

# HULL CLEANING SYSTEMS USING CAVIJET®

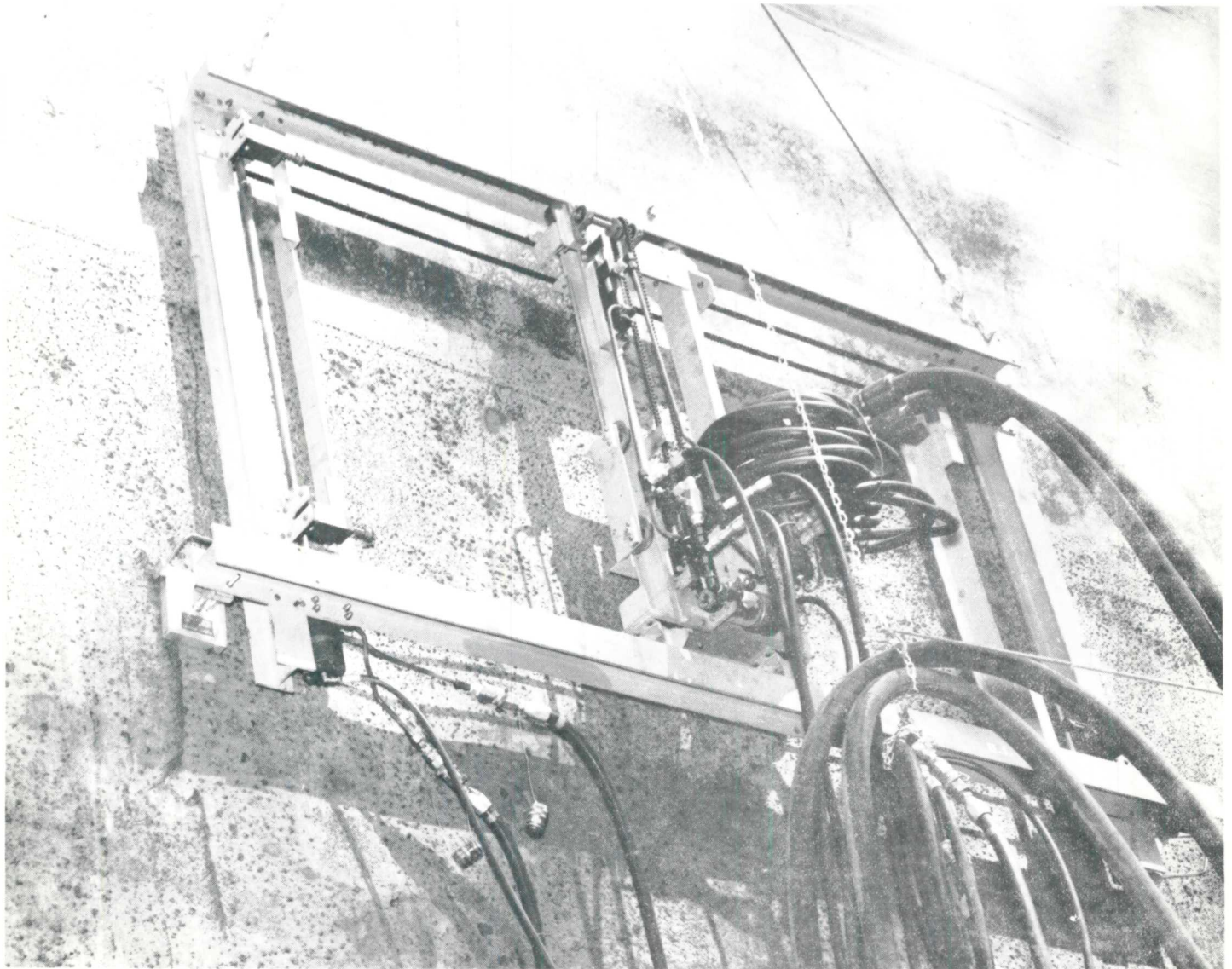
## CAVITATING FLUID JETS:

### A FEASIBILITY STUDY

JANUARY 1979



U. S. DEPARTMENT OF COMMERCE / Maritime Administration / Office of Advanced Ship Development



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HULL CLEANING SYSTEMS USING  
CAVIJET<sup>®</sup> CAVITATING FLUID JETS:  
A FEASIBILITY STUDY



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January 1979



U. S. DEPARTMENT OF COMMERCE, Maritime Administration  
Office of Advanced Ship Development

Co-Sponsored by:

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| Cavitation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |  | Pollution Abatement                              |                                                |                              |
| Cavitating Water Jets                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  | Marine Fouling Removal                           |                                                |                              |
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16. Abstract (Continued)

of 13.8 MPa (2,000 psi) or less were achieved. In comparison with the rate of about 90 m<sup>2</sup>/hr (1,000 ft<sup>2</sup>/hr) now achieved by a conventional hand-held sandsweeping device, this demonstrates the practicality of the CAVIJET technology for commercial hull cleaning systems.

FOREWARD

The project described in this report was conducted by HYDRONAUTICS, Incorporated, Howard County, Laurel, Maryland, under the support of Contract Number 7-38001 with the U.S. Department of Commerce, Office of Maritime Administration. A portion of the costs of the program were shared by the Maryland Shipbuilding and Drydock Company.

The CAVIJET<sup>®</sup> cavitating fluid jet technology used in this program has been patented by HYDRONAUTICS, Incorporated,\* and is currently being developed for a variety of commercial applications.

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\* U.S. Patent Nos. 3,528,704; 3,713,699; and 3,807,632. Other U.S. and Foreign patents are pending or have been granted. CAVIJET is a registered trademark of HYDRONAUTICS, Incorporated.

ABSTRACT

New methods for removing fouling from ship hulls are now being actively sought, both for Maritime and Naval craft, motivated by concerns of energy consumption and environmental protection. This report describes the second phase of a developmental program, which has bridged the gap between the earlier successful laboratory cleaning with the CAVIJET® cavitating water jet method (Reference 1), and the design and fabrication of prototype hull cleaners using this method.

Equipment for testing full-scale removal of fouling was developed and used in field trials on actual ship hulls in dry dock. This same six-nozzle CAVIJET cleaning system was also used for underwater trials. Cleaning rates of over 500 m<sup>2</sup>/hr (5,400 ft<sup>2</sup>/hr) using pump pressures of 13.8 MPa (2,000 psi) or less were achieved. In comparison with the rate of about 90 m<sup>2</sup>/hr (1,000 ft<sup>2</sup>/hr) now achieved by a conventional hand-held sandsweeping device, this demonstrates the practicality of the CAVIJET technology for commercial hull cleaning systems.



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## I. INTRODUCTION

### A. Background

The current standard dry dock practice of using either sand or fine metal particles to remove fouling and loose paint from ship hulls provides, with the use of sufficient manpower, a rapid way to clean those surfaces and allow the ship to return to service. However, both economic considerations due to the rising costs of labor, and the cost of the grit used for sandsweeping as well as increasing pressure from environmental protection groups because of the air and water pollution associated with this method, have made shipyard owners seek new techniques for cleaning hulls in dry dock. For instance, a yard has informed us that to clean a typical hull area of about 4,600 m<sup>2</sup> (50,000 ft<sup>2</sup>) in eight hours, they must use three teams of five men each, consisting of a crane operator, two men with the sandblasters, and two backup men operating the equipment. The grit cost alone is over \$32.00 per 100 m<sup>2</sup> (\$30.00 per 1000 ft<sup>2</sup>), and adding labor, power and capital costs, one can estimate that a total of over \$54.00 per 100 m<sup>2</sup> (\$50.00 per 1000 ft<sup>2</sup>) is required to clean by sandsweeping.

Also the rates of repair and replacement for various components of sandsweeping equipment are high because of the extremely erosive nature of the grit material. And, in many situations it is necessary to erect shielding to protect workers and equipment that are involved in repairs on other parts of the ship. In addition, extremely fine particles of the sandblasting grit are carried great distances and cause clean-up problems in other areas than in the dry dock itself. Periodic cleaning is required for support components such as cranes, and the area of contamination even extends to private automobiles in distant parking lots. However, it should be

emphasized that from the point of view of the time required and the effectiveness of the sandsweeping and sandblasting techniques, satisfactory results are now being obtained. Any replacement device, such as a CAVIJET cleaning system, must be competitive with regard to the present rate of cleaning and cleaning effectiveness, as well as comparable or better with regard to the cost per square foot cleaned.

The rising costs of fuel, and possible shortages, have caused ship owners to become interested in the possibilities of regular underwater hull cleaning, between dry docking, in order to maximize efficiency by keeping the hull friction as low as possible. Also, periodic underwater cleanings can provide an additional reduction in costs by extending the time between dry dockings. The wide spread availability of an economical, rapid, and effective method for removing fouling underwater, while a ship is receiving cargo, would greatly reduce the fuel costs for our Maritime industry. However, any new system must be capable of removing most of the fouling, with minimal damage to coatings, and obviously the costs must be below anticipated savings. A recent estimate (2) shows that over a five year cycle, five periodic underwater cleanings at \$6,495.00 each\* would net a savings, from reduced dry dockings alone, of over \$500,000.00. The reduction in fuel consumption would thus be an added bonus to the decreases in out-of-service and maintenance costs.

Fuel savings, due to variations in ship configuration, ports-of-call, and time in port, are difficult to estimate in general. The U.S. Navy has estimated (3) that keeping the

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\* Based on a 360 m (1181 ft) crude carrier, at \$1.50 per meter (\$5 per foot) cleaning cost (about 0.3-0.4¢ per m<sup>2</sup> (3-4¢ per ft<sup>2</sup>)).



hulls and propellers relatively free of fouling could save \$20,000,000 per year in fuel for the destroyer fleet alone. The Butterworth Company estimates (4) that a 250 MDWT VLCC can save 6 tons of fuel per day with periodic underwater cleaning. A review by Jourdain and Muntjeiverf (5) shows that fouling on the hull and propellers of merchant ships causes between 10% and 23% more power to achieve a given speed, even during the first year out of dry dock. Thus, it is clear that a considerable reduction in fuel costs can be achieved by regular underwater removal of fouling. This could be performed while the ship is transferring cargo, thus minimizing the time out of service.

An additional important benefit of a CAVIJET system for dry dock hull cleaning is the elimination of the air pollution associated with the sandsweeping method. Environmental limitations are causing shipyards to either abandon hull cleaning services, or seek alternative methods. The CAVIJET method, which requires no additives to the water (which can be taken from any source--river or sea), is therefore a logical alternative for hull cleaning in dry dock.

B. Hull Cleaning with the CAVIJET<sup>®</sup>

An investigation has been completed, using the CAVIJET to remove fouling and rust from steel panels in the laboratory, in order to determine whether this method would be capable of providing the basis for new equipment to clean hulls, either while in dry dock or while submerged. Using an existing laboratory test and evaluation facility, a series of tests were run on heavily fouled panels, and on severely rusted and pitted steel plates, to determine the effectiveness of the CAVIJET method in terms of rates of cleaning, and the costs associated with this new technique.

The detailed results of this investigation may be found in Reference 1, where the following conclusions were listed:

- a. In laboratory testing with various CAVIJET nozzles, using water at 13.8 MPa (2000 psi) or less, with no additives or abrasives, fouling removal rates have been achieved which are comparable or better than the hand-held sandsweeping methods now used for dry dock cleaning.
- b. A CAVIJET system, using two submerged 3.2-mm (1/8-in.) nozzles, can provide fouling removal rates of over 90 m<sup>2</sup>/hr (1000 ft<sup>2</sup>/hr), at power costs of about \$1.60 per 100 m<sup>2</sup> (\$1.50 per 1000 ft<sup>2</sup>).

If the costs for labor and capital are added, assuming the use of hand-held CAVIJET units\* analogous to the sandsweeping devices, then a total cost of about \$27.00 per 100 m<sup>2</sup> (\$25.00 per 1000 ft<sup>2</sup>) might be estimated for hand-held hull cleaning in dry dock with the CAVIJET method. With the use of semi-automated equipment, such as discussed below, the large reduction in labor should more than offset increased capital expenses and thus provide further savings in the cost for hull cleaning.

The competitive barnacle removal rates achieved in these laboratory tests were, however, obtained on surfaces which were fully submerged. Substantially lower cleaning rates are achieved for CAVIJET nozzles operated in-air, as would be required for dry dock usage. To gain some of the advantages afforded by submerged operation, with the commensurate improved rates of cleaning, various methods were initially examined in Phase I for providing a flow of water around an in-air operated CAVIJET nozzle. Further development of this technique, known as "dynamic sheathing" is described in this report.

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\* A hand-held CAVIJET device would require thrust compensation to minimize operator fatigue.

Summaries of Phase I of this MARAD-supported program have been reported at several technical symposia (6,7,8,9). As a result of these presentations, and their subsequent publication, considerable commercial interest has been sparked. HYDRONAUTICS has recently entered into a license agreement with a company in Hawaii to use the CAVIJET technology for underwater cleaning of ships and other surfaces such as docks and pilings. Commercial arrangements with other organizations are at various stages of discussion.

C. Objectives of Phase II

The second phase of this program, which is described in this report, has several objectives which were found to be logical follow-ons to the first phase of this work, and necessary steps in the development and eventual fabrication of prototype ship hull cleaning systems which utilize the CAVIJET cavitating water jet technology. One objective was to continue the optimization of the dynamic sheathing method for augmenting the performance of CAVIJET nozzles when operated for cleaning surfaces in air. The second objective was to develop test equipment, to use either for tests of cleaning ship hull surfaces in dry dock, or for comparable removal of fouling on surfaces underwater. These field trial components would then be utilized to satisfy the objective of establishing the constraints imposed by the realities of the actual operating conditions in shipyards. The development and operation of such equipment, although far from the configuration of an operational system would, it was felt, provide the ability to learn what these realities were, and thus to use what was learned to guide the conceptual design of such prototype operational equipment. The final objective of this Phase II program was to outline, in a conceptual design, the parameters



and design options for actual systems which might be used to clean either dry docked ship hulls or submerged ship hulls.

D. Scope of This Report

The subsequent chapters of this report contain a description of the CAVIJET cavitating water jet technology, as well as the HYDRONAUTICS CAVIJET test and evaluation facility which was utilized for optimization of the dynamic sheathing method. The development of this dynamic sheathing technique is described in Chapter III. A detailed description of each component of the field trial equipment is provided in Chapter IV, and a discussion of these trials, both in dry dock as well as underwater, can be found in Chapter V. The conceptual design concepts of CAVIJET hull cleaning systems, which might be used either for dry dock production sweeping of ship hulls, or for the cleaning of hulls underwater, are presented in Chapter VI. The final chapter of this report summarizes the Phase II program with concluding remarks, and recommendations are given for the remaining efforts required to complete the design of operational CAVIJET hull cleaning systems.



## II. THE CAVIJET® CAVITATING FLUID JET TECHNOLOGY

### A. The CAVIJET® Cavitating Jet Concept

A CAVIJET cavitating fluid jet is one of the very few successful attempts to harness, for useful purposes, the destructive power of cavitation, which has for decades plagued the designers of certain types of hydrodynamic equipment. The basic concept consists of stimulating the growth of vapor-filled cavities within a relatively low velocity liquid jet by appropriate nozzle design. With proper adjustment of the distance between the nozzle and the surface to be fragmented, these cavities are permitted to grow from the point of formation and then to collapse on that surface in the high pressure stagnation region where the jet impacts the solid material. Because the collapse energy is concentrated over many, very small areas at collapse, extremely high, very localized stresses are produced. This local amplification of pressure provides the CAVIJET cavitating fluid jet with a great advantage over any steady noncavitating jet operating at the same pump pressure and flow rate.

### B. The HYDRONAUTICS CAVIJET® Cavitating Jet Test Facility

An experimental facility was designed and built at HYDRONAUTICS, Incorporated for studying and developing practical devices which utilize the CAVIJET cavitating water jet principles. After basic research was completed, leading to the first invention of the method, the original facility was constructed. Research, motivated by a tunneling application, was sponsored by the Office of High Speed Ground Transportation for their high speed train program. Since construction of the original facility, a number of changes have been made, and the components used for this program are shown schematically in Figure 1.

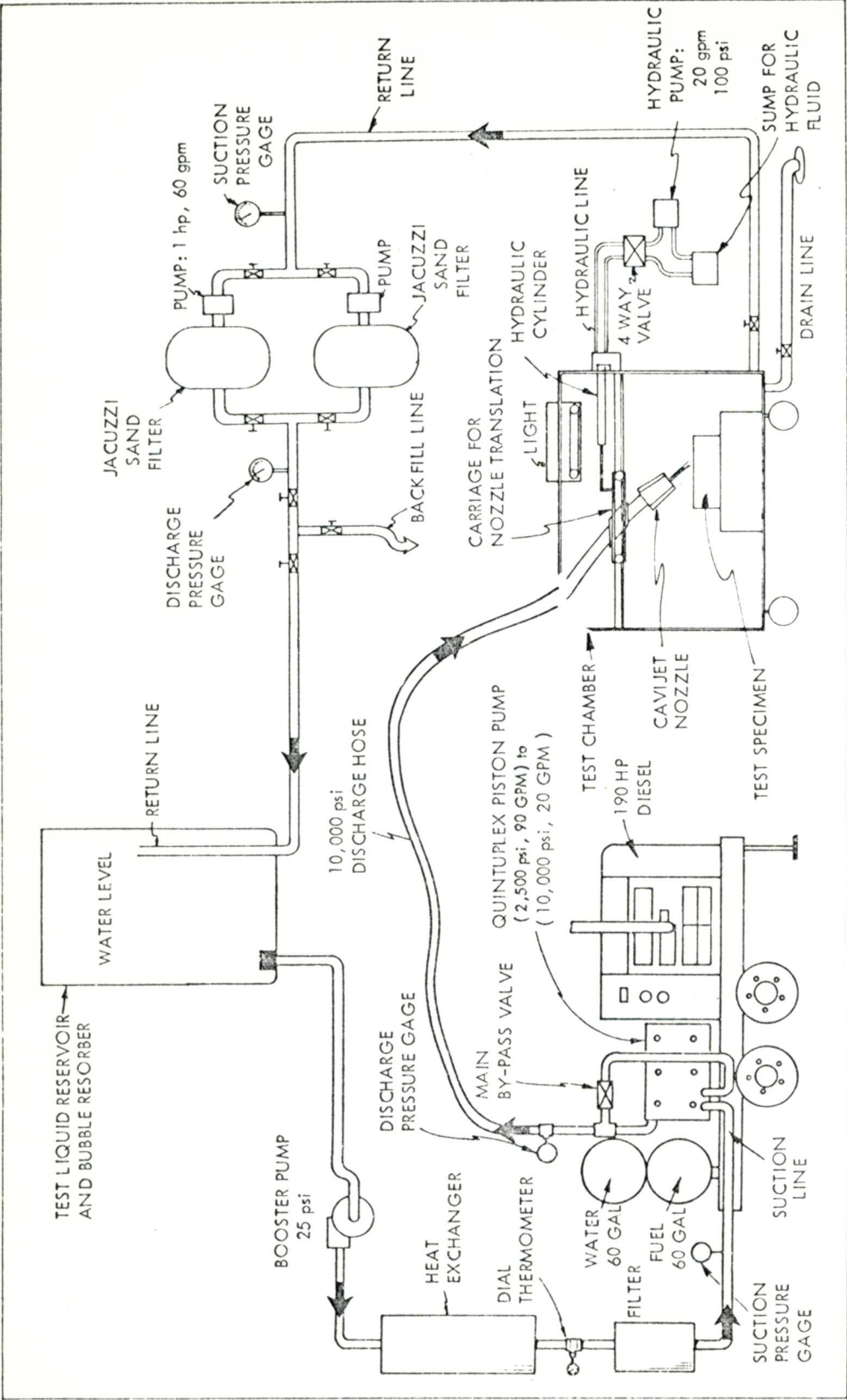


FIGURE 1 - SCHEMATIC OF CAVIJET® CAVITATING FLUID JET TEST FACILITY:  
indicating modifications to provide 68.9 MPa (10,000 psi) operation.

The primary components of the facility include a pump, reservoirs to recover and store the water, suitable filters, controls, pressure and temperature gauges, and flow measuring devices for accurately measuring all system parameters, and a large test chamber which contains the means for translation of the CAVIJET nozzle relative to test specimens at precisely controlled rates of motion and at any desired angle of attack. Within this test chamber, tests may be conducted on specimens either in air or in a submerged configuration. Further details about this facility may be found in Reference 1, which summarizes the first phase of this program.

One major modification to the facility since Phase I is the introduction of the portable quintuplex pump seen in Figure 1. This pump, which is described in further detail in Chapter IV, provides a range of flow and pressure combinations up to 5.7  $\ell/s$  (90 gpm) at 17.3 MPa (2,500 psi) or 68.9 MPa (10,000 psi) at 1.3  $\ell/s$  (20 gpm). The original triplex pump is still optionally available, and can yield up to 5.1  $\ell/s$  (80 gpm) and 13.8 MPa (2000 psi).

The second change is the larger main test chamber which replaced the tank used for the earlier work. This new chamber is 1.5 m wide, 1.8 m long, and 1.2 m deep (5 ft by 6 ft by 4 ft deep), and has a working capacity of 2,840  $\ell$  (750 gallons). It can be used for either stationary, translating, or manual operation of CAVIJET cavitating water jets, which have been extended by 5.1 cm (2 in.) or 1.9 cm (0.75 in.) flexible high-pressure hoses for any of these modes of usage. This chamber is fitted with a removable wooden cover which serves to retain the splash to facilitate in-air testing, and contains lights to permit viewing or photography during the testing. A hydraulic system for controlling nozzle translation is also a part of the test



chamber. A hydraulic cylinder, gear pump, sump, and four-way control valve complete this system, which provides translation velocities from less than 2.5 cm/sec (1 in./sec) to well over 90 cm/sec (36 in./sec) in either direction.

A schematic showing some typical CAVIJET nozzle configurations is given in Figure 2. The centerbody design is usually more effective for in-air applications, while the turning vane is often preferable for submerged cutting or drilling situations. For certain applications such as fouling removal, the "plain" CAVIJET nozzle, i.e., the CAVIJET nozzle body without inserts, provides sufficient intensity of cavitation. As discussed in Chapter III, the combination of a plain CAVIJET nozzle with "dynamic sheathing" has provided the most effective dry dock hull cleaning configuration.



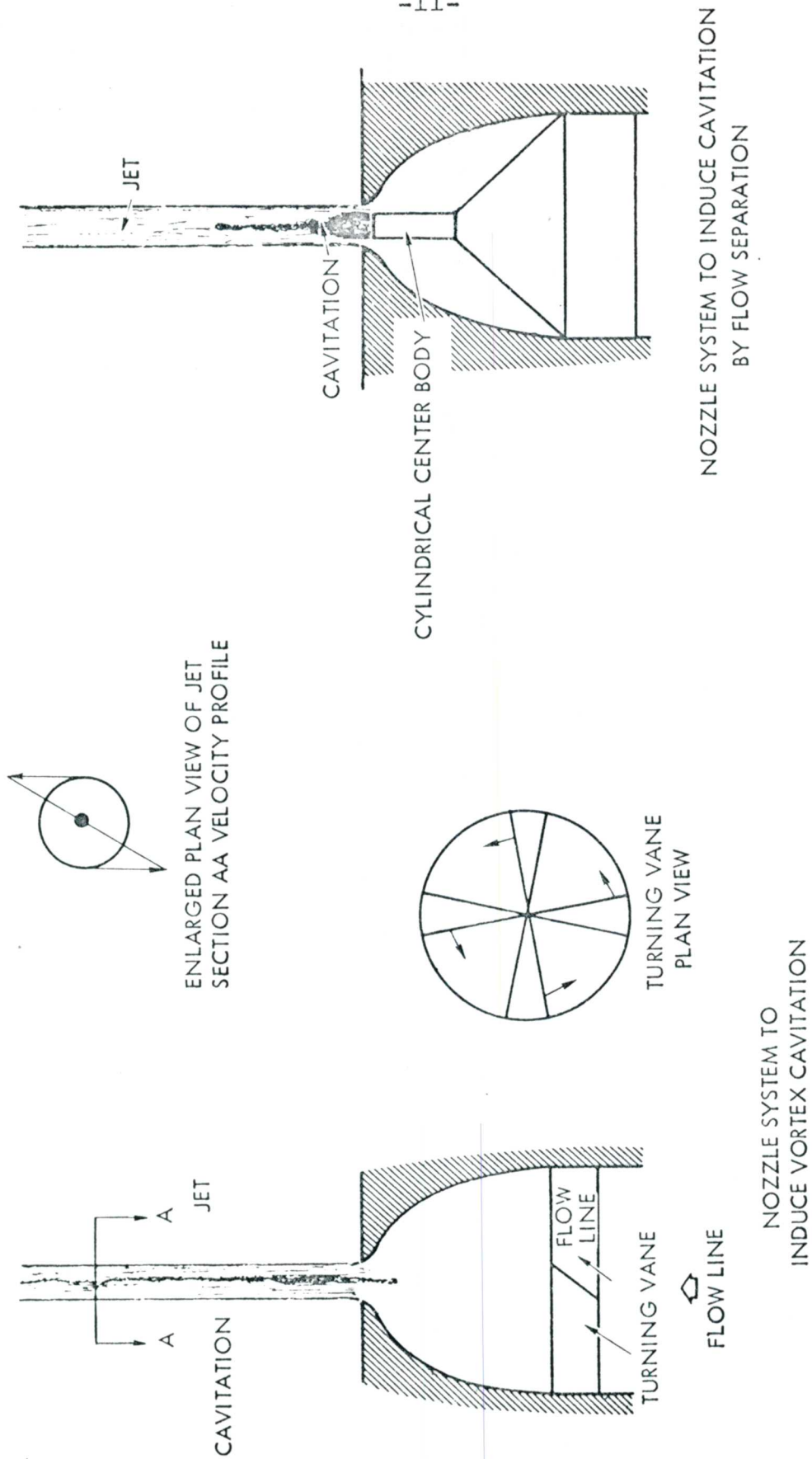


FIGURE 2 - TYPICAL CAVIJET® CAVITATING FLUID JET NOZZLE CONFIGURATIONS

### III. DEVELOPMENT OF THE DYNAMIC SHEATHING TECHNIQUE

In this chapter we will summarize highlights of the development of the dynamic sheathing technique which was installed on the field trial equipment and used in the dry dock testing. The improved submerged performance of the CAVIJET fluid jet technique, for either cleaning or cutting operations, has been observed for virtually any application we have investigated. This improvement in fouling removal was documented during the first phase of this program (1) wherein cleaning of fouling was conducted on panels both in air as well as submerged. During this first phase an initial development of a method to provide some of the enhanced cleaning afforded by underwater operation of the CAVIJET nozzles was begun. These attempts fall into two categories, namely "artificial submergence", and "dynamic sheathing".

In the first case a CAVIJET nozzle, while operating in air, was surrounded by various types of containers which attempted to prevent the escape of the high pressure flow emerging from the jet. In this manner a local, artificial submergence of the jet was achieved. We found that in stationary operation of the CAVIJET nozzle, for instance, while drilling into a block of concrete, improved performance could be achieved with this artificial submergence. However, if one attempted to sweep with the CAVIJET nozzle with its surrounding artificial submergence container, it was extremely difficult to maintain the proper positioning of the container adjacent to this surface. The precise gap required to accurately throttle the flow out of the container could not be maintained, particularly when the surface was extremely roughened by barnacles and other fouling growth. For this reason, the artificial submergence technique was not pursued during the present phase of the program.

In Phase I an attempt to provide dynamic sheathing was initiated. This dynamic sheathing concept refers to providing a flow of low velocity, low pressure water in an annulus around the relatively high velocity flow emerging from the CAVIJET nozzle. In this manner, in a region quite local to the jet, some of the effects provided by actual submergence of the CAVIJET nozzle flow could be achieved. The results of these early attempts are summarized in Table 1, along with the eventual result of this developmental effort under the second phase of the program. No further attempts to optimize the dynamic sheathing technique for the 6.4-mm (1/4-in.) CAVIJET nozzle were attempted in Phase II. The higher effectiveness of CAVIJET nozzles having an orifice on the order of 3.2-mm (1/8-in.), and hence the more effective overall usage of the available flow from the main pump to be used in the field trials was the motivation for the concentration of effort on this smaller CAVIJET nozzle size.

A summary of the various dynamic sheathing configurations examined during Phase II are summarized in Table 2. Sketches of several of these typical configurations are shown in Figures 3 through 6. The design termed "DS-9" was the one which provided the maximum improvement to the performance of the 3.2-mm (1/8-in.) CAVIJET nozzle, and hence was chosen as the design utilized in the field trial equipment. In the following sections of this chapter we will describe some of the tests which were conducted that led to this selection of the DS-9 dynamic sheathing configuration as well as the required flow rate for this design.

