	4	1.0	2	140	Calm
23	4	1.0	4	140	Calm
24	4	1.0	6	140	Calm
25	6	1.0	2	280	Calm
26	6	1.0	4	280	Calm
27	6	1.0	6	280	Calm
28	2	1.0	2	70	0.6 m HC
29	2	1.0	4	70	0.6 m HC
30	2	1.0	6	70	0.6 m HC
31	4	1.0	2	140	0.6 m HC
32	4	1.0	4	140	0.6 m HC
33	4	1.0	6	140	0.6 m HC
34	6	1.0	2	280	0.6 m HC
35	6	1.0	4	280	0.6 m HC
36	6	1.0	6	280	0.6 m HC
37	4	1.0	6	70	Calm
38	4	1.0	6	280	Calm
39	4	1.0	6	420	Calm
40	4	2.0	6	70	Calm
41	4	2.0	6	140	Calm
42	4	2.0	6	280	Calm
43	4	2.0	6	420	Calm

TABLE 2. MATRIX FOR SLICK DIVERGENCE TESTS

Test no.	Tow speed (kts)	Slick thk. (mm)	Nozzle I.D. (cm)	Pressure kPa	Wave (mm)
1	2 to 6	1.0	2.1	0	Calm
2	2	1.0	2.1	140	Calm
3	2	1.0	2.1	280	Calm
4	2	1.0	2.1	560	Calm
5	4	1.0	2.1	140	Calm
6	4	1.0	2.1	280	Calm
7	4	1.0	2.1	560	Calm
8	6	1.0	2.1	140	Calm
9	6	1.0	2.1	280	Calm
10	6	1.0	2.1	560	Calm
11	2	1.0	2.7	140	Calm
12	2	1.0	2.7	280	Calm
13	2	1.0	2.7	560	Calm
14	4	1.0	2.7	140	Calm
15	4	1.0	2.7	280	Calm
16	4	1.0	2.7	560	Calm
17	6	1.0	2.7	140	Calm
18	6	1.0	2.7	280	Calm
19	6	1.0	2.7	560	Calm
20	2 to 6	3.0	2.7	0	Calm
21	2	3.0	2.7	280	Calm
22	4	3.0	2.7	280	Calm
23	6	3.0	2.7	280	Calm
24	2 to 6	1.0	2.7	0	0.5x12.1
25	2	1.0	2.7	560	0.5x12.1
26	4	1.0	2.7	560	0.5x12.1
27	6	1.0	2.7	560	0.5x12.1
28	2 to 6	1.0	2.7	0	1.2 m HC
29	2	1.0	2.7	280	1.2 m HC
30	4	1.0	2.7	280	1.2 m HC
31	6	1.0	2.7	280	1.2 m HC
32	2	1.0	2.7	560	1.2 m HC
33	4	1.0	2.7	560	1.2 m HC
34	6	1.0	2.7	560	1.2 m HC

TABLE 3. TEST MATRIX FOR WATER JET HEIGHT EFFECTS

Test no.	Tow speed (kts)	Nozzle I.D. (cm)	Pressure (kPa)	Slick thk. (mm)	Nozzle height (m)	Wave
1	4	2.1	560	1.0	0.6	Calm
2	6	2.1	560	1.0	1.8	Calm
3	4	2.1	560	1.0	1.8	Calm
4	6	2.1	560	1.0	0.6	Calm
5	4	2.1	560	1.0	0.3	Calm
6	6	2.1	560	1.0	0.3	Calm

monitor the movement of the oil slick. Towing markers was impractical because the slick was to be observed for one minute and a large number of markers would have been needed. Besides, the markers would have been too far from the bridge to be photographed well. Time constraints prevented gridding the tank with small anchored floats to be used a references. The slick was monitored using the simply constructed sighting apparatus described earlier. Two sighting boards were slid along the rail on the main bridge until the operators were lined up with the inside edge of the slick they were following. Every 15 seconds, for one minute, a position reading was taken from both of the sight board operators. The water jet nozzle was mounted in the center of the main bridge so the readings indicated how far the slick was split on either side of the jet. The original test plan was designed to move the water jet down one side of the oil slick, but wind would have biased the readings.

DISCUSSION OF RESULTS

The tests were successful in revealing how the independent parameters tested effect water jet performance. The graphs presented herein were developed from the tabulated test results (Tables 4, 5, and 6). Direct comparison of slick movement between the convergence tests and oil slick parting tests is difficult. Oil movement in the convergency tests was less than that recorded during the slick parting tests due to the opposing currents developed by the pairs of jets and the build up of oil between them. Other causes for the different results were the longer pipe nozzles used in the slick parting tests and the difference in height from the water of the nozzles. The longer pipe (length greater than 15 ID) resulted in a more coherent water stream being delivered. Such a water stream entrained air well without the jet splattering onto the oil slick and thereby entraining oil. A coherent water jet of the size and at the pressure tested performed best at a height of 0.4 to 1.0 m above the water's surface. The parting slick tests had the nozzle heights within this preferred range while the convergence slick tests had nozzle heights above 1.0 m. However, general effects of the independent variables can be qualitatively compared between the tests. In this regard the convergent and divergent tests can be discussed together. The graphs which depict the effects of the parameters are clearly labeled as to which tests they pertain to.

The oil slick sighters were tested against known widths of 5 m over a 30 m distance and resulted in accuracy within 0.3 m. Data for the slick convergence tests were taken from Polaroid pictures. The accuracy of this method was about the same.

The effects of the independent parameters on oil slick movement are discussed individually.

Tow Speed

The time required to part a slick a given distance was inversely proportional to the tow speed using the same water jet, (Figure 12). If a water jet parted a slick 3 m in 15 seconds when run at 2 kts, the same jet would require 30 seconds to part the slick 3 m at 4 kts. This generally held for the slick convergence tests until interaction occurred between the jets on either side of the slick (Figure 13). Such a relationship would probably break down for smaller water jets and faster tow speeds. Surface tension effects would probably cause a small water jet to splatter somewhat upon impact rather than penetrate and entrain air.

TABLE 4A. CONTROL TESTS, 29 AUGUST 1978, CALM WATER (SLICK CONVERGENCE TESTS)

Test no.	Speed (kts)	Slick thick @ 0 m (mm)	Slick width @15 m (m)	Slick width @30 m (m)	% Expan @15 m	% Expan @30 m	Slick thick @15 m (mm)	Slick thick @30 m (mm)
31	2	1.21	4.8	6.06	7	33	1.13	0.91
32	4	1.20	4.8	5.75	7	27	1.13	0.95
33	6	0.95	4.8	5.15	7	13	0.89	0.84
34	2	2.40	5.75	6.66	27	47	1.89	1.64
35	4	2.16	5.45	6.06	20	33	1.80	1.62
36	6	2.16			CAMERA MALFUNCTION			
36R	6	2.21	5.15	5.45	13	17	1.95	1.84
37	2	3.24	6.06	7.27	33	60	2.43	2.03
38	4	3.29	6.06	6.96	33	53	2.47	2.15
39	6	3.09	6.06	6.36	33	40	2.32	2.21
39R	6	3.12	6.06	6.36	33	40	2.34	2.23

TABLE 4B. CONTROL TESTS, 31 AUGUST 1978, 0.6 m HARBOR CHOP (SLICK CONVERGENCE TESTS)

Test no.	Speed (kts)	Slick thick @ 0 m (mm)	Slick width @15 m (m)	Slick width @30 m (m)	% Expan @15 m	% Expan @30 m	Slick thick @15 m (mm)	Slick thick @30 m (mm)
40	2	1.27	5.15	5.75	13	27	1.12	1.00
41	4	1.02	4.8	5.15	7	13	0.96	0.90
42	6	0.97	4.8	4.8	7	7	0.91	0.91
43	2	2.04	5.15	5.45	13	20	1.80	1.70
44	4	1.62	4.54	6.66	0	47	1.62	1.10
45	6	2.11	6.06	5.45	33	20	1.58	1.76
46	2	3.23	6.66	6.06	47	33	2.20	2.42
47	4	3.18	5.75	6.66	27	47	2.51	2.17
48	6	3.62	4.8	4.8	7	7	3.39	3.39

TABLE 4C. WATER JET TESTS, 30 AUGUST 1978, CALM WATER (SLICK CONVERGENCE TESTS)

Test no.	Speed (kts)	Slick thick @0 m (mm)	Slick width @15 m (m)	Slick width @30 m (m)	Slick thick @15 m (mm)	Slick thick @15 m (mm)	Number of nozzles	Water press. (kPa)
1	2	1.14	3.63	2.72	1.43	1.90	2	70
2	2	1.19	1.5	2.12	3.57	2.55	4	70
3	2	1.09	1.51	1.81	3.27	2.73	6	70
4	4	1.09	3.63	3.33	1.36	1.49	2	140
5	4	1.04	2.72	1.51	1.73	3.12	4	140
6	4	1.15	2.42	0.90	2.16	5.75	6	140
7	6	1.16	3.63	2.72	1.45	1.93	2	280
8	6	1.08	2.42	0.60	2.03	8.10	4	280
9	6	1.01	2.72	0.90	1.68	5.05	6	280
10	6	1.11	3.03	2.72	1.67	1.85	2	560
11	4	1.03	1.21	0.90	3.86	5.15	4	560
14	2	0.92	0.90	2.72	4.60	1.53	6	420
16	2	1.11	3.03	2.72	1.67	1.85	2	140

TABLE 4D. WATER JET TESTS, 31 AUGUST 1978, 0.6 m HARBOR CHOP (SLICK CONVERGENCE TESTS)

Test no.	Speed (kts)	Slick thick @0 m (mm)	Slick width @15 m (m)	Slick width @30 m (m)	Slick thick @15 m (mm)	Slick thick @15 m (mm)	Number of nozzles	Water press. (kPa)
16	2	1.13	3.63	3.03	1.41	1.70	2	70
17	2	1.13	1.81	1.81	2.82	2.82	4	70
18	2	1.16	2.12	1.51	2.49	3.48	6	70
19	4	1.08	3.93	3.63	1.25	1.35	2	140
20	4	1.17	2.42	1.51	2.19	3.51	4	140
21	4	1.17	2.42	1.21	2.19	4.39	6	140
22	6	0.95	3.93	3.33	1.09	1.30	2	280
23	6	1.23	2.72	0.90	2.05	6.15	4	280
24	6	1.16	2.42	1.81	2.18	2.89	6	280

TABLE 4E. WATER JET TESTS, 1 SEPTEMBER 1978, CALM WATER (SLICK CONVERGENCE TESTS)

Test no.	Speed (kts)	Slick thick @0 m (mm)	Slick width @15 m (m)	Slick width @30 m (m)	Slick thick @15 m (mm)	Slick thick @15 m (mm)	Number of nozzles	Water press. (kPa)
49	4	1.05	2.72	1.81	1.5	2.63	6	70
50	4	1.08	2.12	0.90	2.31	5.40	6	280
41	4	1.05	1.51	0.90	3.15	5.25	6	420
52	4	2.26	3.03	1.81	3.39	5.65	6	70
53	4	2.21	2.42	1.51	4.14	6.63	6	280
55	4	2.26	2.12	1.51	4.84	6.78	6	420

TABLE 4F. WATER JET TESTS, 1 SEPTEMBER 1978, 1.2 m HARBOR CHOP (SLICK CONVERGENCE TESTS)

Test no.	Speed (kts)	Slick thick @0 m (mm)	Slick width @15 m (m)	Slick width @30 m (m)	Slick thick @15 m (mm)	Slick thick @30 m (mm)	Number of nozzles	Water press. (kPa)
56	4	1.25	1.81	1.51	3.13	3.75	6	560
57	4	6.23	2.42	2.72	11.68	10.38	4	280
58	4	6.23	2.42	2.12	11.68	13.35	4	560

TABLE 5. SINGLE JET TEST RESULTS (SLICK PARTING TESTS).

Test no.	Tow speed (kts)	Nozzle ID (cm)	Slick thick (mm)	Water press (kPa)	Wave	Elapsed Time (sec) 15	30	45	60
						Slick Movement (m)			
7	2	2.1	0.9	140	Calm	2.4	2.8	3.1	3.4
8	2	2.1	1.2	280	Calm	2.7	3.4	3.8	4.0
9	2	2.1	1.2	560	Calm	3.4	4.2	4.5	4.8
10	2	2.1	1.2	0	Calm	7.6	8.0	8.5	8.8
11	4	2.1	0.8	140	Calm	2.0	2.4	2.4	2.6
12	4	2.1	1.0	280	Calm	2.2	2.6	2.9	3.1
13	4	2.1	1.1	560	Calm	2.2	3.0	3.8	4.5
14	6	2.1	1.0	140	Calm	1.3	1.8	2.3	2.5
15	6	2.1	1.0	280	Calm	1.8	2.3	2.7	2.9
16	6	2.1	1.0	560	Calm	2.1	2.6	3.0	3.5
17	2	2.7	1.4	140	Calm	2.7	3.5	3.8	4.1
18	2	2.7	1.2	280	Calm	2.8	3.6	4.2	4.5
19	2	2.7	1.2	560	Calm	4.2	5.1	5.4	5.7
20	4	2.7	1.2	140	Calm	1.8	2.6	3.0	3.2
21	4	2.7	1.2	280	Calm	2.4	2.9	3.6	4.5
22	4	2.7	1.2	560	Calm	2.7	3.5	4.4	5.1
23	6	2.7	1.0	140	Calm	2.0	2.6	2.9	3.2
24	6	2.7	0.9	280	Calm	2.1	2.8	3.5	3.9
25	6	2.7	1.1	560	Calm	2.7	3.2	3.8	3.9
26	2	2.7	2.7	280	Calm	3.0	4.5	5.0	5.4
27	4	2.7	4.8	280	Calm				3.5
28	6	2.7	3.3	280	Calm				3.4
29	2	2.7	1.4	560		3.6	3.9	4.8	5.8
30	4	2.7	1.1	560		2.4	3.6	4.2	4.7

(Continued)

TABLE 5. (Continued)

Test no.	Tow speed (kts)	Nozzle ID (cm)	Slick thick (mm)	Water press (kPa)	Wave	Elapsed Time (sec) 15	30	45	60
						Slick Movement (m)			
31	6	2.7	0.7	560		2.3	3.3	3.6	4.2
32	2	2.7	1.3	280	1.2HC	2.1	3.0	3.9	4.5
33	4	2.7	0.7	560	1.2HC	3.0	4.2	5.2	4.9
34	4	2.7	1.1	280	1.2HC	2.1	3.3	3.5	3.7
35	2	2.7	1.3	560	1.2HC				6.1
36	6	2.7	0.9	280	1.2HC				2.7
37	6	2.7	0.9	560	1.2HC				4.6
26R	2	2.7	3.5	280	Calm				4.2
21R	4	2.7	1.1	280	Calm				3.6
22R	4	2.7	0.9	560	Calm				4.8

TABLE 6. WATER JET HEIGHT EFFECTS TEST RESULTS (SLICK PARTING TESTS)

Test no.	Tow speed (kts)	Nozzle ID (cm)	Height of exit above water (m)	Slick thick (mm)	Water press. (kPa)	Wave (m)	Elapsed Time (sec) 10	20	30	40
							Slick Movement (m)			
1	4	2.1	0.6	3	560	Calm	2.4	3.2	3.9	4.4
2	6	2.1	0.6	3	560	Calm	2.3	2.8	3.4	3.6
3	6	2.1	1.2	3	560	Calm	1.6	2.2	2.5	2.8
4	4	2.1	1.2	3	560	Calm	2.0	3.0	3.3	3.5
5	4 to 6	Observation run				Calm				
6	4 to 6	Observation run				Calm				
7	4	2.1	0.3	3	560	Calm	2.7	2.9	3.4	3.6
8	6	2.1	0.3	3	560	Calm	2.6	2.6	2.8	3.1
9*	4	2.1	-0.6	3	210	Calm	1.7	1.7	1.9	2.0

*Test run with 210 kPa of pressurized air being fed through a 2.1 cm ID pipe extended 0.6 m below the water's surface.

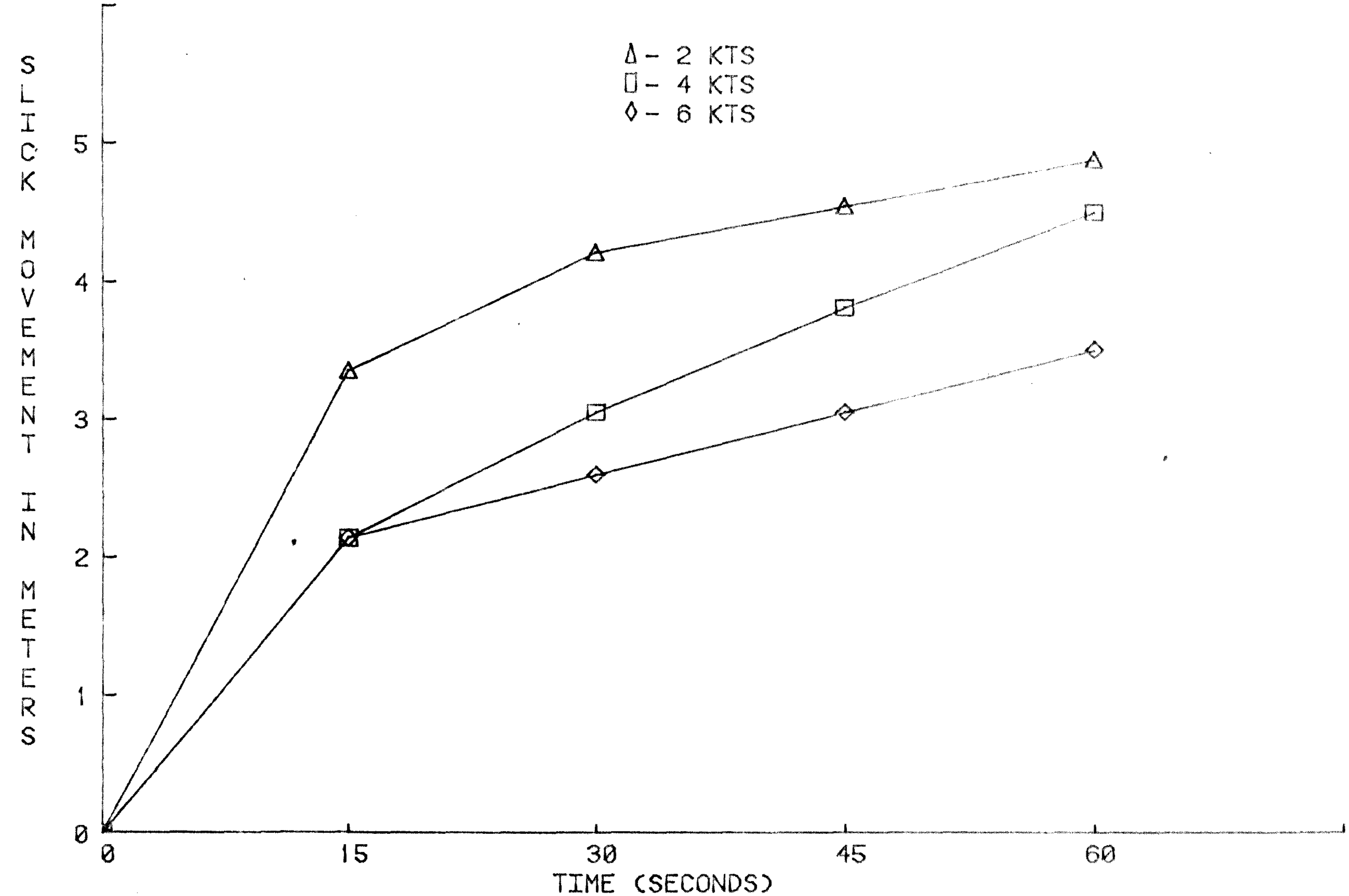


Figure 12. Effect of tow speed on oil slick movement - 1-mm slick, calm water, 2.1-cm ID nozzle at 560 Kpa (slick parting tests).

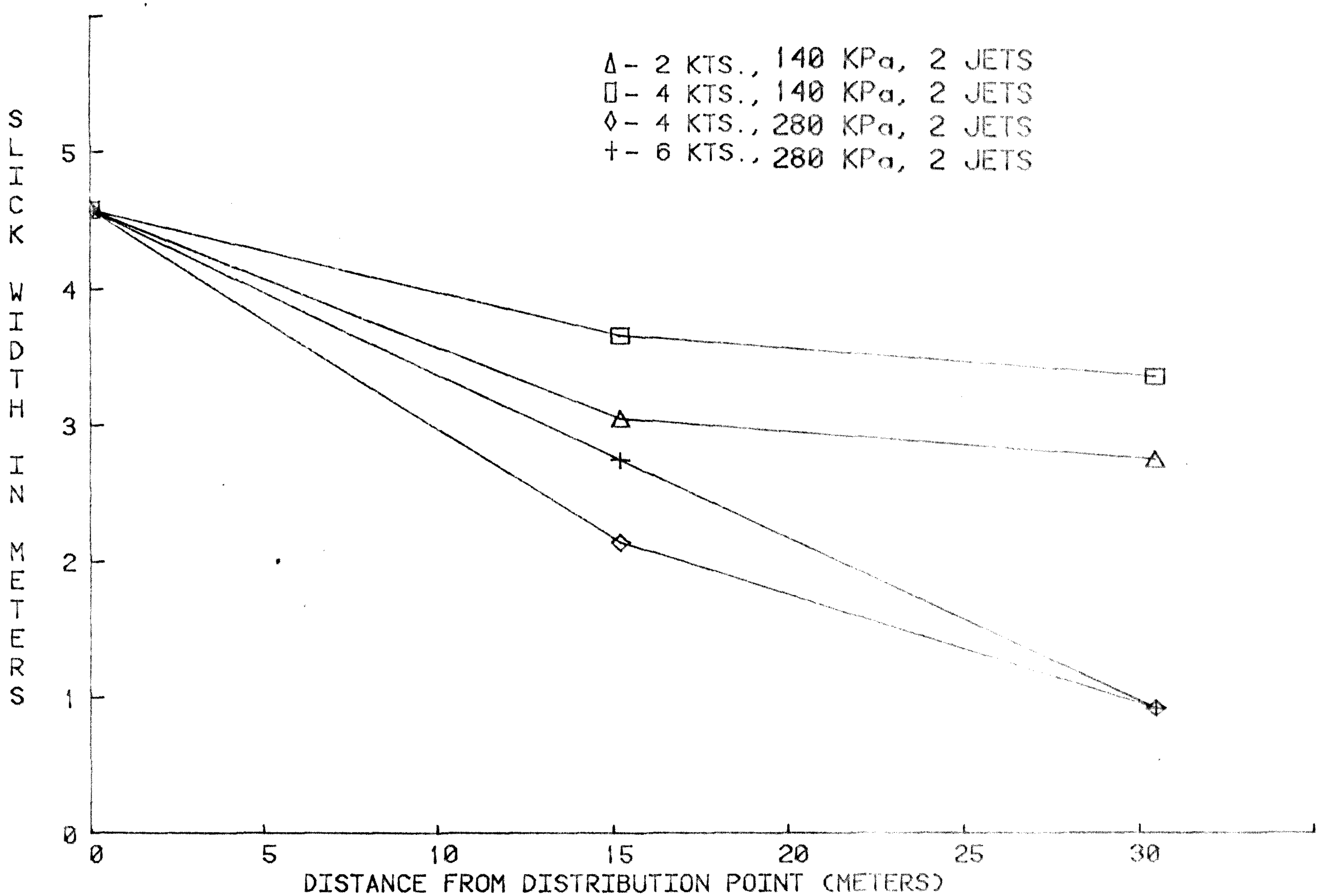


Figure 13. Effect of tow speed on oil slick movement - 1-mm slick thickness, calm water, 2.1-cm ID nozzles (slick convergence tests).

Wave Conditions

Non-breaking waves appeared to have little or no effect on water jet performance (Figures 14 and 15). Inherent difficulties in distributing a uniform slick onto a harbor chop sea state resulted in oil slick width variations. Such variations can account for the relatively minor deviations of the harbor chop results from the calm water results.

Number of Water Jets

The results declare that the more water jets that are employed, the greater the control of the oil slick (Figure 16). This is reasonable since surface current controls the oil slick and the more water jets in operation the greater the surface current produced. Since the slick parting tests used only one nozzle in the tests there is no graph from those tests to illustrate this point.

Water Jet Pressure

The greater the water jet pressure the greater the control over the oil slick (Figures 17 and 18). However, in the convergence tests there was a point of diminishing returns. For the first 15 m in the 6 nozzle case at 4 knots, 140 kPa pressure was sufficient to move the oil slick from 62 to 88 percent of the distance that water jets using 420 kPa moved the slick. For the second 15 m, 140 kPa moved the slick 100% of the distance moved using 420 kPa. When using only two nozzles the higher possible pressures resulted in greater slick control over the entire observation time (Figure 16). These tests also showed that a converged slick will spread again quickly once the currents produced by the two water jets subside.