Table 1

Summary of Dynamic Sheathing Optimization Effort  
 Tests with plain 3.2-mm (1/8-in.) CAVIJET<sup>®</sup> nozzle at  
 30.5 cm/s (1 ft/s), 13.8 MPa (2,000 psi) pressure.

| Parameter                                                                                               | At Completion<br>of Phase I | Under Phase II <sup>a</sup> |
|---------------------------------------------------------------------------------------------------------|-----------------------------|-----------------------------|
| 99% cleared path<br>width, w, mm (in.)                                                                  | 17.8 (0.70)                 | 25.4 (1.0)                  |
| Cleaning Rate,<br>$\dot{A}$ , m <sup>2</sup> /hr (ft <sup>2</sup> /hr)                                  | 19.5 (210)                  | 27.9 (300)                  |
| Area Cleaning<br>Effectiveness <sup>b</sup> , $e_a$ ,<br>m <sup>2</sup> /kw-hr (ft <sup>2</sup> /hp-hr) | 1.77 (14.2)                 | 2.54 (20.3)                 |
| Dynamic Sheathing<br>Flow,<br>l/s (gpm)                                                                 | 1.3 to 2.5<br>(20 to 40)    | 0.94 (15)                   |

Notes:

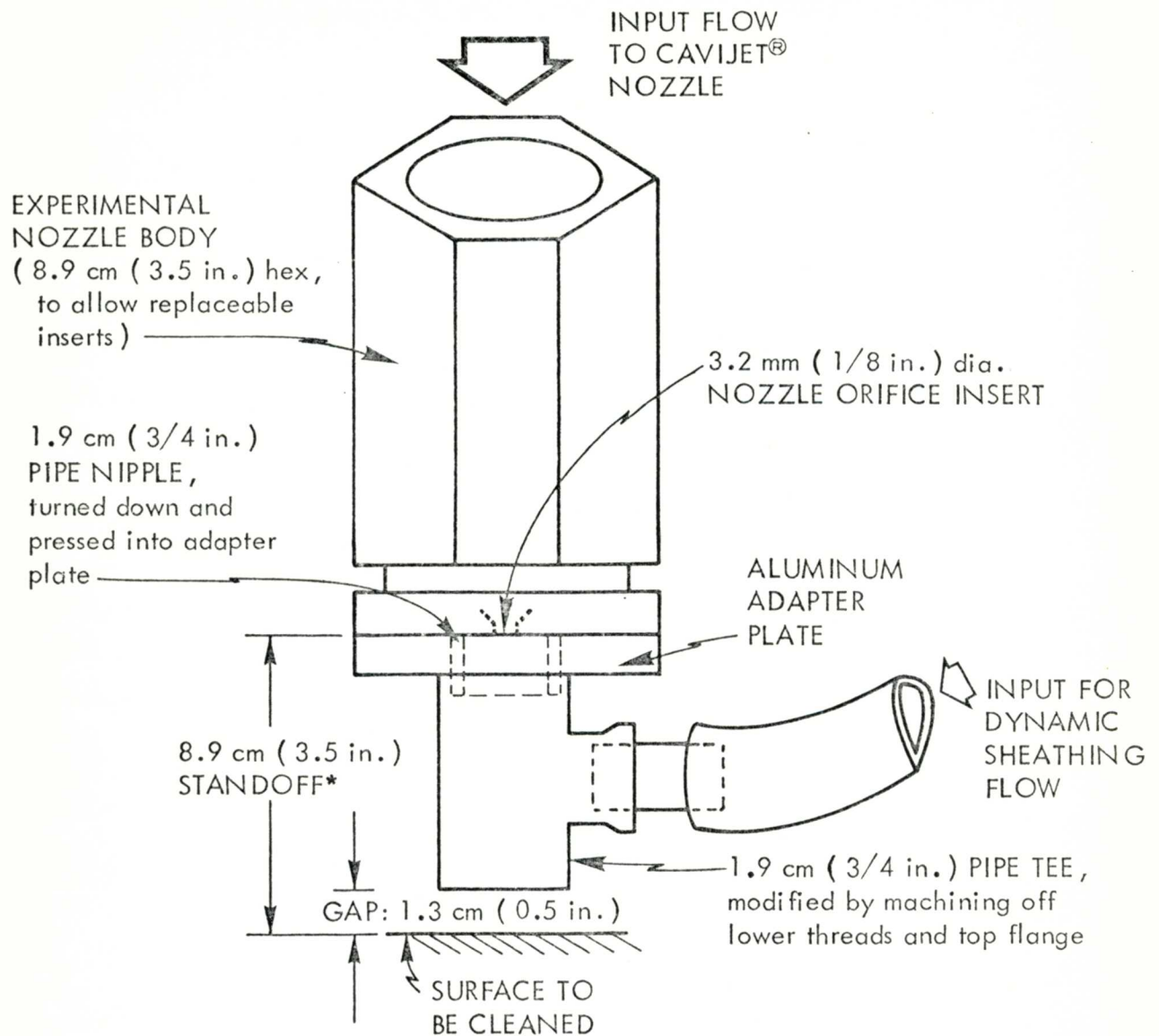
<sup>a</sup>Using the DS-9 dynamic sheathing configuration.

<sup>b</sup>The plain 3.2-mm (1/8-in.) CAVIJET nozzle at 13.8 MPa (2,000 psi) has a flow of 0.80 l/s (12.7 gpm) and a hydraulic power of 11.0 kw (14.8 hp).



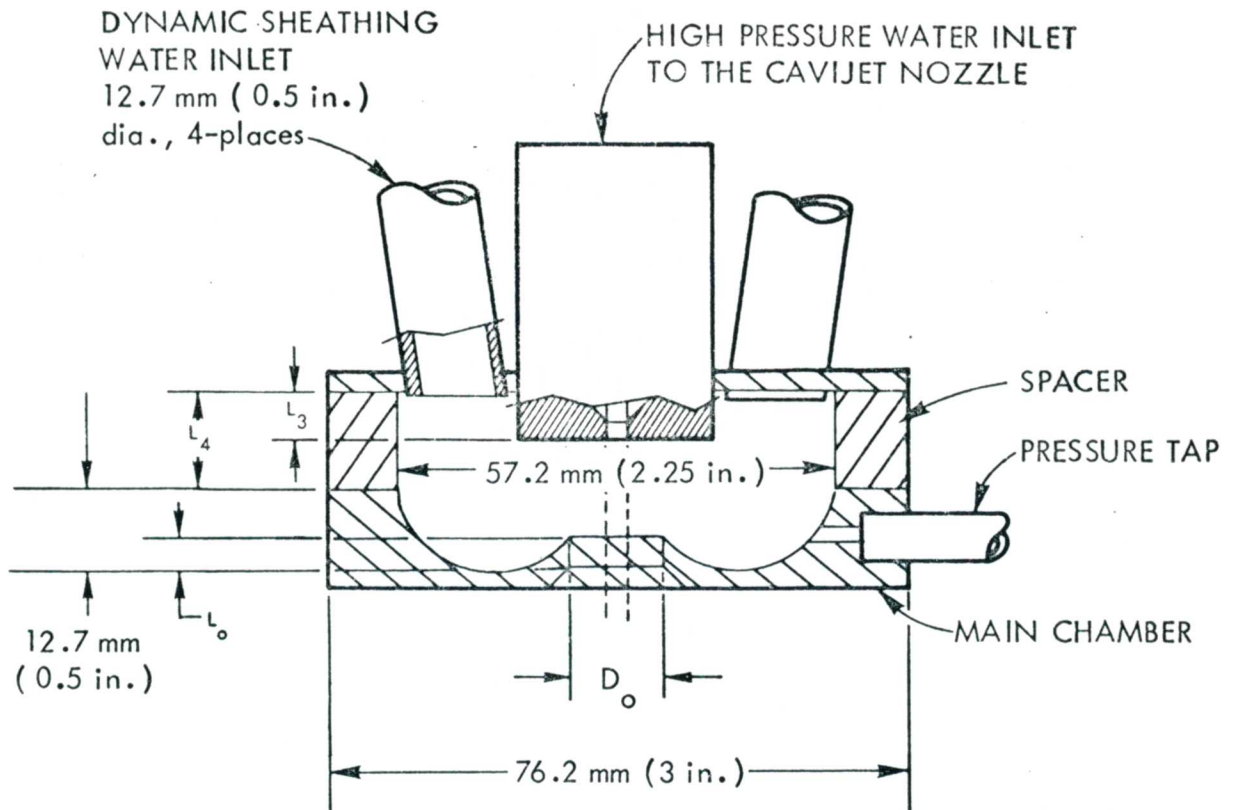
Table 2  
Types of Dynamic Sheathing Devices

| Dynamic Sheathing Type                       | Configuration                                                 | Remarks                                                                                                   |
|----------------------------------------------|---------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| DS-1                                         | 19-mm ( $\frac{3}{4}$ -in.) pipe tee                          | Used with 6.4-mm ( $\frac{1}{4}$ -in.) CAVIJET nozzle in Phase I                                          |
| DS-2                                         |                                                               | Used with 3.2-mm ( $\frac{1}{8}$ -in.) CAVIJET nozzle in Phase I                                          |
| DS-3<br>DS-4<br>DS-5<br>DS-6<br>DS-7<br>DS-8 | Aluminum, dish-shaped chamber                                 | The geometries of each of these are given in Figure 4. They vary chiefly in their exit orifice diameters. |
| DS-9                                         | Modified<br><br>19-mm ( $\frac{3}{4}$ -in.)<br><br>pipe cross | See drawing in Figure 5                                                                                   |
| DS-11                                        |                                                               | Same as DS-9, but with straight ID sleeve to reduce exit diameter to 0.5 in.                              |
| DS-12                                        |                                                               | Same as DS-9, but with tapered converging-diverging ID sleeve, reducing minimum exit diameter to 0.5 in.  |
| DS-10                                        | Three nozzle chamber with dish-shaped bases for each nozzle.  | See drawing in Figure 6.                                                                                  |



\* This standoff is larger than the optimum range of 2.5 to 5.1 cm (1 to 2 in.) for this nozzle.

FIGURE 3 - CONFIGURATION OF DYNAMIC SHEATHING DEVICE:  
Type DS-2



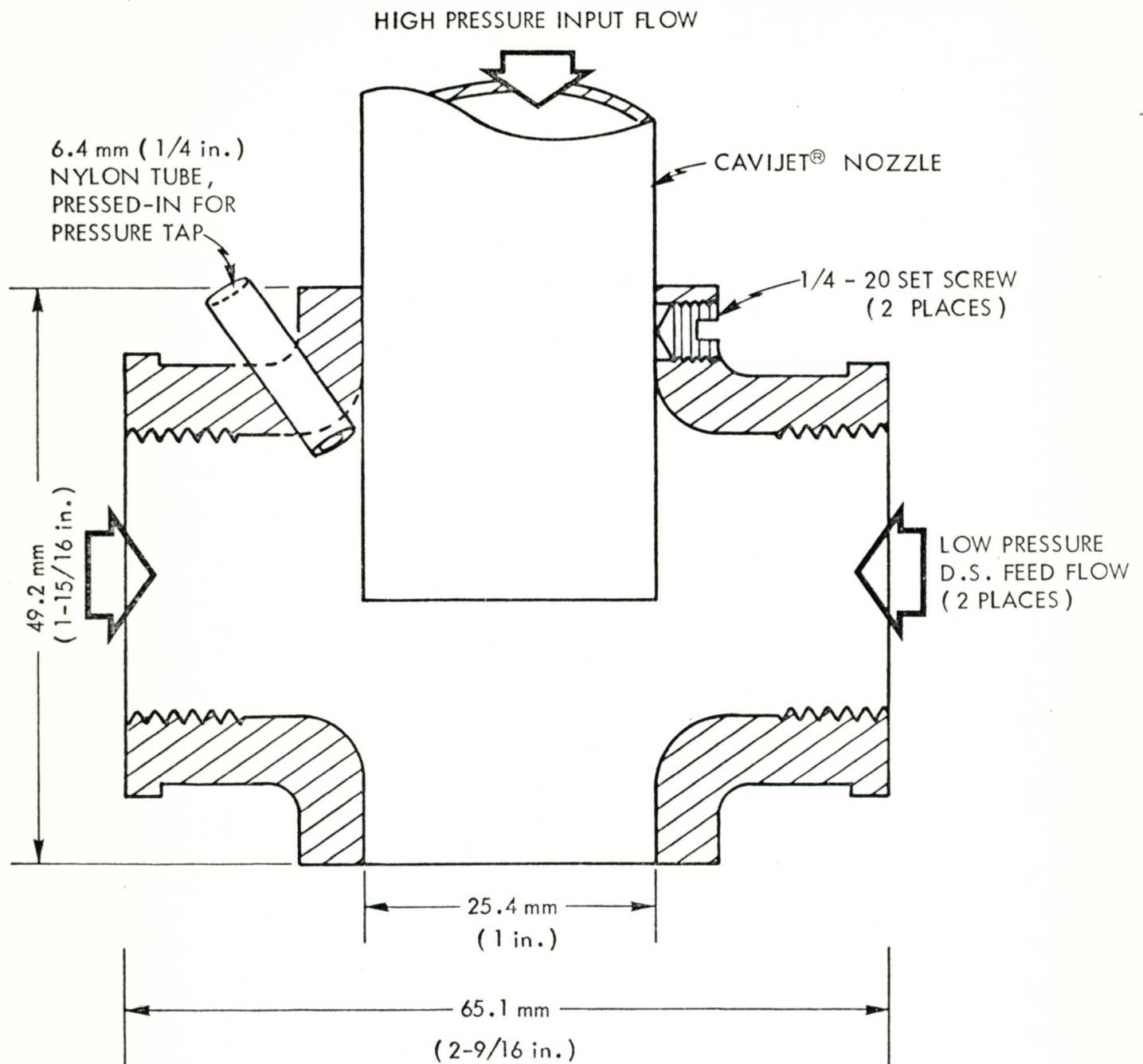
## SOME RELEVANT VARIABLES:

- $D_o$  - diameter of exit orifice  
 $L_o$  - length of exit orifice  
 $L_3$  - penetration of nozzle into chamber  
 $L_4$  - thickness of spacer

| DYNAMIC SHEATHING TYPE | $D_o$ |       | $L_o$ |        | $L_3$ |      | $L_4$ |      |
|------------------------|-------|-------|-------|--------|-------|------|-------|------|
|                        | mm    | in.   | mm    | in.    | mm    | in.  | mm    | in.  |
| DS-3                   | 6.4   | 0.250 | 2.3   | 0.090  | 12.7  | 0.50 | 14.2  | 0.56 |
| DS-4                   | 7.9   | 0.312 | 1.6   | 0.063  | 12.7  | 0.50 | 12.7  | 0.50 |
| DS-5                   | 9.5   | 0.375 | 1.6   | 0.063  | 12.7  | 0.50 | 12.7  | 0.50 |
| DS-6                   | 12.7  | 0.500 | 2.0   | 0.078  | 12.7  | 0.50 | 12.7  | 0.50 |
| DS-7                   | 19.0  | 0.750 | 3.3   | 0.130  | 12.7  | 0.50 | 12.7  | 0.50 |
| DS-8                   | 9.5   | 0.375 | 11.9* | 0.469* | 12.7  | 0.50 | 12.7  | 0.50 |

\* A segment of 12.7 mm (0.5 in.) O.D. copper tubing was inserted in DS-6 to create DS-8.

FIGURE 4 - CONFIGURATION OF DYNAMIC SHEATHING DEVICES:  
Types DS-3 to DS-8



THIS DS-9 CONFIGURATION WAS CREATED BY MODIFYING A 19 mm (3/4 in.), SCHEDULE 40 PIPE CROSS. THE TOP AND BOTTOM THREADS WERE MACHINED AWAY, TO AN I.D. OF 25.4 mm (1 in.) AND SET-SCREWS WERE USED TO FASTEN THE CAVIJET® NOZZLE.

FIGURE 5 - CONFIGURATION OF DYNAMIC SHEATHING DEVICE:  
Type DS-9



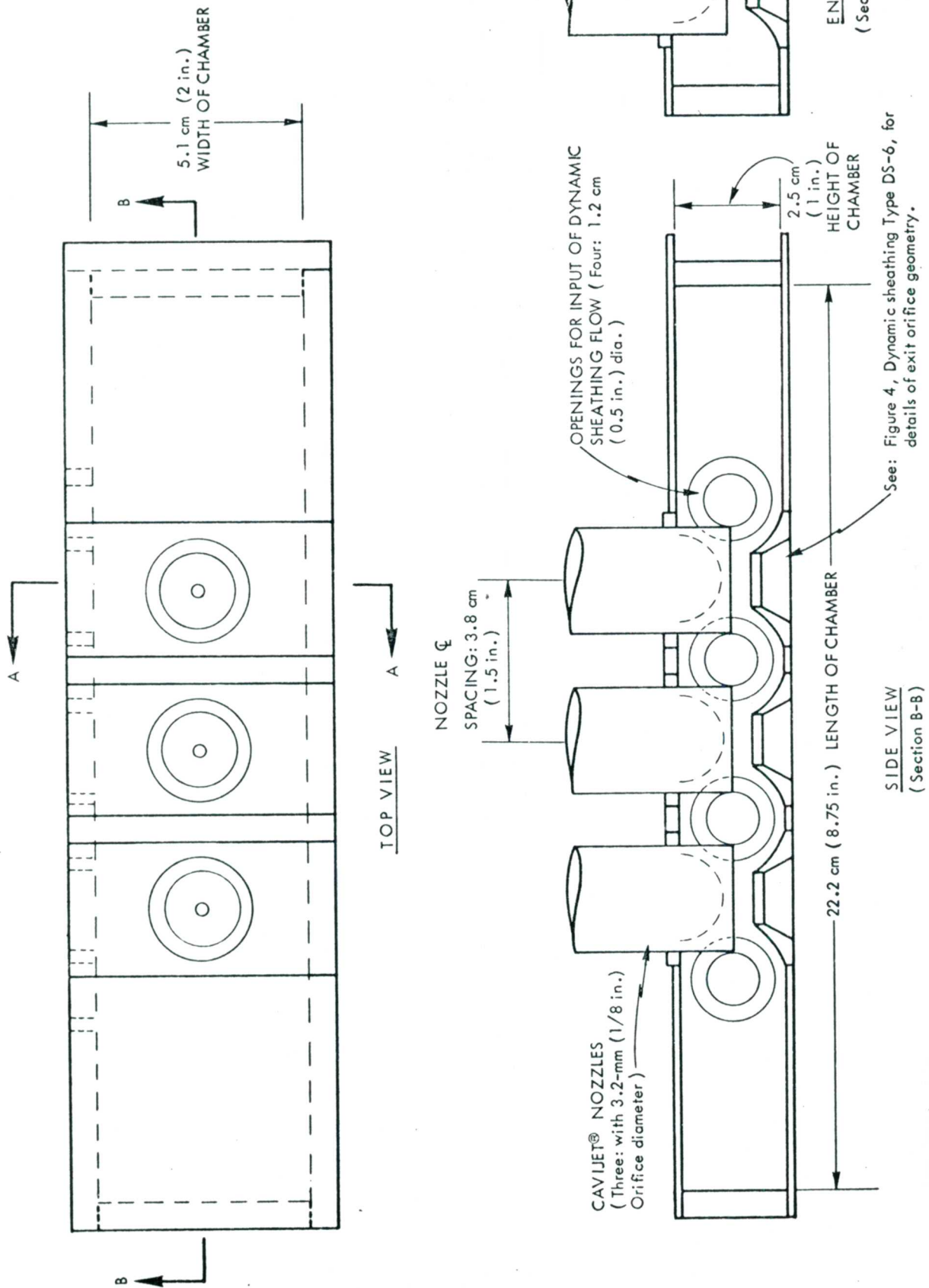


FIGURE 6 - CONFIGURATION OF DYNAMIC SHEATHING DEVICE:  
Type DS-10

#### A. Test Panels

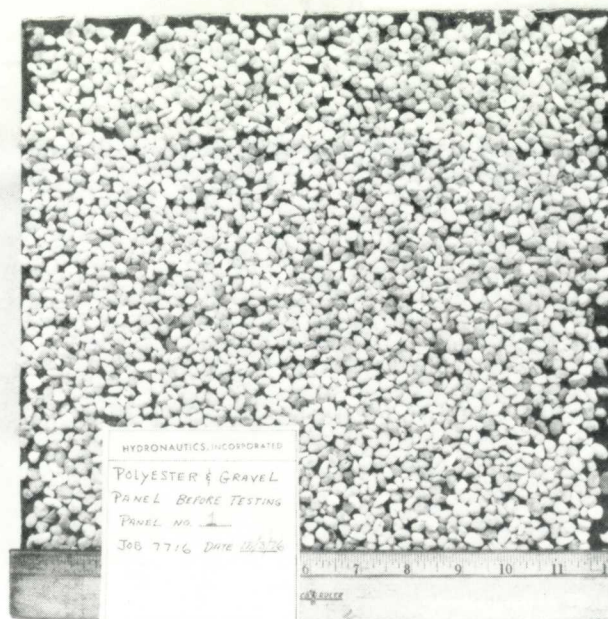
The test panels used in this development of the dynamic sheathing technique were, for the most part, of the same type as those used during the first phase of this study. Indeed, several of the 12 gauge steel 30.5 x 30.5 cm (12 x 12 in.) plates were returned to the Miami Marine Research, Inc. (MMRI) and exposed for fouling in the same method as in Phase I. For reasons of economy, however, an "artificial fouling" was developed in order to provide a series of test panels which would allow preliminary screening of the various dynamic sheathing techniques. Several of the preliminary attempts to develop this artificial fouling may be seen in Figure 7. In addition to the several types shown here, namely: a polyester-based resin with either wood chips, sweeping compounds, or small gravel (pea size), several other resins and glues were examined.

We found that the most reliable results were achieved with the polyester and gravel combination. By reasonably controlled application of the resin and its drying history we were able to create this artificial fouling so that reproducible and consistent results were achieved. The appearance of the polyester and gravel artificial fouling is shown before testing in Figure 8a and after being exposed to several tests in Figure 8b. It may be seen that a relatively well defined cleaned path width could be determined by means of this approach. The path width obtained with this artificial fouling was narrower than the width of path achieved for the same conditions with actual fouling. However, it was not intended that the artificial fouling should provide a one-to-one reproduction of actual fouling, but merely to furnish a technique whereby relative effects of various dynamic sheathing configurations could be examined. This coating of polyester and gravel provided the

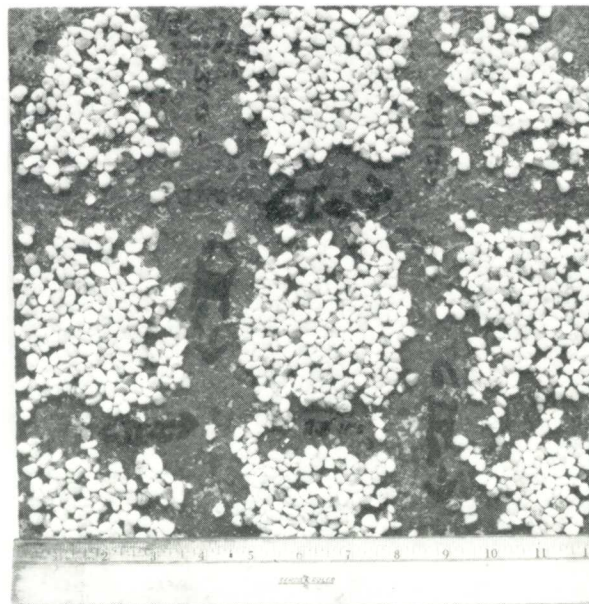




FIGURE 7 - SEVERAL CANDIDATE TYPES OF ARTIFICIAL FOULING:  
(left-to-right: polyester resin with wood chips; polyester  
resin with sweeping compound; polyester resin with gravel).



a. BEFORE TESTING



b. AFTER SEVERAL CLEANING PASSES:  
at 13.8 MPa (2,000 psi) with 3.2-mm  
(0.125 in.) CAVIJET nozzle, submerged.

FIGURE 8 - THE ARTIFICIAL FOULING USED: A polyester resin with a single layer of pea-sized gravel.



desired economical alternative to the relatively expensive actual fouled panels, which were used in the final evaluation of the most promising dynamic sheathing techniques.

The steel panels used for the fouling exposure at MMRI had been sandblasted prior to spray painting. The coating applied to these panels was a commercial epoxy-phenolic primer, known as "Rust-Ban", manufactured by Exxon and has the designation EP6841; color designation is Oxide Red. After the paint was dried it was scrubbed by hand with soap and water to remove any residual oils in order to accelerate the onset of fouling.

After sufficient exposure to fully cover the surface of the panels with encrustating foulants such as barnacles and tubeworms these panels were wrapped in wet seawater-soaked newspapers, carefully packaged, and sent live to our laboratories. The fouling was kept alive within a large artificial seawater-filled tank until testing was performed. We found it possible to keep the fouling alive for several weeks after receiving them in this fashion, thereby insuring testing conditions similar to those that might be encountered in the field. However, as noted later in this report, the problem of removing fouling from the very hard epoxy-coated surface was a considerably more difficult task than one encounters in the field wherein the coated surface is a considerably softer antifoulant, anticorrosing type of paint. A typical epoxy-coated fouled panel is shown in Figure 9a before testing and a series of cleared paths on such a panel are shown in Figure 9b.

A limited amount of tests were performed on a third type of fouled panel, also provided by MMRI. These panels had been coated with an experimental antifoulant paint, which had been exposed for a sufficient time period for it to have lost its



FIGURE 9a - A TYPICAL FOULED PANEL: After immersion at Miami Marine Research, Inc. for three months

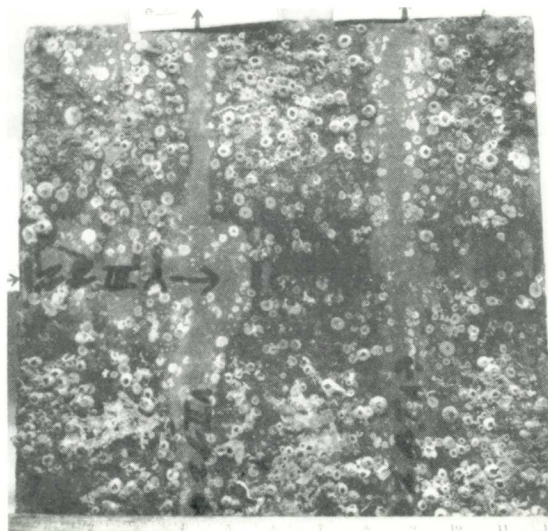


FIGURE 9b - A TYPICAL FOULED PANEL AFTER TESTING: Runs with 3.2-mm (0.125-in.) CAVIJET<sup>®</sup> nozzle at 13.8MPa (2,000 psi); in-air, submerged, and with dynamic sheathing.



effectiveness. This coal tar-based coating was used in some of the final tests with the six nozzle array in the actual field trial equipment.

#### B. Single Nozzle Tests

The tests discussed in this section were conducted within the test and evaluation facility described in Chapter II. All tests were run by translating the CAVIJET nozzle in a single, straight line pass across the panel, with the jet impingement perpendicular to the panel surface. Measurements of cleared path width were then made.

Considerable effort was involved in a study to determine the optimal parameters for the dynamic sheathing types as shown in Figure 4. For instance, Figure 10 (data for this figure is listed in Table 3) shows the effect of the diameter of the orifice for this type of dynamic sheathing design on the path width cleared on panels coated with the artificial fouling. The parameter: "90 percent clear path width" was selected to typify the results obtained from tests coated with this artificial fouling in order to discount the occasional stray pebble that might adhere within an essentially cleared path. It is seen in Figure 10 that the optimum orifice diameter for this configuration is about 12.7 mm (0.5 in.).