Slick Thickness

The slick convergence tests showed consistently that the thicker the oil slick, the more difficult it is to move (Figure 19). With the arrangement of water jets tested, a 4.5 m wide oil slick of 1 to 2 mm thick could be thickened to 5 to 6 mm, (3 to 5 times as thick). The spreading forces of the oil and jet interaction appear to limit convergence and thickening of an oil slick beyond this. A thicker slick of 6.23 mm was driven to a 13.35 mm thickness. However, this is a reduction of width and an increase in slick thickness of only a factor of 2.14. The slick parting tests were not as consistent with their results (Figure 20). Some tests turned in higher performance in a thicker slick while others delivered the expected poorer performance. Since a thicker oil slick spreads faster than a thin slick, parting a heavy slick should be more difficult than parting a thin slick. The better performance in heavy slicks is probably an abnormality in the data caused by wind and/or errors in slick sighting.

Nozzle Size

The larger the nozzle the better the performance at the same pressure. The 2.7 cm ID nozzle outperformed the 2.1 cm ID nozzle at all speeds tested. A typical comparison is presented for the four knot tests (Figure 21). This result is logical since more water will flow through a larger pipe than a smaller pipe for a given pressure. A greater fluid flow should be expected to entrain more air and thus create a stronger surface current.

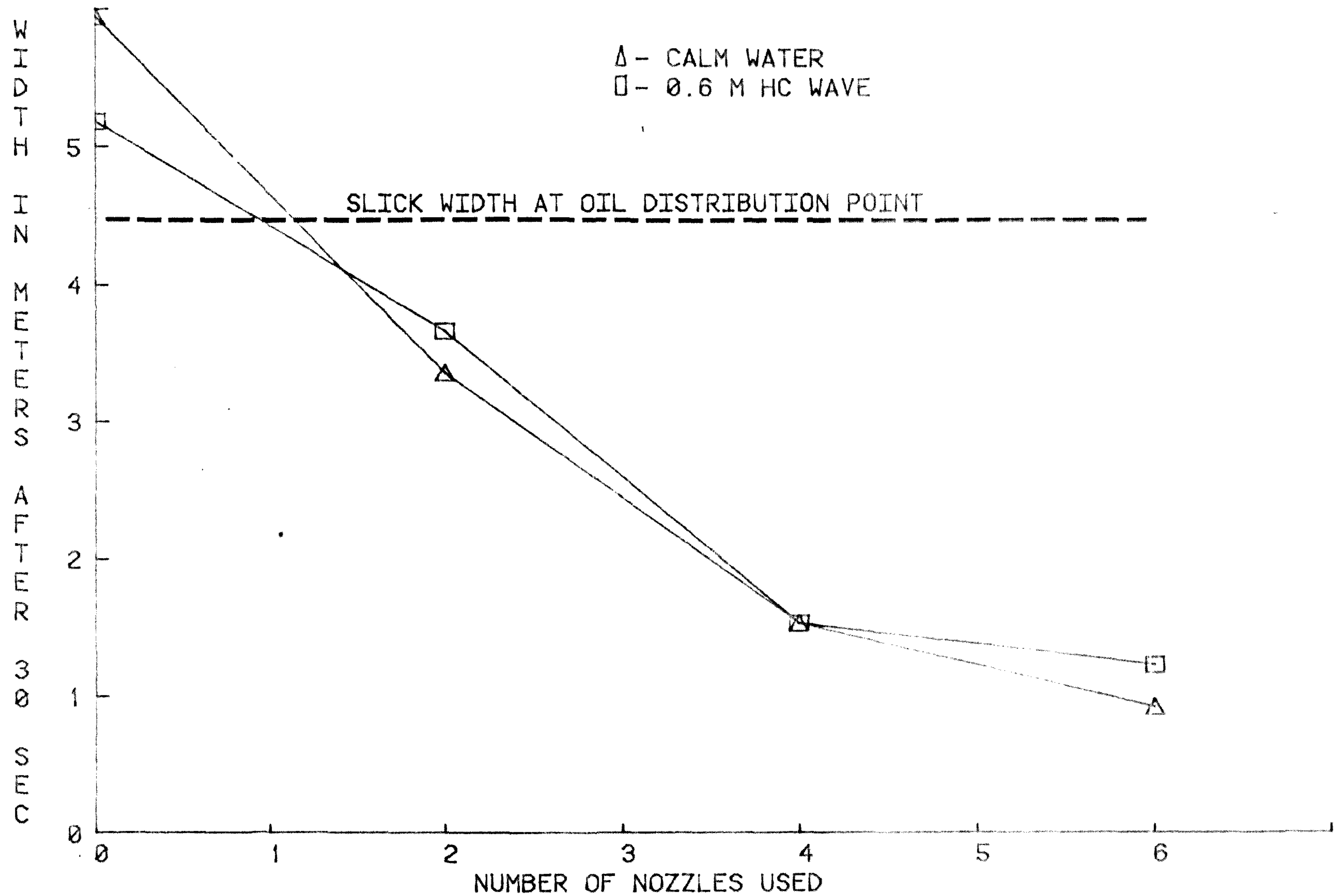


Figure 14. Water jet performance in calm water and waves - 1-mm slick, 4 kt, 2.1-cm ID nozzle at 140 kPa (slick convergence tests).

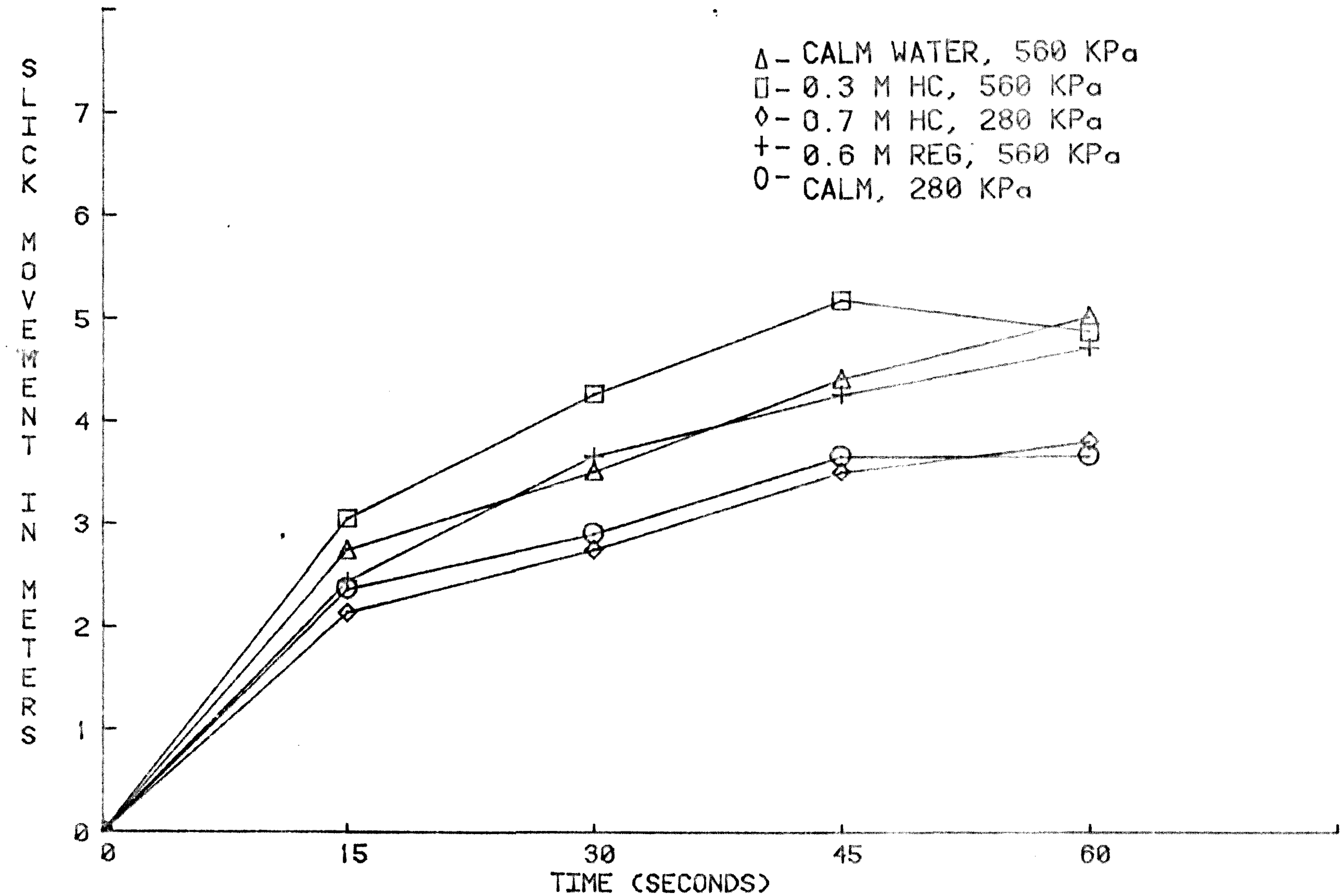


Figure 15. Water jet performance in calm water and waves - 1-mm slick, 2.6-cm ID nozzle, 4 kt (slick parting tests).

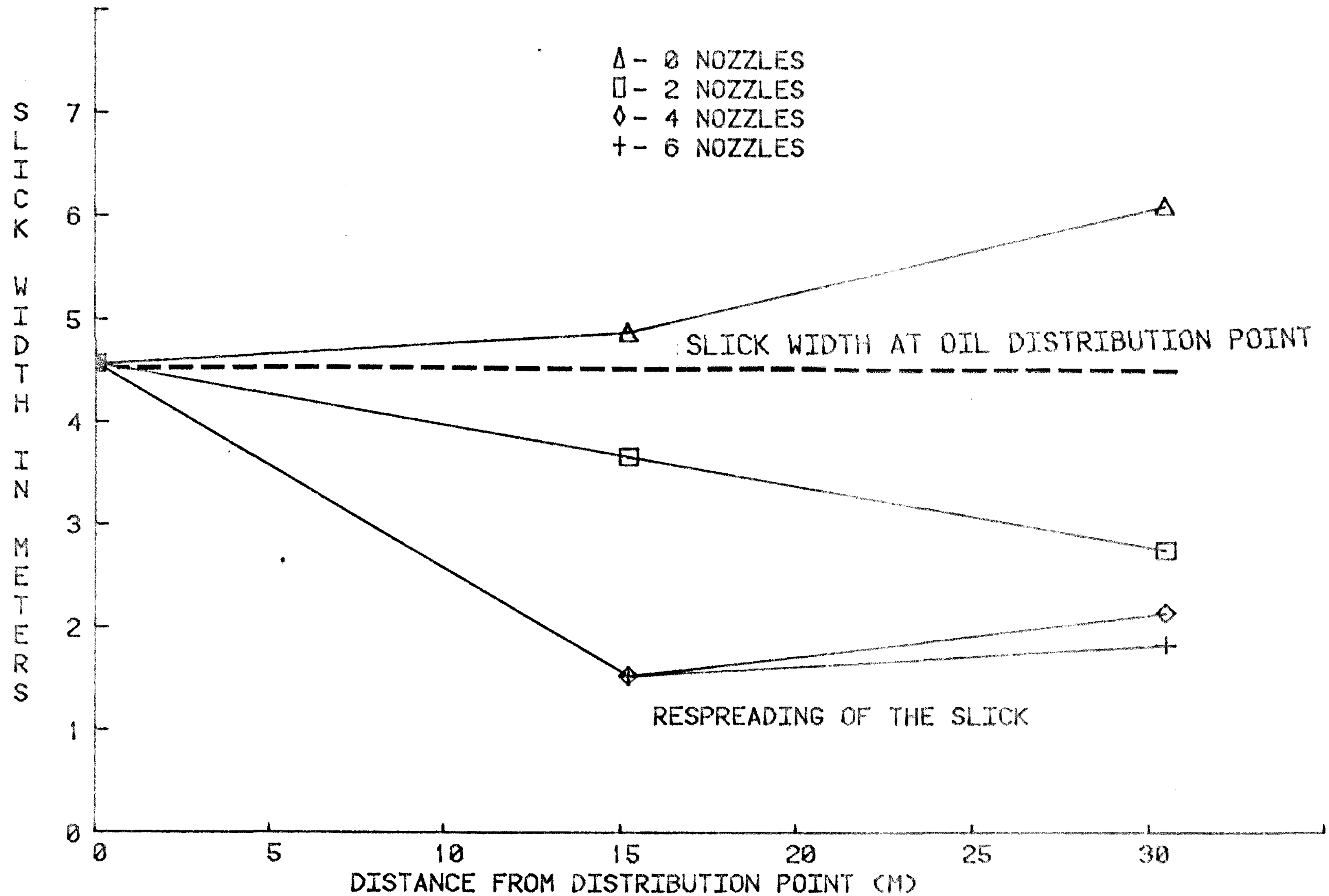


Figure 16. Effect of the number of water jets on oil slick movement - 1-mm slick, 2 kt, 1.6-cm ID nozzle at 70 kPa (slick convergence tests).

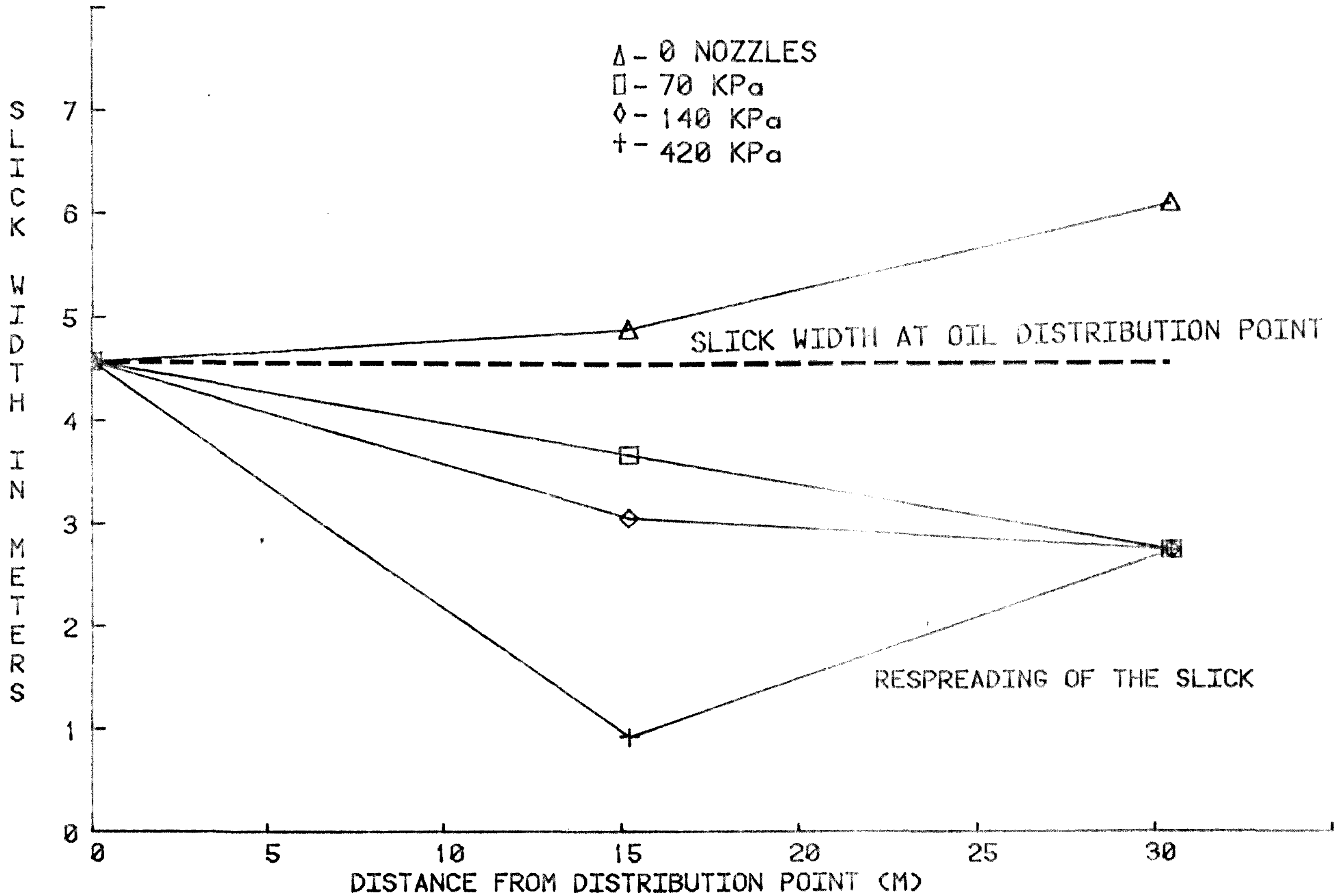


Figure 17. Effect of water jet pressure on oil slick movement - 2 kt, 1-mm slick, 2 nozzles, 1.6-cm ID nozzles (slick convergence tests).

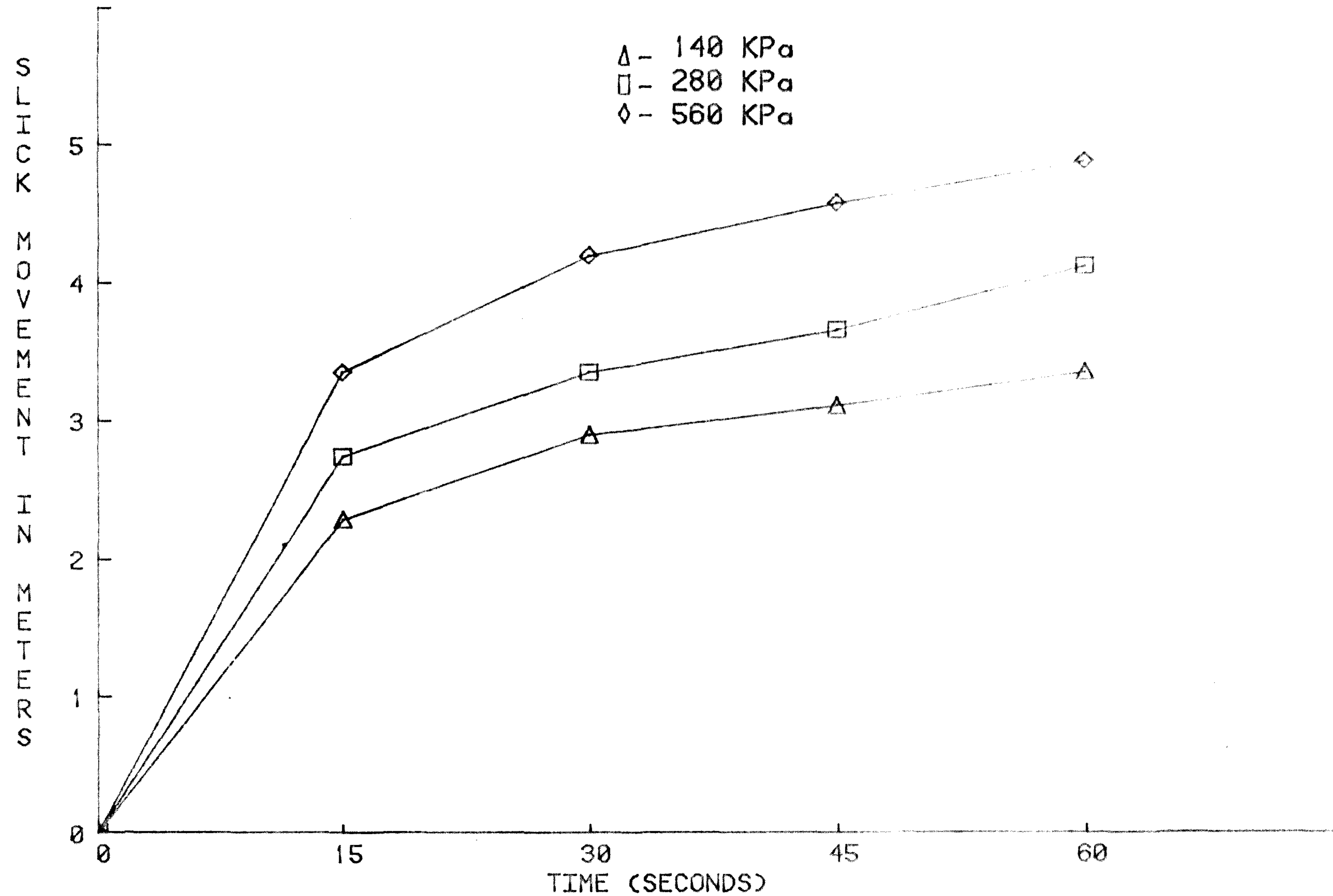


Figure 18. Effect of water jet pressure on oil movement - 2 kt, 1-mm slick, 2.1-cm ID nozzle (slick parting tests).

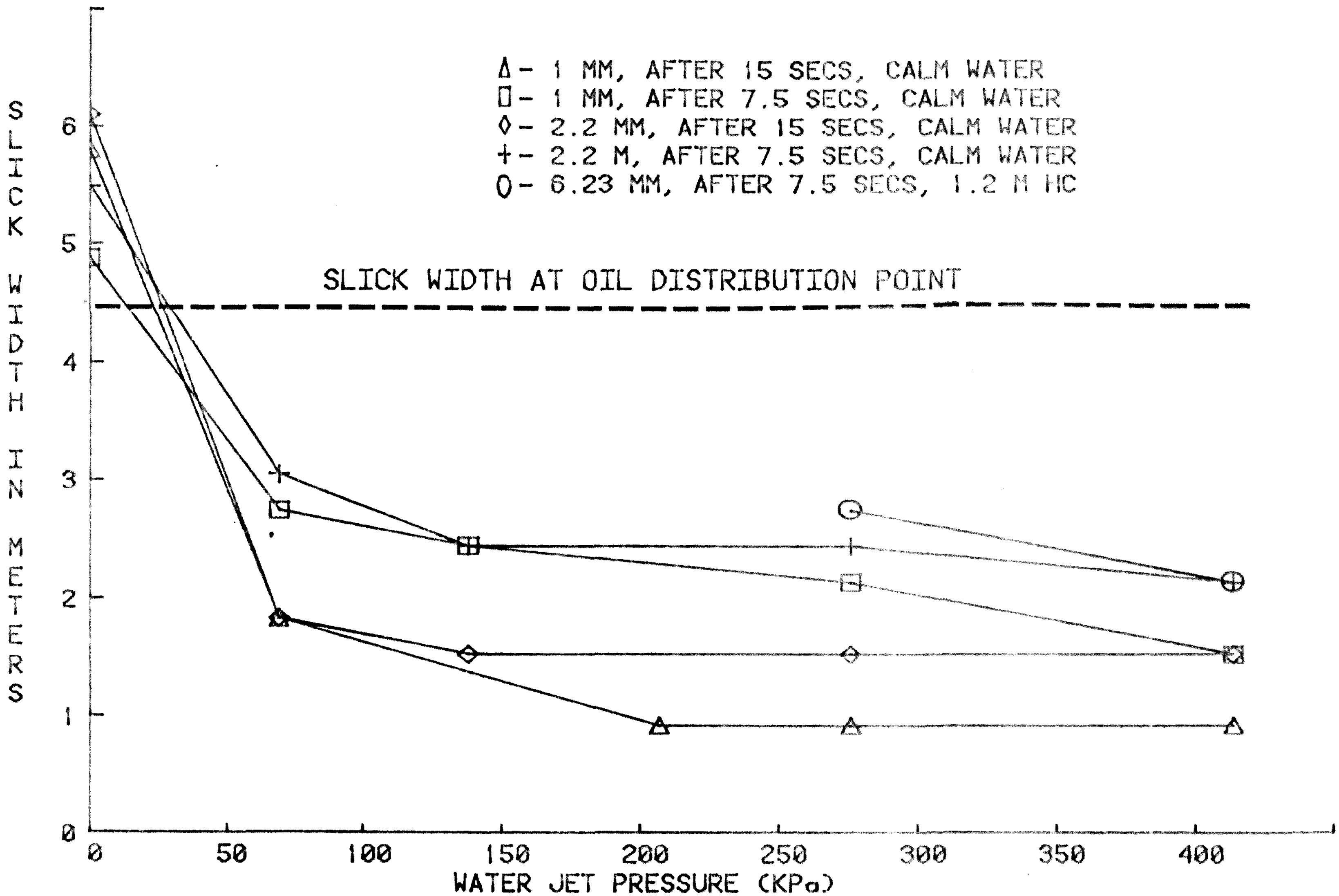


Figure 19. Effect of water jet pressure and slick thickness on oil slick movement 4 kt, 6 nozzles - 1.6-cm ID nozzles (slick convergence tests).

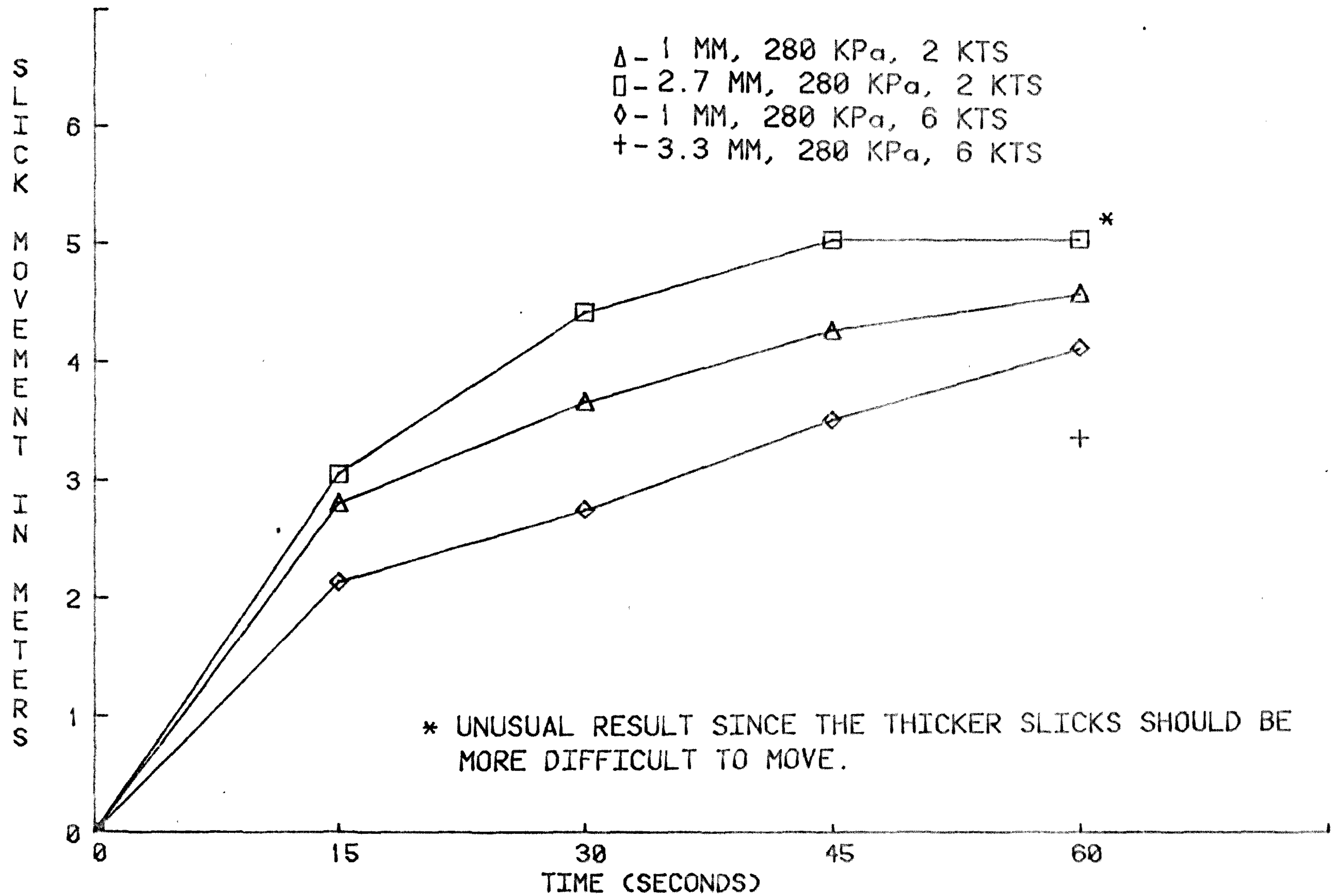


Figure 20. Effect of slick thickness on oil slick movement - 2.1-cm ID nozzle (slick parting tests).

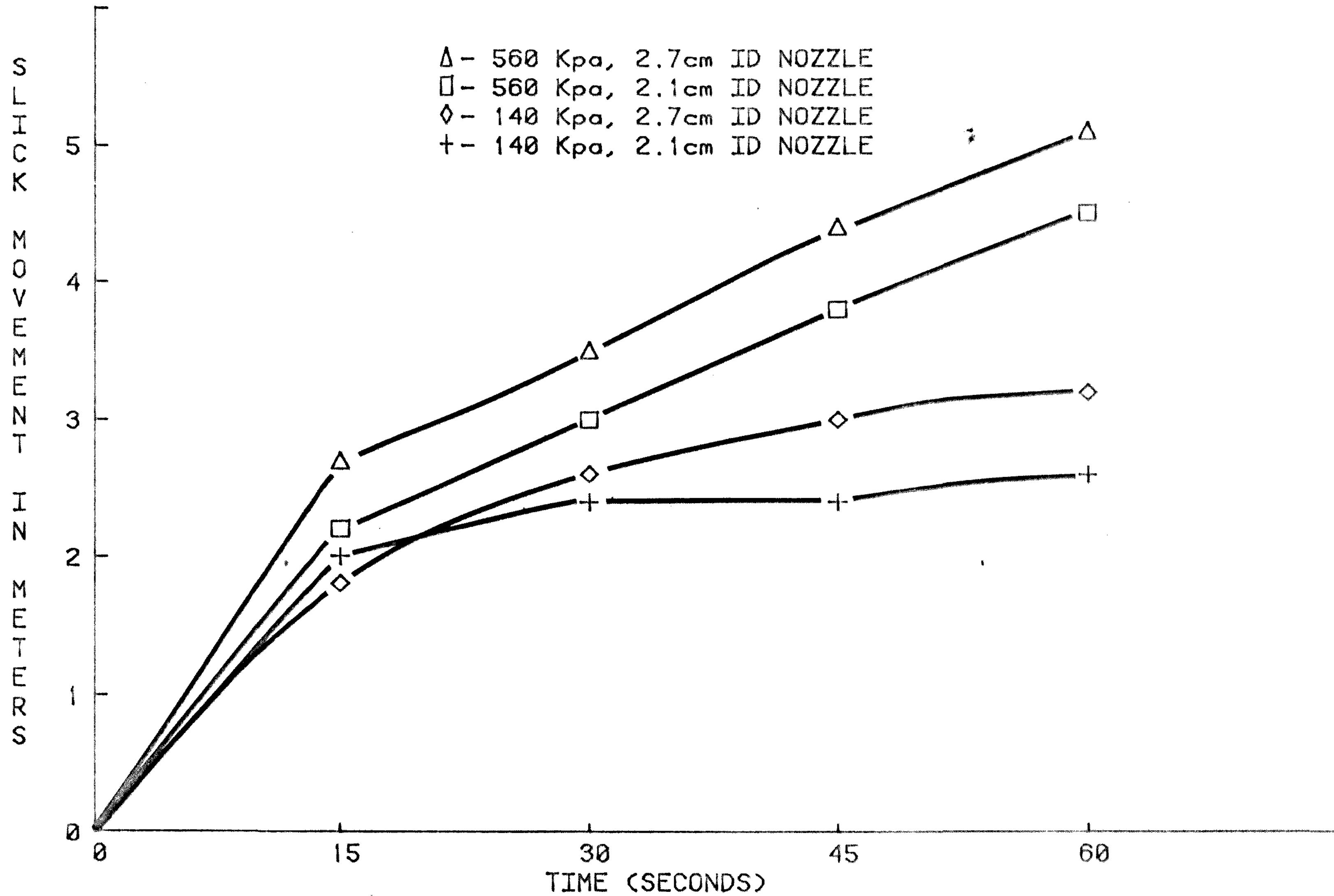


Figure 21. Effect of nozzle diameter on oil slick movement in calm water, 1-mm slick, 4 kt (slick parting tests).

Nozzle Height

The best performance was achieved when the nozzle exit was 0.4 to 1.0 m above the water's surface (Figure 22). Above the optimum height the water stream was given a chance to spread and it lost its coherence. Penetration was reduced and thus the amount of air entrained was reduced. Below the optimum height the jet did not have enough time to fully develop the turbulent boundary layer which transported air along with it into the receiving water. The result was the same as having the nozzle too high--less air was entrained into the water column and thus less surface current was produced. The crater which served to prevent oil from getting beneath the jet was also reduced in both cases and more oil entrainment resulted. This result may not hold true for other types of nozzles or water pressures not in the range tested.

The waves produced by a moving jet were observed to entrain oil to a maximum depth of about 15 cm. The oil rose quickly to the surface as it moved away from the point of impact. The jet was recorded to entrain air to beyond 1 meter depth. No oil was seen to be entrained to such depths. This gave good evidence to the effectiveness of the crater to part the oil slick and keep it from beneath the water jet. The rapid rise of the wave entrained oil to the surface was probably the result of the small bubbles of air entrained by the jet rising into the oil droplets and making them more buoyant.

A nomograph was developed from the results of the convergence tests (Figure 23). It is used to determine the size and number of water jets and the water pressure to the jets necessary to converge a 1 mm oil slick at four knots. A different arrangement of water jets would render a different nomograph.

To use the nomograph one must decide how wide of a slick (e.g. 3 m) is to be converged to the necessary width (e.g. 1 m). A straight line is drawn between the two widths. The number of nozzles (4) and the pressure necessary (90 kPa) is read from the scales.

A test run was carried out using a submerged pipe discharging compressed air to part an oil slick. A 50 Kw, gasoline engine air compressor supplied the 2.0 cm ID pipe with 210 kPa air pressure. The tests were run at four knots and calm water through a 1 mm slick. The results showed a very clean path cut through the oil, but the oil slick movement was significantly less than that produced by a 2.1 cm ID water jet at 140 kPa water pressure (Figure 24). During tank cleanup one day, a 6.1 cm ID hose connected to a 225 Kw, 1250 m^3/hr air compressor was used to move oil away from a tank wall. The air pressure was approximately 560 kPa pressure. The air was directed at the oil slick from above and it was also submerged to bubble up air. In all configurations attempted, the compressed air source could not match the oil slick movement capability of a single 2.1 cm ID fire hose at approximately 420 kPa water pressure. The power required to drive the fire hose was about 20 Kw.

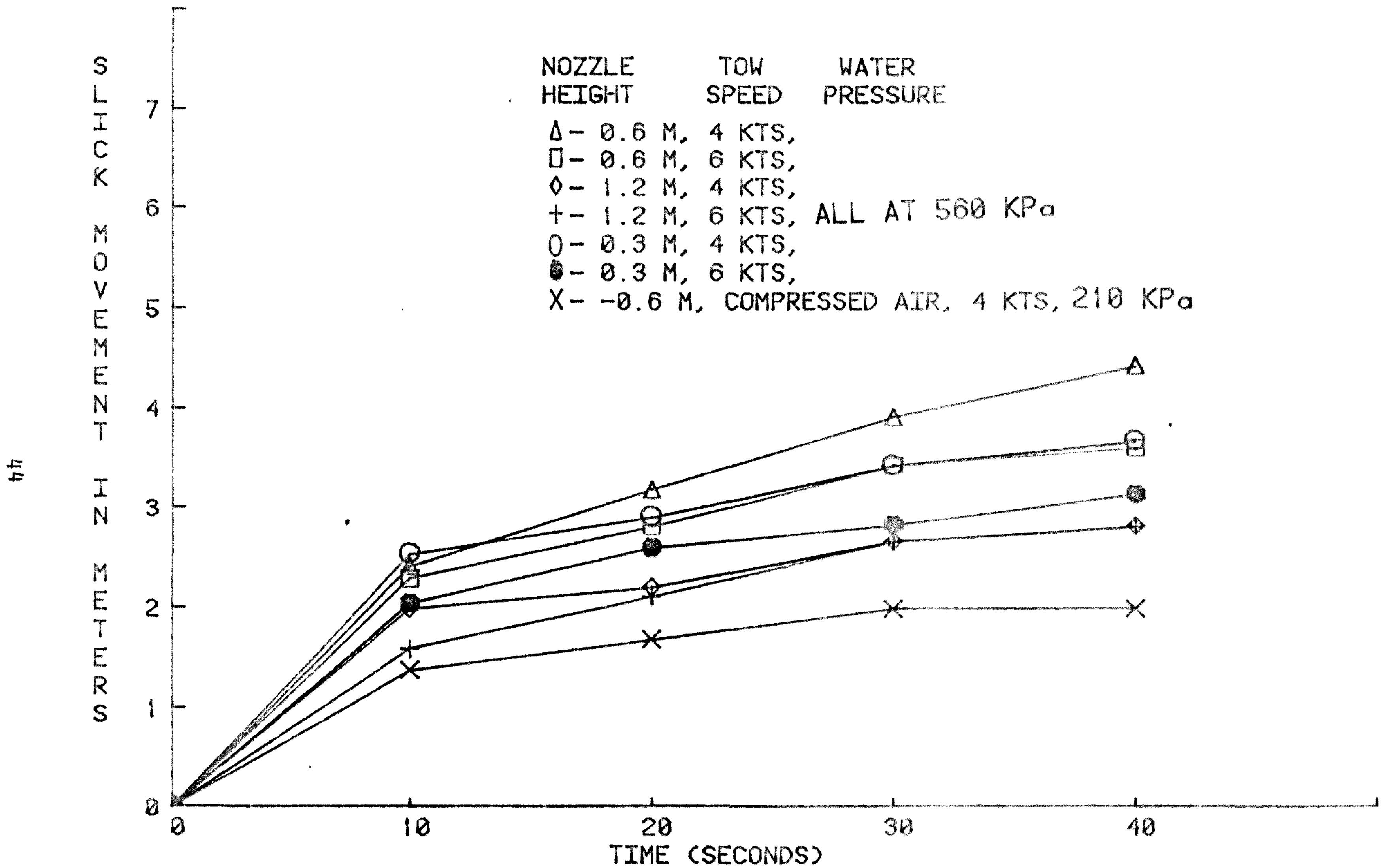


Figure 22. Effect of water jet nozzle height on oil slick movement - 1-mm slick, calm water, 2.1-cm ID nozzle (slick parting tests).

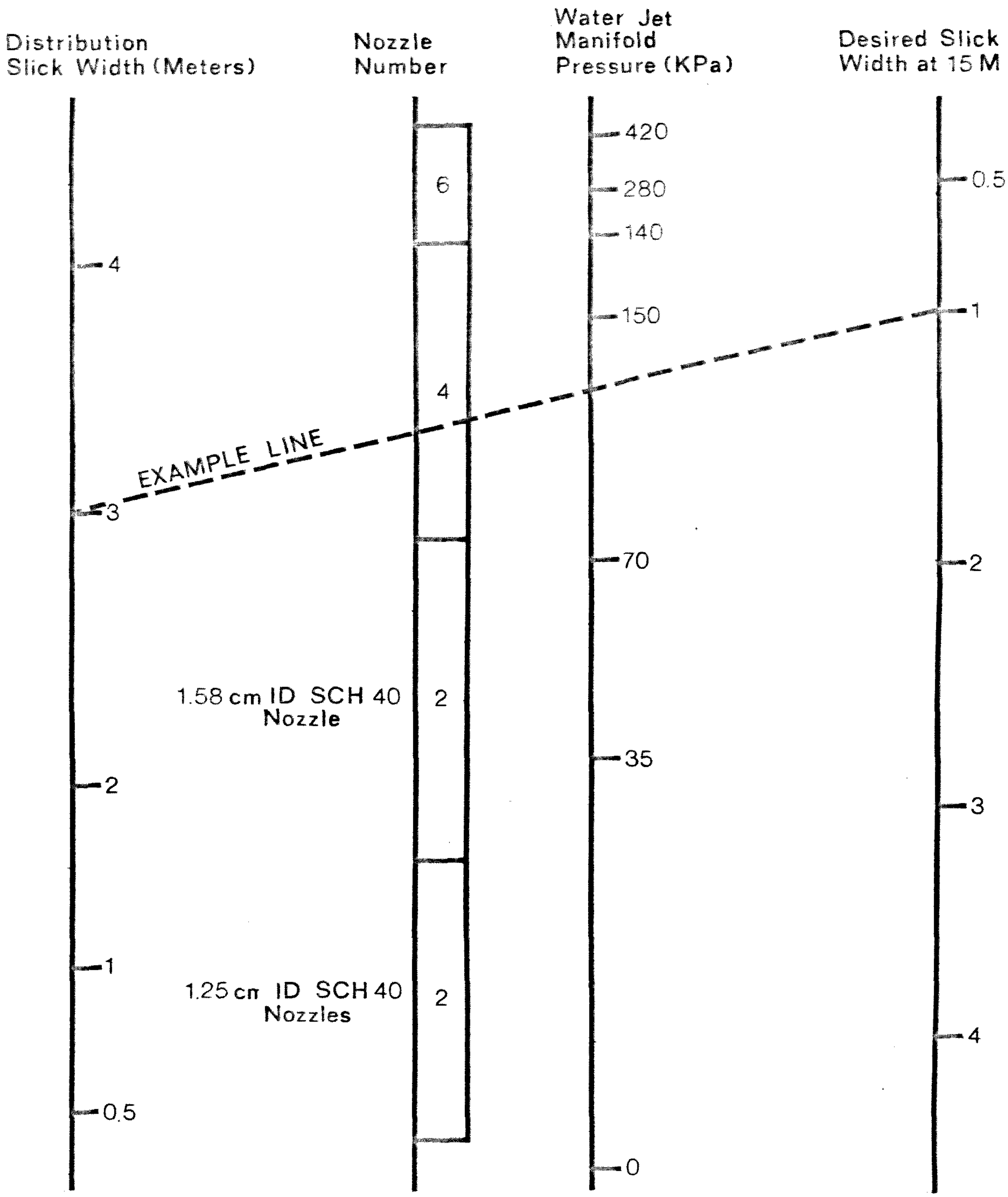


Figure 23. OHMSETT water jet nomagraph used for converging a 1-mm slick at 4 kt.

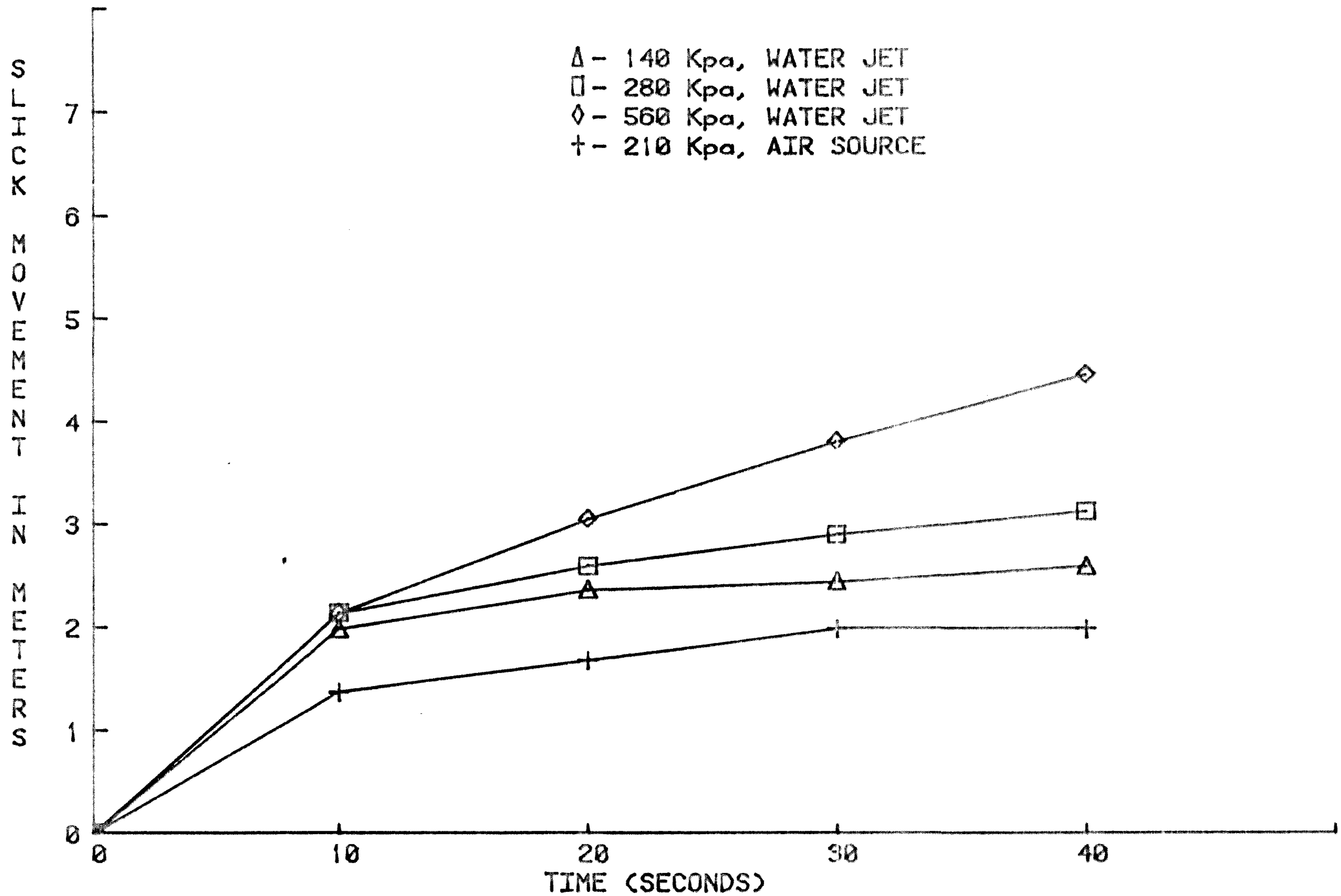


Figure 24. Comparison of water jet performance to that of a compressed air source, 1-mm slick, calm water, 2.1-cm ID nozzle, (slick parting tests).

SECTION 3

WATER JETS MOUNTED ON A MOVING OIL SKIMMER

INTRODUCTION

To have a practical application to large scale oil spill recovery, the water jets must be able to be mounted and perform well on a moving oil skimmer. Tests conducted at OHMSETT in this regard were designed to develop an oil converging system to be incorporated with the U.S. Coast Guard's Zero Relative Velocity (ZRV) fast current oil skimmer[4] (Figure 25). The objective was to converge a 6 m wide slick in to a 2.7 m wide slick (oil skimmer inlet size) at 6 knots in various wave conditions. Since the principle of the ZRV skimmer consisted of oil absorbtion and adsorbtion onto a floating composite belt, the oil slick had to be on the surface when it was in the reduced width. Oil entrained during the slick convergence would not be recovered by the skimmer.

The test program looked at the ability of a pair of water jets to converge a slick while mounted on a catamaran and at the entrainment developed by the water jets. The independent variables of the test were water jet nozzle size, tow speed, oil slick thickness, wave condition, water pressure, number of water jet nozzles in service and water jet nozzle attitude. The dependent variables were oil slick movement and the amount of oil entrainment.

CONCLUSIONS

Water jet booms can be successfully incorporated onto a moving oil skimmer to converge a wide thin slick into a narrow thick one for easier oil recovery.

Vertically directed jets proved to be the best all-wave performers. Angled jets performed slightly better than the vertical jets in calm water, but performed erratically in wave situations. The point of impact of a stream from angled jets and the distance between the nozzle exit and the point of impact changed drastically when the long booms on which the jets were mounted reacted to the catamaran's pitch and heave in waves.

Using the electric motor driven fire pump available on the OHMSETT main bridge, the best performance at different tow speeds by water jets on the 7.25 m is presented below:

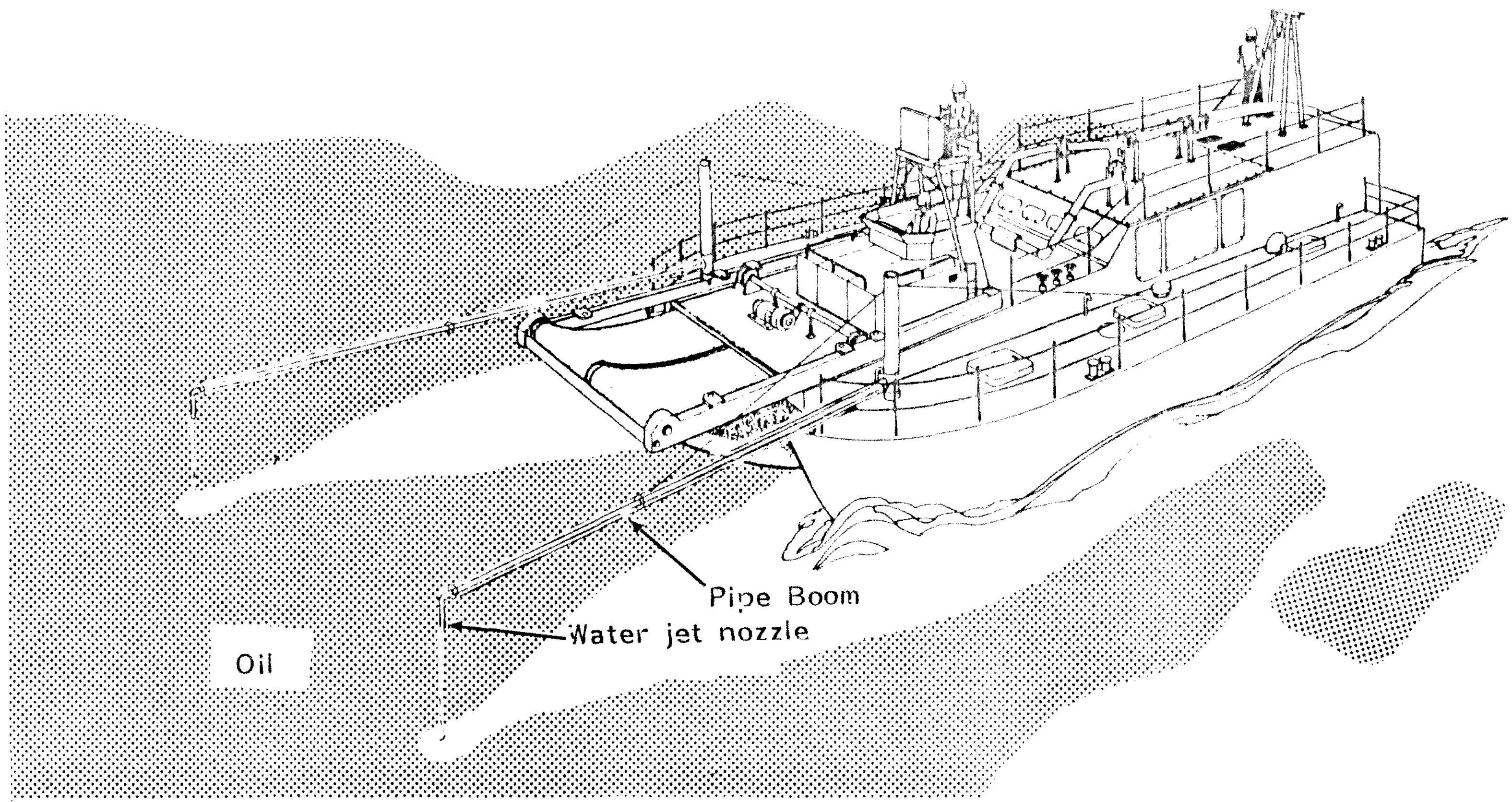


Figure 25. USCG ZRV skimmer using water jets to sweep oil

Tow speed kts	Nozzle size cm	Pressure kPa	Water jet angle in/fwd degrees	Wave cond.	Orig. slick width m	Final slick width m	Slick movement m
2	2.1	210	0/0	calm	6.1	1.7	4.4
4	2.1	560	20/0	calm	4.2	1.1	3.2
6	2.1	600	10/45	calm	6.1	2.9	3.2

Note: Not all nozzle sizes were tested at all pressures and tow speeds.