A comparison of the cleaning ability of each of the configurations within the category shown in Figure 4 is shown in Figure 11. These data in Figure 11 are average results for the data which are listed in Table 4. It is seen that of the various types tested having this geometry the version known as DS-6 achieved the maximum improvement relative to in-air cleaning. The DS-6 geometry provided, at a translation velocity of 30.5 cm/s (1 ft/s) an average path width of about

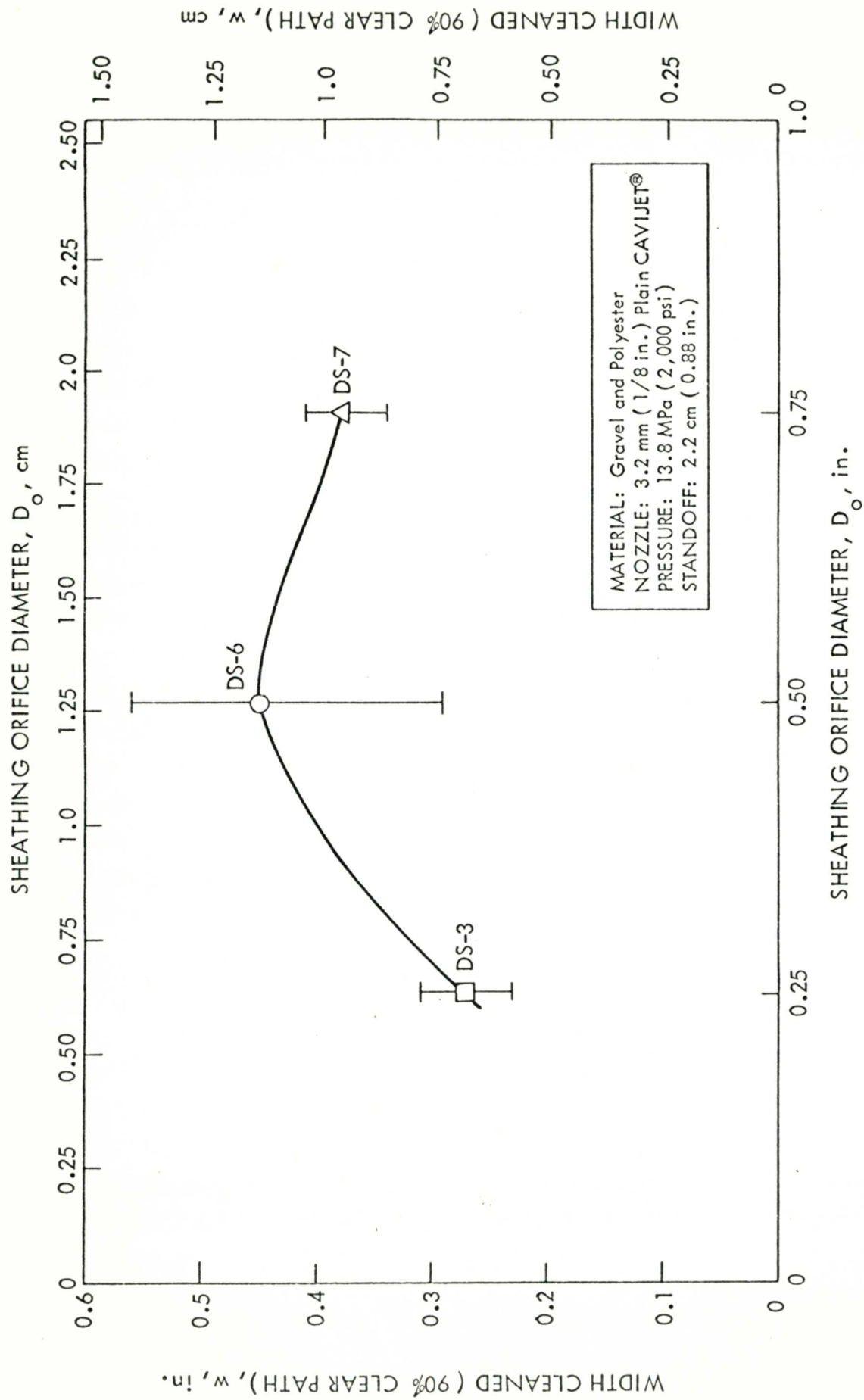


FIGURE 10 - EFFECT OF DYNAMIC SHEATHING ORIFICE DIAMETER



TABLE 3

## EFFECT OF DYNAMIC SHEATHING ORIFICE DIAMETER

Tests with 3.2 mm (1/8-in.) CAVIJET<sup>®</sup> Nozzle  
 13.8 MPa (2000 psi) Pump Pressures;  
 Translation Velocity: 30.5 cm/s (1 ft/s);  
 Standoff: 2.2 cm (0.88 in.)  
 Artificial Fouling  
 In Air, Without Centerbody

| Sheathing<br>Orifice<br>Diameter | Dynamic<br>Sheathing<br>Type* | Run<br>No. | Width Cleaned ** (90% clear path) |      |
|----------------------------------|-------------------------------|------------|-----------------------------------|------|
|                                  |                               |            | mm                                | in.  |
| 6.35 mm<br>(0.25 in.)            | D S -3                        | 23 VI a    | 7.9                               | 0.31 |
|                                  |                               | 24 I a     | 5.8                               | 0.23 |
| 12.7 mm<br>(0.50 in.)            | D S -6                        | 22 VI a    | 12.7                              | 0.50 |
|                                  |                               | 23 VII a   | 14.2                              | 0.56 |
|                                  |                               | 23 III a   | 14.2                              | 0.56 |
|                                  |                               | 24 II a    | 8.9                               | 0.35 |
|                                  |                               | 25 IV a    | 11.2                              | 0.44 |
|                                  |                               | 25 V a     | 7.4                               | 0.29 |
|                                  |                               | 26 II a    | 12.4                              | 0.49 |
|                                  |                               | 26 III a   | 12.4                              | 0.49 |
|                                  |                               | 27 I a     | 12.4                              | 0.49 |
|                                  |                               | 27 II a    | 8.4                               | 0.33 |
|                                  |                               | 27 III a   | 11.2                              | 0.44 |
| 19.1 mm<br>(0.75 in.)            | D S -7                        | 24 VII a   | 10.4                              | 0.41 |
|                                  |                               | 25 I a     | 9.1                               | 0.36 |
|                                  |                               | 26 IV a    | 9.9                               | 0.39 |
|                                  |                               | 26 V a     | 8.6                               | 0.34 |
|                                  |                               | 26 VI a    | 9.9                               | 0.39 |

\* See Figure 4 for dimensions.

\*\* All data normalized by means of a calibration run.

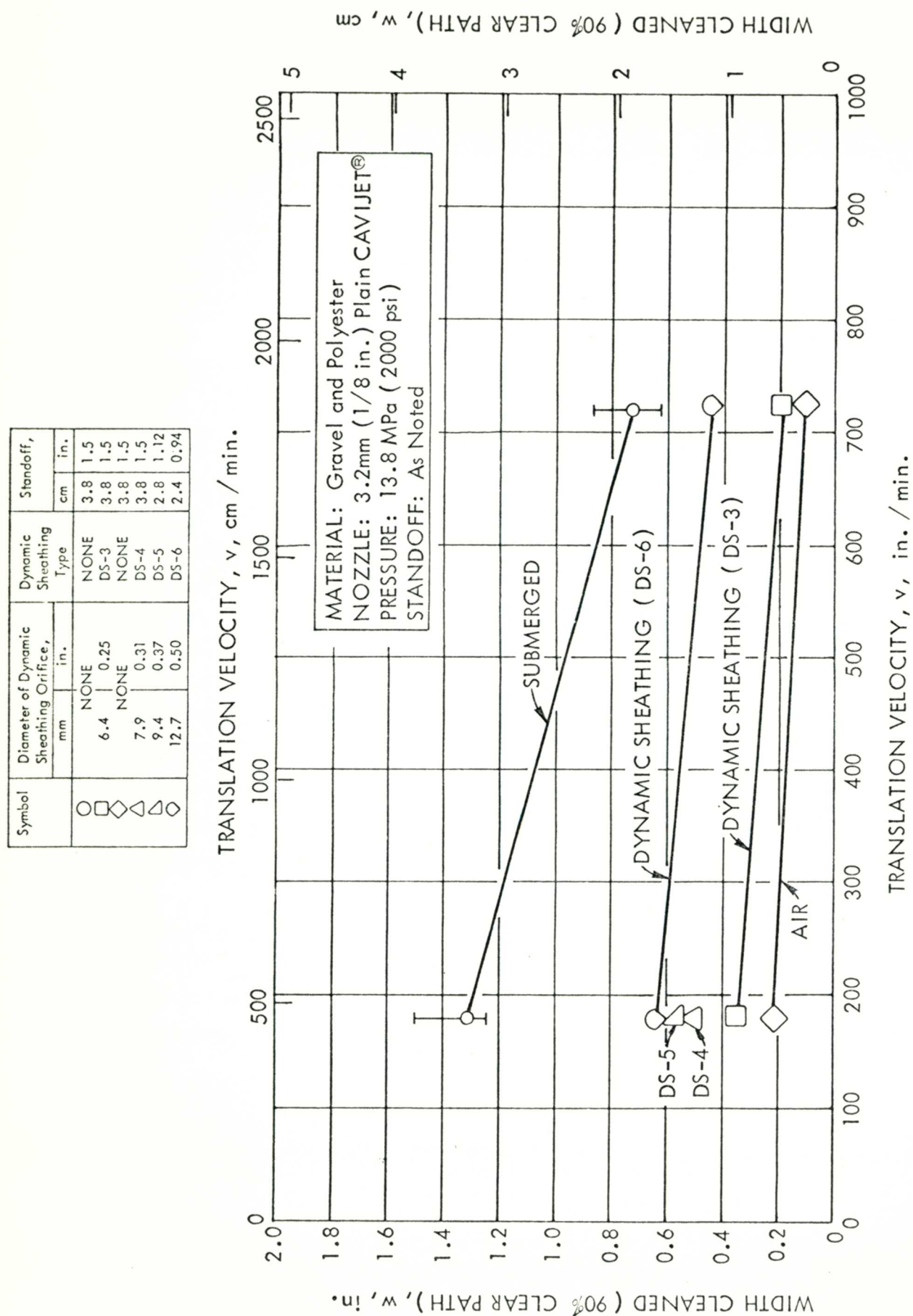


FIGURE 11 - REMOVAL OF ARTIFICIAL FOULING WITH SEVERAL DYNAMIC SHEATHING TYPES

TABLE 4

## PERFORMANCE OF DYNAMIC SHEATHING VS SUBMERGED AND IN AIR TEST MODES.

Tests with 3.2 mm (1/8 in.) CAVIJET<sup>®</sup> Nozzle;  
 13.8 MPa (2000 psi) Pump Pressure;  
 Standoff: 23.8 to 38.1 mm (15/16 to 1-1/2 in.);  
 Artificial Fouling

| Test Mode &<br>Dynamic<br>Sheathing Type              | Run<br>No. | Width Cleaned (90% clear path) |      |
|-------------------------------------------------------|------------|--------------------------------|------|
|                                                       |            | mm                             | in.  |
| Translation velocity: 7.6 cm/s (0.25 ft/s)            |            |                                |      |
| Submerged<br>No Centerbody<br>No Dynamic<br>Sheathing | 2 I a      | 31.8                           | 1.25 |
|                                                       | 3 I a      | 38.1                           | 1.50 |
|                                                       | 3 IV a     | 33.5                           | 1.32 |
|                                                       | 5 I a      | 31.8                           | 1.25 |
|                                                       | 5 III a    | 31.8                           | 1.25 |
|                                                       | 6 I a      | 31.8                           | 1.25 |
|                                                       | 6 III a    | 35.1                           | 1.38 |
| In Air<br>With Centerbody<br>No D. S.                 | 14 V a     | 4.8                            | 0.19 |
|                                                       | 15 II a    | 6.4                            | 0.25 |
| D S - 3 *                                             | 12 III a   | 9.7                            | 0.38 |
|                                                       | 13 III a   | 7.9                            | 0.31 |
| D S - 4 *                                             | 14 II a    | 12.7                           | 0.50 |
| D S - 5 *                                             | 16 III a   | 14.2                           | 0.56 |
| D S - 6 *                                             | 18 III a   | 17.5                           | 0.69 |
|                                                       | 19 III a   | 14.2                           | 0.56 |
| Translation velocity: 30.5 cm/s (1 ft/s)              |            |                                |      |
| Submerged<br>No Centerbody<br>No D. S.                | 2 IV a     | 15.7                           | 0.62 |
|                                                       | 5 IV a     | 22.4                           | 0.88 |
|                                                       | 6 II a     | 17.5                           | 0.69 |
| In Air<br>With Centerbody<br>No D. S.                 | 14 VI a    | 2.3                            | 0.09 |
|                                                       | 15 I a     | 3.3                            | 0.13 |
| D S - 3 *                                             | 12 II a    | 4.8                            | 0.19 |
|                                                       | 13 IV a    | 4.8                            | 0.19 |
| D S - 6 *                                             | 20 III a   | 11.2                           | 0.44 |
|                                                       | 20 IV a    | 11.2                           | 0.44 |

\* In Air. no centerbody



1.1 cm (0.44 in.). Thus, relative to the in-air and submerged modes which respectively provided path widths of about 0.3 and 1.9 cm (0.11 and 0.73 in.) in cleaning trials on the gravel and polyester artificial foulant, the dynamic sheathing type DS-6 provided an improvement of 53 percent of the difference between these two cleaning modes.

The second type of dynamic sheathing geometry which was examined is typified by the DS-9 design seen in Figure 5. The DS-9 was fabricated from a 19 mm (0.75 in.) pipe cross. A study of the effect of varying the dynamic sheathing flow through the DS-9 configuration is summarized in Figure 12 with the data for these tests listed in Table 5. It is seen here in Figure 12 that the optimum sheathing flow for this DS-9 design is about 0.95  $\ell/s$  (15 gpm). A comparison of the DS-6 with the DS-9 design using tests on actual fouled plates is summarized in Figure 13. The data for this figure are listed in Table 6. It is seen that on the actual fouled panels a somewhat wider path width is obtained (compare the results summarized in Figure 11). Figure 13 shows, relative to the DS-6 type of configuration, the DS-9 is the preferred design, and hence this DS-9 design was incorporated into the field testing equipment. The DS-9 dynamic sheathing design provided a 49 percent improvement of the difference between in-air operation and submerged operation of the 3.2-mm (1/8-in.) CAVIJET nozzle for removal of actual fouling. The comparable improvement achieved at the end of Phase I was only about 11 percent.

### C. Multiple Nozzle Tests

The actual cleaning head in the field trial device was designed to utilize a multiple set of CAVIJET nozzles. For this reason, as part of our laboratory tests to develop an





FIGURE 12 - EFFECT OF DYNAMIC SHEATHING FLOW ON TYPE DS-9 PERFORMANCE

TABLE 5

Effect Of Dynamic Sheathing Flow On Type DS-9 Performance  
 Tests with 3.2 mm (1/8-in.) CAVIJET<sup>®</sup> Nozzle;  
 13.8 MPa (2000 psi) Pump Pressure;  
 Translation Velocity: 30.5 cm/s (1 ft/s);  
 Standoff: 31.8 mm (1.25 in.)  
 Actual Fouling

| Run No.   | Dynamic Sheathing Flow |      | Cleaned Path Width |      |            |      | Area Cleaning Rate |                     |                    |                     |
|-----------|------------------------|------|--------------------|------|------------|------|--------------------|---------------------|--------------------|---------------------|
|           | 1/s                    | gpm  | 90% clear          |      | 100% clear |      | 90% clear          |                     | 100% clear         |                     |
|           |                        |      | mm                 | in.  | mm         | in.  | m <sup>2</sup> /hr | ft <sup>2</sup> /hr | m <sup>2</sup> /hr | ft <sup>2</sup> /hr |
| 7 A III a | 0.45                   | 7.2  | 35.1               | 1.38 | 12.7       | 0.50 | 38.8               | 417                 | 14.1               | 152                 |
| 7 A IV a  | 0.63                   | 10.0 | 33.4               | 1.31 | 9.7        | 0.38 | 36.4               | 392                 | 10.4               | 112                 |
| 7 A I a   | 0.76                   | 12.0 | 35.1               | 1.38 | 12.7       | 0.50 | 38.0               | 409                 | 13.8               | 149                 |
| 7 A V a   | 0.95                   | 15.0 | 38.1               | 1.50 | 23.9       | 0.94 | 41.6               | 448                 | 26.0               | 280                 |
| 7 B I a   | 0.95                   | 15.0 | 41.4               | 1.63 | 19.1       | 0.75 | 45.4               | 488                 | 20.9               | 225                 |
| 7 B V a   | 0.95                   | 15.0 | 41.4               | 1.63 | 22.4       | 0.88 | 45.4               | 488                 | 24.4               | 263                 |
| 7 B II a  | 1.07                   | 17.0 | 33.4               | 1.31 | 7.9        | 0.31 | 36.6               | 394                 | 8.7                | 94                  |
| 7 B III a | 1.26                   | 20.0 | 38.1               | 1.50 | 12.7       | 0.50 | 42.3               | 455                 | 14.1               | 152                 |
| 7 B IV a  | 1.58                   | 25.0 | 38.1               | 1.50 | 12.7       | 0.50 | 41.8               | 450                 | 13.9               | 150                 |

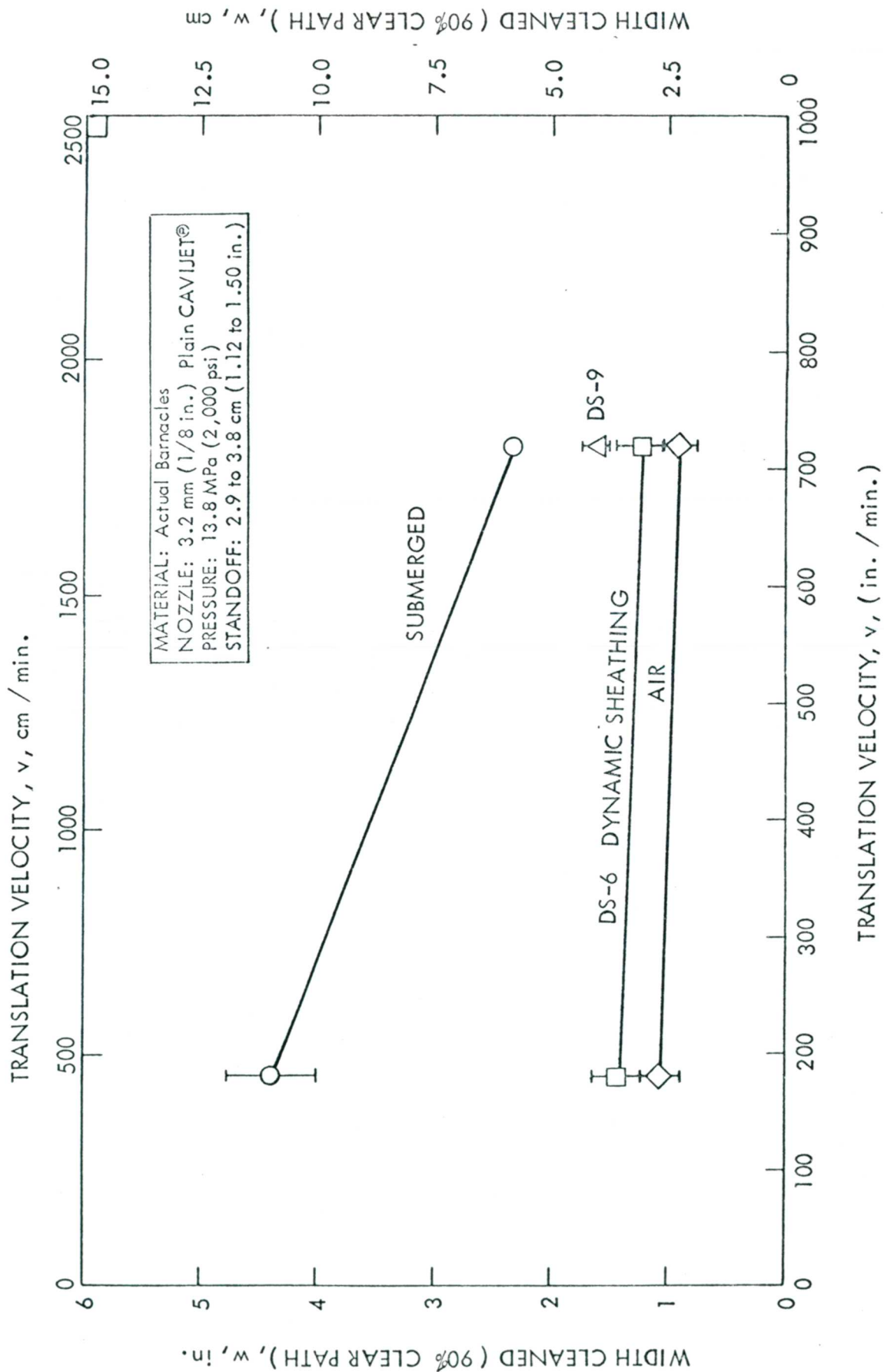


FIGURE 13 - COMPARISON OF FOULING REMOVAL PATH WIDTHS



TABLE 6

## PERFORMANCE OF DYNAMIC SHEATHING VS SUBMERGED AND IN AIR TEST MODES

Tests with 3.2 mm (1/8-in.) CAVIJET<sup>®</sup> Nozzle;  
 13.8 MPa (2000 psi) Pump Pressure;  
 Standoff: 28.6 to 38.1 mm (1-1/8 to 1-1/2 in.)  
 Actual Fouling

| Test Mode &<br>Dynamic<br>Sheathing Type           | Run<br>No. | Width Cleaned (90% clear path) |      |
|----------------------------------------------------|------------|--------------------------------|------|
|                                                    |            | mm                             | in.  |
| Translation velocity: 7.6 cm/s (0.25 ft/s)         |            |                                |      |
| Submerged<br>No Centerbody<br>No Dynamic Sheathing | 2 A V a    | 101.6                          | 4.00 |
|                                                    | 2 B III a  | 120.7                          | 4.75 |
| In Air<br>With Centerbody<br>No Dynamic Sheathing  | 2 A IV a   | 22.4                           | 0.88 |
|                                                    | 2 B II a   | 31.8                           | 1.25 |
| In Air<br>No Centerbody<br>D S - 6                 | 2 A III a  | 30.2                           | 1.19 |
|                                                    | 2 B I a    | 41.4                           | 1.63 |
| Translation velocity: 30.5 cm/s (1 ft/s)           |            |                                |      |
| Submerged<br>No Centerbody<br>No Dynamic Sheathing | 1 B I a    | 58.7                           | 2.31 |
|                                                    | 1 B II a   | 58.7                           | 2.31 |
| In Air<br>With Centerbody<br>No Dynamic Sheathing  | 1 A III a  | 23.9                           | 0.94 |
|                                                    | 1 A IV a   | 22.4                           | 0.88 |
| In Air<br>No Centerbody<br>D S - 6                 | 1 A I a    | 35.1                           | 1.38 |
|                                                    | 1 A II a   | 36.6                           | 1.44 |
|                                                    | 1 B III a  | 28.7                           | 1.13 |
|                                                    | 2 A I a    | 25.4                           | 1.00 |
| In Air<br>No Centerbody<br>D S - 9                 | 7 A V a    | 38.1                           | 1.50 |
|                                                    | 7 B I a    | 41.4                           | 1.63 |
|                                                    | 7 B V a    | 41.4                           | 1.63 |

optimum dynamic sheathing technique, it was decided to conduct a limited series of multiple nozzle tests. The purpose of these laboratory tests was to determine whether or not any unforeseen factors would arise with regard to jet interactions during the cleaning trials of the full scale multiple CAVIJET nozzle cleaning head.

The first set of multiple nozzle laboratory trials, also conducted within the CAVIJET test and evaluation facility described in Chapter II, utilized a set of three CAVIJET nozzles. Comparative tests were run with the dynamic sheathing design, labeled "DS-10", as seen in Figure 6. This type of dynamic sheathing device utilized an open chamber wherein three CAVIJET nozzles, ~~each having an orifice diameter of 3.2 mm (1/8 in.)~~ were inserted. The bottom of this chamber utilized the configuration, pictured in Figure 4, of the DS-6 type. This configuration, as discussed above, was found to be the most effective of this saucer-configuration of dynamic sheathing concepts.

To compare the results for the type DS-9 design, a comparative series of tests were performed with three side-by-side, and staggered 3.0-mm (1/8-in.) CAVIJET nozzles, each having their flow augmented by a dynamic sheathing device of the DS-9 type (see Figure 5). The results of these tests are summarized in Figure 14. It may be seen that apparently the flow interaction served to adversely affect the performance of the center CAVIJET nozzle. It is seen that the path width obtained for the center nozzle in each test was somewhat narrower than those of the outer two nozzles. However, the center nozzle for the DS-10 design was seen to suffer a greater drop in performance relative to the DS-9 design. This suggested that flow interactions within the dynamic sheathing chamber, as well as interactions in the region where the jets impinged the surface

CAVIJET NOZZLES: 3.2 mm ( 0.125 in. ) ORIFICE DIAMETER  
 NOZZLE PRESSURE: 13.8 MPa ( 2,000 psi )  
 TRANSLATION VELOCITY: 30.5 cm/s ( 1 ft / s )  
 TEST PANELS: ACTUAL BARNACLES

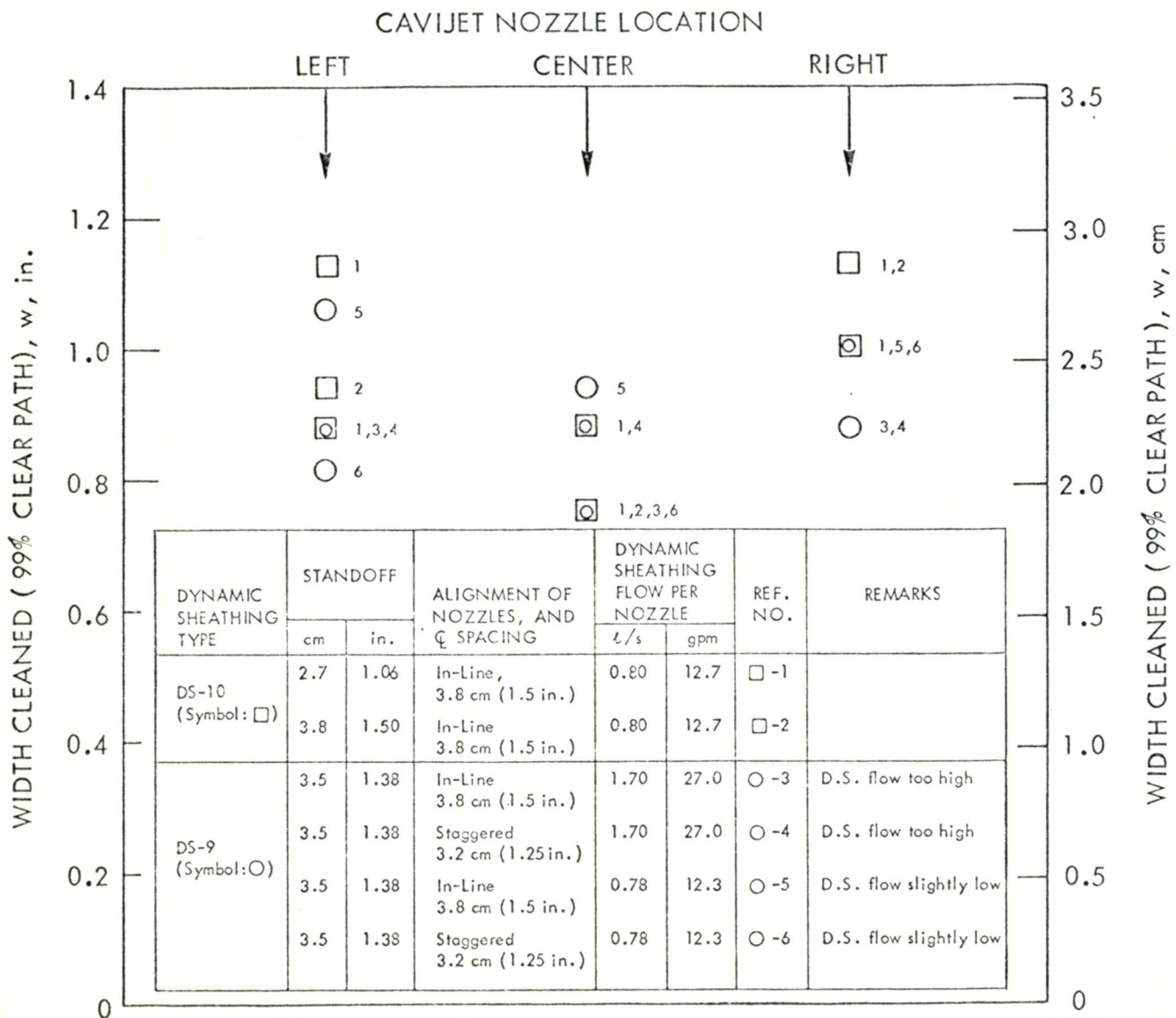


FIGURE 14 - COMPARATIVE THREE-NOZZLE DYNAMIC SHEATHING TESTS

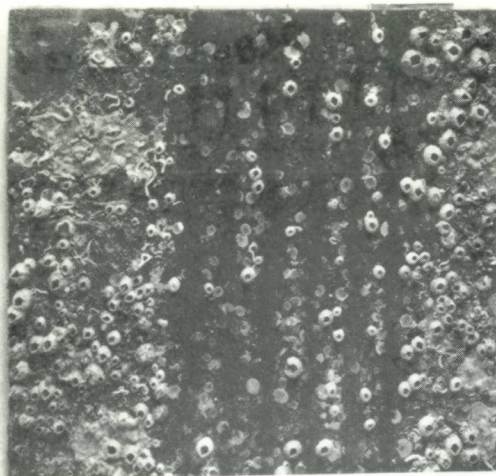


to be cleaned, were adversely affecting the center nozzle. Since each DS-9 unit received an independent dynamic sheathing flow, the former type of adverse flow interactions could not occur.