A satisfactory boom length for a water jet off the bow of a skimmer 10 to 15 m in length appears to be from 6 to 12 m. A longer water jet extension improves performance in calm water. However, any pitching and heaving of the vessel is amplified by the long boom. If the boom is too long, vessel movement can cause the water jet to be raised high above the water's surface and plunged into the water regularly. Such action renders the water jets ineffective.

The stationary tests revealed that some oil is entrained by a passing water jet, but that almost all of the oil slick remains on the surface. Oil that is entrained is carried away from the water jet impact point as it rises to the surface. The angled jets appeared to entrain more oil.

A pair of water jets can be expected to essentially double the sweep width of the U.S. Coast Guard's ZRV skimmer from 2.7 to 5.4 m at speeds up to 4 kts. To perform as well at 6 kts a longer boom would be required.

RECOMMENDATIONS

Designs of collapsible water jet booms should be investigated. Transportability and longevity of the booms would be enhanced if they could be folded for storage on the bow of a skimmer.

Water jet/skimmer tests should be conducted with the skimmer traveling with the waves to reduce the pitch and heave of the vessel.

The U.S. Coast Guard Zero Relative Velocity Skimmer should be fitted with water jet booms divided into two 3 m and two 1.5 m sections for each side. A suitable length boom can then be assembled depending upon skimming operations and sea conditions.

The water jet boom sections should be stiffened and reinforced to eliminate whip from the booms when operating in waves and to withstand rough handling. Such protective construction could be placed inside the boom pipe rather than outside as was done for the system used in these tests. Using internal reinforcing members would require special consideration to ensure adequate water flow with minimal pressure drop.

TEST DESCRIPTION

Test Equipment

The OHMSETT catamaran, 10.4 m long and 9.1 m wide was mounted with two vertical stanchions to support the water jet booms. A movable collar was placed at the base of each stanchion to mount the water jet booms (Figure 26). The water jet booms were constructed from sections of aluminum pipe welded together. The pipe served as a structural member and as a conduit for the water used by the jets. The booms were supported and held in place by 0.32 cm aircraft cable and turnbuckles (Figure 27). The water jets were constructed as to allow rotation in every plane (Figure 28). Operators were able to splay the booms to various widths, angle the jets in towards the centerline of the system and tilt them forward. The water jet nozzles were 30 cm long standard pipe of various inside diameters (i.e. 1.25, 1.6, 2.1, 2.7 cm). The nozzles were wrapped with bands of black tape for identification in photographs. The smallest had one band, the next size had two, the next size had three and the largest had none.

The catamaran with stanchions and booms was placed in the tank and rigged for towing by the main bridge (Figure 29). The main bridge fire pump supplied the water jets via 5 cm diameter hoses. Pressure gauges were mounted along the water jet boom in order to determine the water pressure close to the water jet outlet.

Oil was distributed from either a manifold or individual outlets located on the south side of the main bridge. For oil slicks greater than 4.5 m in width the individual outlets were used, otherwise the oil manifold was used. Medium oil (see Appendix B) was used for these tests since its properties most closely match those of the kind of oil which the U.S. Coast Guard determined the ZRV skimmer would be recovering in actual oil spill situations.

To observe the oil entraining properties of a water jet, the catamaran was held stationary in an oil slick with the water jet nozzle positioned directly above an underwater window (Figure 30). The boom was swung through an arc by pulling it with a rope from the video bridge. The rate of swing was calculated to have the water jet moving at about 4 knots. The action of the water jet impacting the oil and water was recorded via slow-motion 16 mm movie photography and sequential 35 mm still photography through the underwater window (Figure 31 A through K). A small workboat was positioned against the tank wall over the underwater window to prevent oil from being driven down onto the glass by the water jet. A barrel was positioned on the tank deck to receive the flow from the water jet prior to the test.

Test Plan

All tests were conducted according to the following test procedures:

1. Prepare appropriate photo/video equipment (shoot test record boards).

2. Prepare oil distribution for tow test or stationary slick.

3. Adjust the water jet nozzle and booms to the appropriate angles.*

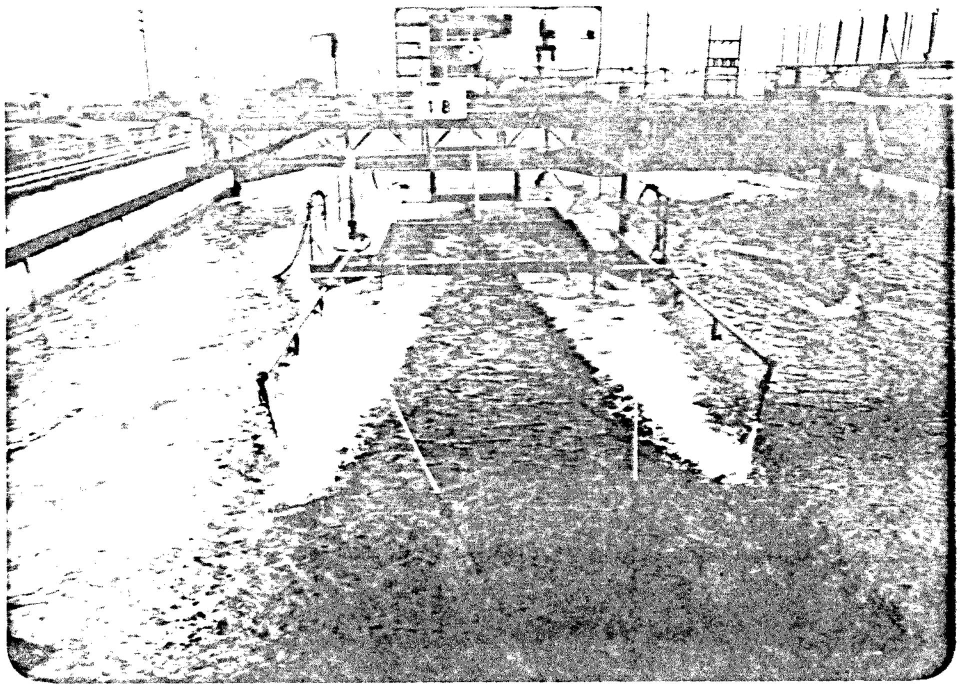


Figure 26. First generation water jet booms

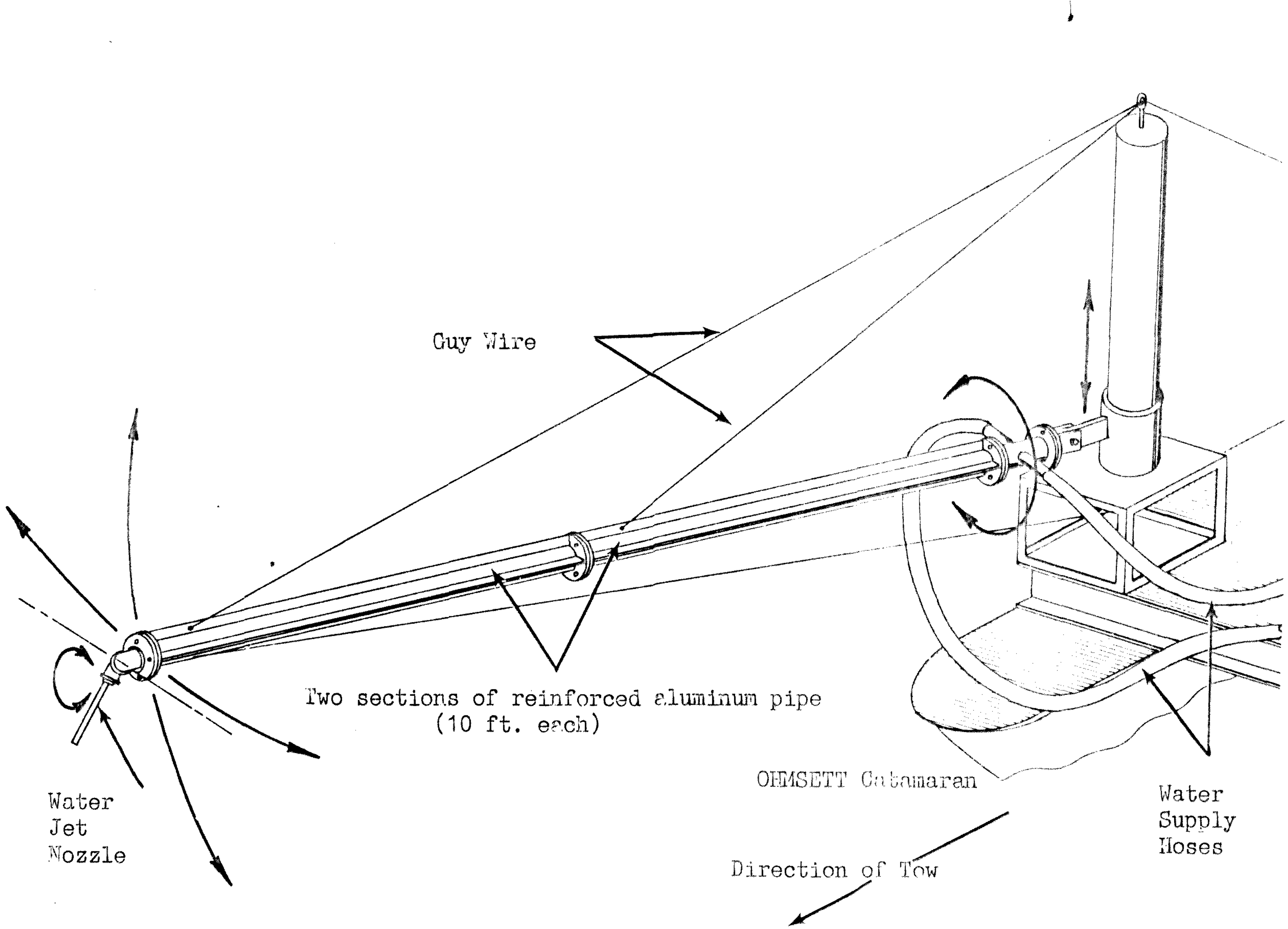


Figure 27. Second generation water jets mounted on OHMSETT catamaran.

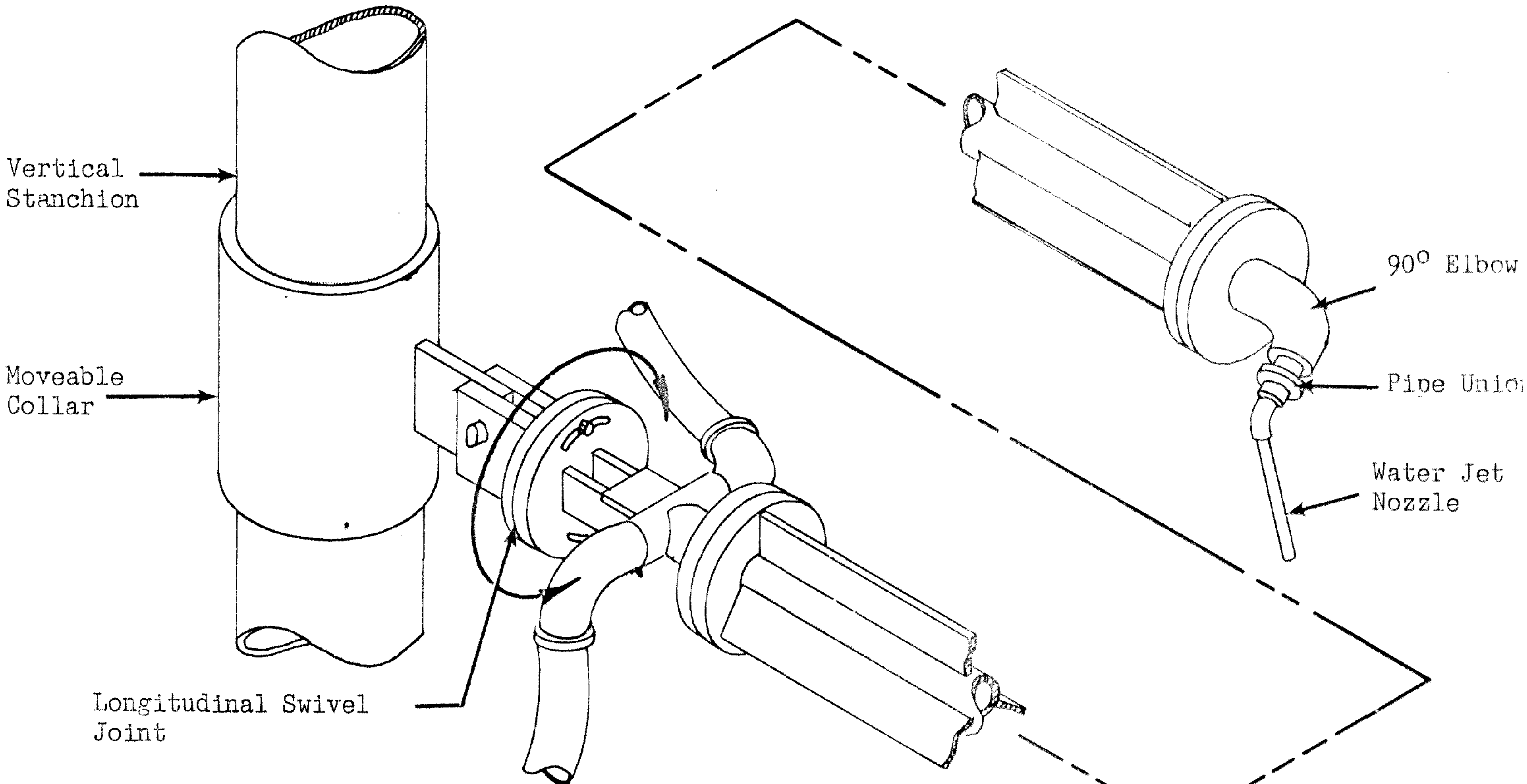


Figure 28. Details of second generation water jet.

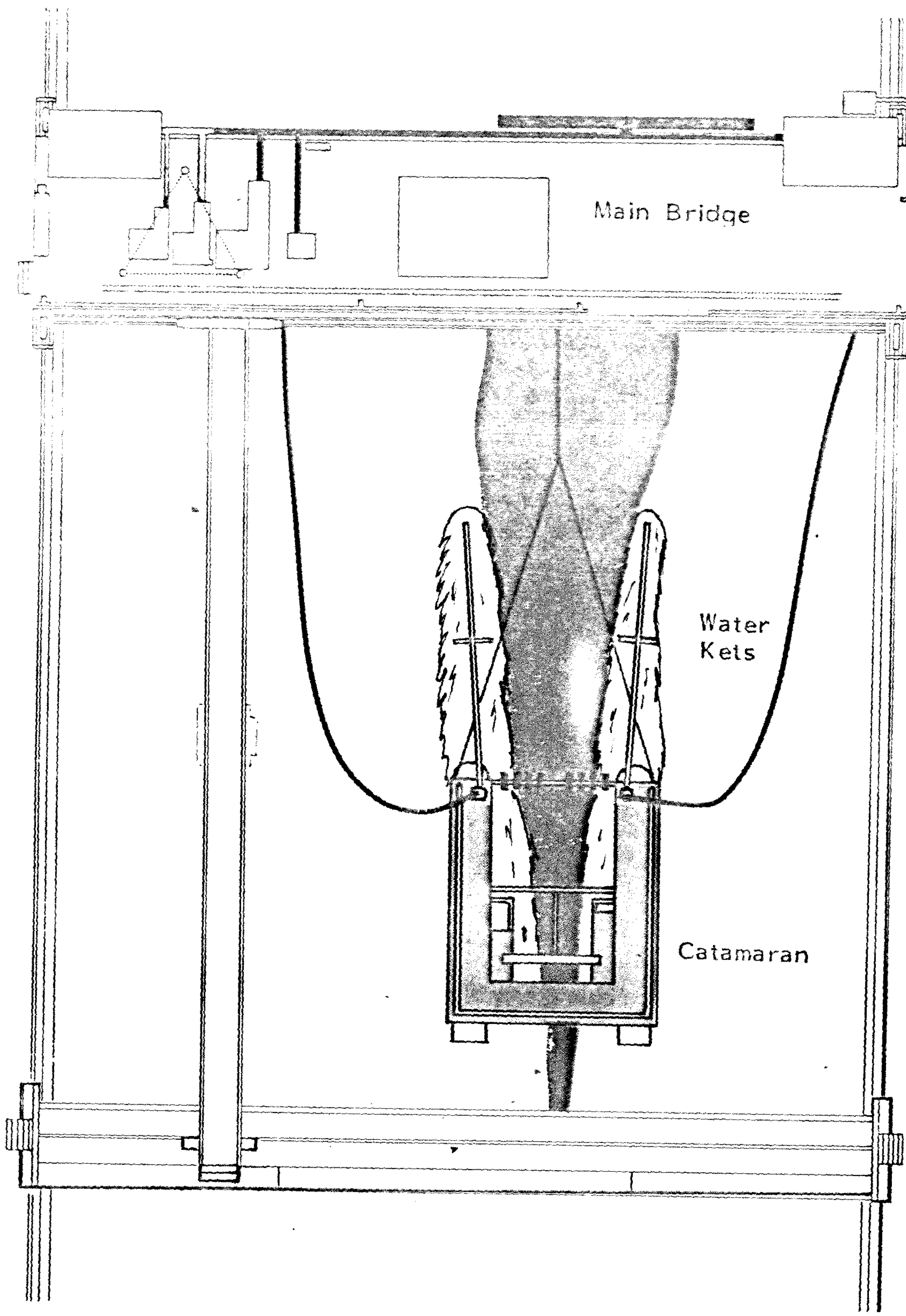


Figure 29. Test set up for oil skimmer/water jet tests.

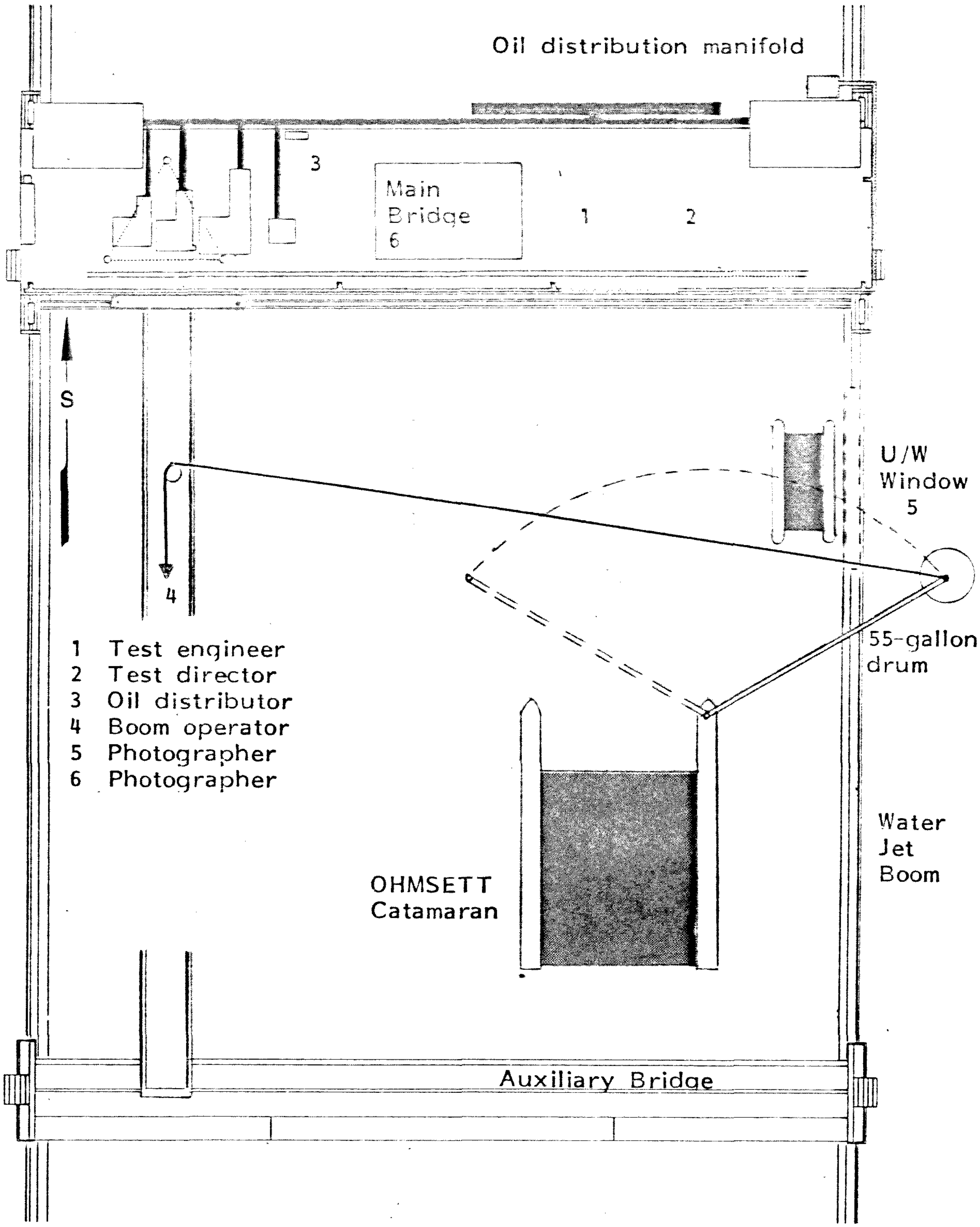


Figure 30. Test set up for stationary tests - pivoting a water jet boom.

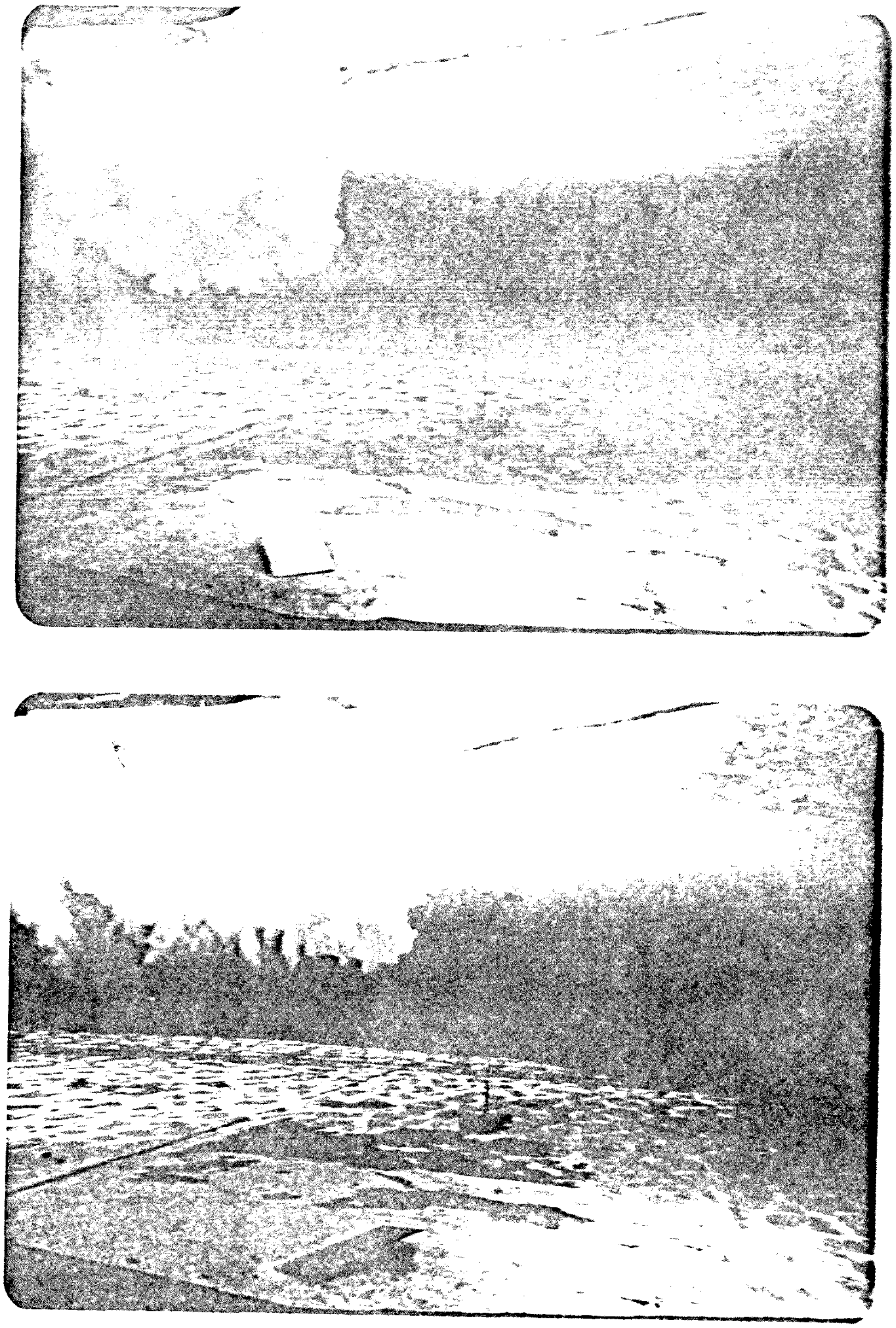


Figure 31. Underwater sequence of a water jet parting an oil slick. Note the aluminum plate in the foreground which was blown from the workboat by the water jet.

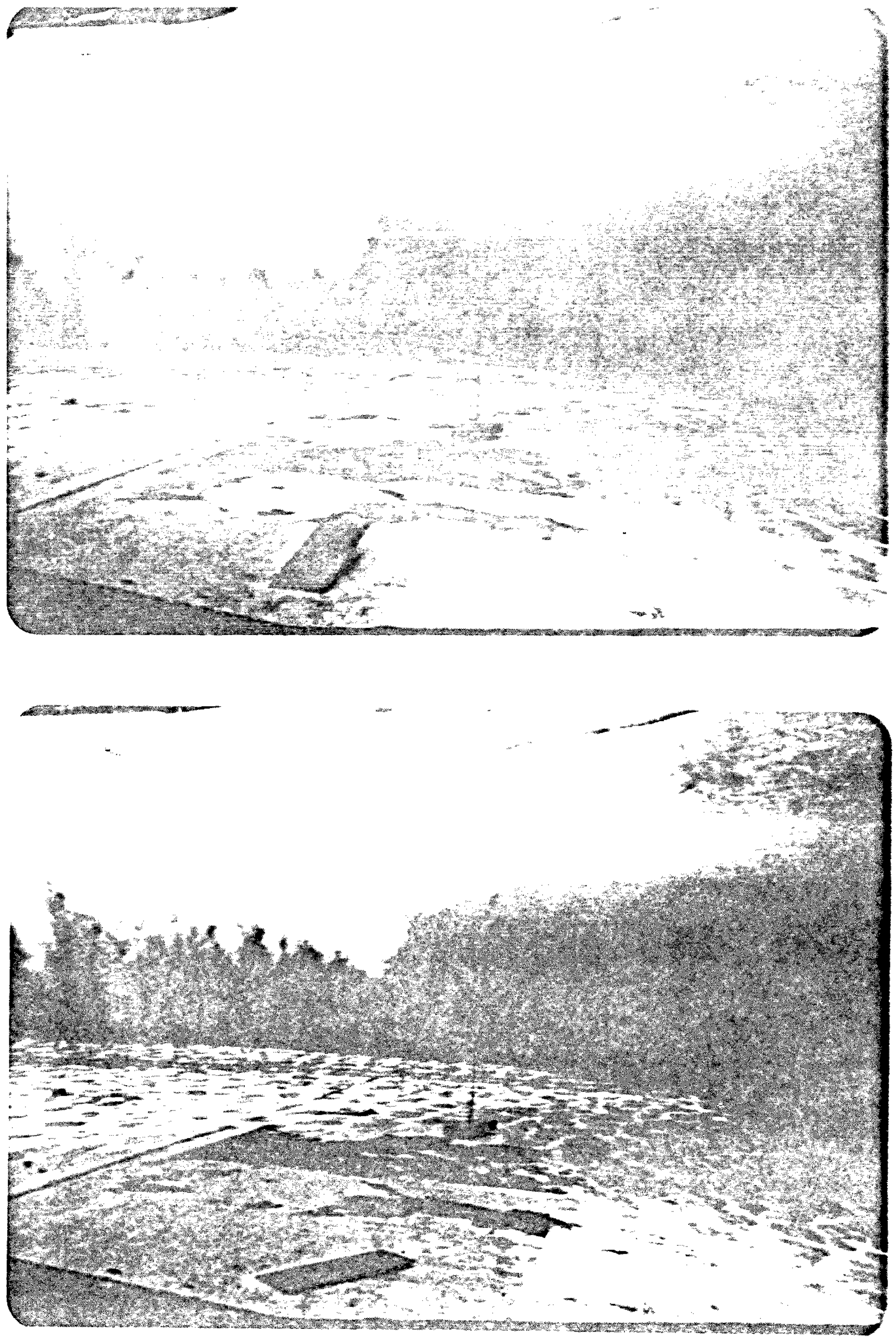


Figure 31. Continued.

Figure 31. Continued.

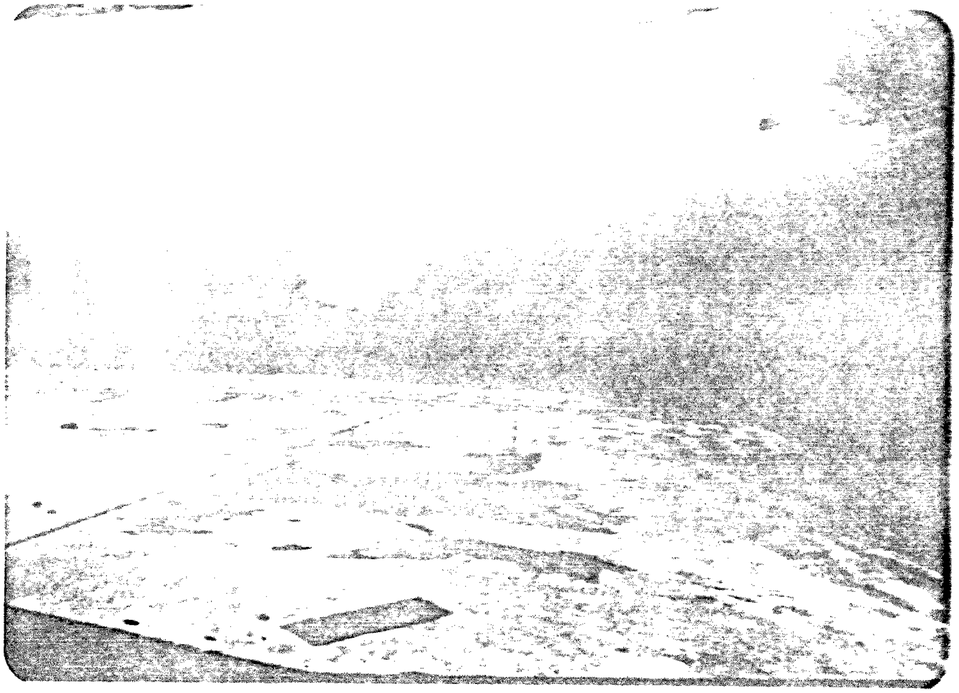


Figure 31. Continued.

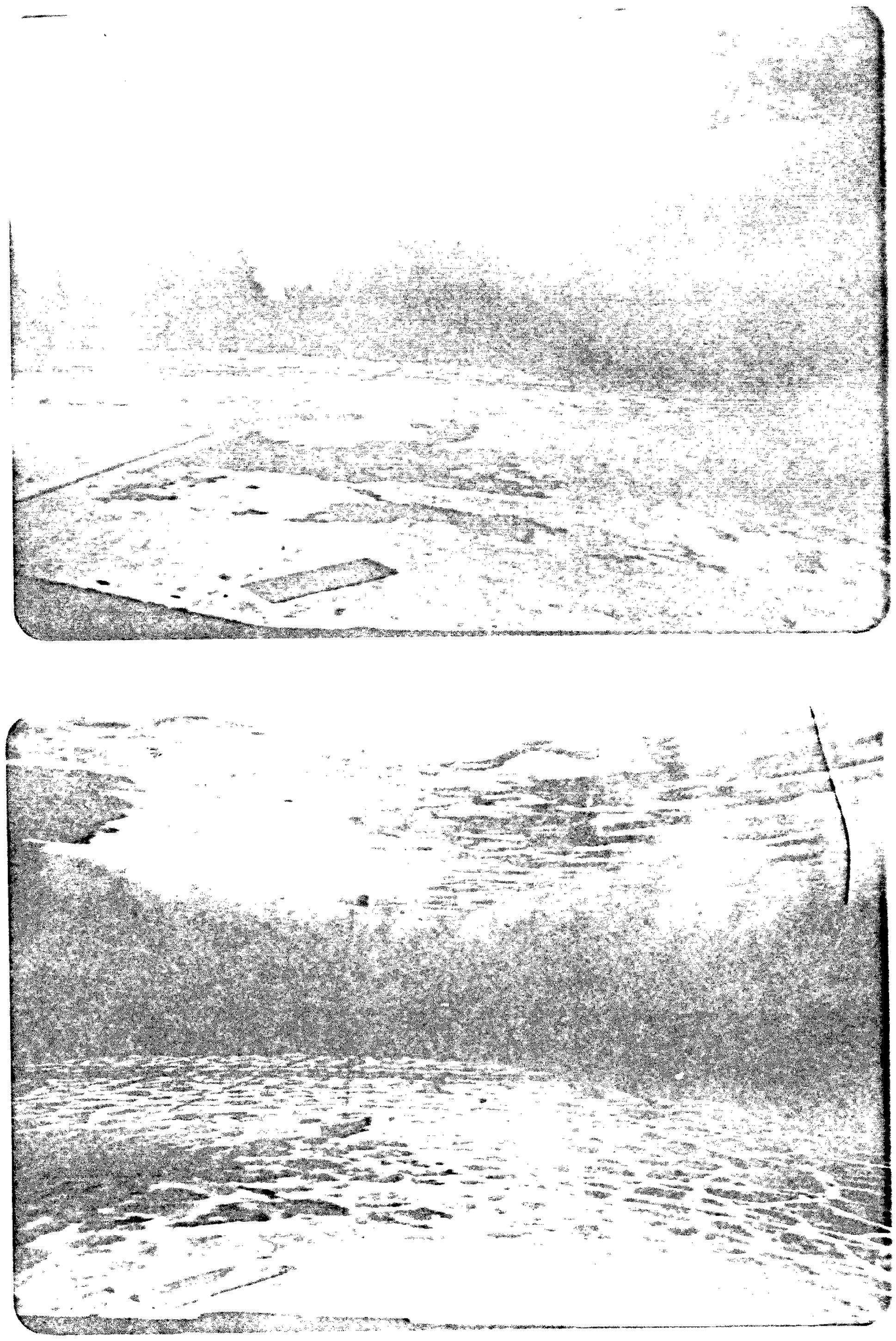


Figure 31. Continued.

4. Obtain the desired sea state.

5. Start the water pump and bring the water jet to the correct pressure.

6. Alert the photo video department that the test is commencing.

7. In the case of a stationary test the oil slick was distributed, the bridge horn sounded and the boom swung through the oil slick.

8. In the case of a tow test the bridge horn was sounded, the tow begun and oil distribution begun when the correct tow speed was achieved.

9. At the conclusion of the test run remove the oil from the water's surface using the skimming boom or fire hoses.

10. Prepare for the next test.

*Consistent sweep widths were maintained for test comparison purposes. In order to compensate for the movement of the water jet impact point due to the inward angle of the nozzle, the boom splay angle was adjusted.

Both tow tests and stationary tests were conducted according to matrices (Tables 7 and 8) developed by the OHMSETT engineering staff in conjunction with the US EPA project officer. The results from the tow tests (Table 9) were organized to clarify the relationship of the independent parameters to the dependent parameters. The stationary tests were qualitatively analyzed and are commented on later in this report. Due to time constraints, all of the tests in the original test matrices could not be run.

The objective of the first pair of water jet booms made was to be from 6 to 12 m long, strong enough to survive in waves and light enough to be handled and supported easily. The booms were constructed from 1.8 m sections of 6.4 cm ID standard aluminum pipe welded together. The first boom failed at a welded point due to the force of the water inside of it and the guy wire forces outside. The joint was rewelded and stiffeners were incorporated at each joint to add strength. Stiffeners were not welded over the entire length of the pipe boom until the next generation of water jet booms were made. The repaired booms proved able to support themselves and the water with the aid of the guy wires but they were still too flexible. During tow tests in the 0.5 m harbor chop, the water jet on the end of the 12 m boom was whipped between 3 m above the water's surface and 0.5 m below the surface due to vessel pitch. The flexibility of the boom also caused problems in rigging the booms on the catamaran since the guy wires supporting the booms placed loads down the longitudinal axis of the boom. Any twist of the collar which held the boom to the vertical stanchion caused a bow to develop in the aluminum piping of the boom. As a result the collar had to be positioned carefully on the stanchion and tightened hard to prevent it from turning. Despite the problems, the booms performed well through the seven days of testing.

The second generation of water jet booms were made from 3 m sections of 7.6 cm ID standard aluminum pipe with three 0.64 cm x 3.8 cm aluminum strips welded symmetrically (120° spacing) down the length of the pipe (Figure 27). Standard weld

TABLE 7. WATER JET/OIL SKIMMER FEASIBILITY TEST MATRIX

Test no.	Tow speed (kts)	Wave	Slick thk (mm)	Slick width (m)	Nozzle ID (cm)	No. of nozzles*	Pressure (kPa)	Nozzle angle in/fwd (deg)	Length of boom (m)
SD-1	0-4	Calm	0	0	---	0	0	0/0	---
SD-2	0-6	Calm	0	0	---	0	0	0/0	---
1	4	Calm	2	4.25	---	0	0	0/0	7
2	4	Calm	2	4.25	2.1	1	210	0/0	7
3	4	Calm	2	4.25	2.1	1	420	0/0	7
4	4	Calm	2	4.25	2.1	1	560	0/0	7
5	4	Calm	2	4.25	2.7	1	210	0/0	7
6	4	Calm	2	4.25	2.7	1	420	0/0	7
7	4	Calm	2	4.25	2.7	1	560	0/0	7
8	4	Calm	2	4.25	1.58	1	210	0/0	7
9	4	Calm	2	4.25	1.58	1	420	0/0	7
10	4	Calm	2	4.25	1.58	1	560	0/0	7
11	4	Calm	2	4.25	1.58	1	690	0/0	7
12	4	Calm	2	4.25	1.05	1	210	0/0	7
13	4	Calm	2	4.25	1.05	1	420	0/0	7
14	4	Calm	2	4.25	1.05	1	690	0/0	7
15	4	Calm	2	4.25	1.05	1	210	10/0	7
16	4	Calm	2	4.25	1.05	1	420	10/0	7
17	4	Calm	2	4.25	1.05	1	690	10/0	7
18	4	Calm	2	4.25	1.58	1	210	10/0	7
19	4	Calm	2	4.25	1.58	1	280	10/0	7
20	4	Calm	2	4.25	1.58	1	420	10/0	7
21	4	Calm	2	4.25	1.58	1	690	10/0	7
22	4	Calm	2	4.25	2.1	1	210	10/0	7
23	4	Calm	2	4.25	2.1	1	420	10/0	7
24	4	Calm	2	4.25	2.1	1	560	10/0	7
25	4	Calm	2	4.25	2.7	1	420	10/0	7
26	4	Calm	2	4.25	2.7	1	420	10/0	7
27	4	Calm	2	4.25	2.7	1	560	10/0	7
28	4	Calm	2	4.25	2.7	1	210	20/0	7
29	4	Calm	2	4.25	2.7	1	420	20/0	7
30	4	Calm	2	4.25	2.7	1	560	20/0	7
31	4	Calm	2	4.25	2.1	1	210	20/0	7
32	4	Calm	2	4.25	2.1	1	420	20/0	7
33	4	Calm	2	4.25	2.1	1	560	20/0	7
34	2	Calm	2	6	2.1	3	210	0/0	7
35	4	Calm	2	6	2.1	3	210	0/0	7
36	6	Calm	2	6	2.1	3	210	0/0	7

Continued

TABLE 7. (Continued)

Test no.	Tow speed (kts)	Wave	Slick thk (mm)	Slick width (m)	Nozzle ID (cm)	No. of nozzles*	Pressure (kPa)	Nozzle angle in/fwd (deg)	Length of boom (m)
37	4	Calm	2	6	2.1	3	210	10/0	7
38	4	Calm	2	6	1.58	3	210	10/0	7
39	4	Calm	2	6	1.58	3	210	0/0	7
40	4	Calm	2	6	1.58	3	210	0/0	7
41	4	Calm	2	6	1.58	3	210	0/0	7
42	4	Calm	2	6	2.1	1	420	0/0	7
43	4	Calm	2	6	2.1	1	560	0/0	7
44	4	Calm	2	6	2.7	1	420	0/0	7
45	4	Calm	2	6	2.7	1	560	0/0	7
46	4	Calm	2	6	2.7	1	420	10/0	7
47	4	Calm	2	6	2.7	1	560	10/0	7
48	4	Calm	2	6	2.1	1	420	10/0	7
49	4	Calm	2	6	2.1	1	560	10/0	7
50	4	Calm	2	6	2.1	1	420	20/0	7
51	4	Calm	2	6	2.1	1	560	20/0	7
52	4	Calm	2	6	2.7	1	420	20/0	7
53	4	Calm	2	6	2.7	1	560	20/0	7
54	4	Calm	2	6	2.7	1	560	0/45	7
55	4	Calm	2	6	2.7	1	560	10/45	7
56	4	Calm	2	6	2.7	1	560	20/45	7
57	4	Calm	TBD	6	2.7	1	560	TBD	7
58	4	Calm	TBD	6	2.7	1	560	TBD	7
59	4	Calm	2	6	2.1	1	TBD	0/0	12
60	4	Calm	2	6	2.1	1	TBD	0/0	12
61	6	Calm	2	6	2.1	1	TBD	0/0	12
62	6	Calm	2	6	2.1	1	TBD	0/0	12
63	4	Calm	2	6	2.7	1	TBD	0/0	12
64	4	Calm	2	6	2.7	1	TBD	0/0	12
65	6	Calm	2	6	2.7	1	TBD	0/0	12
66	6	Calm	2	6	2.7	1	TBD	0/0	12
67	4	Calm	2	6	2.7	1	TBD	10/0	
68	4	Calm	2	6	2.7	1	TBD	20/0	
69	6	Calm	2	6	2.7	1	TBD	10/0	
70	6	Calm	2	6	2.7	1	TBD	20/0	
71	2	0.5m HC		2	6	2.7	1	TBD	
72	4	0.5m HC		2	6	2.7	1	TBD	
73	6	0.5m HC		2	6	2.7	1	TBD	

TABLE 8. U.S COAST GUARD SKIMMER/WATER JET TEST MATRIX (STATIONARY TEST)

Test no.	Wave (m)	Nozzle ID (cm)	No. of nozzles	Water press. (kPa)	Nozzle tilt angle (deg)	Nozzle Angle fwd (deg)	Slick width (m)	Tow speed (kts)
1	0	2.1	1	560	0	0	None	0
2	0	2.1	1	560	22½	0	None	0
3	0	2.1	1	560	45	0	None	0
4	0	2.1	1	560	0	22½	None	0
5	0	2.1	1	560	0	45	None	0
6	0	2.1	1	560	22½	22½	None	0
7	0	2.1	1	560	45	45	None	0
8	0	2.1	1	560	0	0	3	4
9	0	2.1	1	560	22½	0	3	4
10	0	2.1	1	560	45	0	3	4
11	0	2.1	1	560	0	22½	3	4
12	0	2.1	1	560	0	45	3	4
13	0	2.1	1	560	22½	22½	3	4
14	0	·2.1	1	560	45	45	3	4
15	0	2.1	1	560	TBD	TBD	3	6
16	0	2.1	1	560	TBD	TBD	3	6
17	0.5HC	2.1	1	560	TBD	TBD	3	4
18	0.5HC	2.1	1	560	TBD	TBD	3	4
19	0.5HC	2.1	1	560	TBD	TBD	3	6
20	0.5HC	2.1	1	560	TBD	TBD	3	6
21	0.3HC	2.1	1	560	TBD	TBD	3	4
22	0.3HC	2.1	1	560	TBD	TBD	3	4
23	0.3HC	2.1	1	560	TBD	TBD	3	6
24	0.3HC	2.1	1	560	TBD	TBD	3	6

Notes:

1. Stationary tests had photos and movies taken through the underwater window.
2. Tow speed was simulated by swinging the water jet boom.
3. Oil slick was delivered on the water from a stationary bridge. Slick thickness was about 2 mm.

TABLE 9. U.S. COAST GUARD SKIMMER/WATER JET TEST MATRIX (SLICK CONVERGENCE TESTS)

Test no.	Wave (m)	Nozzle ID (cm)	No. of nozzles on one side	Water press. (kPa)	Nozzle Tilt angle (deg)	Nozzle Angle fwd. (deg)	Slick width (m)	Tow speed (kts)	Length of boom (m)
25	0	2.1	1	560	TBD	TBD	6	4	20
26	0	2.1	1	560	TBD	TBD	6	6	20
27	0.5 HC	2.1	1	560	0	0	6	4	20
28	0.5 HC	2.1	1	560	0	0	6	6	20
29	0.5 HC	2.1	1	560	0	45	6	4	20
30	0.5 HC	2.1	1	560	0	45	6	6	20
31	0.5 HC	2.1	1	560	0	TBD	6	4	9
32	0.5 HC	2.1	1	560	0	TBD	6	6	9
33	0.5 HC	2.1	1	560	0	TBD	6	4	12
34	0.5 HC	2.1	1	560	0	TBD	6	6	12
35	0.5 x 15	2.1	1	560	0	TBD	6	4	12
36	0.5 x 15	2.1	1	560	0	TBD	6	6	12
37	0.5 x 15	2.1	1	560	0	TBD	6	4	9
38	0.5 x 15	2.1	1	560	0	TBD	6	6	9
39	0.5 x 15	2.1	1	560	0	TBD	6	4	20
40	0.5 x 15	2.1	1	560	0	TBD	6	6	20

Notes:

1. Non-stationary testing.
2. Slick length 45 m.
3. Oil slick thickness 2 mm.

flanges were welded at each end of the pipe sections. These allowed the sections to be joined and separated easily. With a rubber gasket between the flanges very little water leaked even at a pressure of 700 kPa. The construction proved to be lightweight, easy to handle, capable of holding the water pressure, and stiff enough for easy rigging and consistent performance in waves. This design was used for the stationary boom pivoting tests, some tow tests on the catamaran, and then was stored to be used on the U.S. Coast Guard's ZRV skimmer when it came to OHMSETT for testing.

DISCUSSION OF RESULTS

The results obtained from earlier tests were again proven by these series of tests (Table 10)--the larger the nozzle and the greater the pressure, the better the performance. Comparison of the plots of slick movement using water jets from 1.25 to 2.66 cm ID bear this out clearly.

The benefit of angling the jets was also established in these tests. By angling the jet in the direction of the desired oil movement performance was increased on 7 m booms. Even an angle of ten degrees was beneficial (Figures 32 through 34). The tests only included inwardly directed angles up to 20°. The reason for the increased performance in the use of the horizontal component of force of the angled water stream to push the oil. The reduction of the amount of air entrained deeply by not having the jet vertical did not have an effect on these tests since the objective was to move the oil quickly--not to hold the oil in place after it had been moved. Using a 7 m boom (including nozzle fittings and swivel joints at the vertical stanchion) on the catamaran the slick had to be converged in 3.6 seconds at four knots. The slick holding potential of the water jets was not required for such a short interaction interval. The slick was moved further using a 12-m boom and the angling of the jets inward did not seem to consistently increase performance (Figures 35 and 36).