The tests summarized in Figure 14 were run before we had established the optimum dynamic sheathing flow for the DS-9 device (see Figure 12 and Table 5). Thus the flows in Figure 14 were either well above or somewhat below the optimum 0.95  $\ell/s$  (15 gpm) for this design. Hence, since the 90 percent clear path width of about 40 mm (1.6 in.) achieved by the DS-9 design is much wider than those for the DS-10 design (in Figure 14) we concluded that these results tended to confirm the earlier single nozzle development effort. This served to finalize our decision to proceed with the design of the cleaning head for the field trials and to incorporate six of the DS-9 type dynamic sheathing devices in this equipment.

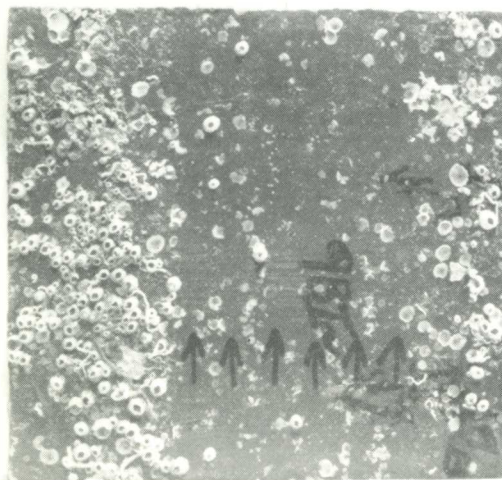
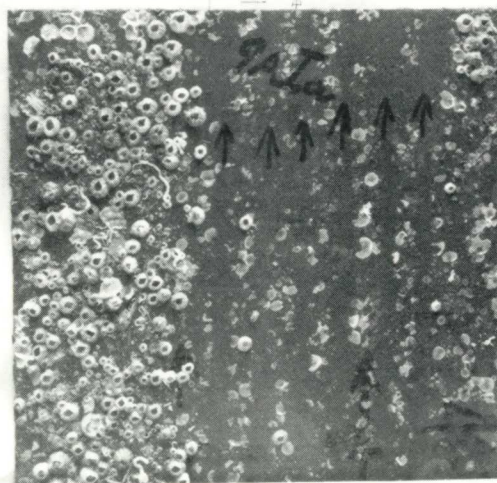
Upon completion of the field trial equipment, and prior to transporting this hardware to the dry dock, a limited checkout running of the equipment was performed. As part of these trials we rigged a temporary support frame which would allow us to run trials of the full set of six CAVIJET nozzles in the actual cleaning head across some of the fouled steel panels provided to us by Miami Marine Research, Inc. Photographic record of the results of some of these six nozzle panel cleaning trials are shown in Figure 15 and 16. The importance of the correct volume flow of dynamic sheathing for such in-air cleaning with the CAVIJET method can be seen by comparing the results in Figure 15a with those of Figures 15b and 15c. In Figure 15a the total sheathing flow was 3.2  $\ell/s$  (50 gpm). The desired sheathing flow for the six nozzles was 5.7  $\ell/s$  (90 gpm) (i.e., six times the 0.95  $\ell/s$  (15 gpm) found to be optimum for a single nozzle). It is seen in Figure 15a that, with the nozzles set at a





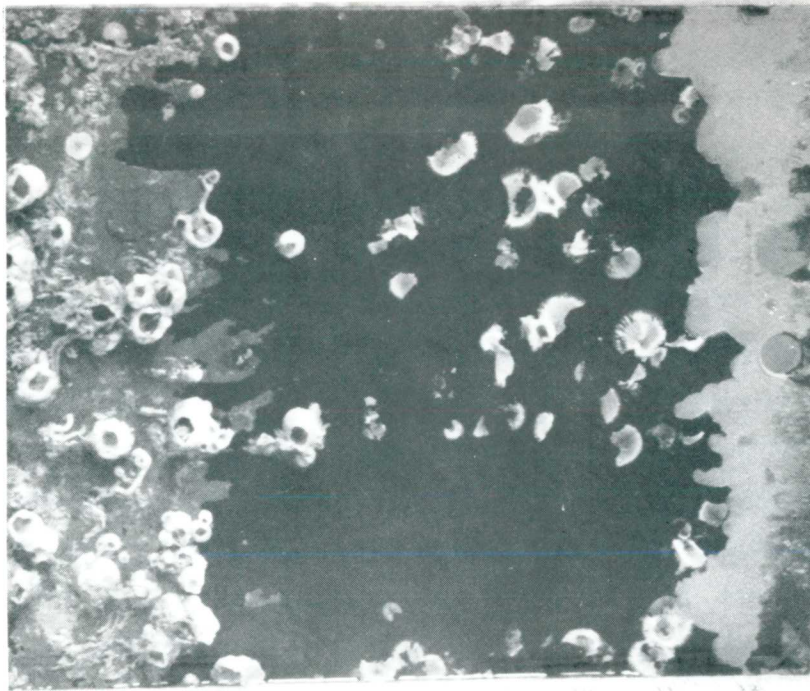
- a. DYNAMIC SHEATHING FLOW:  $3.2 \text{ l/s}$  (50 gpm);  
PUMP PRESSURE:  $13.8 \text{ MPa}$  (2,000 psi);  
TRANSLATION VELOCITY:  $0.3 \text{ m/s}$  (1 ft/s)

- b. DYNAMIC SHEATHING FLOW:  $4.8 \text{ l/s}$  (76 gpm);  
PUMP PRESSURE:  $17.2 \text{ MPa}$  (2,500 psi);  
TRANSLATION VELOCITY:  $0.28 \text{ m/s}$  (0.92 ft/s)

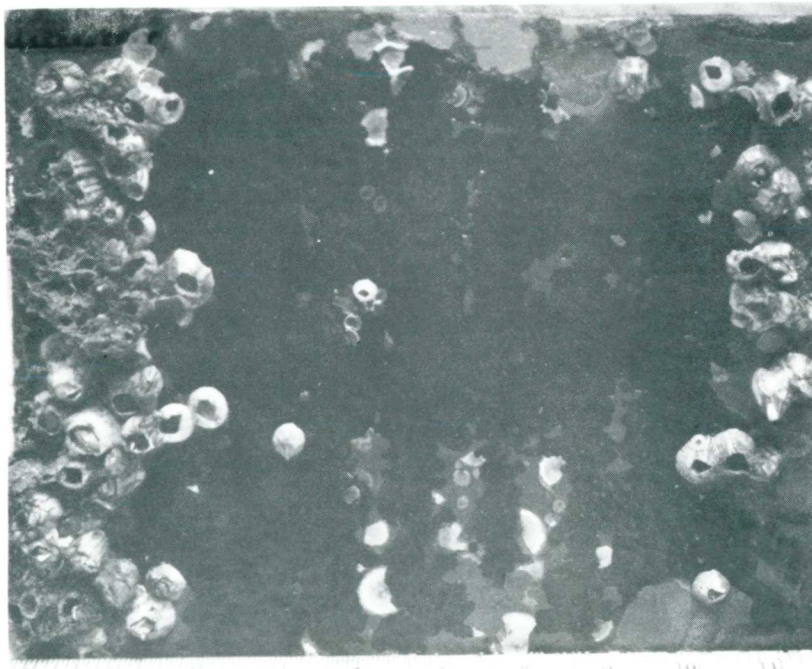


- c. DYNAMIC SHEATHING FLOW:  $4.4 \text{ l/s}$  (70 gpm);  
PUMP PRESSURE:  $13.8 \text{ MPa}$  (2,000 psi);  
TRANSLATION VELOCITY:  $0.26 \text{ m/s}$  (0.84 ft/s)

FIGURE 15 - LABORATORY TRIALS OF THE SIX-NOZZLE CAVIJET® CLEANING HEAD. Nozzle orifice diameter:  $3.0 \text{ mm}$  (0.12 in.); tests on epoxy-coated steel panels



a. DYNAMIC SHEATHING FLOW ZERO: PUMP PRESSURE: 17.9 MPa ( 2600 psi ); TRANSLATION VELOCITY: 0.3 m/s ( 1 ft / s )



b. DYNAMIC SHEATHING FLOW: 4.3 l/s ( 71 gpm ); PUMP PRESSURE: 14.1 MPa ( 2050 psi ); TRANSLATION VELOCITY: 0.18 m / s ( 0.6 ft / s )

FIGURE 16 - LABORATORY TRIALS OF THE SIX-NOZZLE CAVIJET® CLEANING HEAD. Nozzle orifice diameter: 3.0 mm ( 0.12 in. ); tests on coal tar based coating on steel panels



center-to-center distance of 2.5 cm (1 in.) there were gaps left between the cleared paths. Hence each nozzle did not clean the full 2.5 cm (1 in.) or wider path which had been achieved in the single nozzle trials with the correct 0.95  $\ell/s$  (15 gpm) dynamic sheathing flow. Due to limitations of the pumps in our laboratory trials which were providing the dynamic sheathing flow, the maximum flow which we could provide was only 4.4  $\ell/s$  (70 gpm) total. This improved dynamic sheathing flow did, however, as seen in Figures 15b and 15c, provide a definite improvement to the cleared paths provided by the six nozzle array. Indeed, in the latter two trials only a few stray barnacles (which were unfortunatously exactly half-way between two adjacent nozzles) were left on these epoxy coated panels.

In addition to these six-nozzle trials on the hard, epoxy-coated steel panels, we ran a few tests on some coal tar-based antifoulant coated panels which MMRI had sent to us. These panels, which had been coated with experimental types of antifoulant paints were of no further use to their manufacturer, and knowing of our interest, MMRI kindly provided them to us for our testing. It is seen, in Figures 16a and 16b that a dramatic difference in the cleaning patterns may be obtained when attempting to clean such panels. The coatings of this type represent a more realistic picture of what we subsequently found to be the situation on the actual ship hulls during our field trials. Because it is possible to remove a few millimeters of the surface of such relatively soft antifoulant paints, it is much easier to do a cleaning that is equivalent to the sandsweeping type of surface typically desired in a commercial shipyard. Thus, using the same test conditions as in the tests on the hard epoxy coating, even without the use of dynamic sheathing flow as in Figure 16a, it was possible to remove a



considerable amount of the fouling over the region impinged by these six CAVIJET nozzles. As seen in Figure 16b, when a dynamic sheathing flow was utilized, even though below the desired optimum of 5.7 l/s (90 gpm), a very complete cleaning was obtainable. With the conclusion of these six nozzle cleaning trials in the field equipment, we then proceeded to prepare for the field trials as discussed in Chapter V.

#### IV. DESCRIPTION OF FIELD TRIAL EQUIPMENT

The main components of the CAVIJET field trial hull cleaning system are: (a) a pump having the capability of meeting the pressure and flow rate requirements called for in the cleaning process; (b) the main test frame, which is designed to house the CAVIJET cleaning head in a moveable carriage, and to provide controlled horizontal and vertical sweeping motions of this carriage; (c) the CAVIJET cleaning head where six CAVIJET nozzles are arranged; (d) the underwater observation and photography unit, which allows diver observation in silted water and has underwater photography capability; and (e) a hydraulic control unit where the motion of the cleaning head can be regulated. In the following sections of this chapter detailed descriptions of each of these components will be provided.

##### A. Pump for CAVIJET® Nozzles

The original plan for this program involved the conversion of an existing WOMA pump, owned by the Maryland Shipbuilding and Drydock Company, to meet the required low pressure high volume flow rate conditions. This plan was modified, however, when HYDRONAUTICS decided to expand their internal CAVIJET research and development program capabilities. A portable pump (see Figure 17) was purchased as part of this program expansion. One of the special features of this pump is that the plungers and/or the fluid end of the pump are replaceable. When the low pressure fluid end is used, the pump can deliver 5.7 l/s (90 gpm) flow at 17.2 MPa (2,500 psi) pressure, while 1.3 l/s (20 gpm) flow at 68.9 MPa (10,000 psi) can be obtained with the high pressure fluid end. This large spectrum of pressure and flow rate combinations, as shown in Figure 18,

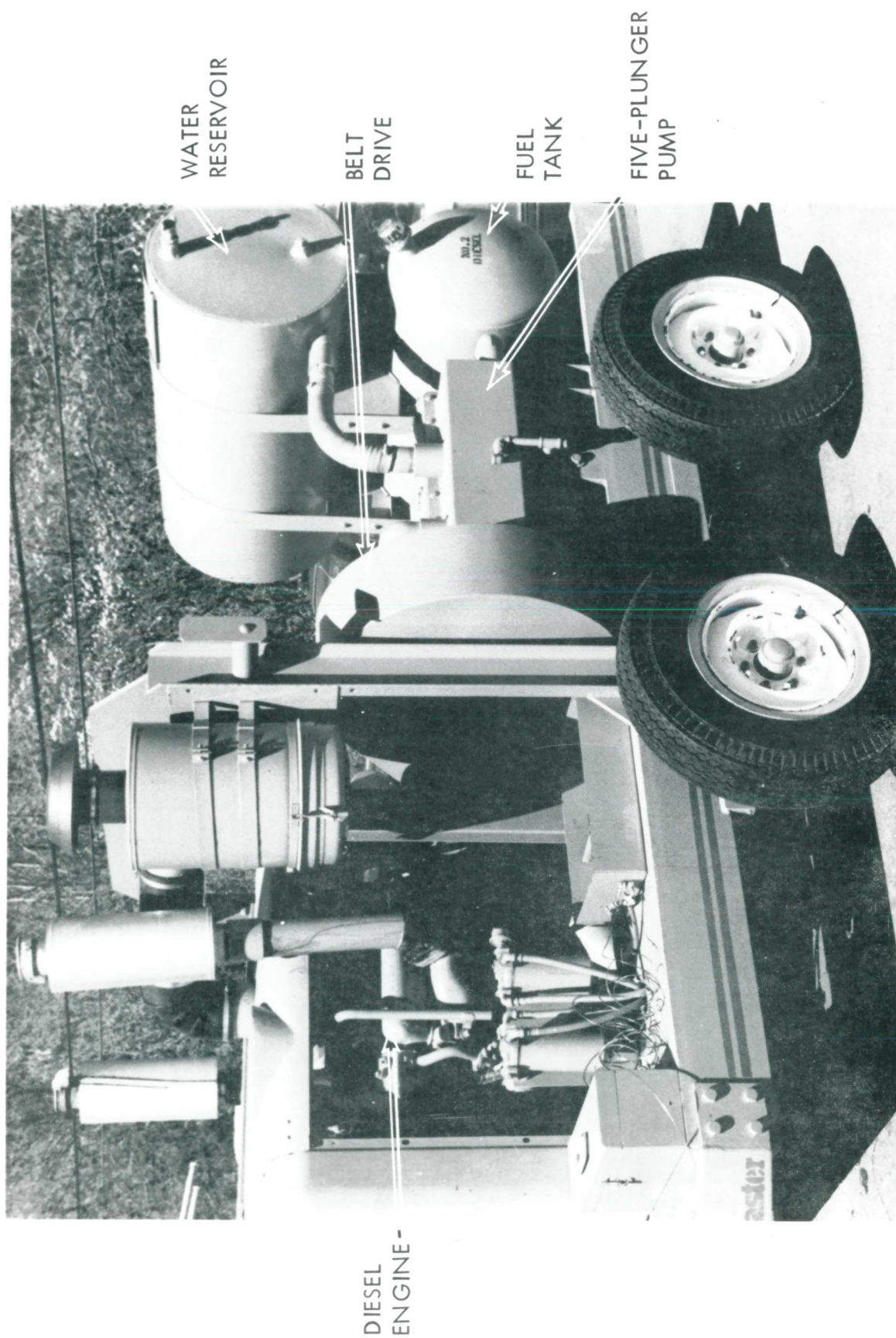


FIGURE 17 - PUMP SYSTEM FOR CAVIJET® NOZZLES: American Aero, Inc.  
Model WBD-190V



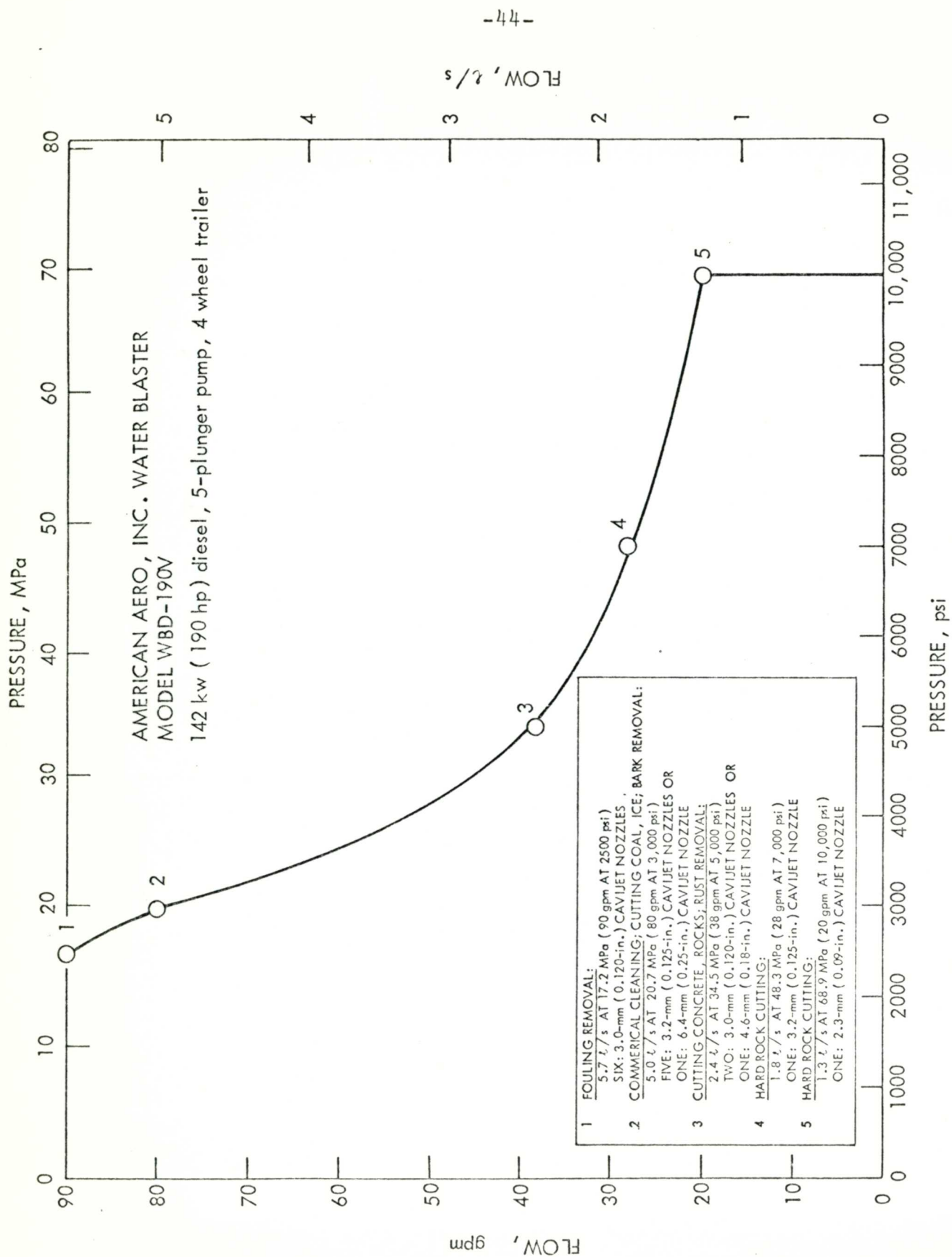


FIGURE 18 - PERFORMANCE SPECIFICATIONS OF THE MAIN PUMP USED FOR THE FIELD TRIALS

has allowed greater flexibility for CAVIJET research and development projects. This new pump was used both for the present laboratory work as well as the field trial studies.

This pump is manufactured by American Aero Inc., of Houston, Texas, and has their Model No. WBD-190V. It has five plungers and is driven by a diesel engine, rated for 142 kw (190 BHP). The engine and the pump are mounted on a four-wheeled tandem trailer. The detailed specifications of this pump and engine, as supplied by the manufacturer, are shown in Table 7.

After receiving the pump, we made several modifications to provide maximum use of the engine power and easier operation of the system. Directly related to the present field trial studies are:

a. The pump by-pass loop:

A by-pass loop was set up between the pump and the reservoir. During initial diesel engine speed adjustment, much of the pump flow can be directed into the reservoir mounted on the trailer. Since little flow is delivered to the nozzles, there is minimal water use in this tuning stage. Once the engine speed has reached the desired value, the by-pass line can be closed and the flow sent to the nozzles to begin the cleaning.

b. Remote on-off control box:

This enables the operator to engage the throttle while at distances away from the diesel. This concept can be integrated into the main control panel for the whole cleaning system. This remote control unit has an on-off switch which is wired to the electric system of the diesel engine. When in the "on" position, the throttle is engaged and full pump pressure is delivered to the nozzles for cleaning. The circuit diagram for this remote

Table 7

Specifications of American Aero, Inc. Engine/Pump System  
Used for Field Trials

|                                                                                                                                                                                                                                                                   |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <u>Engine:</u><br><br>Model: GMC-6V-53 diesel<br>Power: 142 kw (190 BHP)<br>Fuel: #2 diesel fuel<br>Fuel Tank Capacity: 145 l (55 gal.) (8 hours)<br>Water Reservoir Capacity: 145 l (55 gal.)                                                                    |
| <u>Pump:</u><br><br>Model: WBD-190V<br>Flow Rate: 0.33 l/s (90 gpm) at 17.2 MPa (2,500 psi)<br>Plungers: 5<br>Power End: Model Union Q-100<br>Fluid End: Model Union Q-100 (high flow type)<br>Drive: V-belt and belt guard                                       |
| <u>Trailer:</u><br><br>Type: 4-wheel, tandem axle<br>Load Capacity: 44.6 kN (10,000 lb)<br>Brakes: Electric<br>Support: Stabilizing jackstand<br>Accessories: ICC lighting package (brakes, turn, license)<br>Gross Weight: 33.5 kN (7,500 lb) (of entire system) |



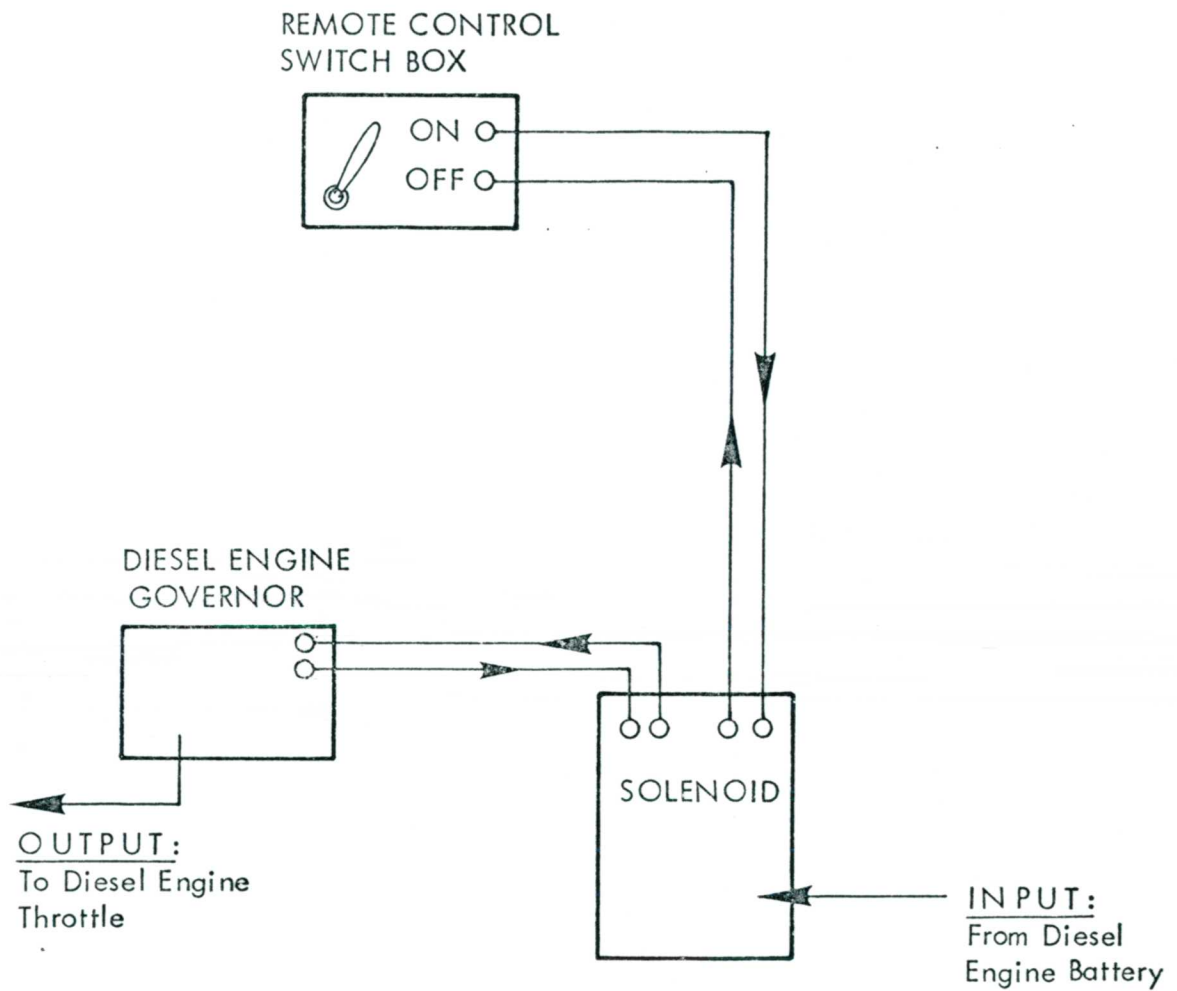


FIGURE 19 - BLOCK DIAGRAM OF REMOTE CONTROL FOR MAIN PUMP:  
For CAVIJET® nozzle cleaning head on-off control.

control is shown in Figure 19. Also, a circuit breaker was added to the electric system of the engine, allowing power to be drawn from the diesel engine starter battery to supply the illumination system for underwater photography.

Various combinations of flow rate and pressure can be achieved with this pump by a number of ways: (a) changing the fluid end, (b) changing plunger sets, (c) regulating the engine RPM, and, (d) selection of nozzle(s). For instance, as seen in Figure 18, at 68.9 MPa (10,000 psi) pump pressure, the pump can discharge a maximum of 1.3  $\ell/s$  (20 gpm) of flow which is suitable for the cutting of hard rock with a 2.3-mm (0.09-in.) CAVIJET nozzle (10). While operated at 20.7 MPa (3000 psi), the maximum flow from pump is 5.0  $\ell/s$  (80 gpm). This flow rate is large enough to supply, for instance, five 3.2-mm (0.125-in.) CAVIJET nozzles or a single 6.4-mm (0.25-in.) nozzle for commercial cleaning, cutting coal or ice, or bark removal (11,12,13).

#### B. Main Test Frame

The components to carry the CAVIJET cleaning head and provide either up-and-down or left-to-right traversing motions, are supported by a specially designed test frame. The overall dimensions of this frame are 1.8 m high by 2.4 m wide (6 by 8 ft) but the area that can be cleaned by the jets is about 1.2 by 1.8 m (4 by 6 ft). The carriage which supports and traverses the cleaning head is controlled by a hydraulic system which is designed to run underwater. The horizontal speed of the carriage can be varied from 0 to 0.9 m/s (0 to 3 ft/s). The vertical motion can be indexed, either manually or automatically over a preset distance. In the automatic mode, the cleaning head can be made to sweep the entire cleaning area with a continuous motion of the carriage.

## 1. Description of Test Frame Components

Descriptions of the components which make up the test frame (see Figure 20) are provided in the following sections. A list of principal purchased components is in Table 8.

### a. Support Frame:

The outer frame has dimensions of 1.8 by 2.4 m (6 by 8 ft) and is constructed from 10.2-cm (4-in.) steel I-beams. On the upper and lower I-beams, steel 90-degree angle-beams are welded longitudinally for the full length of the frame. These serve as guides for the wheels during the horizontal motion of the carriage.

### b. Carriage:

The carriage is constructed from 5-cm (2-in.) steel U-channels to form a rectangular frame. Four grooved wheels are mounted on this frame to permit horizontal movement of the carriage. Inside the carriage, there is another four-wheeled base frame which supports the cleaning head. Vertical motion of the base frame is guided by the U-channels of the carriage. The power required for these horizontal and vertical motions is provided by hydraulic motors.