The forward angle of the water jets was not beneficial to performance (Figures 37 and 38). The theory behind the forward angle was to place the point of impact further ahead of the skimmer, essentially increasing the length of the boom. The use of a longer boom increased performance (Figures 35 and 36) but the water jet nozzle needs to be relatively close (approximately 1 m) to the point of impact to perform well. By angling the jet forward the travel path of the water stream was increased beyond the distance where the stream began to lose coherence. Penetration and air entrainment was reduced and the impact area of the water was increased. The horizontal force component of the water stream was directed forward, which did not help to converge the slick. At times the forward angled jet did produce a dramatic initial wave which rolled the oil away from the jet. It appeared to "plow" the surface of the water over and give the oil a push off to the side. The plowing effect was especially noticeable when the jet was angled forward and inward (Figure 39). However, this initial push was not enough to make up for the loss in current usually developed by the entrained air and the set of rolling, breaking waves which a vertically directed jet produced (Figures 35 and 36).

The pitch of the catamaran in waves resulted in the worst performance by the angled water jets. Vessel roll and heave also caused changes in impact point and length of travel of the water jets but the effects were not as dramatic as those caused by pitch (Figure 40). Because the jets were extended over 6 m beyond the bows of the

TABLE 10. WATER JETS TEST RESULTS (SLICK CONVERGENCE TESTS).

Boom lgt (m)	Nozzle I.D. (cm)	Tow speed (kts)	Press. (kPa)	Nozzle Angle in/fwd (deg)	Slick thk (mm)	No. of nozzles on one side	Slick move (m)	Wave (m)	Orig width (m)	Final width (m)	Test no.
7	1.25	4	210	0/0	2.2	1	1.37	C	4.26	2.89	16
7	1.25	4	210	10/0	2.2	1	1.52	C	4.26	2.74	19
7	1.25	4	420	0/0	2.2	1	1.98	C	4.26	2.28	15
7	1.25	4	700	0/0	2.2	1	2.28	C	4.26	1.98	14
7	1.25	4	700	10/0	2.2	1	2.59	C	4.26	1.67	17
7	1.25	4	700	10/0	2.2	1	2.51	C	4.26	1.75	18
7	1.6	4	210	0/0	2.2	1	1.60	C	4.26	2.66	13
7	1.6	4	210	10/0	2.2	1	1.98	C	4.26	2.28	23
7	1.6	4	280	0/0	2.9	1	1.82	C	4.26	2.43	12
7	1.6	4	280	10/0	2.2	1	2.28	C	4.26	1.98	22
7	1.6	4	330	0/0	1.7	3	1.82	C	6.08	4.26	45
7	1.6	4	330	0/0	2.1	3	2.13	C	6.08	3.95	47
7	1.6	4	420	0/0	2.2	1	1.98	C	4.26	2.28	11
7	1.6	4	420	10/0	2.2	1	2.43	C	4.26	1.82	21
7	1.6	4	700	0/0	2.9	1	2.28	C	4.26	1.98	10
7	1.6	4	700	0/0	2.1	1	2.28	C	6.08	3.81	48
7	1.6	4	700	10/0	2.2	1	2.97	C	4.26	1.37	20
7	1.6	6	330	0/0	3.1	3	1.67	C	6.08	4.41	46
7	2.1	2	210	0/0	1.2	3	4.41	C	6.08	1.67	37
7	2.1	4	210	0/0	2.1	3	2.74	C	6.08	3.35	38
7	2.1	4	210	10/0	1.5	3	3.04	C	6.08	3.04	40
7	2.1	4	245	0/0	2.1	1	2.20	C	4.26	2.05	6
7	2.1	4	245	10/0	2.9	1	2.28	C	4.26	1.98	26
7	2.1	4	420	0/0	2.2	1	2.59	C	4.26	1.67	7
7	2.1	4	420	10/0	2.2	1	2.89	C	4.26	1.37	25
7	2.1	4	560	0/0	2.2	1	2.59	C	4.26	1.67	5
7	2.1	4	560	0/0	2.1	1	2.59	C	4.26	1.67	33
7	2.1	4	560	0/0	2.1	1	2.59	C	4.26	1.67	34

(Continued)

TABLE 10. (Continued)

Boom lgt (m)	Nozzle I.D. (cm)	Tow speed (kts)	Press. (kPa)	Nozzle Angle in/fwd (deg)	Slick thk (mm)	No. of nozzles on one side	Slick move (m)	Wave (m)	Orig width (m)	Final width (m)	Test no.
7	2.1	4	560	10/0	2.2	1	2.97	C	4.26	1.29	24
7	2.1	4	560	10/0	2.1	1	2.89	C	4.26	4.41	35
7	2.1	4	560	10/0	2.1	1	2.89	C	4.26	4.41	32
7	2.1	4	560	20/0	2.1	1	3.20	C	4.26	1.06	31
7	2.1	4	560	20/0	2.1	1	3.04	C	4.26	1.21	36
7	2.1	4	590	10/0	1.6	1	2.59	C	6.08	3.50	42
7	2.1	4	590	10/0	2.1	1	2.74	C	6.08	3.35	41
7	2.1	4	590	10/0	3.0	1	2.13	C	6.08	3.96	44
7	2.1	4	590	0/45	2.1	1	2.43	C	4.26	1.82	71
7	2.1	4	590	0/45	2.1	1	2.59	C	6.08	3.50	70
7	2.1	4	590	10/45	2.1	1	3.65	C	6.08	2.43	S-7
7	2.1	4	590	20/45	2.0	1	2.74	0.5 HC	4.26	1.52	78
7	2.1	4	590	20/45	3.0	1	2.43	0.5 HC	6.08	3.65	67
7	2.1	4	590	20/45	2.1	1	2.74	C	4.26	1.52	76
7	2.1	4	590	45/45	2.9	1	2.28	C	4.26	1.98	80
7	2.1	4	590	45/45	3.0	1	Ind	0.5 HC	4.26	Ind	82
7	2.1	6	210	0/0	3.1	3	2.13	C	6.08	3.96	39
7	2.1	6	590	0/45	2.0	1	1.67	C	4.26	2.89	72
7	2.1	6	590	10/45	3.1	1	2.43	C	4.26	1.82	S-8
7	2.1	6	590	10/45	3.1	1	1.67	C	4.57	2.89	S-9
7	2.1	6	590	20/45	3.1	1	1.52	C	4.57	3.04	S-10
7	2.1	6	590	20/45	2.9	1	2.13	C	4.26	2.13	77
7	2.1	6	590	20/45	2.9	1	2.59	0.5 HC	4.26	1.82	79
7	2.1	6	590	20/45	2.1	1	Ind	0.5 HC	20	Ind	66
7	2.1	6	590	45/45	2.9	1	2.13	C	4.26	2.13	81
12	2.1	4	590	0/0	2.1	1	3.12	C	20	2.97	49

(Continued)

TABLE 10. (Continued)

Boom lgt (m)	Nozzle I.D. (cm)	Tow speed (kts)	Press. (kPa)	Nozzle Angle in/fwd (deg)	Slick thk (mm)	No. of nozzles on one side	Slick move (m)	Wave (m)	Orig width (m)	Final width (m)	Test no.
12	2.1	6	590	0/0	3.1	1	2.43	C	6.08	3.65	50
7	2.7	4	210	0/0	2.9	1	1.67	C	4.26	2.59	9
7	2.7	4	245	10/0	1.1	1	2.13	C	4.26	2.13	28
7	2.7	4	245	20/0	2.2	1	1.82	C	4.26	2.43	30
7	2.7	4	420	0/0	2.2	1	2.13	C	4.26	2.13	8
7	2.7	4	420	10/0	1.1	1	2.66	C	4.26	1.60	27
7	2.7	4	420	20/0	1.1	1	2.59	C	4.26	1.67	29
7	2.7	4	490	20/0	2.1	1	Ind	C	6.08	Ind	68
7	2.7	6	490	20/0	2.1	1	2.13	C	6.08	3.95	69
12	2.7	2	180	20/0	2.2	1	Ind	0.5 HC	6.08	Ind	63
12	2.7	4	180	0/0	2.3	1	2.89	C	6.08	3.20	57
12	2.7	4	180	10/0	2.1	1	3.20	C	6.08	2.89	59
12	2.7	4	180	20/0	2.0	1	3.35	C	6.08	2.74	61
12	2.7	4	180	20/0	2.1	1	Ind	0.5 HC	6.08	Ind	64
12	2.7	4	490	0/0	2.1	1	3.81	C	6.08	2.28	56
12	2.7	4	490	10/0	2.1	1	3.81	C	6.08	2.28	55
12	2.7	4	490	20/0	2.1	1	3.50	C	6.08	2.59	54
12	2.7	6	180	0/0	3.1	1	2.43	C	6.08	3.65	58
12	2.7	6	180	10/0	3.1	1	2.28	C	6.08	3.81	60
12	2.7	6	180	20/0	3.0	1	3.04	C	6.08	3.04	62
12	2.7	6	180	20/0	2.1	1	1.82	0.5 HC	6.08	4.26	65
12	2.7	6	490	0/0	4.6	1	2.43	C	6.08	3.65	51
12	2.7	6	490	10/0	3.1	1	2.59	C	6.08	3.50	52
12	2.7	6	490	20/0	3.1	1	2.89	C	6.08	3.20	53
6	2.1	4	590	0/45	2.1	1	2.74	0.3 HC	4.57	1.82	18
6	2.1	4	590	0/45	2.3	1	1.82	0.6 HC	4.57	2.74	17
6	2.1	4	590	45/45	2.4	1	2.28	C	4.57	2.28	15
6	2.1	4	590	0.45	2.4	1	2.13	0.3 HC	4.57	2.43	19
6	2.1	6	590	45/45	2.2	1	2.43	C	4.57	2.13	16
9	2.1	4	590	0/45	2.0	1	2.28	C	4.57	2.28	20

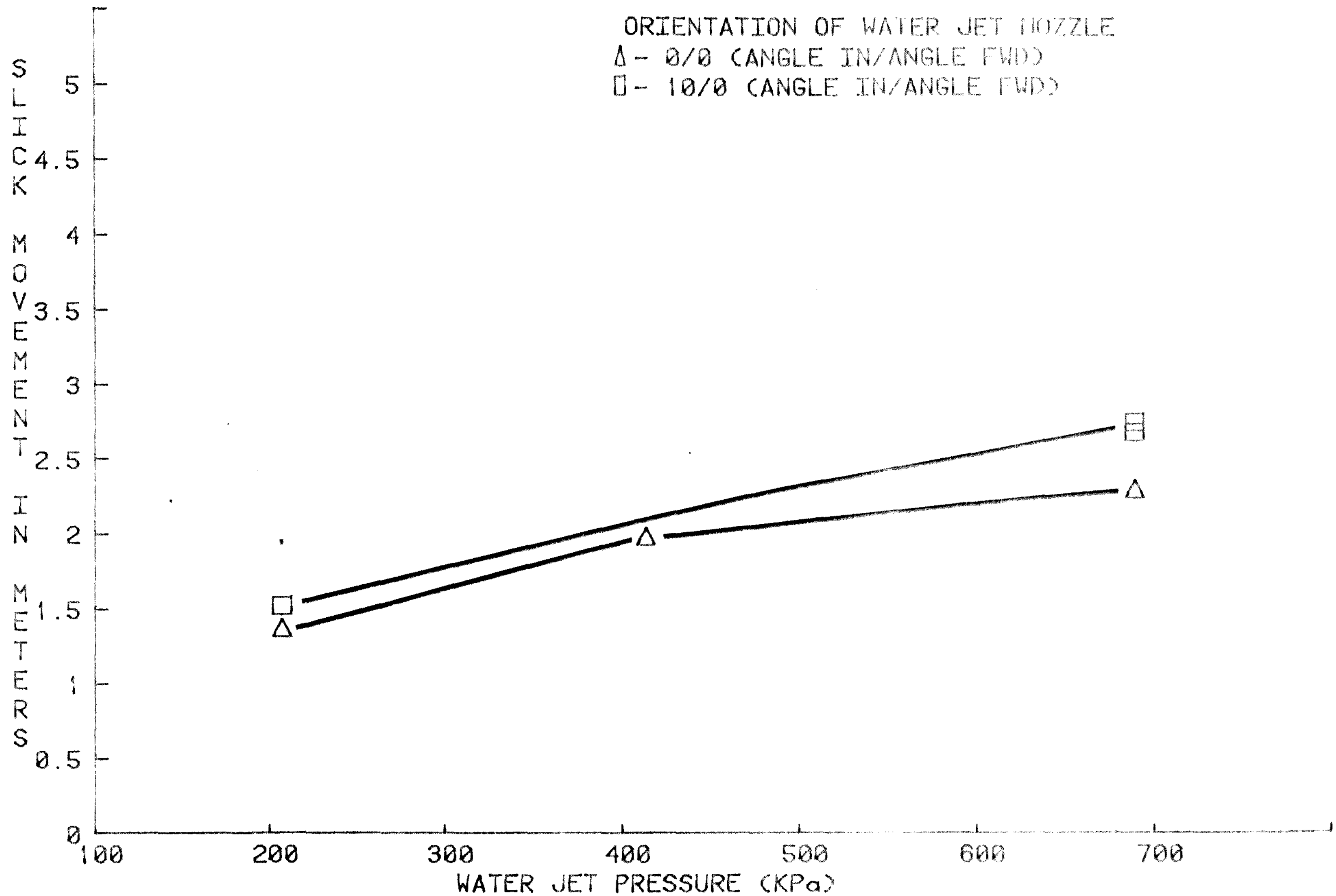


Figure 32. Performance of a 1.25-cm ID water jet at 4 kt in calm water (oil slick convergence test), 2.2-mm slick.

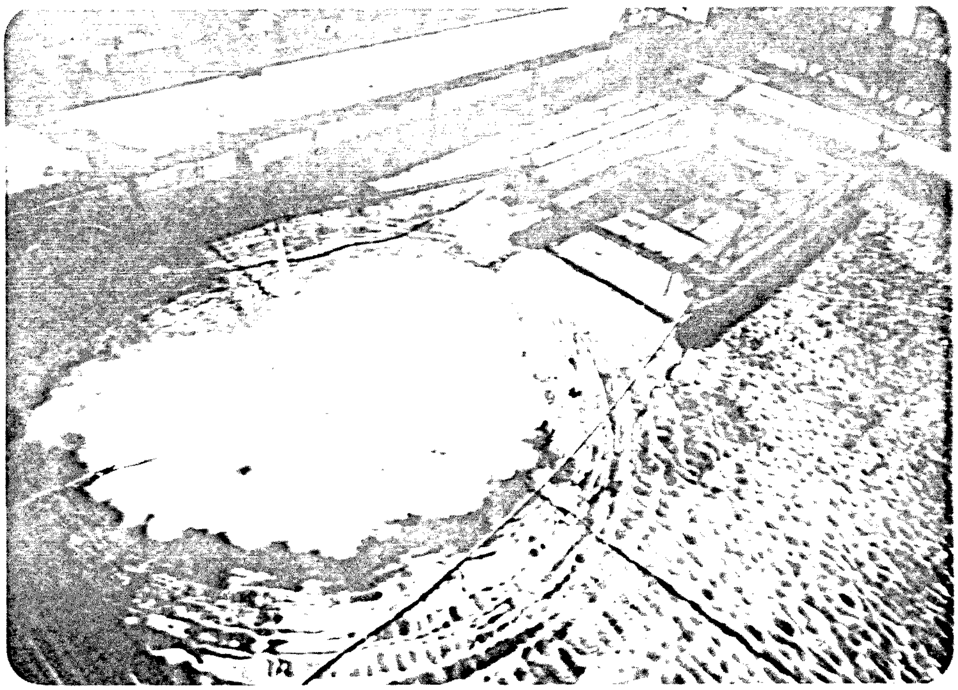


Figure 33. An inwardly directed nozzle on a single water jet boom mounted on the OHMSETT catamaran. Note that the greatest portion of current energy is directed in towards the centerline of the system.

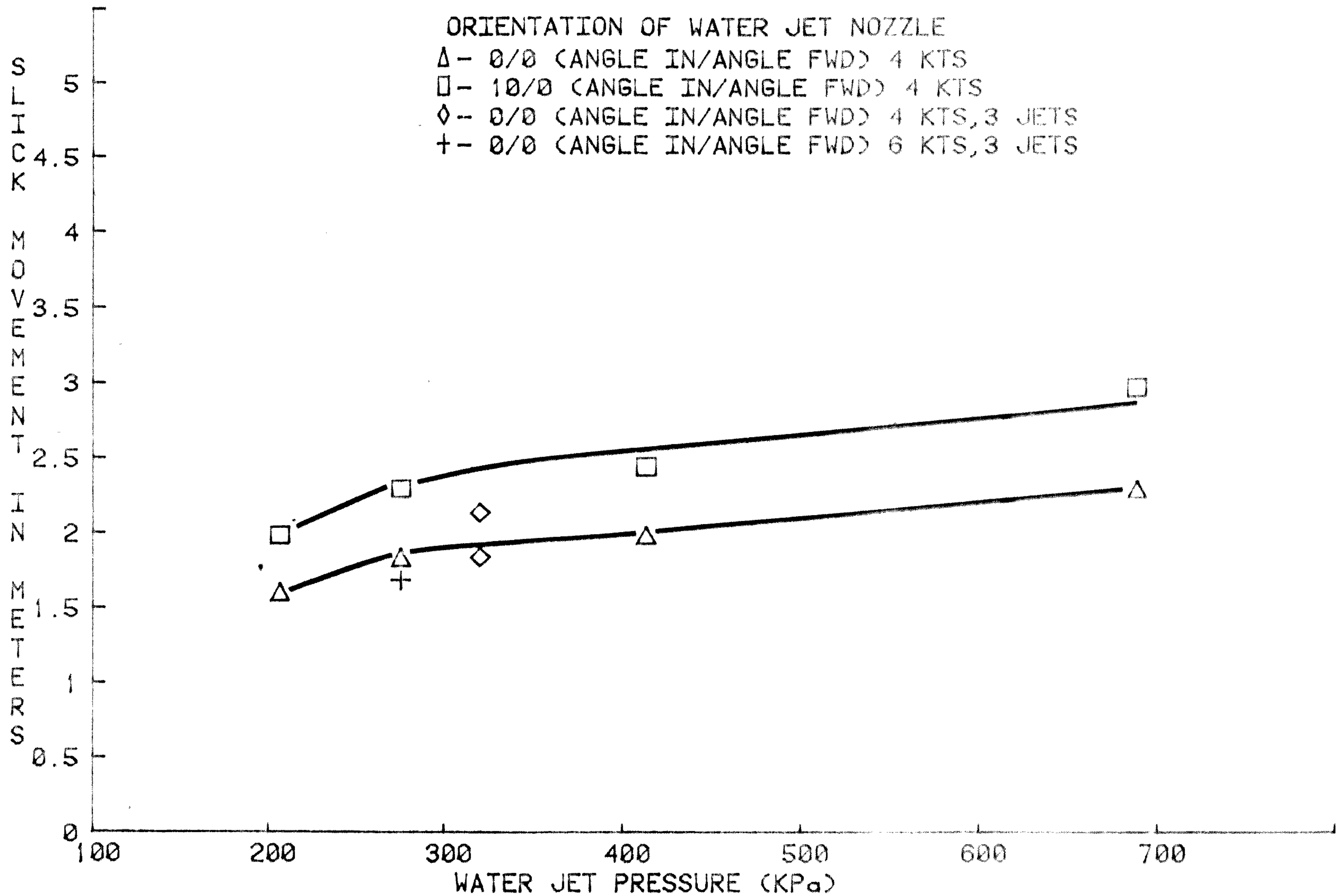


Figure 34. Performance of a 1.6-cm ID water jet at 4 kt and 6 kt operating in calm water, (oil slick convergence test) 2 to 3-mm slick.

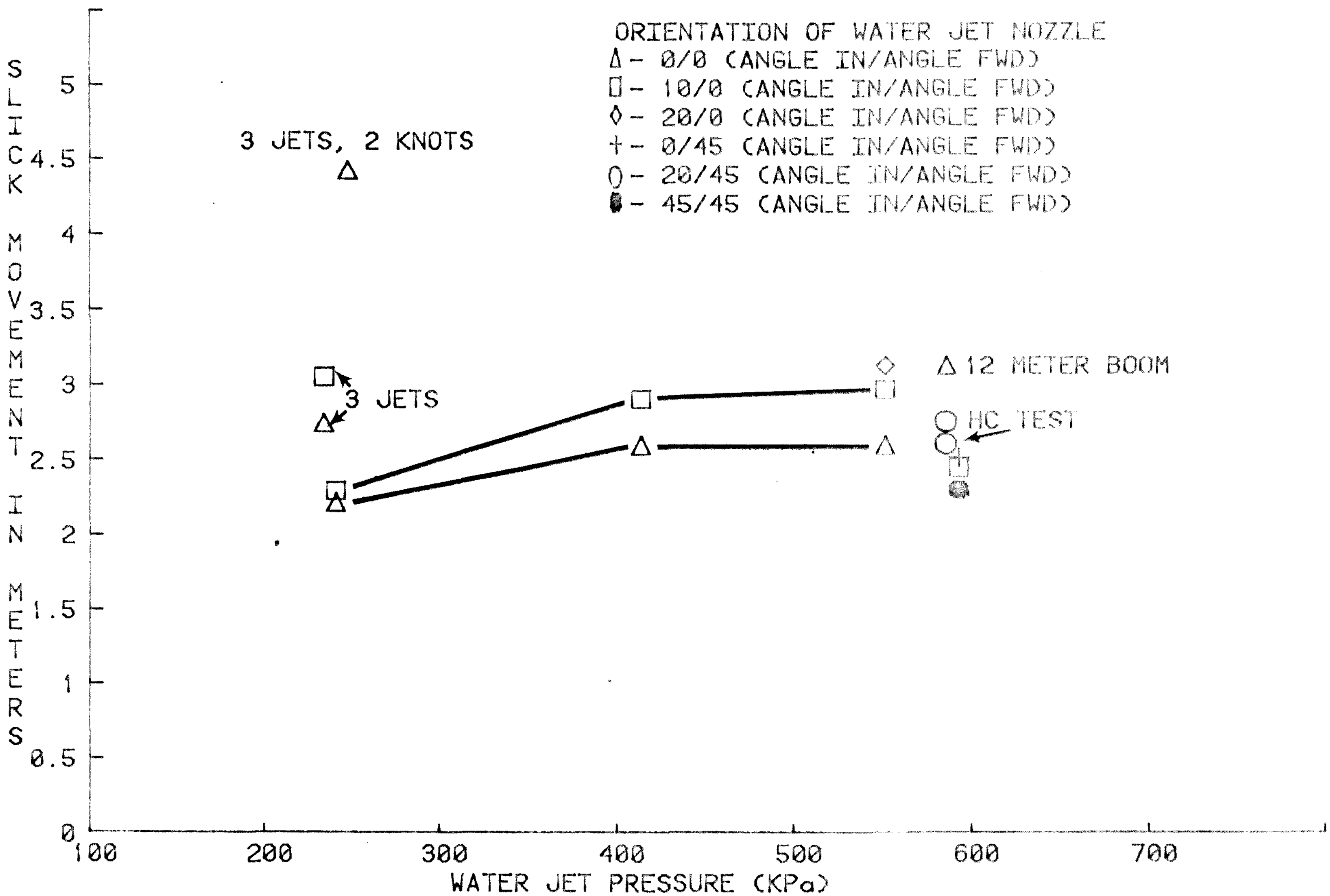


Figure 35. Performance of a 2.1-cm ID water jet at 4 kt. Oil slick of 2-3-mm thickness, calm water, 7-m boom (oil slick convergence test). Note: A harbor chop test at 4 kt, a calm water test at 2 kt, a 12-m boom test, and a test using three jets were plotted for comparison.

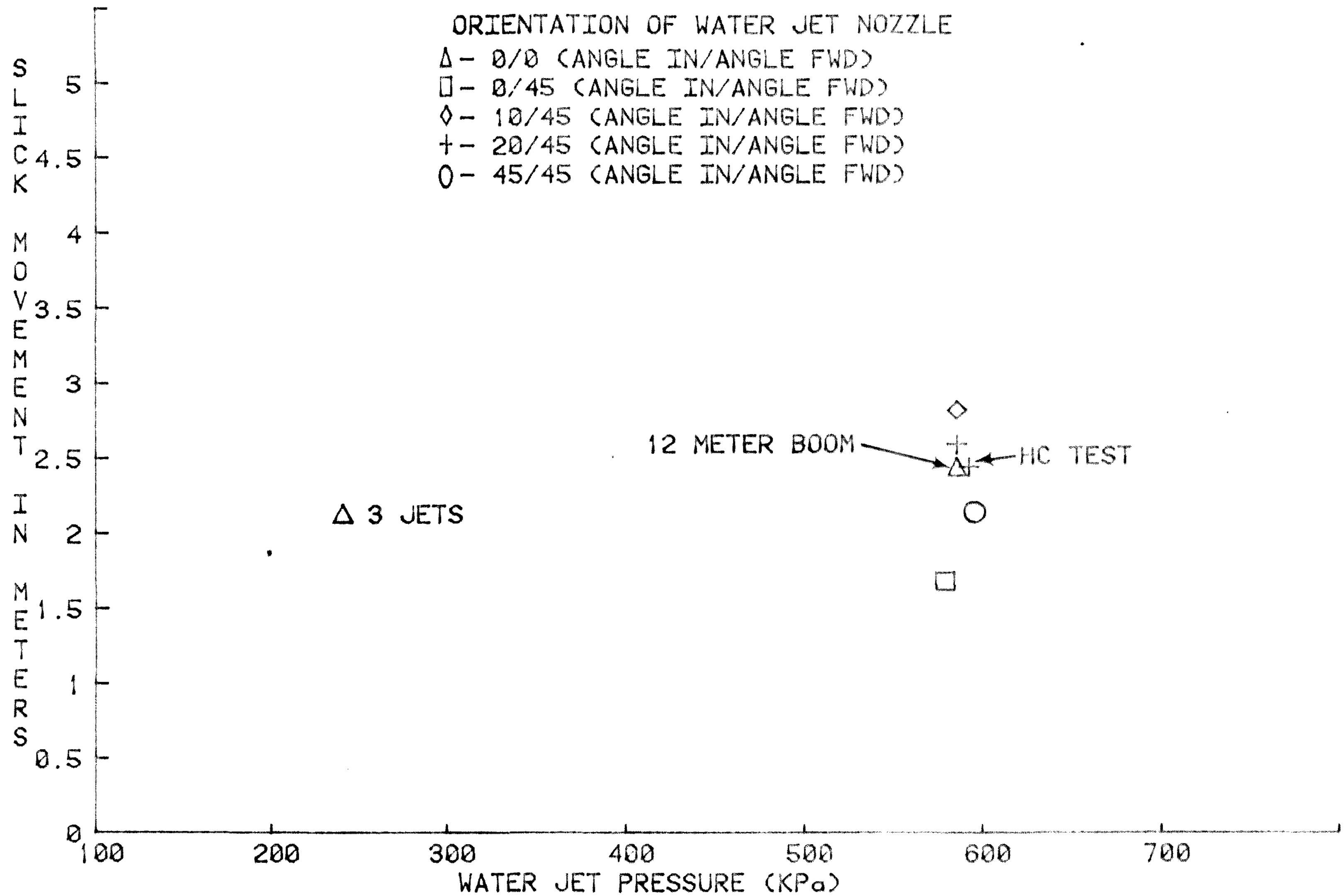


Figure 36. Performance of a 2.1-cm ID water jet at 6 kt operating on a 7-m boom in calm water (oil slick convergence test). Note: A harbor chop test, a 12-m boom test and a multiple jet test were plotted for comparison, all with 2-3-mm slick.

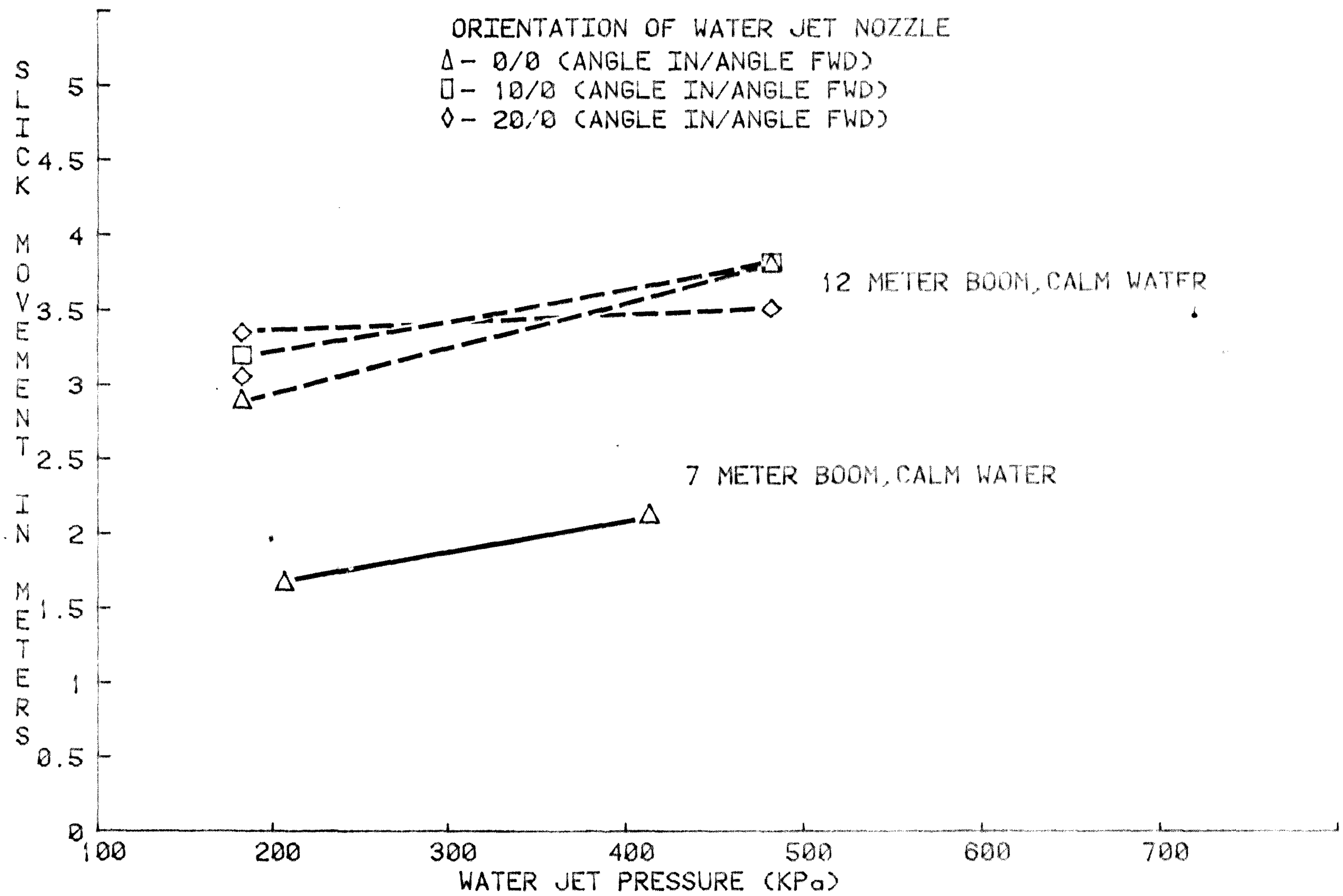


Figure 37. Performance of a 2.7-cm ID water jet at 4 kt on a 7-m and 12-m boom (oil slick convergence test), 2.3-m slick.

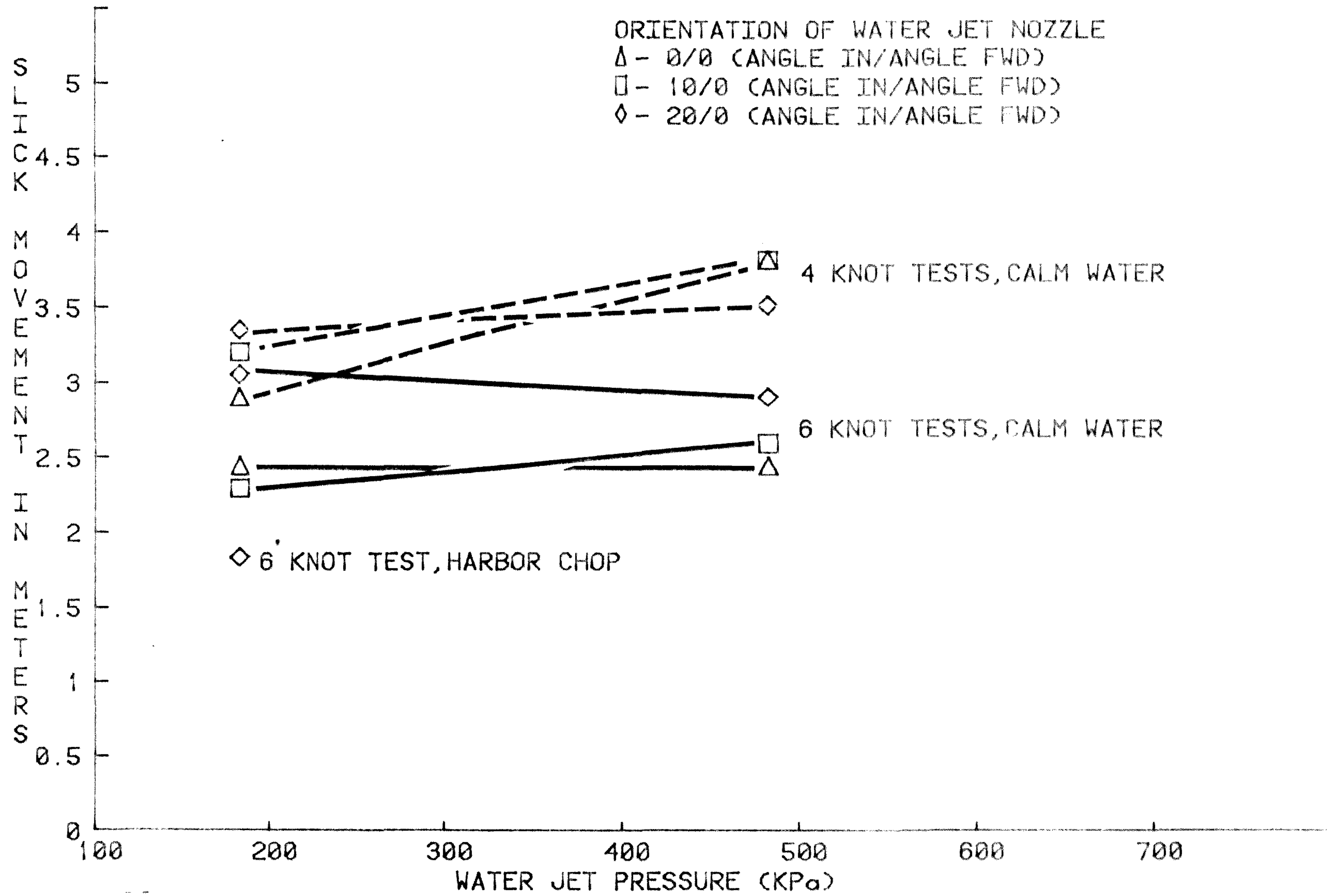


Figure 38. Performance of a 2.7-cm ID water jet at 4 kt and 6 kt operating on a 12-m boom (oil slick convergence test).

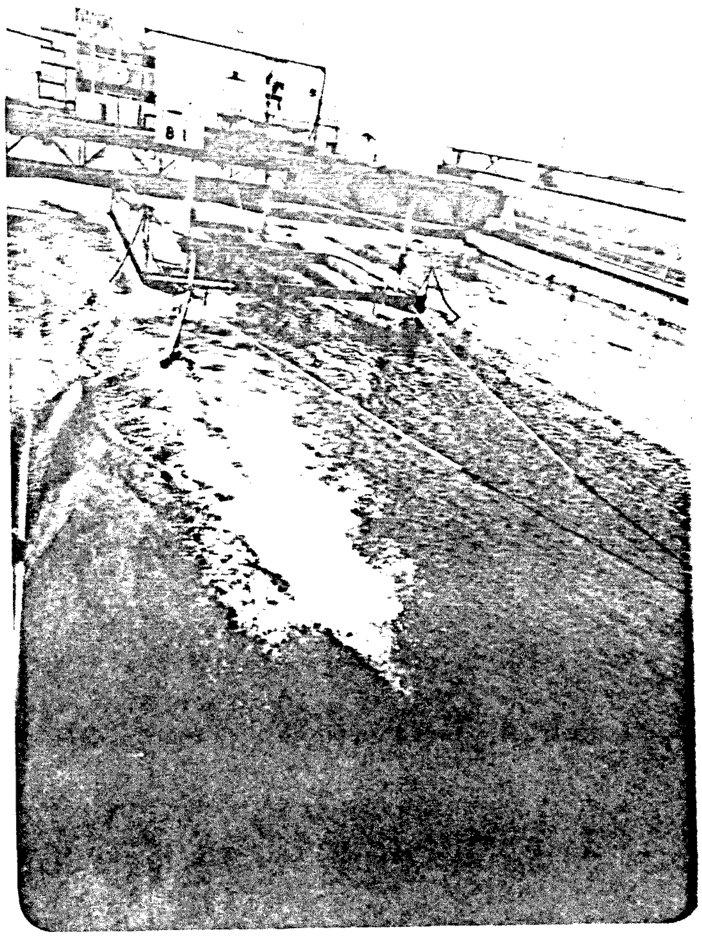


Figure 39. Water jet angled forward and inward during a clam water test. (Note the rolling wave produced at the impact point).

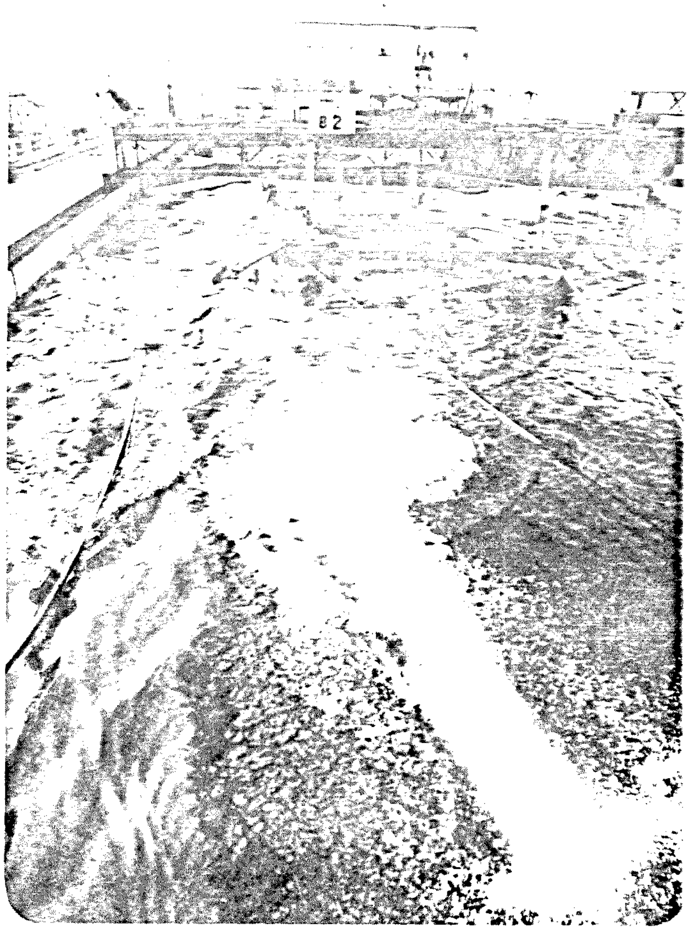


Figure 40. Water jet angled forward and inward during a wave test. (Note the impact point traveling far forward and onto the oil slick due to the rear pitch of the catamaran).

hulls, the amplitude of pitch was increased at the water jet nozzles. When the nozzles were raised upward during a stern pitch of the catamaran the point of impact moved dramatically forward from its calm water or intended position. When the jet was angled at 45° inward and 45° forward, the water sprayed over the oil slick entraining oil and caused an irregularly-shaped slick. This also lengthened the path of travel of the water stream and thus decreased the effectiveness of the jet. When a bow pitch was experienced the impact point was brought back across the slick to directly beneath the nozzles. During some wave tests the performance of the water jet was indeterminant because the resulting slick was so irregular.

One of the most important finds of this test program was that angling the water jet nozzles is not beneficial when operating in wave conditions which cause the vessel to pitch, roll, and heave. Since such conditions are the norm in oil spill recovery a general operation rule can be made--point the jets straight down into the water. This simplifies the construction and use of the water jets. Those of us in the relatively pristine world of test tanks are prone to strive for the optimum angle and operating pressures to tweak the last bit of performance from the system. Those people who work in the usually oil-blackened and uncomfortable field operations are prone to use a simple, dependable, and rugged deployment of a system. Their attention is often called for in areas of personnel safety and labor-intensive duties. They have little time to determine if the pitch of the skimmer has changed sufficiently over the last 15 minutes to warrant a change in water jet impingement angle. A system which has the best chances of performing well when used in its simpliest configuration will probably be looked upon favorably by field operators.

Three water jets in tandem, spaced about 1 m apart, performed as well as or better than one water jet at the same pressure (Figures 34 and 35). But by using more than one jet, a significant drop in available water jet pressure was experienced. In some instances an increase in pressure of one water jet could equal the performance of the three jets with reduced pressure. A possible drawback to using the tandem arrangement at high tow speed was that the wave train produced by the three jets persisted longer than that produced by a single jet (Figure 41). Although the breaking waves move oil, they also entrain it slightly below the surface. The entrained oil may not have sufficient time to rise if the breaking wave persists into the mouth of the skimmer.

The tests conducted with the catamaran stationary and pivoting the water jet boom in an arc provided an interesting view of oil slick movement mechanisms and entrainment characteristics of a water jet. From the underwater window the point of view of a particle behind and beneath a water jet was available. The vertically directed jets appeared to entrain the most air and to a greater depth, which maintained the surface current caused by the rising air bubbles for the longest period of time. The angled jet moved the oil the fastest but also entrained the most oil.

Figure 41. Tandem water jets during a tow test. (Note the bow wave of the second water jet coincided with the second wave of the first jet).

SECTION 4

WATER JETS MOUNTED ON INDIVIDUAL FLOATS

INTRODUCTION

Water jets on individual floats have the potential to solve many problems associated with oil spill recovery operations. Equipment deployment, wave effects, ship traffic interference, and fire are some of the hindrances which could be coped with by proper use of water jets on floats.

Equipment deployment--an oil barge offloading site is often required to ring the barge with a fabric boom before oil can be offloaded. Obviously the boom cannot be in place before the barge arrives and therefore a trained boom deployment/retrieval team must be employed after the barge arrives and before it leaves. A water jet system could be used in place of a fabric boom. Water jets on floats could be supplied by submerged hoses, can be left in position, and the only action required would be to start a pump and turn a valve or two. The water jet floats could be bumped aside or even momentarily submerged by the barge and tug as they arrive or leave.

Wave effects--when using conventional fabric booms to converge an oil slick into a skimmer the reflection of small waves between the booms cause problems. The waves are finally concentrated in front of the skimmer inlet causing oil entrainment, oil loss from the booms, and a decrease in skimmer performance. A series of water jet floats used in place of the booms (Figure 42) could allow waves to pass and yet converge the oil.

Ship traffic interference--if an oil spill occured and oil retaining had to be conducted in a ship channel the damage caused by a wayward vessel could be minimized if it passed into the retained oil slick through a water jet float line. Many a fabric boom busy retaining oil has been destroyed by errant ship traffic. The result is a loss of oil retention until the vessel is removed and the boom repaired.

Fire--the possibility of damage to water jet floats by a fire is less than to a conventional fabric boom since the floats and jets can be made from steel. Since the action of the water jets maintain the oil away from the equipment, the flames may not even reach the water jet floats to endanger them.

Possibilities such as these prompted a series of tests to be conducted at OHMSETT which would determine the feasibility of using water jets on individual floats to control an oil slick. The tests were aimed at the use of such floats in a fast current situation. This chapter presents the results of those tests.

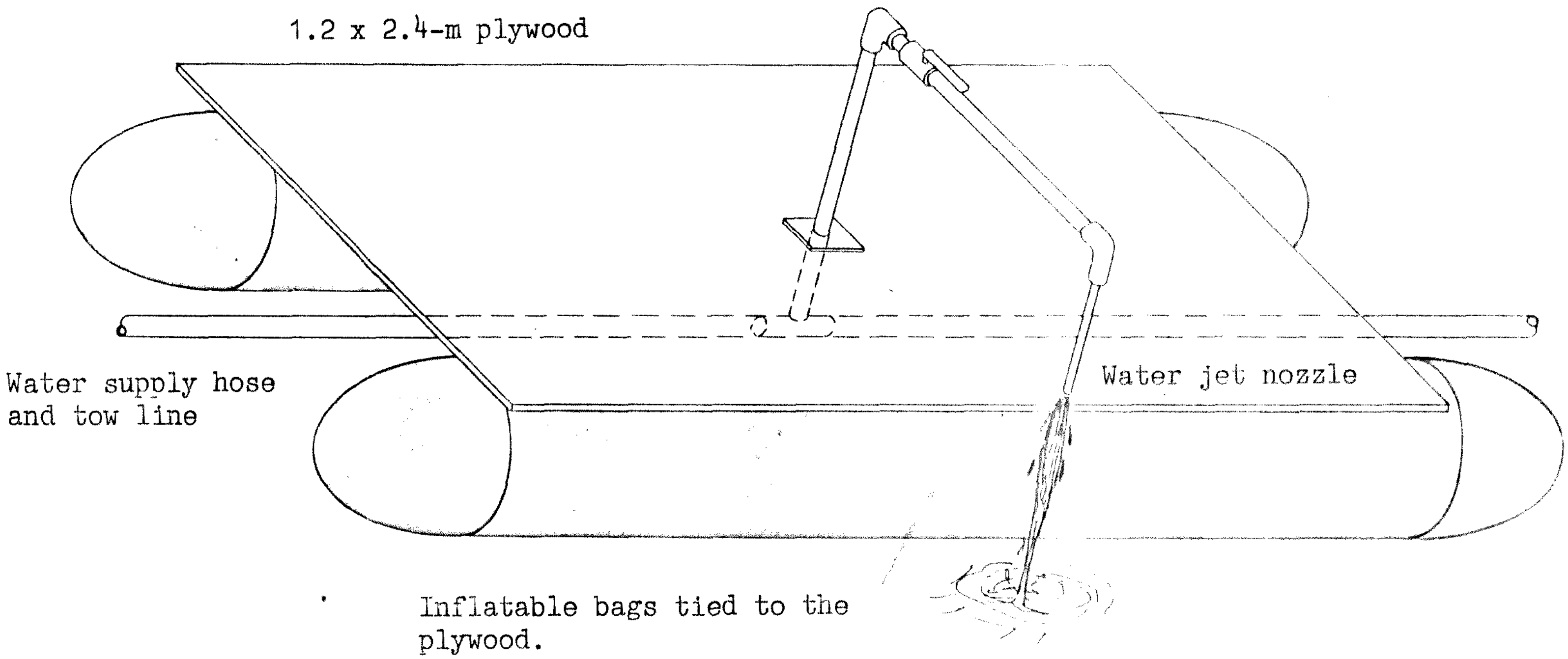


Figure 42. Isometric drawing of a water jet float.

CONCLUSIONS

The use of water jets mounted on individual floats to control an oil slick is feasible. However, there are problems which must be solved before the concept becomes practical for field use.

The construction of water jet floats can be done using plywood, standard pip[illegible] material, and suitable floatation (e.g., inflatable bags, steel drums, logs).

Water jet floats allow waves normally reflected by conven[illegible]al fabric booms to pass while retaining an oil slick.

Maintaining the individual floats in a predesigned orientation and formation while towing proved difficult. Floats drifted behind one another due to the fluid drag. Before proper counterweights were used to counter the forward pitching force of the supply hose, the floats would occasionally submerge at their bow and flip over.

RECOMMENDATIONS

Since only one side of a converging boom system was tested the performance of a complete oil slick converging system can only be extrapolated. Another test series should be conducted using at least three floats per side. The proper orientation and relative position of the floats should be easier to maintain because tie lines could be used across the sweep width. They would serve to stabilize each float by using its mirror image to supply a corrective force to balance the drag forces on the floats.

Three prototype permanent water jet floats could be built and placed in the OHMSETT tank behind the wave generator. They would serve to keep oil from gaining entrance behind the flaps and becoming emulsified. The floats would also show the possible problems which could develop with the water jet floats when used in a rough environment.

A water jet float more suitable for towing in a desired pattern with other floats should be designed and tested. Perhaps a circular float such as a tire inner tube would be advantageous since a slight rotation of the system would not cause a change in the resultant drag forces. A rudder skeg on the underside of the type of floats used in these tests should also be investigated.