### c. Hydraulic systems:

There are two independent hydraulic systems on the test frame: one to provide the vertical motion of the cleaning head and the other to move the carriage in the horizontal direction. The incremental vertical motion of the cleaning head is controlled by two indexing cylinders with a chain drive from one hydraulic motor. When the indexing cylinder is energized from the high pressure hydraulic line, its spring loaded rod will extend for a predetermined time by means of replaceable indexing



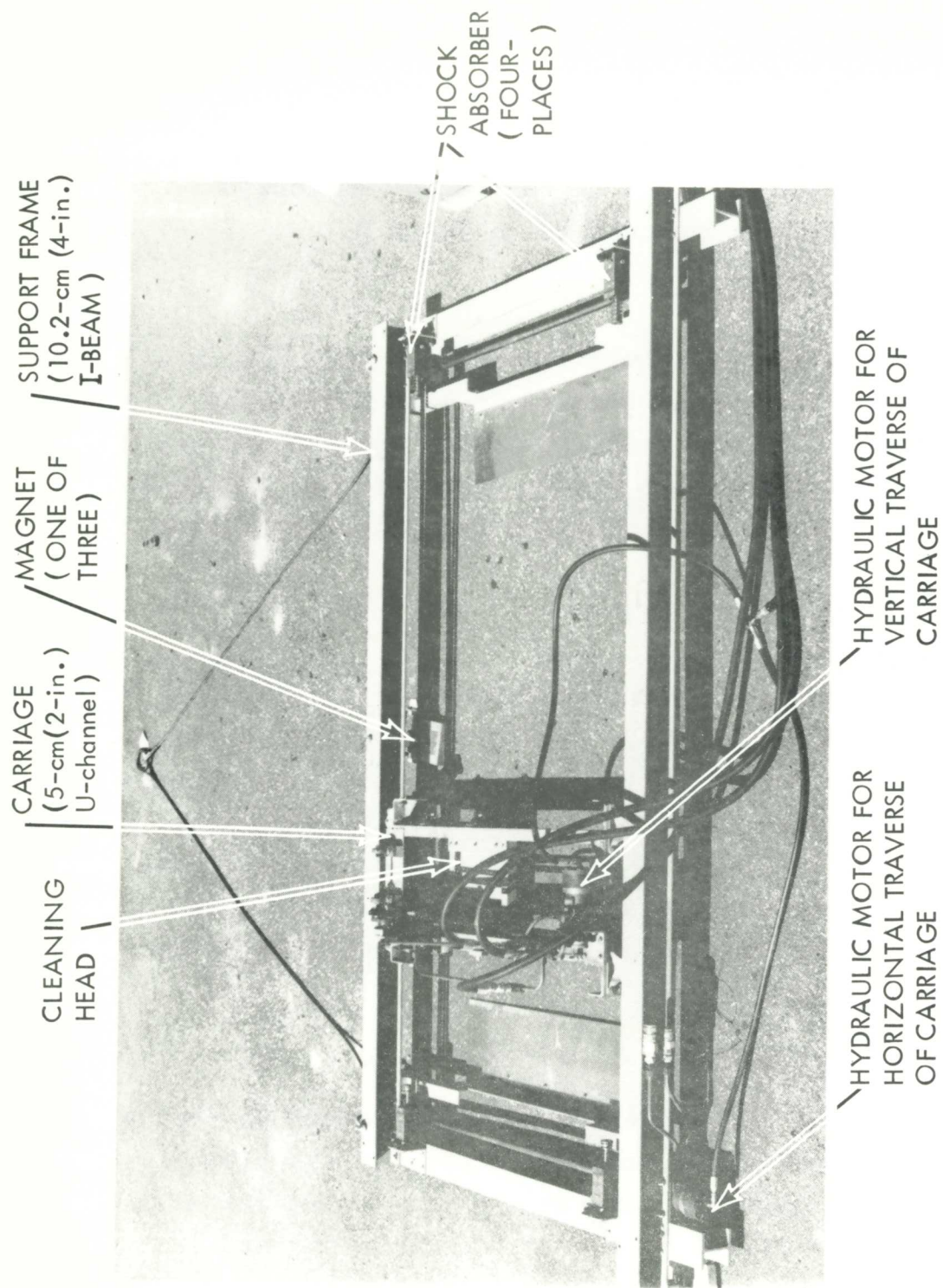


FIGURE 20 - OVERALL VIEW OF MAIN TEST FRAME

Table 8  
List of Components in the Main Test Frame

| Item              | Make/Model Number              |
|-------------------|--------------------------------|
| Indexing Cylinder | Hanna #MS7-L-NC-1.5-2.0-DSM-1A |
| Hydraulic Motor   | Charlynn #103-1007-007         |
| Shock Absorber    | Efdyne #ASB-7/8-2-PS-99        |
| Grooved Wheels    | Bassick #4381-2 CW             |
| Trolley Wheels    | Coffing #TG-10P                |
| Chain Sprocket    | Boston Gear #40A15, 40B15      |
| Chain             | Boston Gear #40                |
| Bearings          | Boston Gear, TB, FB and B      |
| Pillow Blocks     | Boston Gear, 1/2" and 1"       |
| Hydraulic Hoses   | Aeroquip, 3/4", 1/2"           |
| Hose Connectors   | Quick connectors/Aeroquip      |

wheels. This rod in turn controls the number of revolutions of the hydraulic motor. As a consequence of the motor running, a fixed distance of chain travel is introduced. Since the cleaning head assembly is positively engaged to the chain, a fixed increment of vertical motion of the cleaning head is induced. Figures 21a and 21b show the upper and lower parts of the vertical index cylinders, chain drive and motor arrangement. The increment of the vertical carriage motion was set for 15.2 cm (6 in.) since this distance corresponded to the total path anticipated to be cleaned by the six CAVIJET nozzle array.

The horizontal hydraulic system is basically the same as the vertical hydraulic system except there are no indexing cylinders. When the high pressure hydraulic fluid is fed into the hydraulic motor it will force the motor to rotate at a certain speed in proportion to the system flow rate. For horizontal traverses the power derived from the second hydraulic motor is transmitted directly to the carriage through a sprocket and chain arrangement. To stop the horizontal motion of the carriage, pairs of shock absorbers are provided at each end of the runway (see Figure 22). These shock absorbers stop not only the motion but, through an overpressure sensor, also stop the hydraulic power to the system. At the end of a run, a reverse motion of the carriage can be achieved by reversing the direction of the hydraulic motor rotation.

d. Cleaning head:

The design of the multinozzle cleaning head to be mounted on the carriage of the test frame was based on a trade-off of the restraints imposed by the flow capacity of the main pump, and the optimal cleaning effectiveness of the CAVIJET nozzles for fouling removal. As seen in Figure 18 the maximum flow



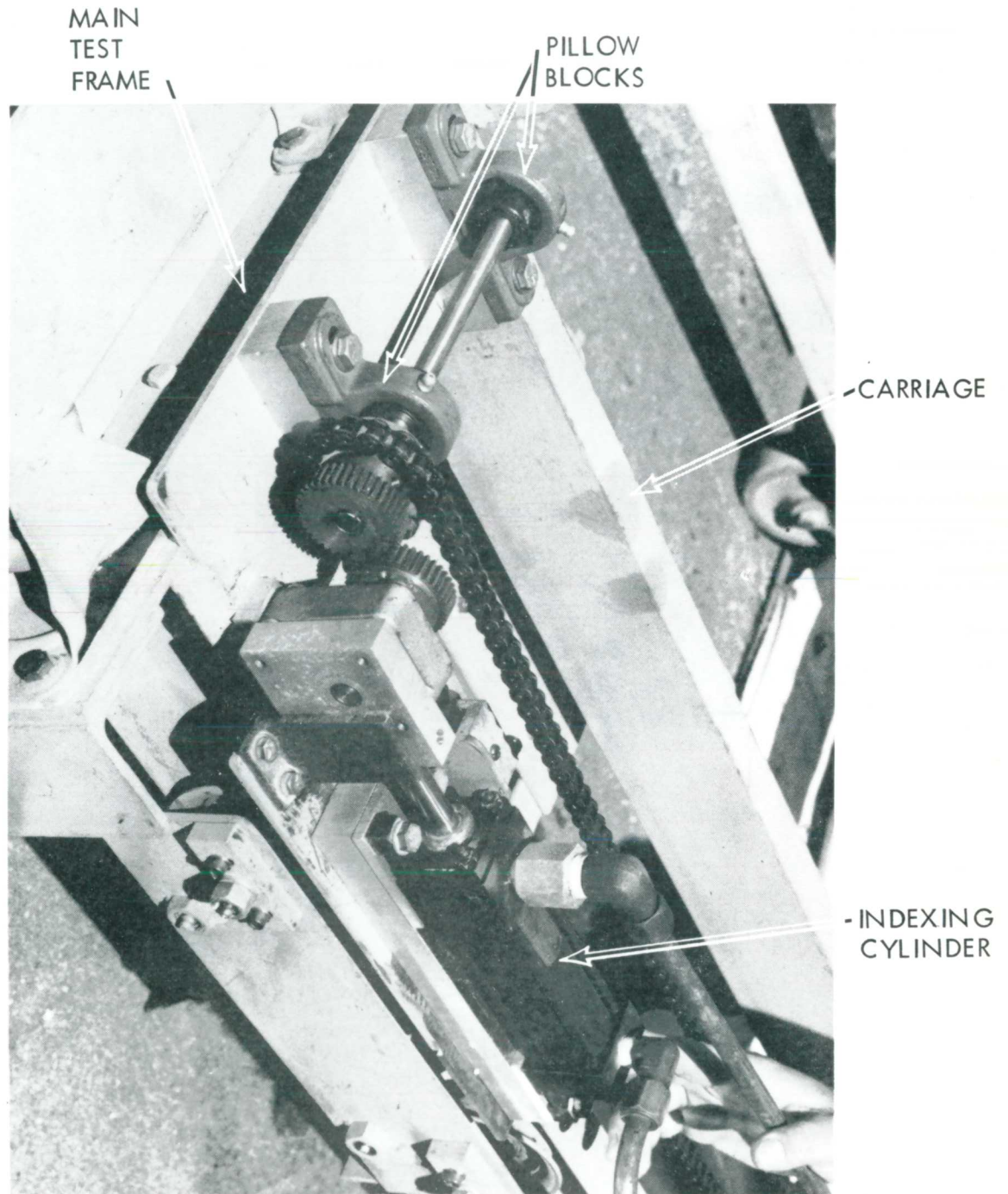


FIGURE 21a - VERTICAL TRAVERSING MECHANISM:  
upper portion

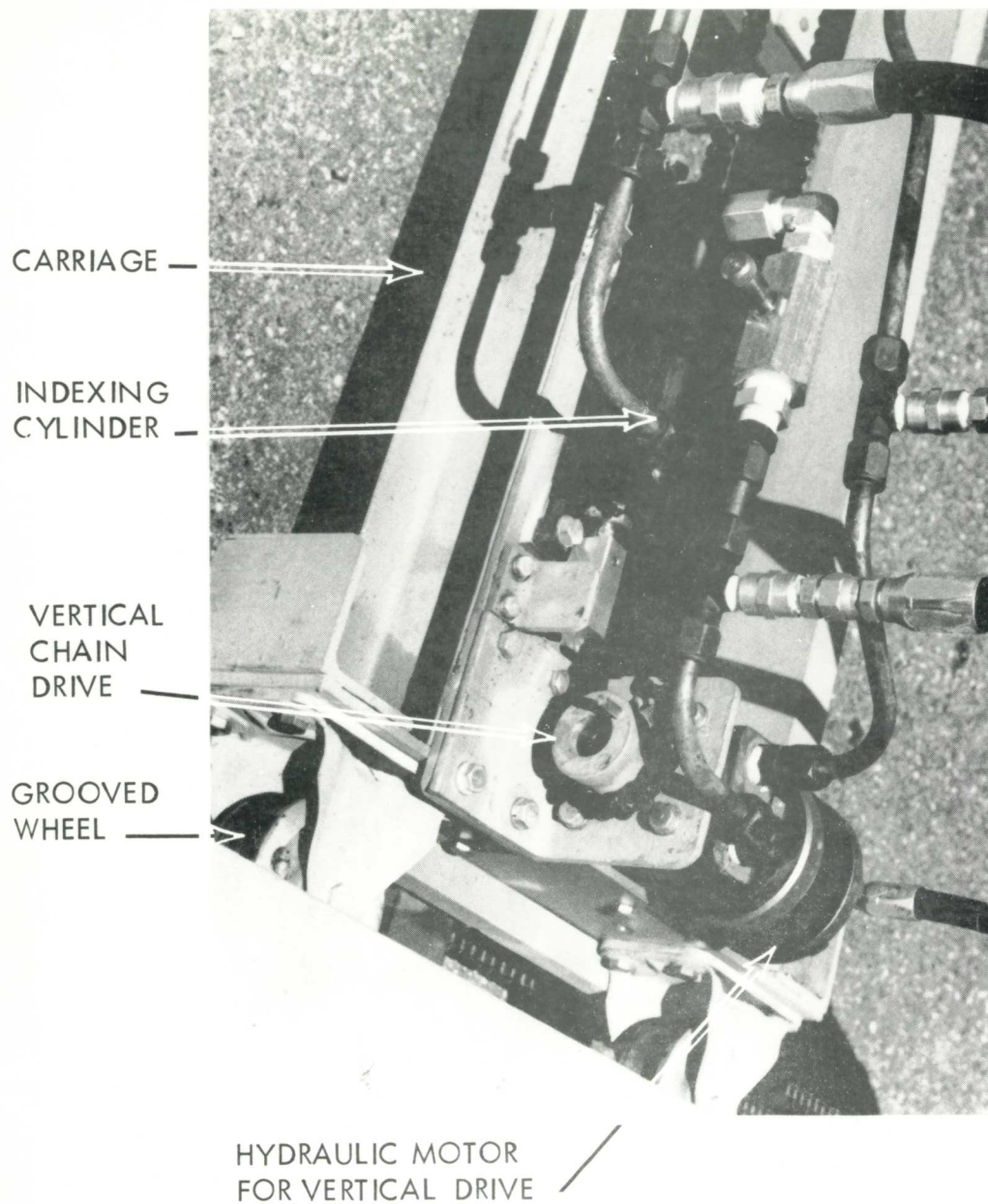


FIGURE 21b - VERTICAL TRAVERSING MECHANISM:  
Lower Portion

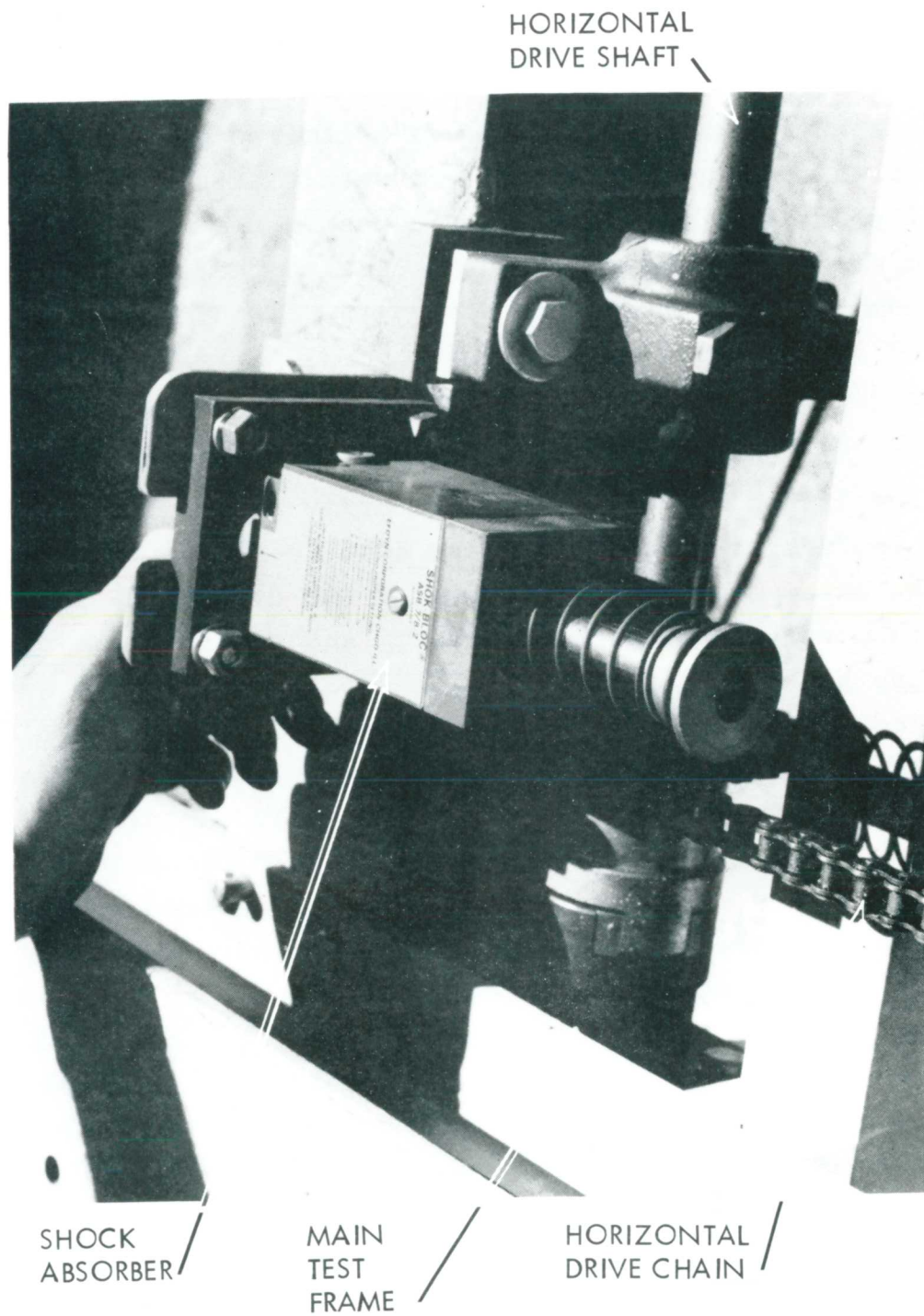


FIGURE 22 - TYPICAL SHOCK ABSORBER



capacity of the main pump at a delivered pressure of 17.2 MPa (2,500 psi) is about 5.7  $\ell/s$  (90 gpm). The earlier work (1) on the effect of nozzle diameter on area cleaning effectiveness is summarized in Figure 23. Although a limited examination was made of this diameter effect it is seen that the peak in area cleaning effectiveness occurs at a nozzle diameter of about 3.2 mm (1/8 in.). Thus, to fully utilize the capacity of our main pump, it was decided to design the cleaning head to contain six CAVIJET nozzles, each having a nozzle orifice diameter of 3.0 mm (0.120 in.). The total flow for the six nozzles was 5.4  $\ell/s$  (85 gpm), thus just within the capacity of the pump.

The layout of this six nozzle array within the carriage is shown in Figures 24 and 25. Also seen in these photographs are the arrangement for the input of the dynamic sheathing flow to each nozzle. Shown in Figures 24 and 25 are pairs of low pressure hoses feeding to the pipe crosses which have been modified and installed to surround each of the six nozzles. Further descriptions of this dynamic sheathing configuration may be found in Chapter III (see Figure 5). As oriented in Figures 24 and 25 the cleaning passes would occur in a left-right direction. In order to provide the desired minimum spacing between adjacent nozzles, the six nozzles were staggered as seen here in these photographs. Thus, a minimum nozzle-to-nozzle spacing of under 25.4 mm (1 in.) could be obtained if desired. In these photographs the nozzle-to-nozzle spacing is set at 25.4 mm (1 in.), which corresponds to the cleared path width obtained in the laboratory trials for the 3.2-mm (1/8-in.) CAVIJET nozzles. The cleaning head was designed to allow independent vertical or horizontal adjustments in the spacing of the nozzles.

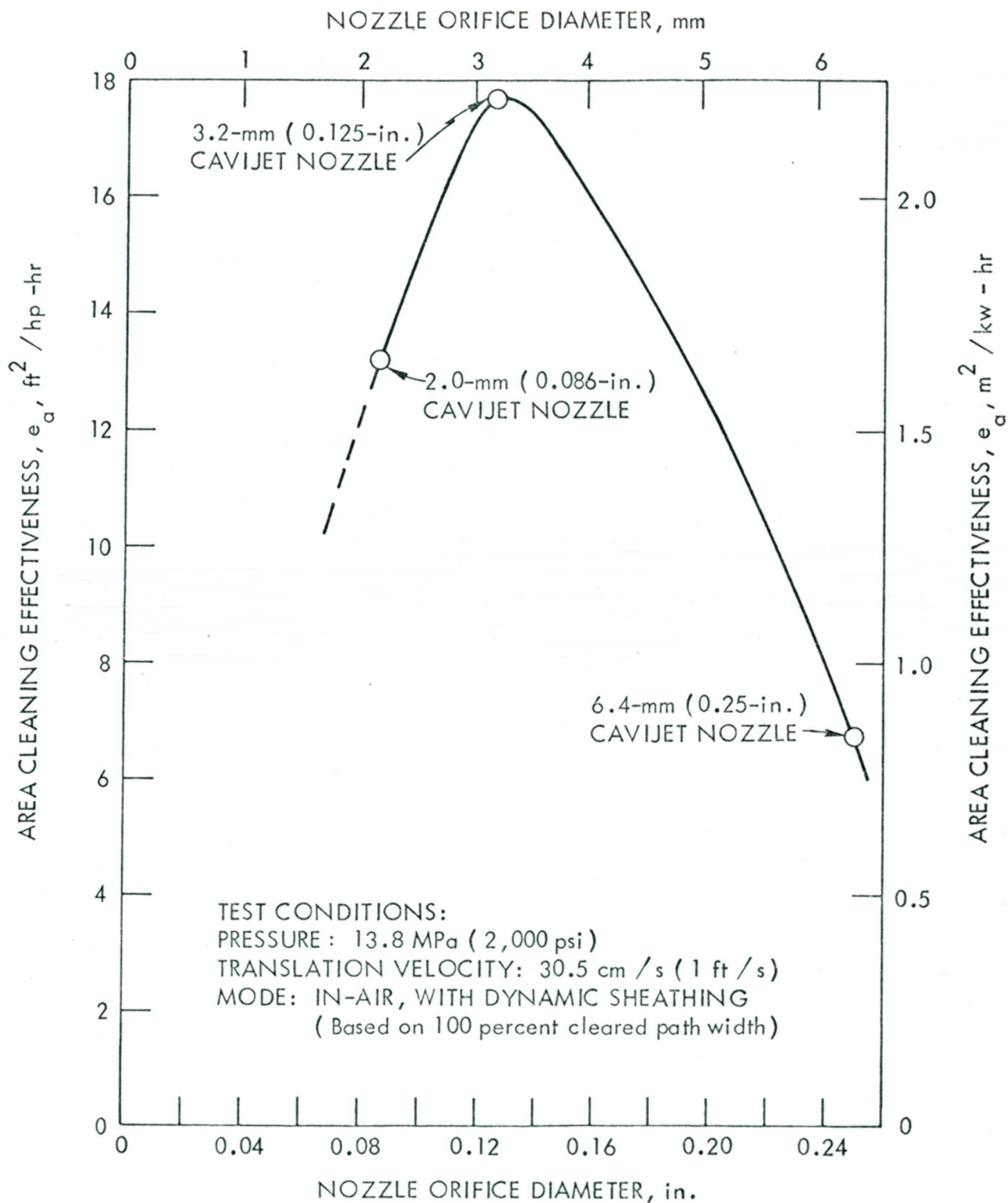


FIGURE 23 - INFLUENCE OF CAVIJET® NOZZLE DIAMETER ON FOULING REMOVAL EFFECTIVENESS



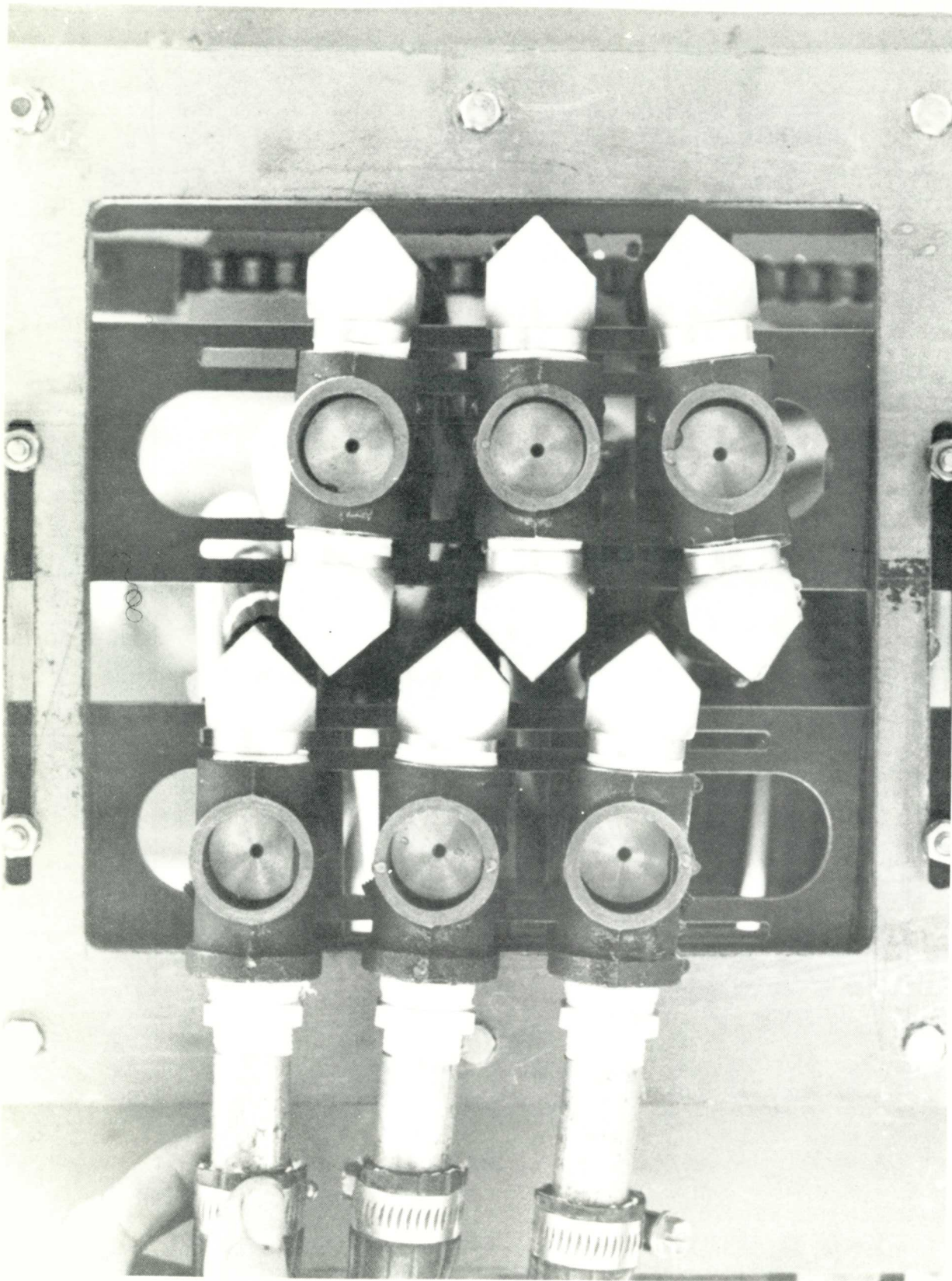


FIGURE 24 - CLOSEUP OF SIX-NOZZLE CAVIJET® ARRAY FOR HULL CLEANING SYSTEM: Showing the 3.0-mm (0.120-in.) dia. nozzles within the dynamic sheathing crosses.



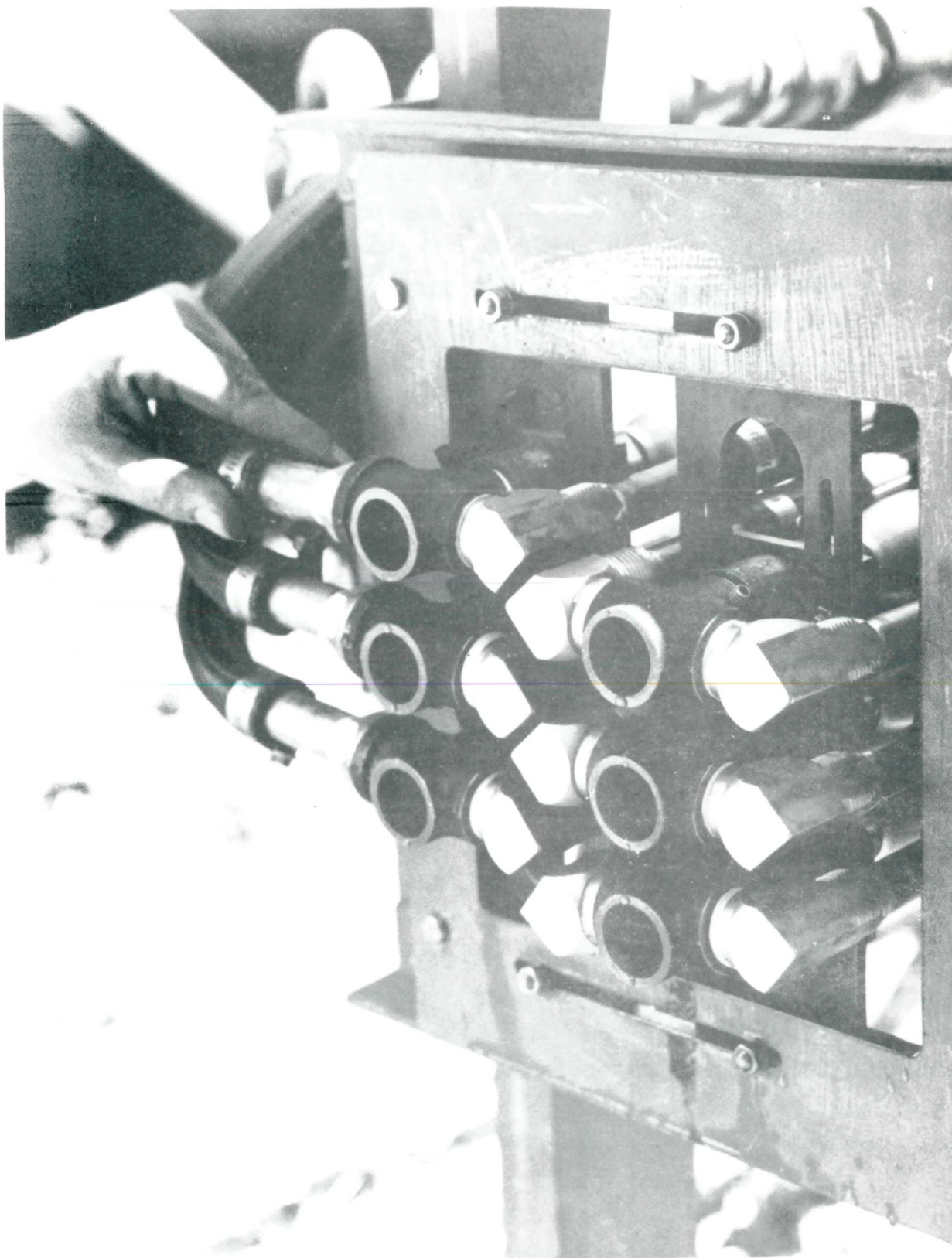


FIGURE 25 - CLOSEUP OF DYNAMIC SHEATHING COMPONENTS FOR  
CAVIJET™ HULL CLEANING SYSTEM

The dynamic sheathing flow feed water for these six nozzles was provided by an adaption to the feed line for the main pump. A 5.1 cm (2 in.) pipe tee was inserted in the suction line to the pump, and a flow measuring capability was provided. This flow measurement was obtained by means of a gauge set into an elbow so that the differential pressure could be read in the flow around this bend. This gauge was then calibrated over the expected required test range of total dynamic sheathing flows. Based on the laboratory results, the optimum dynamic sheathing flow for these CAVIJET nozzles was about 0.95 l/s (15 gpm) per nozzle. The value of the dynamic sheathing flow was one of the parameters monitored during the field trials of this six CAVIJET nozzle array.

## 2. Trial runs in HYDRONAUTICS' Ship Model Basin

After completing the construction of the test frame and camera box, we conducted several trial runs: on land as described in Section C of Chapter III, and underwater in our Ship Model Basin. For the underwater testing a large steel plate was lowered into the basin and fixed in place by weights. The whole test frame was attached to the steel plate by the three magnets built onto the support frame. It was found that the magnets could not properly hold the test frame against the steel plate during the test, mainly because the surface of the steel plate was not clean enough for magnets to develop maximum holding force. Since unclean ship hull surfaces, either due to fouling or rust, were what would be encountered in the field trials, this established that an alternative test frame supporting system would probably have to be sought. In general, these laboratory trial runs proved out the underwater operation of the whole system. During the actual field trial, several new problems were encountered and these will be addressed in the following section.



3. Problem areas in the present design of the test frame.

Through several field trial exercises, we learned that there are several problems associated with the present design. They are not serious in nature but should be kept in mind in any future designs of prototype production equipment.

a. Magnets:

It was proven that using magnets to hold the test frame against the ship hull is not feasible. It was justifiable to use chain falls and cables supported from the deck and the bilge keel or keel blocks in the present demonstration program. For future full scale cleaning equipment, however, a positive support which allows mobility of the cleaning head is an essential requirement.

b. Horizontal traversing wheels:

In the present design, the horizontal traversing wheels are guided by two angle beams welded on the cross-beams of the test frame. This provides only passive holding of the wheels. If the frame is not lifted properly, or if the chain falls are not properly tightened and hence the frame is warped, the wheels can slip off their tracks. This is due to the large carriage width and test frame span. A shorter span or a more positively guided track should be considered in any future designs.

c. Vertical motion of carriage:

It was found in the field trials that the indexing concept for the vertical motion of the carriage was very slow. In full scale cleaning such idle time must be kept to a minimum. Either a larger capacity for the hydraulic drive or a different indexing approach should be implemented in any future designs.



d. Test frame dimension:

The present test frame dimension of 1.8 m by 2.4 m (6 ft by 8 ft) and the desired stand-off distance of 2.5 to 5 cm (1 to 2 in.) between the CAVIJET nozzles and the ship hull are fixed. Once the ship hull surface shows any kind of curvature, the stand-off distance is affected because of the rigidity of the test frame. Curvature of course exists almost everywhere on a ship hull, except in the rather limited midship region. To cope with the curvature problem in a production prototype, the cleaning head and its support must have dimensions small enough so that stand-off distance variations can be kept within tolerable bounds. Also, the nozzles might be provided with self-adjusting mountings, so that they could follow hull curvatures and irregularities.

C. Hydraulic Control Unit

Two views of this system are shown in Figures 26 and 27. As stated earlier, there are two independent hydraulic systems on the test frame. They are interconnected, however, to one main hydraulic pump. The output of this hydraulic pump can be directed to either the horizontal motor or the vertical motor for the carriage. As seen in Figures 26 and 27, a push-pull diverter valve is the selector switch for routing the hydraulic fluid to either of two pressure regulators. The output of each regulator is connected to a two-way valve so that each hydraulic motor on the test frame can be independently reversed.

D. Underwater Observation and Photography Unit

To facilitate the underwater observation and photographic effort, we have designed and built a submersible viewing unit, see Figures 28 and 29. Some unique features of this unit include: a preset focal distance for the camera, fresh water

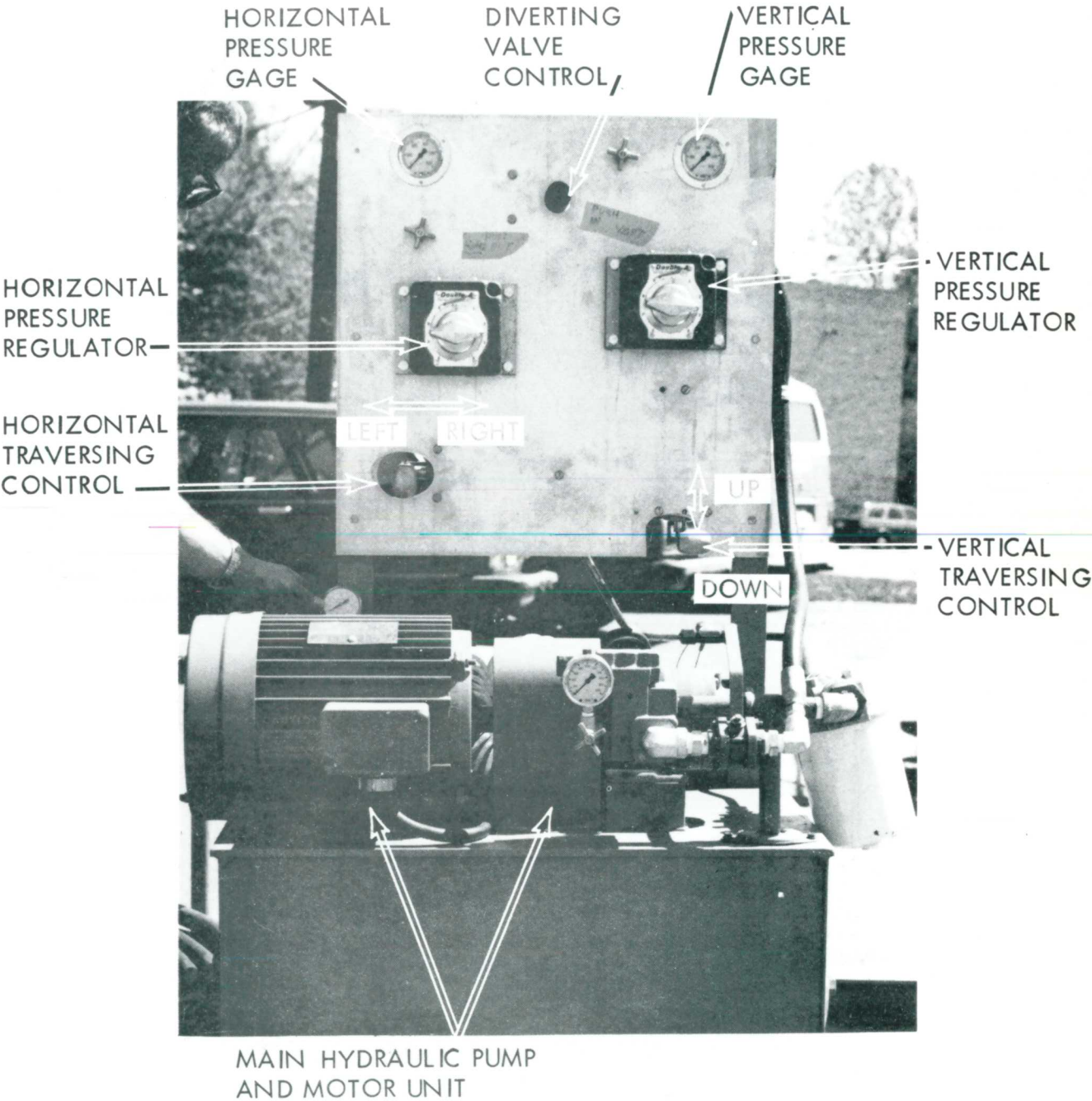


FIGURE 26 - HYDRAULIC CONTROL UNIT: Front view showing control panel.



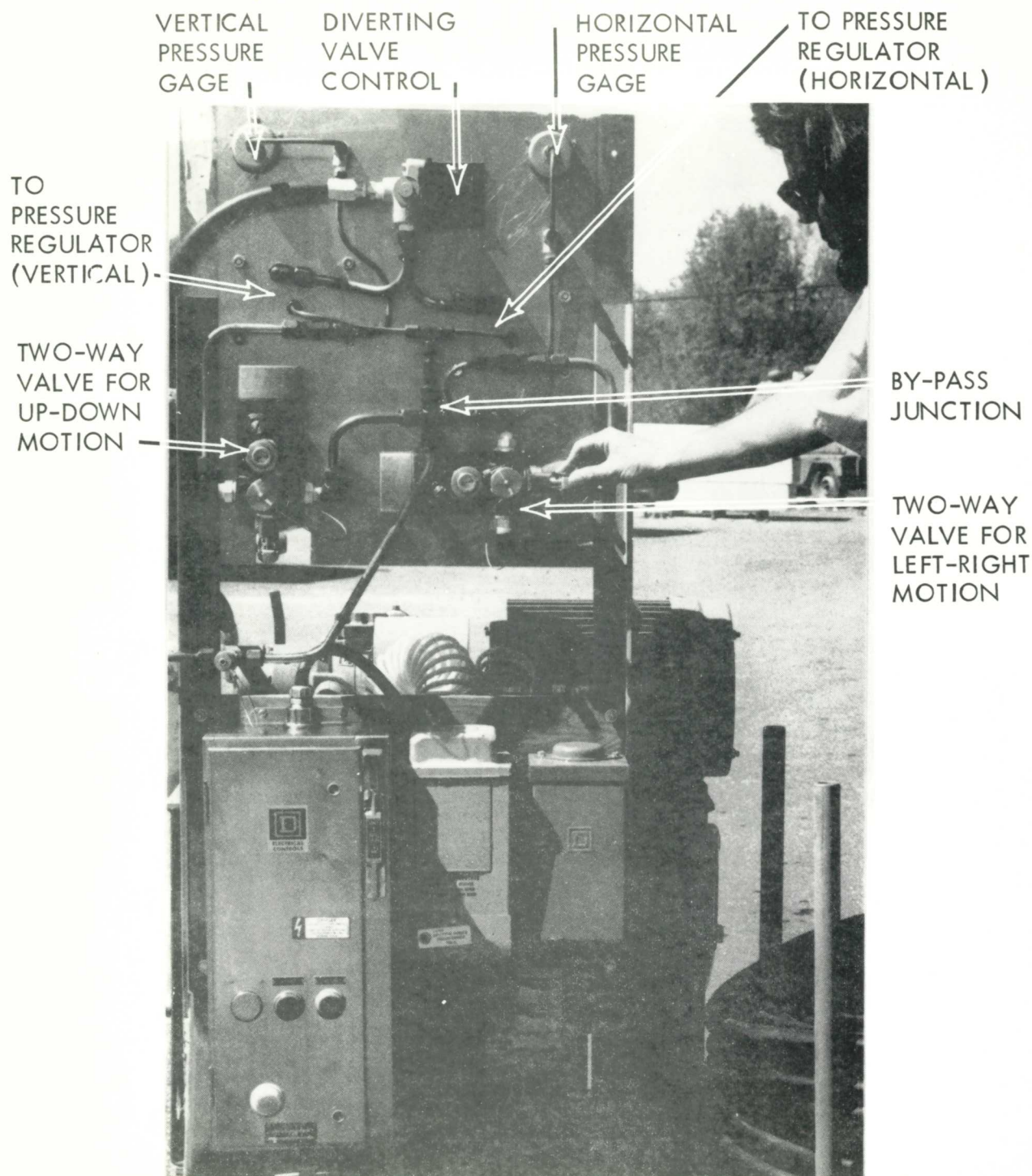


FIGURE 27 - HYDRAULIC CONTROL UNIT: Back view showing hydraulic connections



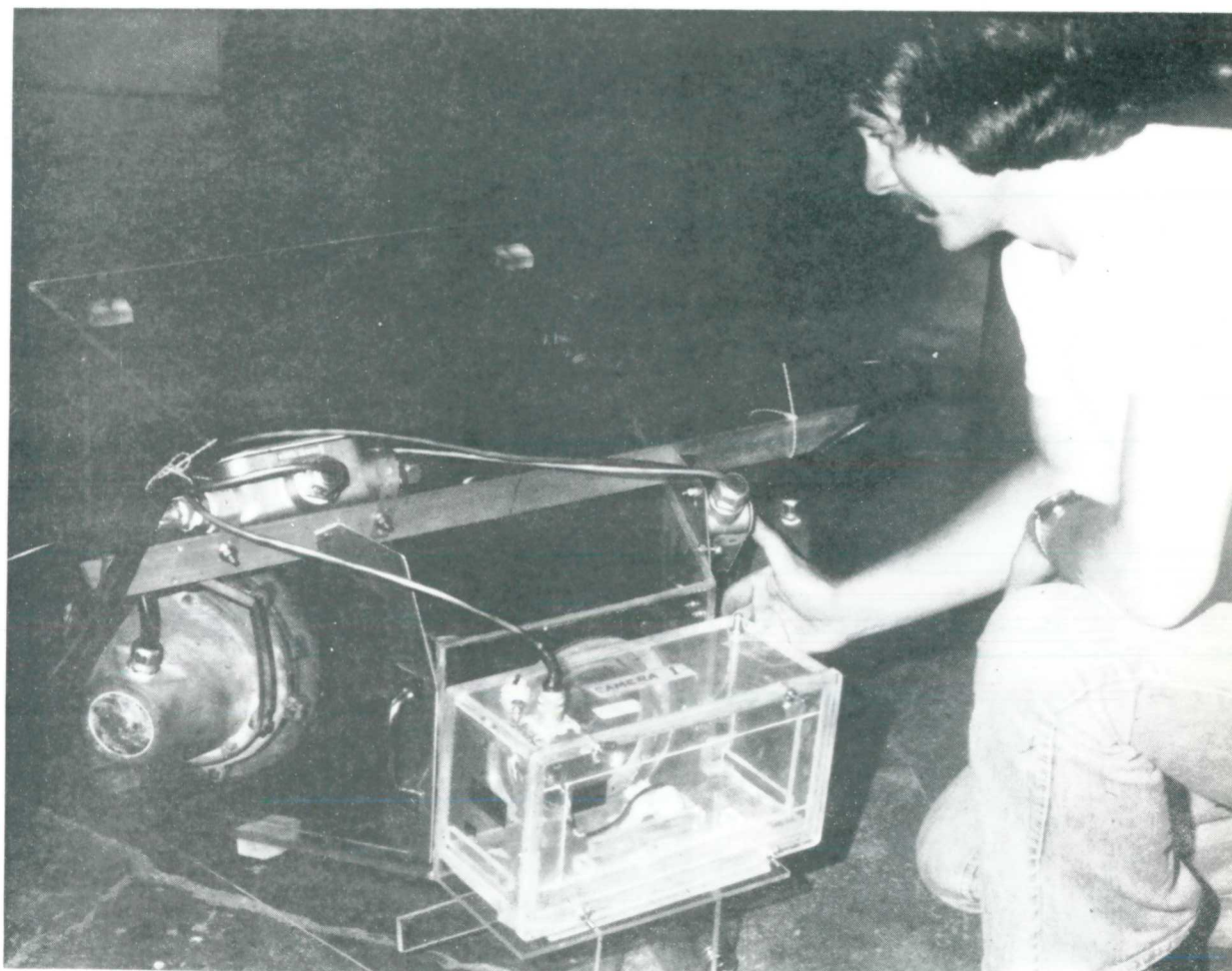


FIGURE 28 - UNDERWATER OBSERVATION AND PHOTOGRAPHY UNIT:  
Showing watertight camera box and one ( of two ) sealed-beam  
lights.

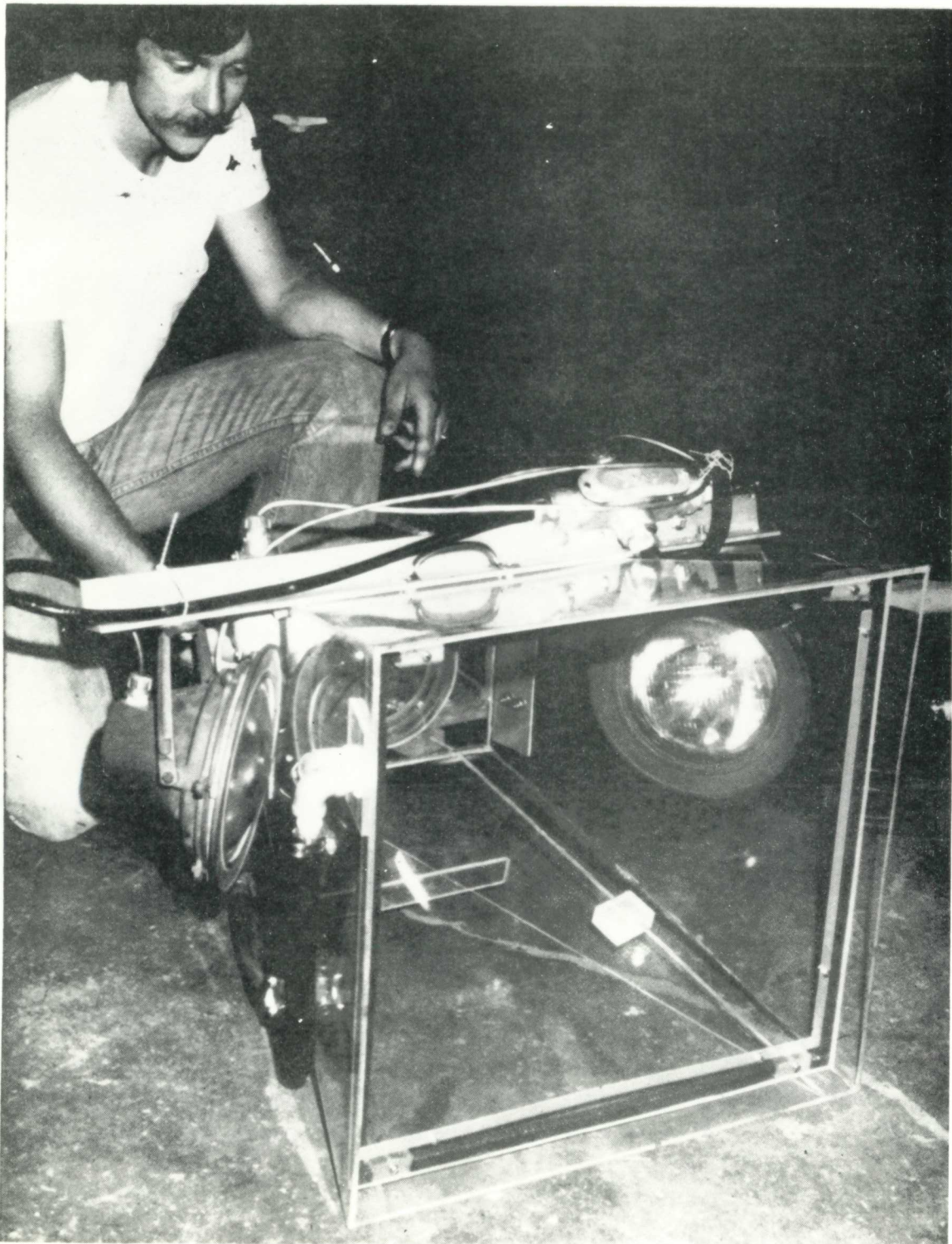


FIGURE 29 - UNDERWATER OBSERVATION AND PHOTOGRAPHY UNIT:  
Showing two sealed-beam lights and clear water chambers.



containers, and an underwater lighting arrangement. It was felt that, since the diver should do minimal adjustment of the camera underwater, the camera must be mounted on the unit with a preadjusted focal distance, namely the depth of the fresh water container. Once the unit is pushed against the surface to be photographed, the focus is set and pictures may be taken. To make sure that silted water will not block the view for either the divers or the camera lens, clear water is steadily pumped into the containers, thereby replacing the dirty water. A clear view is then established. For proper illumination, two sealed-beam automotive headlights are mounted on the supporting structure of the camera box. The power for these two lights is supplied by the 12 volt battery of the diesel engine. We used this camera box successfully to take pictures of the results of the underwater cleaning trial (see for instance Figures 38 and 39).



## V. FOULING REMOVAL FIELD TRIALS WITH THE CAVIJET<sup>®</sup> METHOD

In this chapter we will describe the various field trials (summarized in Table 9) which have been conducted during the duration of this program. Included will be a description of the running of each trial and the results obtained, both in dry dock as well as on a submerged surface of the outside of a dry dock wingwall at the Maryland Shipbuilding and Drydock Company's facility at the Baltimore, Maryland harbor. These trials were performed as part of the MARAD-funded program. In addition, we will briefly mention trials held at various locations (14, 15, 16) using single nozzle, diver-held CAVIJET units, which were performed to determine the effectiveness of underwater fouling removal from various surfaces. The latter, using these single nozzle units, were not actually part of the MARAD program, but are included here in the interest of assembling a complete report of the effectiveness of the CAVIJET method for such applications.

### A. Dry Dock Trials

The set of equipment described in Chapter IV, namely the five piston pump, the test frame, and the hydraulic control package were taken to the Baltimore, Maryland facility of Maryland Shipbuilding and Drydock Company for these trials. After several planning meetings with the various expert personnel at Maryland Ship, all of the required logistics for these trials were defined. These logistics included the technique for putting into place and supporting the main test frame from the deck of the ship to be cleaned, as well as provision for various services required. These services included 220 volt, three phase power to drive the electric motor for the hydraulic package, sufficient water (10.1 l/s) (160 gpm) for the flow to the six 3.0-mm (0.120-in.) orifice

Table 9  
Record of Field Cleaning Trials with CAVIJET® System

| Date                       | 23 June 1977               | 27 July 1977               | 4 August 1978                                   | 20 Sept. 1978              |
|----------------------------|----------------------------|----------------------------|-------------------------------------------------|----------------------------|
| Mode                       | Drydock                    | Drydock                    | Underwater                                      | Drydock                    |
| Surface                    | Austral Pilot              | African Neptune            | Outside of Dry-                                 | Export Agent               |
| Owner                      | Farrell Lines,<br>Inc.     | Farrell Lines,<br>Inc.     | dock No. 1<br>Md. Shipbuilding<br>& Drydock Co. | Farrell Lines,<br>Inc.     |
| Type                       | General Cargo<br>Freighter | General Cargo<br>Freighter | -                                               | General Cargo<br>Freighter |
| Length, B.P., ft           | 508                        | 541                        | -                                               | 470                        |
| Breadth, mld, ft           | 75                         | 75                         | -                                               | 73                         |
| Depth, mld, ft             | 43                         | 43                         | -                                               | 42                         |
| Draft, keel, ft            | 32                         | 31                         | -                                               | 28                         |
| Displacement,<br>long tons | 20,809                     | 20,110                     | -                                               | 17,570                     |
| Deadweight, long<br>tons   | 13,264                     | 12,728                     | -                                               | 11,089                     |

diameter CAVIJET nozzles as well as their respective dynamic sheathing flows, and the rigging and other personnel required to interface these several services. It had been decided that it would not be feasible to support the main test frame in the manner originally suggested, namely with a high-rise fork lift truck, after the difficulty with this approach was described by the personnel at Maryland Shipbuilding. Hence the concept of utilizing one of their large wingwall cranes to initially lift the test frame was established. The test frame, after being elevated into position by the main crane, was then hooked onto a chain fall which had been suspended by cables connected to a hard point on the deck of the ship. A rigger, using a cherrypicker which could be controlled from its platform, as seen in Figure 30, then effected the transfer of the weight of the test frame from the large crane to the hook of the chain fall. In this manner our requirement for one of these main cranes was minimized. This was important since these cranes are needed continually throughout the servicing of one of these ships in dry dock.

Once the main test frame was connected to the upper chain fall it was then possible to raise and lower the frame along a given vertical line to any desired position on the ship hull. For the first trial we attempted to depend on the three magnets affixed to the test frame to provide a force to counter the thrust load of the six CAVIJET nozzles (see Figure 31). However, it was immediately discovered that the attraction of these magnets was not sufficient to maintain the position of the test frame against the hull. Due to the roughness of the hull, and the difficulty of maintaining sufficient cleanliness of the surface area of the hulls and of the magnets it was not possible to obtain sufficient magnetic attraction. Thus during the first trial, as described below, we evolved the technique of



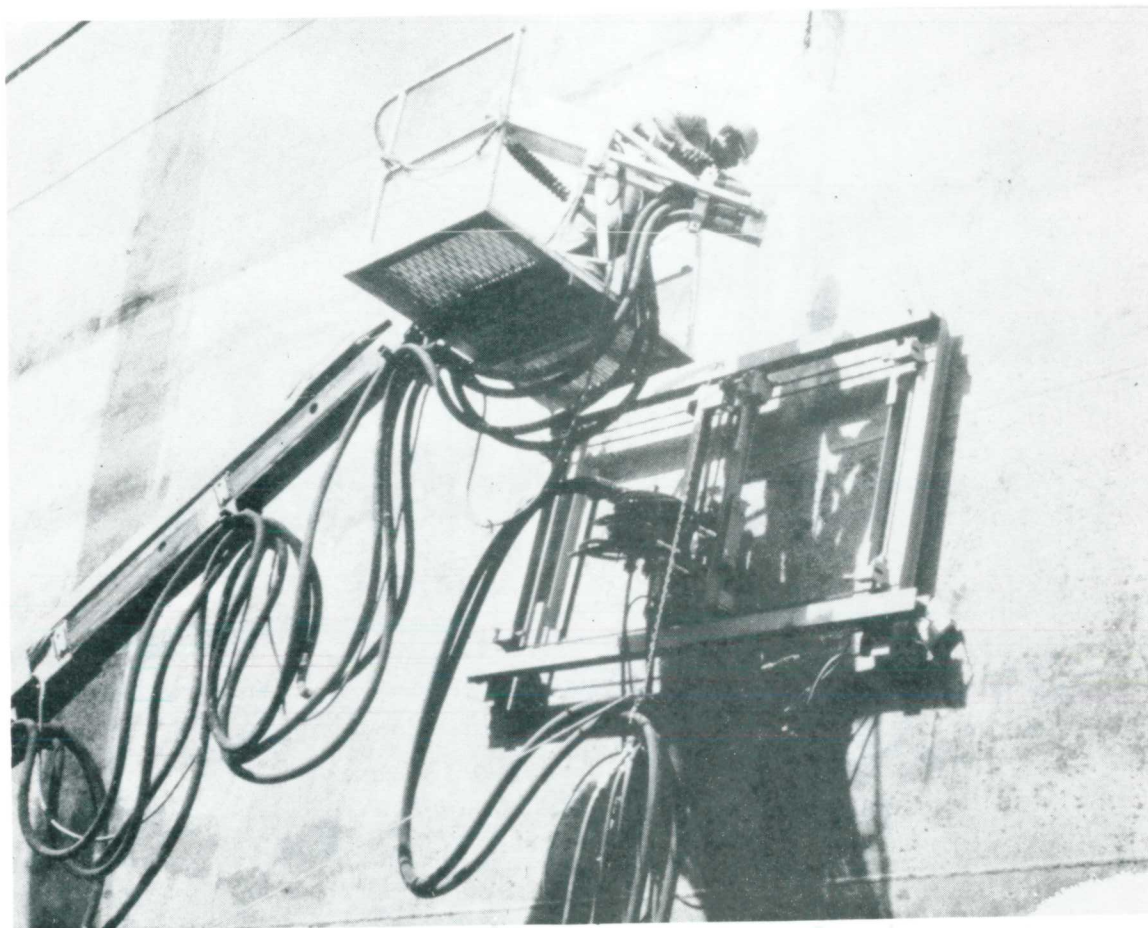


FIGURE 30 - FIRST DRYDOCK TRIAL OF CAVIJET® HULL CLEANING SYSTEM: Using cherry picker to rig the main test frame to chainfall, suspended from deck; June 23, 1977; The Austral Pilot; at Maryland Shipbuilding and Drydock Company.