TEST DESCRIPTION

Test Equipment

The water jet floats (Figure 42) were constructed from inflatable fabric bags lashed by rope to a 1.2 x 2.4 m piece of plywood 1.3 cm thick. A base and brace was bolted to the top of the plywood to support the 2.5 cm ID piping. A reducing elbow was mounted beneath the plywood and inbetween the floats to connect the 7.6 cm water supply hose to the steel piping. A 30 cm long, 2.1 cm ID pipe was used as the nozzle. The nozzle exit was directed vertically downward and set at a mean height of 0.6 m from the water's surface. The 7.6 cm ID flexible water supply hoses doubled as tow cables for the floats. The floats were held in their relative positions by 1 cm rope tied to the auxiliary, video, and main bridges (Figure 43 and 44). Pressure gauges were

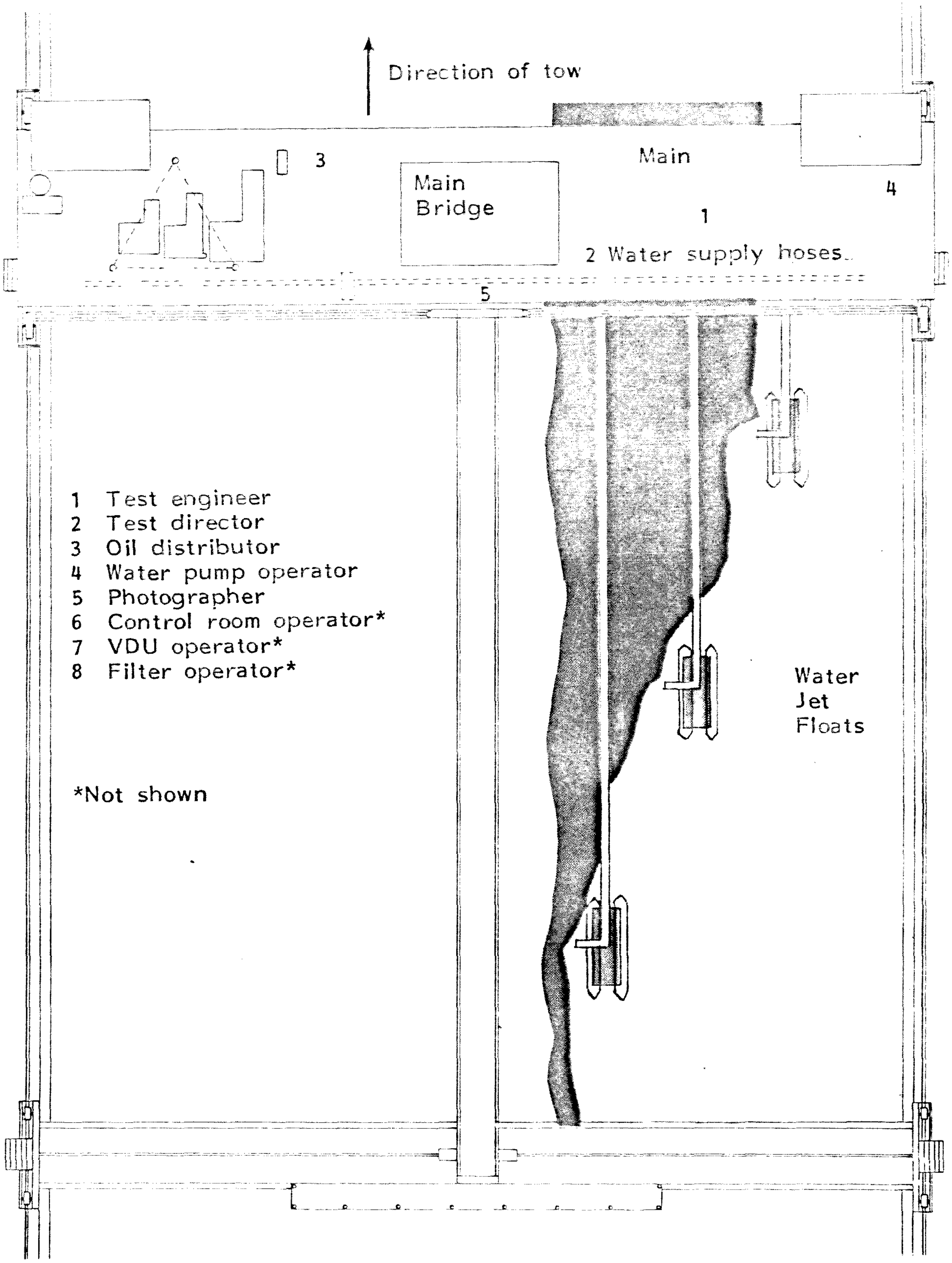


Figure 43. Test set up for water jet float program.

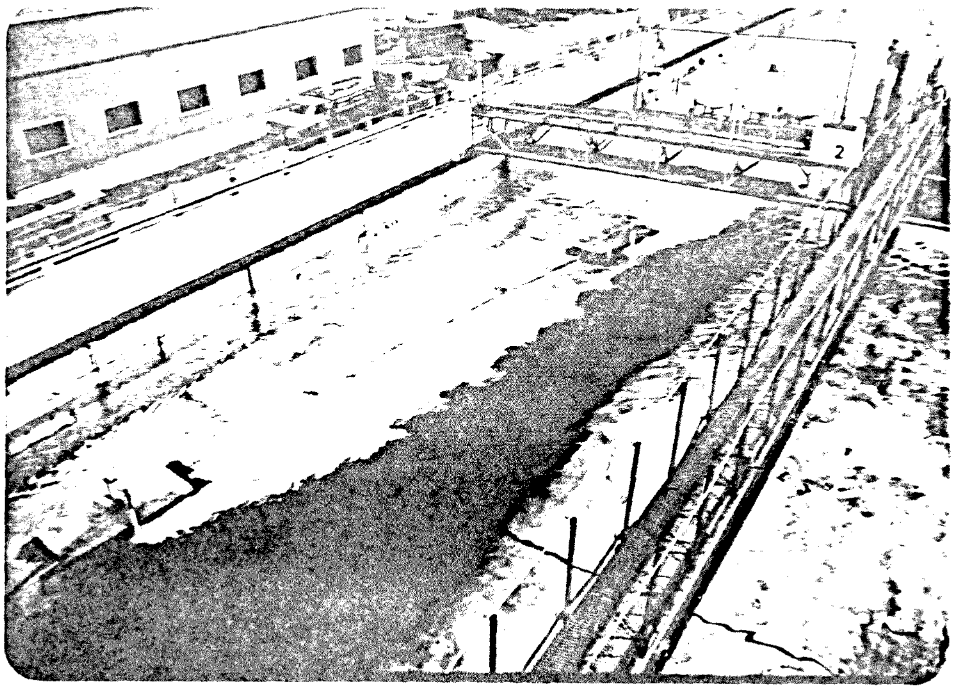


Figure 44. Water jet floats under tow diverting an oil slick.

installed in the water supply lines on the main bridge in advance of the 7.6 cm hose connections. To prevent the floats from nosing down in front due to the weight and drag force of the 7.6 cm supply hose, weights were placed on the floats and over the rear to counter the hose forces.

Towards the end of the test program, an independent water jet float was built. A high pressure (420 kPa) gasoline engine water pump was mounted on a small OHMSETT catamaran work boat (Figure 45) and towed from the main bridge via a 1.3 cm rope.

The slanting pattern of floats across the tank was designed to divert the oil slick across the tank in incremental steps. The floats were separated by 15 m down the tank and 1.8 m across the tank. Oil was distributed from the main bridge in a slick initially 4.5 m wide and 3 mm thick.

Test Plan

A test matrix was designed for these tests (Table 11) in conjunction with the U.S. EPA to investigate the effects that tow speed and waves have upon water jet float performance. Due to the nature of prototype testing, not all of the proposed tests could be conducted.

All tests were conducted according to the test plan presented below in order that the tests could be compared to one another.

Test Procedures

1. The water jet floats were positioned in the test tank.
2. The proper test number was placed in the display board.
3. Oil distribution was set to deliver the desired slick thickness for the tow speed.
4. If the test was to involve a harbor chop wave, the wave generator was started and the waves allowed to build up for 10 minutes.
5. The photo/video department took their positions.
6. Water to the water jet floats was turned on and the desired pressure obtained.
7. The oil skimming booms beneath the auxiliary bridge and main bridge were raised.
8. The tow was begun by bringing the bridges up to the designated tow speed.
9. Oil distribution was started and continued for two hundred feet of tow.

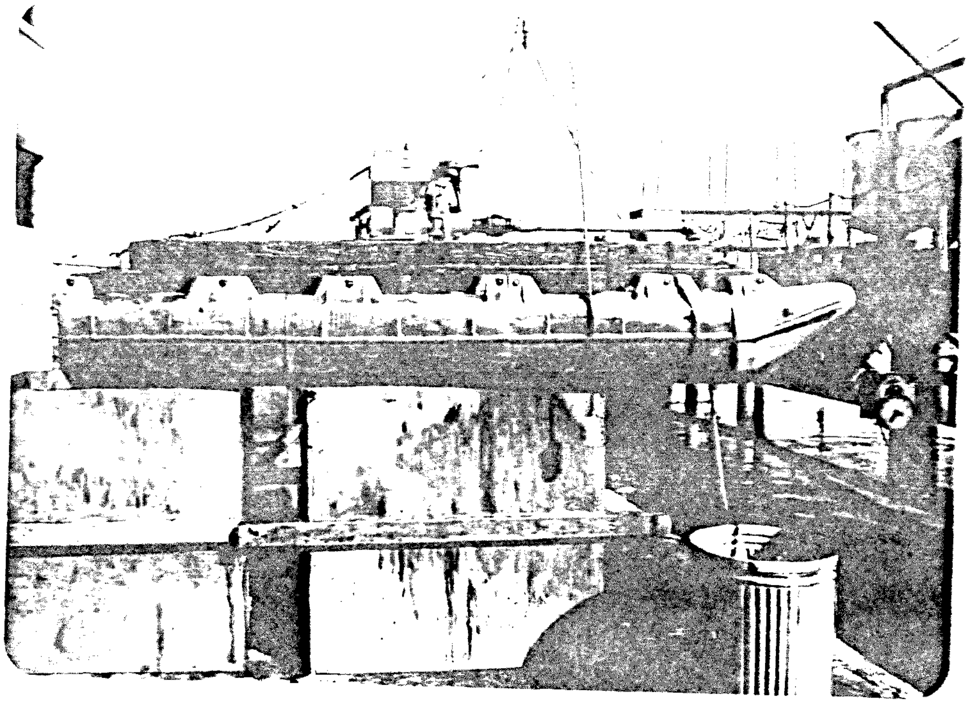


Figure 45. Water jet workboat with gasoline pump.

TABLE 11. WATER JET FLOAT TEST MATRIX

Test no.	Tow speed (kts)	Wave	Water jets in service	Pressure (kPa)	Comments
1	0-4	Calm	0	0	Stability tests
2	4-6	Calm	0	0	Stability tests
3	2	Calm	1	280	Single jet tests
4	4	Calm	1	280	
5	6	Calm	1	280	
6	2	Calm	1	560	
7	4	Calm	1	560	
8	6	Calm	1	560	
9	2	Calm	2	280	Double jet tests
10	4	Calm	2	280	
11	6	Calm	2	280	
12	2	Calm	2	560	
13	4	Calm	2	560	
14	6	Calm	2	560	
15	2	Calm	3	280	Triple jet tests
16	4	Calm	3	280	
17	6	Calm	3	280	
18	2	Calm	3	560	
19	4	Calm	3	560	
20	6	Calm	3	560	
21	2	0.5 m HC	3	280	Wave tests
22	4	0.5 m HC	3	280	
23	6	0.5 m HC	3	280	
24	2	0.5 m HC	3	560	
25	4	0.5 m HC	3	560	
26	6	0.5 m HC	3	560	
27	2	Calm	3	280	Triple jets using gasoline pump
28	4	Calm	3	280	Triple jets using gasoline pump
29	6	Calm	3	280	Triple jets using gasoline pump
30	2	0.5 m HC	3	560	Triple jets using gasoline pump
31	4	0.5 m HC	3	560	Triple jets using gasoline pump
32	6	0.5 m HC	3	560	Triple jets using gasoline pump

10. After oil distribution was completed the bridges were slowed to a halt and the skimming booms lowered.

11. If a harbor chop wave was used during the test, time was allowed for the waves to sufficiently subside to allow for oil skimming by the bridge booms.

12. The bridges were returned to the north end of the towing tank at 0.5 kts. The oil on the surface was thus cleared so not to interfere with the next test.

Results of the tests were recorded by still and movie photography and on video tape.

DISCUSSION OF RESULTS

The water jet float concept performed well but problems with maintaining float position and stability in a diversionary mode of operation must be solved before the floats can be considered a viable alternative to fabric booms. An advantage to the water jet float system over the fabric boom is the ease of relocating a poorly positioned float to divert oil rather than realigning an entire boom section while fighting the current. The floats in the tests were positioned 15 m apart measuring in the longitudinal axis of the tank and 1.8 m in the transverse axis. These positions were selected for tests using tow speeds of from 4 to 6 kts. The spacing seemed to work well for the 4 kts tests but fell a little short for the 6 kts tests. The oil slick was not diverted the entire 1.8 m before the following float contacted the oil slick. However, for 2 kt tests it appeared that the transverse spacing could have been increased to about 3 m. To move a water jet over 1.2 meters would require little effort if the float was positioned by a bridle to two anchor points upstream and on either side of it. The draft of the floats was about 5 cm with a projected cross current length of 0.5 m. This resulted in a projected area of about 0.025 m^2. A fabric boom with a draft of 0.5 m and a projected length of 3 m would have a final projected area of 1.5 m^2. The force required to overcome the fluid drag on the boom would be 60 times that to move the water jet float. Using $\frac{1}{2}\rho A v^2 C_D$ as the equation for drag force and letting $C_D = 1.5$. The force to move the fabric boom in a current of 2 knots would be about 118 kg. While the force required to move the water jet float would be about 2 kg. Problems with ropes stretching and breaking, knots giving way or anchors moving would be greatly reduced using water jet floats.

The structure of the water jet floats used in the test program was dictated by the materials on hand or readily available. The problems of front end submergence, capsizing, and position drift could be solved by proper float design and water supply hose location. The small work boat which had the gasoline driven pump onboard experienced no stability problems. Proper rigging or the use of a rudder skeg could eliminate any position drift problem. If two sets of water jet floats are used in front of a skimmer (Figure 46), the tie lines and drag force of the skimmer should be able to keep the floats in position.

The water jet floats performed as well in harbor chop waves as in calm water. The vertically directed jets maintained their approximate point of impact despite the roll, pitch, and heave of the buoyant floats.

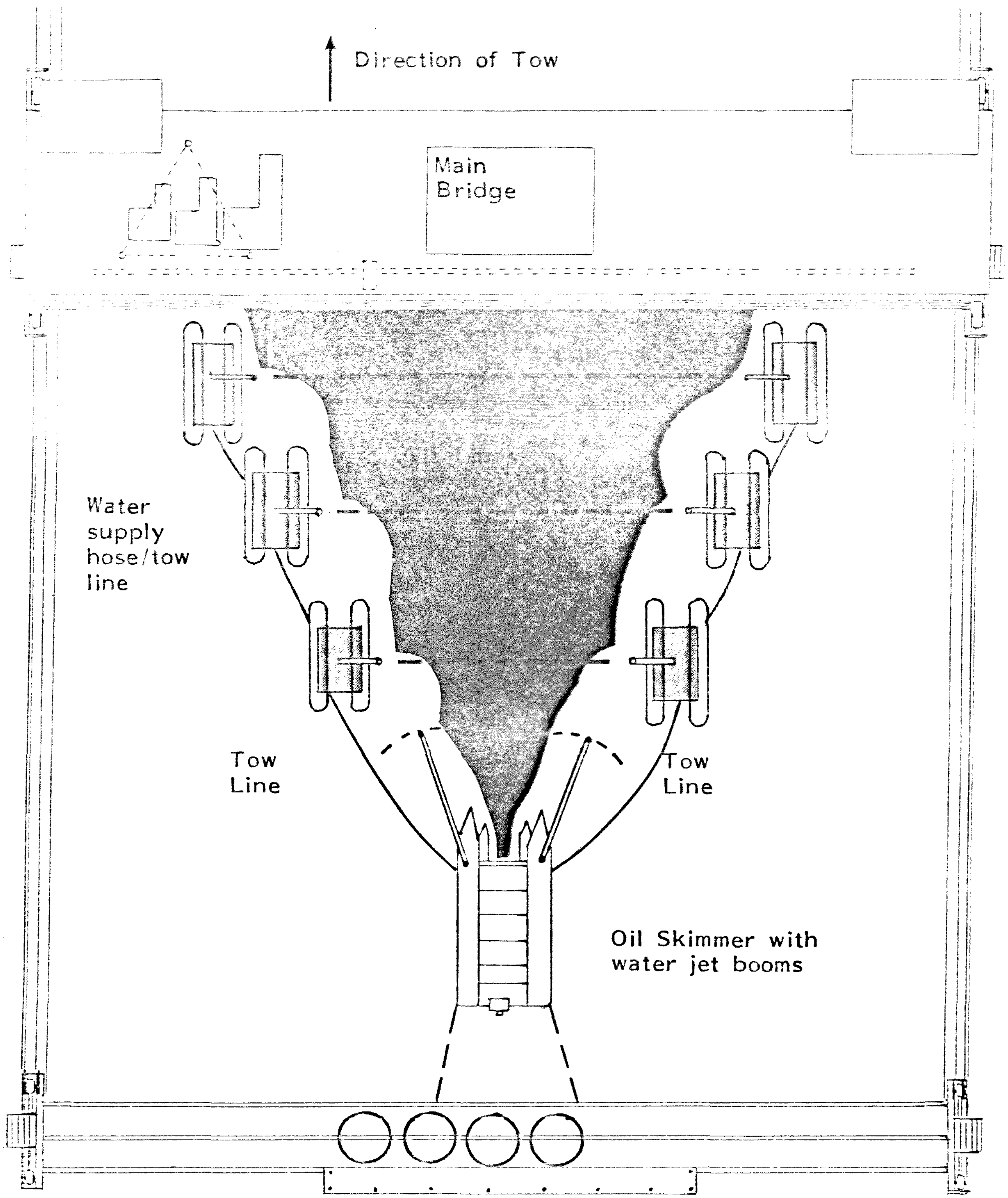


Figure 46. Double-sided water jet boom used in conjunction with a skimmer.

The use of a high pressure gasoline-engine pump to power a water jet instead of using a hose from the bridge pump seemed to have more advantages than disadvantages during the tank tests. During field operations logistic problems may outweigh those advantages. The need for the heavy water supply hose was eliminated with an individual pump on the float. Towing and maintaining float position and stability was made easier. In the field there would be no hose to be deployed, rammed, ruptured, or lost. The drawback is the maintenance of the pump so that it performs continuously. A large gasoline supply can be included on the float, but it must be refilled eventually. The pump inlet may become clogged by debris or the machinery may break down, thus leaving a breach in the oil spreading defenses. However, a more reliable electric-driven pump mounted on shore or a large vessel would necessitate using the supply hose.

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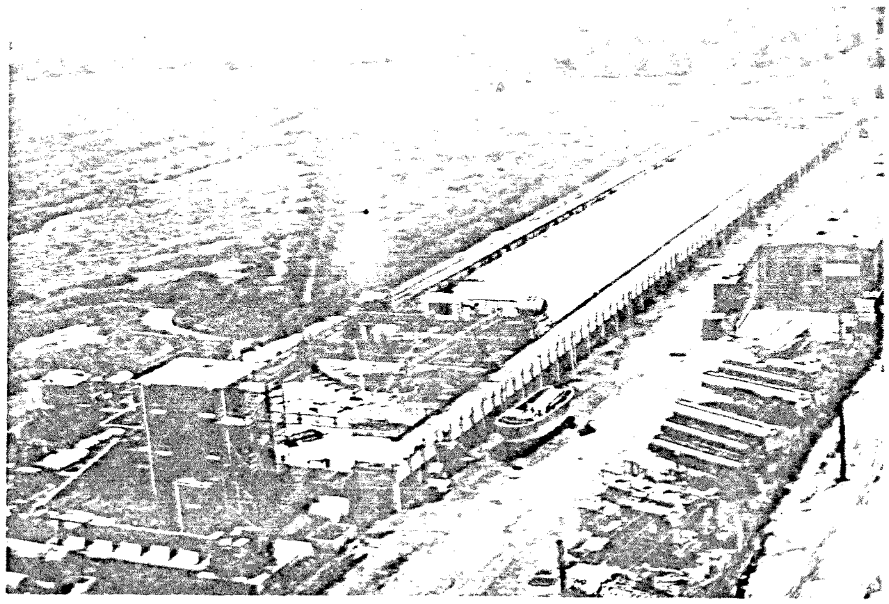
APPENDIX A

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY



The U.S. Environmental Protection Agency operates the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) located in Leonardo, New Jersey. This facility provides an environmentally safe place to conduct testing and development of devices and techniques for the control and clean-up of oil and hazardous material spills.

The primary feature of the facility is a pile-supported, concrete tank with a water surface 203 meters long by 20 meters wide and with a water depth of 2.4 meters. The tank can be filled with fresh or salt water. The tank is spanned by a bridge capable of exerting a horizontal force up to 151 kilonewtons while towing floating equipment at speeds to 3.3 meters/second (6.5 knots) for at least 40 seconds. Slower speeds yield longer test runs. The towing bridge is equipped to lay oil or hazardous materials on the surface of the water several meters ahead of the device being tested, so that reproducible thicknesses and widths of the test slicks can be achieved with minimum interference by wind.

The principal systems of the tank include a wave generator, a beach, and a filter system. The wave generator and absorber beach can produce regular waves to 0.6 meter high and to 45 meters long, as well as a series of 0.7 meters high reflecting, complex waves meant to simulate the water surface of a harbor. The tank water is clarified by recirculation through a 410 cubic meter/hour diatomaceous earth filter system to permit full use of a sophisticated underwater photography and video imagery system and to remove the hydrocarbons that enter the tank water as a result of testing. The towing bridge has a built-in oil barrier which is used to skim oil to the North end of the tank for cleanup and recycling.

When the tank must be emptied for maintenance purposes, the entire water volume of 9800 cubic meters is filtered and treated until it meets all applicable State and Federal water quality standards before being discharged. Additional specialized treatment may be used whenever hazardous materials are used for tests.

Testing at the facility is served from a 650 square meters building adjacent to the tank. This building houses offices, a quality control laboratory (which is very important since test fluids and tank water are both recycled), a small machine shop, and an equipment preparation area.

This government-owned, contractor-operated facility is available for testing purposes on a cost-reimbursable basis. The operating contractor, Mason & Hanger-Silas Mason Co., Inc., provides a permanent staff of eighteen multi-disciplinary personnel. The U.S. Environmental Protection Agency provides expertise in the area of spill control technology and overall project direction.

For additional information, contact: Richard A. Griffiths, OHMSETT Project Officer, U.S. Environmental Protection Agency, Research and Development, MERL, Edison, New Jersey 08837. Telephone: 201-321-6629.

APPENDIX B

OHMSETT OIL PROPERTIES

OHMSETT test fluids (light, medium, and heavy oils) are sampled and analyzed several times during the process of using them in testing. The steps and analyses are detailed below. Some test programs do not involve all sample procedures and sampling frequencies are many times different.

Fluid Properties Before Testing

Test fluids in bridge storage tanks are sampled at least once daily. Some test programs require more frequent sampling when test fluids are pumped onto the bridge more than once a day. Samples are analyzed for the properties detailed in Table B-1.

TABLE B-1. OIL PROPERTIES

Sample Property	Method	Temp °C	Output	Acceptable Range Light	Medium	Heavy
				cSt	cSt	cSt
Viscosity	ASTM D-88 ASTM D-341 ASTM D-2161	Room and 75	Visc. vs. Temp Chart	3-10 @25°C	100-300 @25°C	500-2000 @25°C
Surface Tensions	ASTM D-971	Room	dynes/cm	24 to 34 @25°C	24 to 34 @25°C	24 to 34 @25°C
Interfacial Tension w/ Tank Water	ASTM D-971	Room	dynes/cm	26 to 32 @25°C	26 to 32 @25°C	26 to 32 @25°C
Specific Gravity	ASTM D-287 ASTM D-1298	Room	Sp.Gr. @60/60	0.83-0.91	0.90-0.94	0.94-0.97
Bottom Solids and Water	ASTM D-96 ASTM D-1796	Room	% BS&W		less than 1%	

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE The Use of Coherent Water Jets to Control Oil Spills		5. REPORT DATE 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Michael K. Breslin		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Mason & Hanger-Silas Mason Co., Inc. P.O. Box 117 Leonardo, NJ 07737		10. PROGRAM ELEMENT NO. INE826 11. CONTRACT/GRANT NO. 68-03-2642
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268		13. TYPE OF REPORT AND PERIOD COVERED Final 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

John S. Farlow, Project Officer (201-321-6631)

16. ABSTRACT

The ability of coherent water streams to induce a surface current in water and thus control a floating oil slick was examined at the U.S. Environmental Protection Agency's (USEPA) Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT). The objective of the tests was to evaluate coherent water streams as an alternative to fabric booms and water sprays in concentrating, diverting, and containing oil slicks.

The water jets were constructed from standard pipe fittings and supplied with water from common centrifugal water pumps. They were mounted on the main towing bridge, built into small floats that were angled across the direction of tow, and extended from the bows of a catamaran. Currents of up to six knots were induced by towing the water jets from the main bridge.

The tests showed that coherent jets could induce a significant surface current and move an oil slick with little oil entrainment. The non-breaking waves produced by the OHMSETT wave generator did not greatly affect performance except where the jet nozzels were cantilevered off the front of the catamaran. The best position for the untended water jets tested was to be vertically directed at the surface of the water with the outlet 0.4 to 1.0 meters above the surface. The vertical component of a coherent water stream was found to be as useful, if not more so, as the horizonal component. A water jet supplied by a 30 kw electric motor/centrifugal pump system performed better than a source of compressed air (210 kPA) extended 0.6 m below the surface supplied by a 50 kw gasoline-driven air compressor.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Performance Tests Skimmers Water Pollution Oil	Spilled Oil Cleanup Protected Waters Coastal Waters Oil Booms	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	107
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)