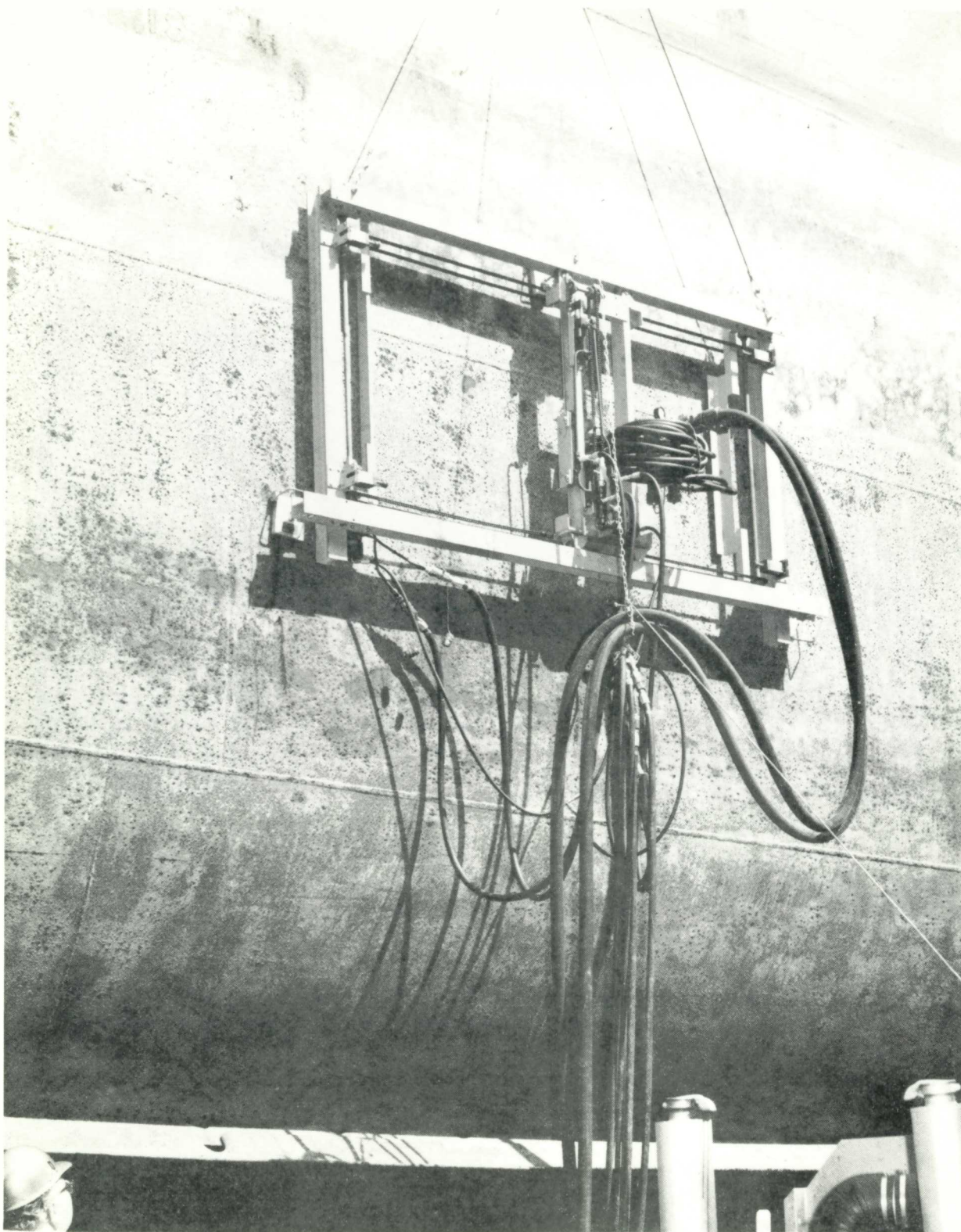


FIGURE 31 - INITIAL ARRANGEMENT FOR FIRST DRYDOCK TRIAL: Attempt to use three permanent magnets to counter the thrust from the CAVIJET® nozzles.



lashing the lower two corners of the test frame with chain falls and lengths of wire cable, as seen in Figure 32. The cables from these lower two corners were connected to either the running keel on the side of the ship or to a convenient location on one of the keel blocks in the dry dock. We also discovered that it was important to balance the loads very carefully on these two lower chain falls. If both were not tightened equally then it was quite possible to spring the test frame out of alignment. The 2.4 m (8 ft) long horizontal span of the steel beams of the frame was sufficient so that the loads provided by the chain falls could readily misalign the tracks for the horizontal traverse of the carriage. During the trials we experienced the problem of the wheels on the main carriage leaving the track due to the misalignment caused by unequal tension in the chain falls. Thereafter we were careful to provide equal tension to each of the lower corners of the main frame.

Another, although anticipated, problem related to the weight of the several water and hydraulic hoses which connected to the test frame carriage. The weight of these hoses had to be supported by an auxilliary chain which was connected to the bundle of hoses and thence to the hook of the chain fall which supported the main frame. By suitable adjustment of this support chain it was possible to minimize the loading on the carriage caused by these hoses and allow for the desired free running of the cleaning head carriage. This problem, as well as the adjustment of chain falls problem discussed above, would not, of course, be present in an actual prototype cleaning device as discussed later in this report. However these problems did serve to teach us the importance of providing a self-contained, self-supporting and movable system for placing a multinozzle CAVIJET cleaning head into position to clean a ship while in dry dock. In addition, the time losses



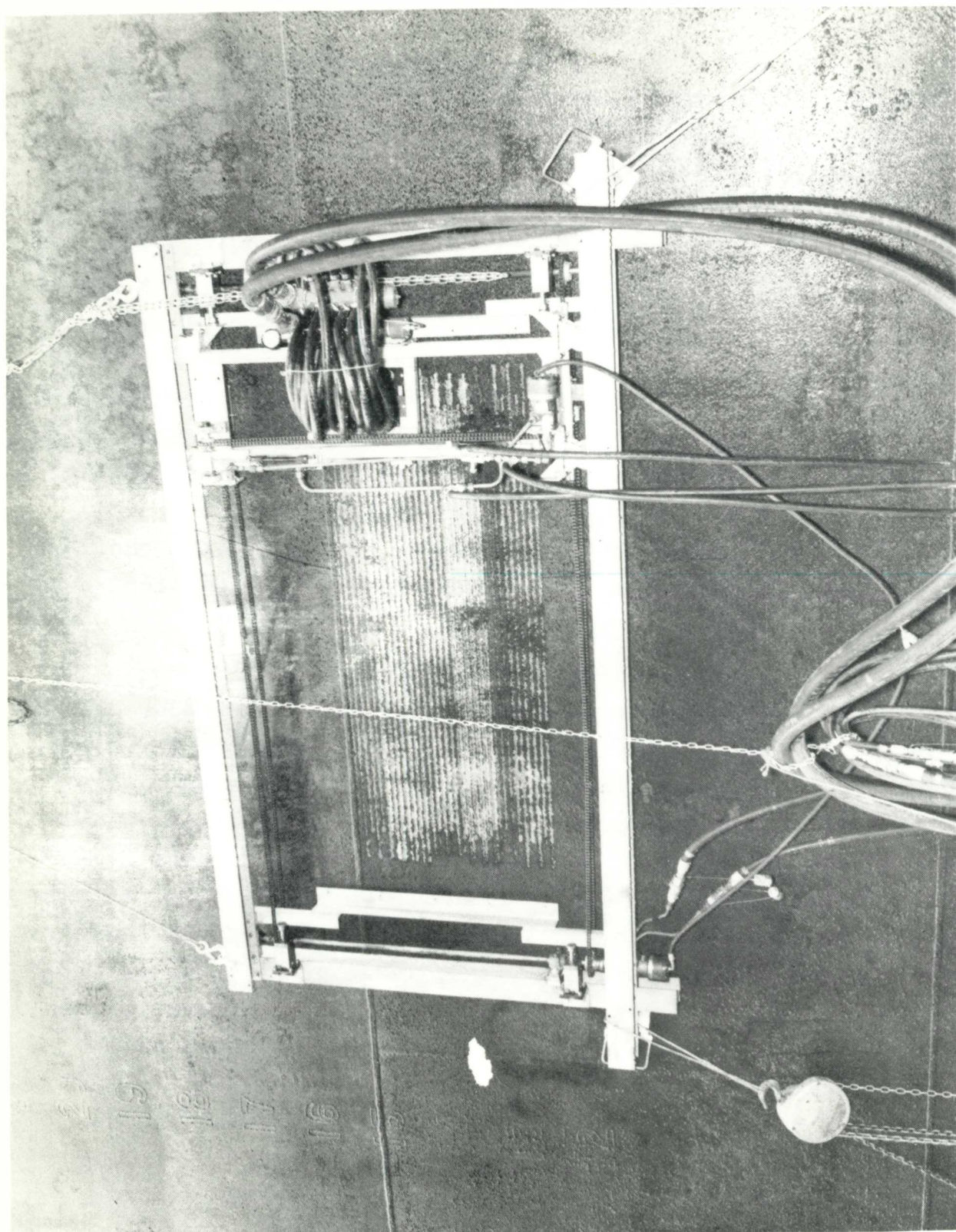


FIGURE 32 - FINAL ARRANGEMENT FOR FIRST DRYDOCK FIELD TRIAL: Chainfalls placed on lower two corners to counter the thrust from the CAVIJET® nozzles.

experienced on each trial because of the delays in provision of logistical support for the various services such as water lines and electrical lines also served to teach us the importance, in designing a prototype CAVIJET cleaning system, of providing a self-contained system for these services as well. Thus it is desirable to provide either electric or direct power takeoff from the main diesel to drive any hydraulic components that might be in this equipment. In addition, the envisioned closed loop for the working water should reduce the reliance on external water hoses that had to be rigged during our field trials.



1. First Dry Dock Cleaning Field Trial - June 23, 1977.

The ship selected for this first field trial was The Austral Pilot, a general cargo freighter of the Farrell Lines, Inc. Coincidentally, as seen in Table 9, all of the ships utilized for these field trials were from the Farrell Lines. After obtaining permission from the Port Engineer for the Farrell Lines, the arrangements for this first trial were finalized. It was decided that, if possible, all of the trials should be run within Drydock Number 3 at Maryland Shipbuilding because this dock provided the maximum space between wingwalls, namely 46 m (150 ft.). This meant that our equipment would provide minimum obstruction for other work going on in the dock at the same time. Incidentally, the overall length of this Number 3 dry dock at Maryland Shipbuilding is 252 m (827 ft.).

It was decided to begin our trials directly at midship where there would be maximum flatness of the hull, which was important because of the large span of our test frame. Also, by starting at midship we provided minimum interference with the conventional grit blasting of the hull surface which was started simultaneously at both the bow and the stern of the ship. As noted above, we began the trial by attempting to rely on the three magnets which had been installed on the test frame. However, when the first cleaning attempt was made, the frame did not stay fastened to the hull. We attempted to improve the adherence of



these magnets by scraping away fouling and loose paint in the regions where the magnets contacted the hull, and later also utilized sandblasting to clean these areas. Neither of these attempts sufficiently improved the load bearing capacity of these magnets to overcome the combined thrust of these six CAVIJET nozzles, which produced a total load of about 800 N (180 lb) at a nozzle pressure of 13.8 MPa (2,000 psi). Thus, as seen in Figure 32 we installed the two additional chain falls at the lower two corners. This technique, subject to care in the tightening of all chain falls, as discussed above, was quite satisfactory, relatively easy to install, and was used for all subsequent trials. Also seen in Figure 32 are the results of some of the first cleaning passes.

The first field running of this CAVIJET system is seen in Figure 33 in a photograph provided to us by a Maryland Shipbuilding photographer. The wide broadcasting of the spray emphasises the need, as discussed later in Chapter VI, of a method to capture the effluent from the cleaning work for recirculation. The initial runs, as summarized in Table 10 were conducted based on our experience in the laboratory, namely utilizing a nozzle pressure of 13.8 MPa (2,000 psi) with a velocity of translation of the carriage of about 0.3 m/s (1 ft/s). However, in these first runs we soon realized that the pressures required to provide the desired sandsweeping degree of cleaning

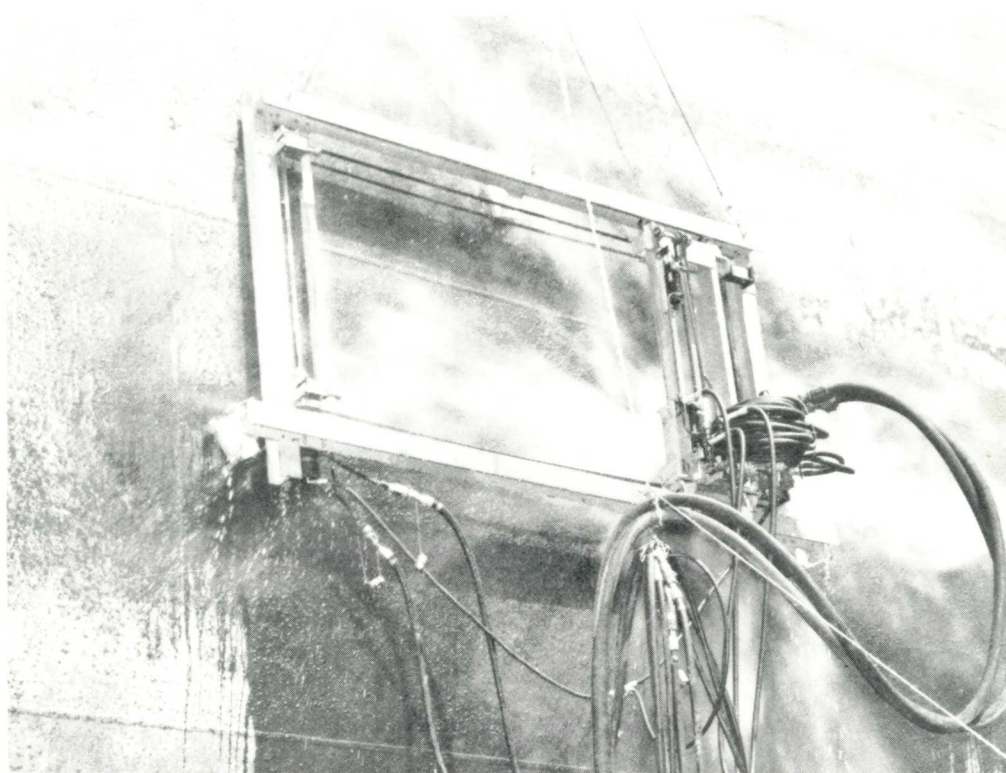


FIGURE 33 - CAVIJET™ HULL CLEANING SYSTEM FOR FIELD TRIALS:  
shown in operation on a ship hull in drydock

Table 10  
Results from First Dry Dock Trial: June 23, 1977, The Austral Pilot

| Run Number | Pump Pressure |     | Translation Velocity |              | Area Cleaning Rate <sup>a</sup> |                     | Area Cleaning Effectiveness <sup>b</sup> |                        | Remarks                                                                                                                                                                                                                                                                                                                                                 |
|------------|---------------|-----|----------------------|--------------|---------------------------------|---------------------|------------------------------------------|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|            | MPa           | ksi | m/s                  | ft/s         | m <sup>2</sup> /hr              | ft <sup>2</sup> /hr | m <sup>2</sup> /kw-hr                    | ft <sup>2</sup> /hp-hr |                                                                                                                                                                                                                                                                                                                                                         |
| 1          | 13.8          | 2.0 | 0.31                 | 1.03         | -                               | -                   | -                                        | -                      | First run to check performance. Magnets would not hold. Cleared areas for magnets, but still unable to counter the thrust from the CAVIJET <sup>®</sup> nozzles. Decided to lash lower corners with chain falls to bilge keel.                                                                                                                          |
| 2          | 13.8          | 2.0 | 0.30                 | 0.97         | 101                             | 1083                | 1.65                                     | 13.2                   | Made five passes, covering entire area of frame. Dynamic sheathing flow too low: only 0.70 $\ell$ /s (11.1 gpm) per nozzle. Bare metal seen, width about 13 to 19 mm (0.5 to 0.75 in.) but gaps between bared paths. Also, standoff was 4.4 cm (1.75 in.) instead of desired 3.2 cm (1.25 in.) Use average path width of 15.7 mm (0.62 in.) per nozzle. |
| 3          | 13.8          | 2.0 | 0.16                 | 0.51         | 64                              | 688                 | 1.05                                     | 8.4                    | Path widths only slightly wider, perhaps 19 mm (0.75 in.) per nozzle. The dynamic sheathing flow was still too low: only 0.79 $\ell$ /s (12.6 gpm) per nozzle, and standoff same as Runs 2.                                                                                                                                                             |
| 4          | 13.8          | 2.0 | 0.15                 | 0.48         | 20                              | 216                 | 0.33                                     | 2.6                    | Made three passes over same area: provided very slight widening to cleared path, and brightened the bare metal paths. Dynamic sheathing flow: 0.70 $\ell$ /s (11.1 gpm) per nozzle.                                                                                                                                                                     |
| 5          | 13.8          | 2.0 | 0.15                 | 0.49         | 21                              | 220                 | 0.34                                     | 2.7                    | This was a repeat of Run 5, in new location. Attempted to increase dynamic sheathing flow but only attained 0.70 to 0.84 $\ell$ /s (11.1 to 13.3 gpm) intermittently.                                                                                                                                                                                   |
| 6          | 10.3          | 1.5 | 0.41                 | 1.36         | 57                              | 612                 | 1.44                                     | 11.5                   | Although run at lower pressure and higher speed, these three passes produced essentially same results as Runs 4 and 5. D.S. flow held at 0.84 $\ell$ /s (13.3 gpm).                                                                                                                                                                                     |
| 7          | 10.3          | 1.5 | 0.58 to 0.61         | 1.90 to 2.00 | 80                              | 859                 | 2.02                                     | 16.2                   | Objective of this run: to check higher velocity performance of carriage. Ran well; path widths and degree of cleaning essentially same as prior runs, although not closely measured. Made three passes. D.S. flow: 0.84 $\ell$ /s (13.3 gpm).                                                                                                           |
| 8          | 10.3          | 1.5 | 0.58                 | 1.90         | 79                              | 855                 | 2.01                                     | 16.1                   | Repeat of the three passes of Run 7; results comparable. D.S. flow: 0.84 $\ell$ /s (13.3 gpm).                                                                                                                                                                                                                                                          |

<sup>a</sup>This rate,  $\dot{A} = w \cdot v$ , where  $w$  is cleared path width, and  $v$  is translation velocity.

<sup>b</sup>Calculated by:  $e = \dot{A}/P$ , where  $P$  is delivered hydraulic power. For six 3.0-mm (0.120-in.) CAVIJET nozzles,  $P = 61.1$  kw (81.9 hp) at 13.8 MPa (2,000 psi). At 10.3 MPa (1,500 psi):  $P = 39.5$  kw (53.0 hp).

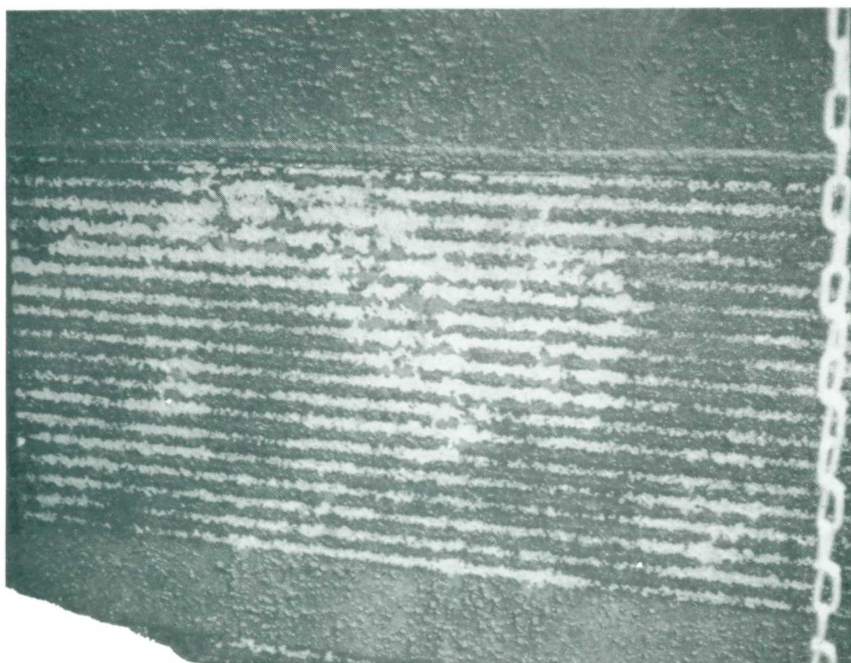


could be considerably lower on an actual ship hull (or the velocities of translation could be higher) relative to the pressures (or velocities) required for our laboratory panels.

The reason for this change in operating parameters is found in the difference between the paint utilized on the test panels versus the relatively softer antifoulant paint on the actual hull. On our laboratory panels we provided an extremely hard epoxy paint which was not readily eroded by the CAVIJET nozzles at the pressures and translation velocities required to remove the fouling growth. Thus in the laboratory trials only the barnacles, tubeworms and other crustaceans were eroded and removed. However, in the field trials a considerably different situation prevailed; namely when the erosive action of the CAVIJET nozzle impinged upon the surface, a few millimeters of paint were readily removed along with the crustaceans, grasses and other fouling. Thus, because the jets could remove this small amount of paint, that is, the outer layers which had been depleted of the antifoulant toxics, a considerably easier cleaning task was presented in these field trials. For this reason, as seen in an overall view in Figure 32 and in the close-ups in Figures 34a, 34b, and 34c we were able to not only remove most of the fouling in the path of the CAVIJET nozzles, but also to clean completely through to bare metal. As blasting to bare metal was not the prime objective of these trials, we therefore

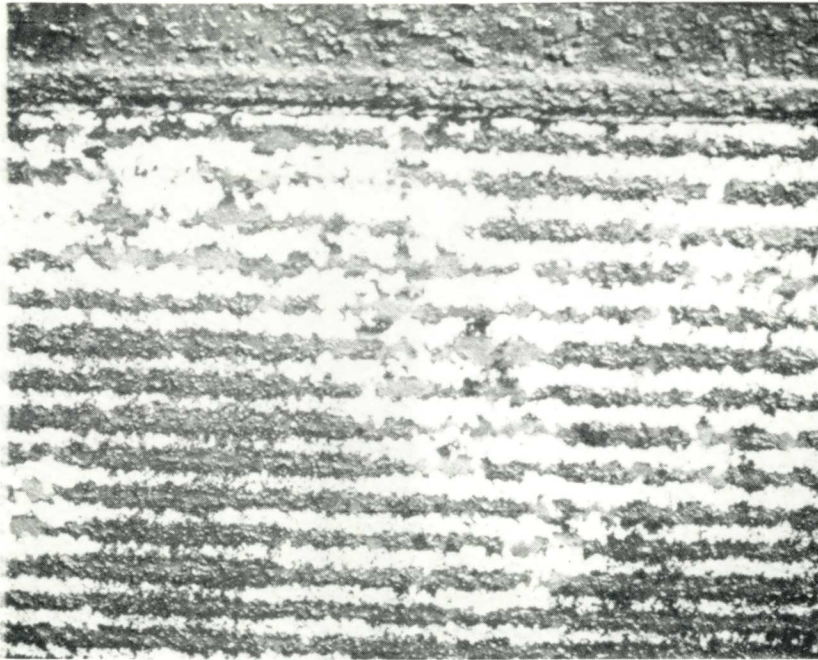


a. HULL CONDITION PRIOR TO CLEANING



b. PATHS CLEANED DURING RUN 2

FIGURE 34 - RESULTS FROM FIRST DRYDOCK CLEANING TRIAL:  
June 23, 1977, The Austral Pilot. Cleaning passes at  
13.8 MPa ( 2,000 psi ), 0.31 m / s ( 1 ft / s ).



c. CLOSEUP SHOWING BARE METAL PATHS,  
RUN 2.

FIGURE 34 - CONCLUDED



were able to operate this CAVIJET system in the field trials either at lower pressures relative to the laboratory trials, or at higher translation velocities, or both. In this manner, as summarized in Figure 35, considerably better area cleaning effectivenesses were obtained in these field trials on actual ship hulls in comparison to our earlier laboratory test results.

In these first trials we found it difficult to obtain sufficient flow for the sheathing to each nozzle. The maximum we were able to obtain was only about 0.84 l/s (13.3 gpm) per nozzle instead of the optimum 0.95 l/s (15 gpm). The problem was found to be caused by pressure drop in the single 3.8 cm (1.5 in.) fresh water line which was used to feed both the suction to our main pump as well as the lines to the six dynamic sheathings. Thus, it was decided for subsequent trials to ask for two parallel lines for the feed water to our system. Due to delays in the setup of this first trial and the aforementioned problems with establishing a technique for firmly fastening the frame to the hull, a minimum of time was available for the trials before the sand blasters had to begin to clean the area where we were working. Thus minimal quantitative data was obtained. However, we did establish clearly, as mentioned, that the required pressures were considerably lower than laboratory trials for all cleaning. We saw little change of results for pressures over a range of 10.3 to 13.8 MPa (1,500 to 2,000 psi),

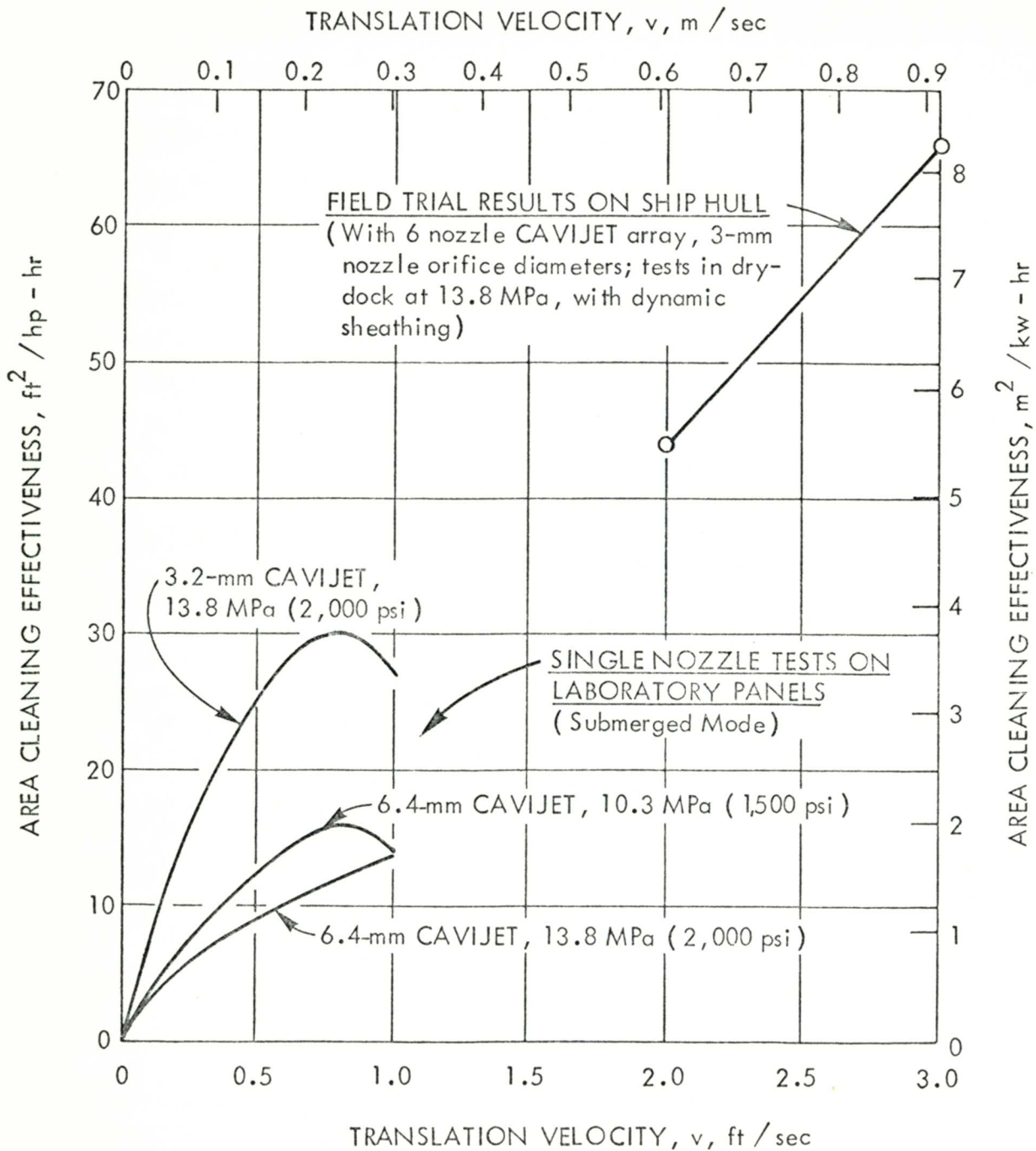


FIGURE 35 - CAVIJET FOULING REMOVAL EFFECTIVENESS, COMPARING LABORATORY AND FIELD TRIAL RESULTS

which corroborated the observations made during the first phase of this program (1). The maximum velocity obtained with the settings on the hydraulic system for this first trial were only about 0.6 m/s (2 ft/s). As a result of these trials we decided to adjust the hydraulic system for the subsequent trials so that velocities up to at least 0.9 m/s (3 ft/s) could be achieved. In addition, we observed that due to the 2.4 m (8 ft) span of the support frame, variations in the flatness of the hull often caused unacceptable changes in the standoff distance between the faces of the CAVIJET nozzles and the hull surface. We therefore learned that this parameter must be more carefully controlled in subsequent trials, making use of the standoff adjustment capability that is built into the main test frame.

The condition of the hull in the region where these trials were performed could not be described as severely fouled. We were advised that the Austral Pilot had last been into dry dock about 14-18 months before, at which time it had received this coating of antifoulant paint. Since this paint is estimated to maintain its antifouling capabilities for about one year, one might estimate that the barnacles observed on this hull were on the order of two to six months old. In the region where we were cleaning, the hull was well covered with small barnacles, none larger than about 6.4-mm (0.25-in.) in dia., heights: about 6.4 mm



(0.25 in.). However, most of the barnacles had diameters on the order of 1.6 to 3.2 mm (1/16 to 1/8 in.). By far, the largest features on the hull were rust blooms, many of which protruded well over 6.4 mm (0.25 in.) out from the hull. Very little grass was present in the midship region. A few patches were seen in isolated areas, all having grass quite short with lengths no longer than 12.7 mm (0.5 in.). In general, the hull was quite smooth, with the welds between panels appearing as the next roughest hull features. The outer surface was fairly soft, however, even by vigorous scraping with hand tools it was quite difficult to clear away the paint down to the metal. As noted, to provide bare hull steel for attempting to adhere the magnets more effectively, it was necessary to provide a hard sandblast in order to clear the hull paint completely away.

2. Second Dry Dock Cleaning Field Trial - July 27, 1977

This trial was conducted on another general cargo freighter of the Farrell Lines, namely the African Neptune. The hull condition of this ship was quite comparable to that of the first trial. The barnacles were slightly larger and more numerous in the second trial, however, but still quite small, with diameters typically in the range of 2 to 4 mm (0.08 to 0.16 in.). However, there was a sufficient population of barnacles in the area where we conducted the cleaning to provide a clear indication of whether or not full removal of barnacles was achieved.

For the second trial we were unable to work in the desired midship area since a repair to the ship had to be made in this region. A plate was being burned out at midship in order to remove a large dent in the hull. Therefore, we had to work in a region toward the bow end of the hull and hence had to contend with somewhat more curvature in this region. Also, since we were forward of the running keel in this position on the African Neptune, it was necessary to fasten the lower two chainfalls to two of the keel blocks.

The results of the second dry dock trials are summarized in Table 11. It is seen that tests were conducted over a range of velocities from 0.30 to 0.76 m/s (1 to 2.5 ft/s) with pressure of 10.3 and 13.8 MPa (1,500 and 2,000 psi). With the addition of a second feed hose we achieved sufficient flow to the dynamic sheathing devices for each nozzle and hence obtained improved path widths in these trials. Again, due to hull curvature, we observed clearly the effect of standoff distance in several of these trials, the variation of standoff due to this curvature of the hull caused variations in the cleaned path widths for each nozzle. These standoff distance effects due to the very large span of this experimental test frame served to emphasize the importance of choosing the correct diameter for a production type cleaning head in a prototype CAVIJET dry dock hull cleaning system, as discussed in Chapter VI.

Table 11  
Results from Second Dry Dock Trial, July 27, 1977, The African Neptune

| Run Number | Pump Pressure |     | Translation Velocity |      | Area Cleaning Rate* |                     | Area Cleaning Effectiveness* |                        | Remarks                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|------------|---------------|-----|----------------------|------|---------------------|---------------------|------------------------------|------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|            | MPa           | ksi | m/s                  | ft/s | m <sup>2</sup> /hr  | ft <sup>2</sup> /hr | m <sup>2</sup> /kw-hr        | ft <sup>2</sup> /hp-hr |                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| 1          | 13.8          | 2.0 | 0.30                 | 1.0  | 125                 | 1350                | 2.05                         | 16.5                   | Clear paths for each jet, about 19 mm (0.75 in.) wide, but gaps in between. Standoff too large: 7.4 cm (2.9 in.), and dynamic sheathing flow slightly low: 0.90 l/s (14.2 gpm) per nozzle.                                                                                                                                                                                                                                                       |
| 2          | 13.8          | 2.0 | 0.30                 | 1.0  | 167                 | 1800                | 2.74                         | 22.0                   | Removed spacers on main frame, and tightened chainfalls, to adjust standoff to 3.6 cm (1.4 in.). D.S. flow varied slightly: 0.90 to 0.95 l/s (14.2 to 15.0 gpm). Gap of about 6 mm (0.25 in.) between paths of bare metal. However, these gaps are free of loose paint and most barnacles are removed. Hence, entire 15.2 cm (6-in.) path is cleaned equivalent to usual sand-sweeping surface preparation.                                      |
| 3          | 13.8          | 2.0 | 0.61                 | 2.0  | 335                 | 3600                | 5.48                         | 44.0                   | At this velocity the bare metal exposure is patchy, instead of the bared paths of Run 2. The entire 15.2 cm (6-in.) path is essentially clear to sand-sweeping standards, with a few stray spots of loose paint or barnacles. D.S. flow: 0.95 l/s (15 gpm). Essentially no bare metal patches. Slightly more loose material than on Run 3 has remained. D.S. flow: 0.95 l/s (15 gpm) on this, and all subsequent runs. Overall, about 90% clear. |
| 4          | 13.8          | 2.0 | 0.76                 | 2.5  | 418                 | 4500                | 6.84                         | 54.9                   | This run made at same place as Run 4. Full path now completely clear, and a few slightly bared metal patches have appeared.                                                                                                                                                                                                                                                                                                                      |
| 5          | 13.8          | 2.0 | 0.76                 | 2.5  | -                   | -                   | -                            | -                      | A repeat of Run 3. However, all barnacles and loose paint are removed. A few patches of bare metal are seen.                                                                                                                                                                                                                                                                                                                                     |
| 6          | 13.8          | 2.0 | 0.61                 | 2.0  | 335                 | 3600                | 5.48                         | 44.0                   | This run was near top of test frame, and jet thrust pushed frame out; hence, standoff was too large. Thus about 30% of fouling was not removed.                                                                                                                                                                                                                                                                                                  |
| 7          | 10.3          | 1.5 | 0.61                 | 2.0  | 234                 | 2520                | 5.93                         | 47.5                   | Same problem as on Run 7 with standoff, due to run-ning at very top of frame. Caused by hull curvature which limits load applicable from lower two chainfalls. About 30% of fouling was not removed.                                                                                                                                                                                                                                             |
| 8          | 10.3          | 1.5 | 0.30                 | 1.0  | 117                 | 1260                | 2.96                         | 23.8                   | Solved the problem of Runs 7 and 8 by shifting position of main frame and readjusting chainfalls. Thus, this repeat of Run 8 has completely cleared entire path; no bare metal patches.                                                                                                                                                                                                                                                          |
| 9          | 10.3          | 1.5 | 0.30                 | 1.0  | 167                 | 1800                | 4.23                         | 34.0                   | This repeat of Run 7 provided fully cleared path during portion of run wherein standoff was correct. However, at one end, due to somewhat loose chainfall, the standoff increased and hence some barnacles were not removed here.                                                                                                                                                                                                                |
| 10         | 10.3          | 1.5 | 0.61                 | 2.0  | 335                 | 3600                | 8.47                         | 67.9                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                  |

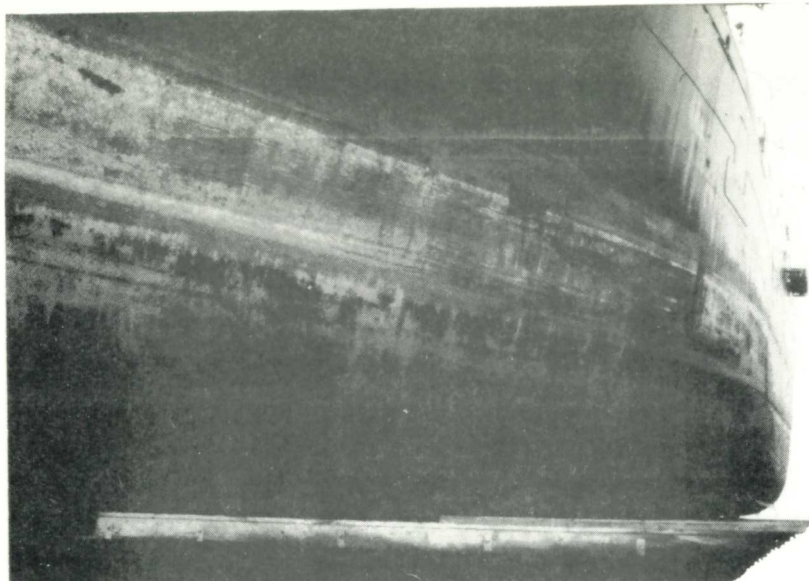
\* See definitions for these parameters in Table 10.



Although it might be tempting to provide as large a cleaning head as possible in order to maximize cleaning rates, the realities imposed by irregularities and curvatures in the hull preclude a cleaning head much larger than about 0.91 to 1.2 m (3 to 4 ft.) in diameter.

3. Third Dry Dock Cleaning Field Trial - September 20, 1978

The trial was conducted on the freighter Export Agent of the Farrell Lines. The fouling on this hull was considerably greater than on the prior two ships. There was a considerable coverage of both barnacles and grasses especially in the midship region where the cleaning trials were conducted. Condition of the hull is indicated by the photographs seen in Figures 36a and 36b. One of the objectives of this trial was to obtain a movie coverage of the trials so that an active record of the cleaning effectiveness of this CAVIJET system could be recorded. This objective, plus delays in gaining access to the ship, minimized the number of trials which could be conducted. The results from these trials are summarized in Table 12 and are typified by the photographs in Figure 37. These results indicate that even with this more severely fouled surface the CAVIJET nozzles were capable of complete removal of fouling in a manner equivalent to that achieved by the conventional sandsweeping technique, even with translation velocities up to 0.91 m/s (3 ft/s).



a. VIEW OF HULL, LOOKING TOWARD STERN



b. MIDSHIP; AREA OF CLEANING TRIALS

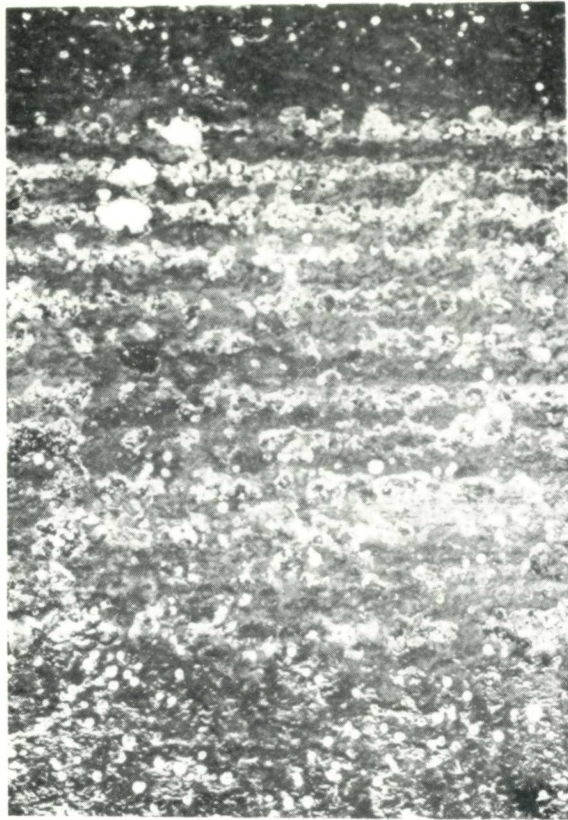
FIGURE 36 - HULL CONDITION OF EXPORT AGENT:  
Prior to cleaning trial; September 20, 1978.

Table 12  
Results from Third Dry Dock Trial: September 20, 1978, The Export Agent

| Run Number | Pump Pressure |     | Translation Velocity |      | Area Cleaning Rate* |                     | Area Cleaning Effectiveness* |                        | Remarks                                                                                                                                                                                                                                                                               |
|------------|---------------|-----|----------------------|------|---------------------|---------------------|------------------------------|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|            | Mpa           | ksi | m/s                  | ft/s | m <sup>2</sup> /hr  | ft <sup>2</sup> /hr | m <sup>2</sup> /kw-hr        | ft <sup>2</sup> /hp-hr |                                                                                                                                                                                                                                                                                       |
| 1          | 13.8          | 2.0 | 0.61                 | 2.0  | 335                 | 3600                | 5.48                         | 44.0                   | All fouling completely removed over 15.2 cm (6 in.) wide path. A few bare metal patches seen. Dynamic sheathing flow: 0.95 $\ell$ /s (15 gpm) as required for optimal performance. Standoff: about 3.6 cm (1.4 in.) is satisfactory and used for all runs.                            |
| 2          | 13.8          | 2.0 | 0.91                 | 3.0  | 502                 | 5400                | 8.21                         | 65.9                   | Although at highest velocity yet, the results are essentially same. A few barnacle basal planes are left, but overall cleaning is equivalent to that achieved by sandsweeping. A few bare metal patches seen. D.S. flow: Same as Run 1                                                |
| 3          | 13.8          | 2.0 | 0.30                 | 1.0  | 167                 | 1800                | 2.74                         | 22.0                   | At this velocity: a deeper, overall removal of the coating is seen; all fouling removed; more bare metal patches and paths than in Runs 1 and 2. D.S. flow: same as Run 1.                                                                                                            |
| 4          | 10.3          | 1.5 | 0.61                 | 2.0  | 335                 | 3600                | 8.47                         | 67.9                   | Results for this run, although at lower pressure, are not noticeably different from Run 1. Reduced D.S. flow to about 0.82 to 0.88 $\ell$ /s (13 to 14 gpm) since the nozzle pressure was lower.                                                                                      |
| 5          | 6.9           | 1.0 | 0.30                 | 1.0  | 167                 | 1800                | 7.06                         | 56.6                   | This very low pressure, combined with a lower translation velocity, achieved essentially the same results as Runs 1 and 4, although a few barnacles which lay midway between two nozzles were left. Used a D.S. flow of 0.63 to 0.76 $\ell$ /s (10-12 gpm) for this low pressure run. |

\* See definitions for these parameters in Table 10. At 6.9 MPa (1,000 psi) the six 3.0-mm (0.120-in.) CAVIJET® nozzles deliver a total hydraulic power:  $P = 23.7$  kw (31.8 hp).

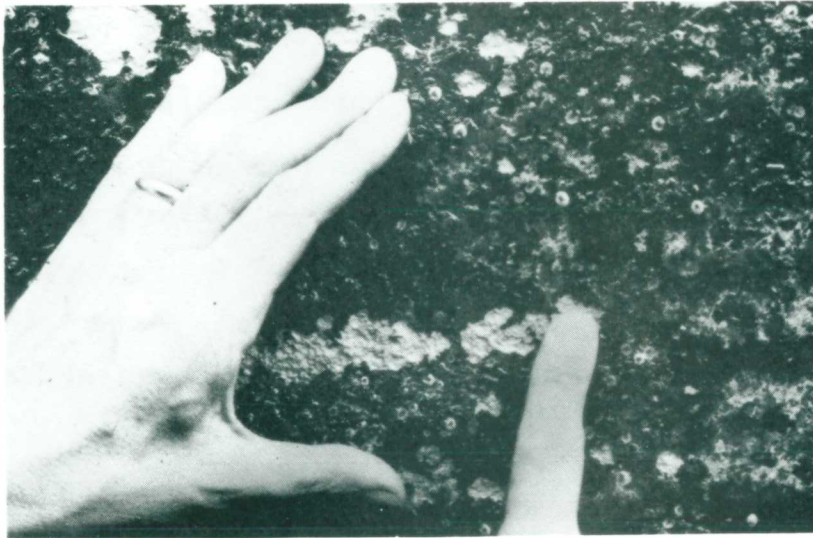




a. RUNS 1 AND 2; INCLUDING REGION AT TOP SHOWING CONDITION PRIOR TO CLEANING



b. CLOSEUP OF RUN 1; CLEANED PATH AND SOME BARE METAL AT 13.8 MPa (2,000 psi); 0.61 m/s (2 ft/s).



c. CLOSEUP OF RUN 2; CLEARED PATHS AND  
SOME BARE METAL AT 13.8 MPa (2,000 psi);  
0.9 m / s ( 3 ft / s ).

FIGURE 37 - CONCLUDED

At this velocity, the maximum area cleaning rate of  $502 \text{ m}^2/\text{hr}$  ( $5,400 \text{ ft}^2/\text{hr}$ ) was attained. The optimum area cleaning effectiveness, however, was achieved at  $0.61 \text{ m/s}$  ( $2 \text{ ft/s}$ ) with  $10.3 \text{ MPa}$  ( $1,500 \text{ psi}$ ) pump pressure. Under these conditions an effectiveness of  $8.47 \text{ m}^2/\text{kw-hr}$  ( $67.9 \text{ ft}^2/\text{hp-hr}$ ) was produced.

B. Underwater Cleaning Field Trial

In order to obtain results to determine the effectiveness of the multinozzle CAVIJET method approach for removing fouling on underwater surfaces it was decided to utilize the test frame in a cleaning trial on the external surface of Drydock Number 1 at the Maryland Shipbuilding and Drydock Company. We were advised that this dry dock has never been cleaned since its installation well over 10 years ago. Examination of the surface by our divers was achieved with the underwater observation and photographic system described in Chapter IV. They found that the steel surface of the dry dock was completely covered with large barnacles, typical diameters on the order of 10 millimeters or more. A photograph taken underwater typifying the condition of this surface is seen in Figure 38.

Our first approach for these underwater trials involved use of some eye bolts which we had been advised were available below surface to which we could lash the lower corners of our test frame. However, diver examination of the dry dock surface





FIGURE 38 - UNDERWATER PHOTOGRAPH OF OUTSIDE OF DRYDOCK:  
Showing areas prior to cleaning and some partial removal  
of fouling.

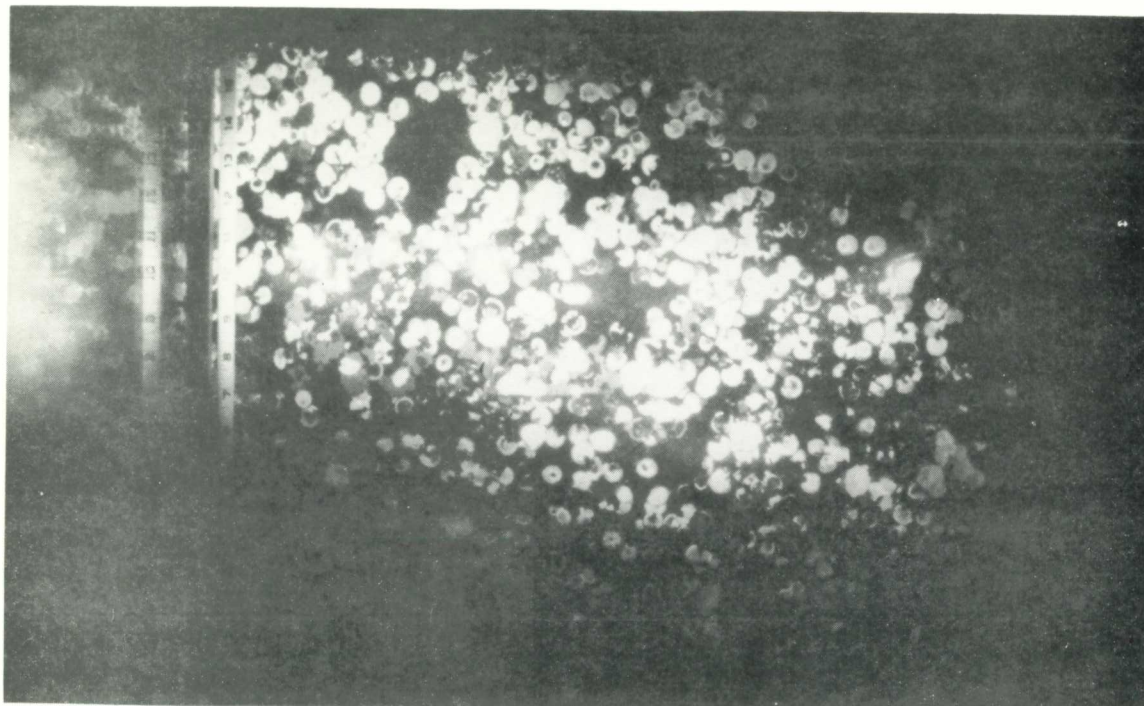
underwater revealed that such tie points were not available. Therefore, we attempted to rig these chainfalls to a 0.12 MN (28,000 lb) weight which was lowered to the bottom adjacent to the outer wingwall of the dry dock. However, the distance from the surface to the bottom, which was about 15.2 m (50 ft.), provided a span of chainfalls and cables which was too large to keep the frame against the surface when the jet thrust was felt on the frame. Therefore, we tried a third approach; namely, using one of Maryland Ship's seagoing "mules" to provide an active push against the frame during the trials. One of these tugboats was rigged with a large metal frame to which we could then lash our test frame. This approach, although quite impractical for any efficient cleaning of a large area, was satisfactory for the purposes of this underwater trial. In this manner we were able to conduct the trials which are summarized in Table 13. Underwater photographs taken of the results of these trials are seen in Figure 39. It may be seen that considerably wider and more thorough cleaning was obtained in these underwater trials, corroborating the results obtained in our earlier laboratory work in Phase I. (1). For these trials, of course, no dynamic sheathing was utilized, and indeed the pipe cross sections were removed from the carriage for these trials. Thus, these underwater tests have served to prove that a hydraulically controlled system, utilizing the CAVIJET method to remove fouling, can be used in a submerged mode.

Table 13  
Results from the Underwater Cleaning Trial: August 4, 1978

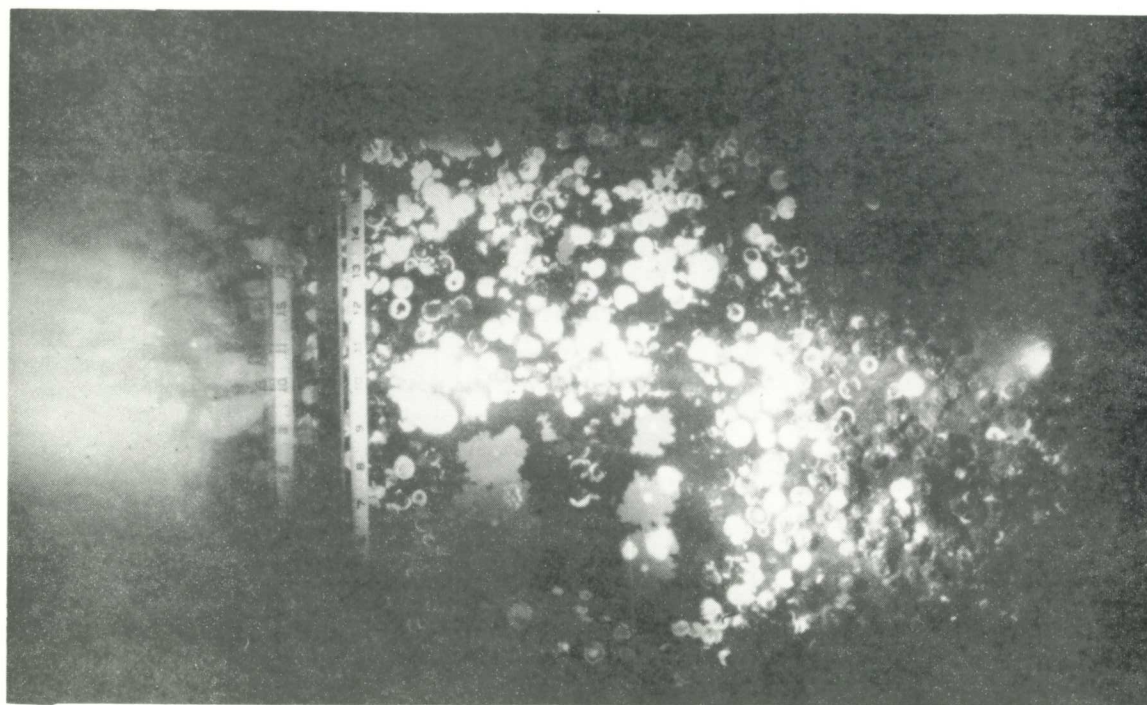
| Run Number | Pump Pressure |     | Translation Velocity |      | Area Cleaning Rate* |                     | Area Cleaning Effectiveness* |                        | Remarks                                                                                                                                                                                                                                              |
|------------|---------------|-----|----------------------|------|---------------------|---------------------|------------------------------|------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|            | MPa           | ksi | m/s                  | ft/s | m <sup>2</sup> /hr  | ft <sup>2</sup> /hr | m <sup>2</sup> /kw-hr        | ft <sup>2</sup> /hp-hr |                                                                                                                                                                                                                                                      |
| 1          | 13.8          | 2.0 | 0.61                 | 2.0  | 335                 | 3600                | 5.48                         | 44.0                   | Divers visual report: good cleaning over total 15.2 cm (6 in.) wide path. Photographs indicated complete removal of barnacles, which were large (over 10 mm in diameter) and numerous. Standoff for this and subsequent runs about 3.6 cm (1.4 in.). |
| 2          | 13.8          | 2.0 | 0.30                 | 1.0  | 167                 | 1800                | 2.74                         | 22.0                   | Divers visual report: essentially same as for Run 1.                                                                                                                                                                                                 |
| 3          | 10.3          | 1.5 | 0.30                 | 1.0  | -                   | -                   | -                            | -                      | Divers visual report: did not seem to clean. Perhaps the vertical translation did not correctly function; hence, this area was skipped over?                                                                                                         |
| 4          | 10.3          | 1.5 | 0.61                 | 2.0  | -                   | -                   | -                            | -                      | Same as for Run 3                                                                                                                                                                                                                                    |
| 5          | 6.9           | 1.0 | 0.61                 | 2.0  | 335                 | 3600                | 14.14                        | 113.2                  | Divers visual report: essentially same as for Run 1.                                                                                                                                                                                                 |
| 6          | 6.9           | 1.0 | 0.30                 | 1.0  | 167                 | 1800                | 7.06                         | 56.6                   | Same as for Run 5.                                                                                                                                                                                                                                   |

\*See definitions for these parameters in Table 10.





a. TYPICAL CLEANED AREAS: Upper part - Run 1 at 13.8 MPa (2,000 psi), 0.61 m/s (2 ft/s); Lower part - Run 2 at 13.8 MPa (2,000 psi), 0.30 m/s (1 ft/s).



b. BEGINNING OF RUN 1 - showing bare metal patches from stationary jets; see uncleaned region at right side.

FIGURE 39 - UNDERWATER PHOTOGRAPHS OF CAVIJET® CLEANING RESULTS: Field Trial on August 4, 1978 at Maryland Shipbuilding and Drydock Company.

Due to the limitations of this device, particularly where direct visual observation was required in order to position the cleaning head both vertically and horizontally, this type of configuration is certainly counter-indicated for a prototype device. Indeed, visual observation by the divers after the cleaning trials suggested that perhaps the cleaning head was not properly positioned for the third and fourth runs during this underwater cleaning trial.

Another feature of this underwater cleaning trial was a prove out of the concept of utilizing a volume of clear water to serve as a means to readily observe and photograph hulls within relatively opaque water. Without this observation equipment it was difficult for the divers to observe the condition of the surface. Indeed it should be noted that the completion of these trials occurred well after dark and, despite the darkness, the built-in lights plus the clear water region in the underwater observation system allowed clear visibility of the surface. An improved method for zeroing the buoyancy of this device should be provided, as it was somewhat difficult to position the observation box due to slightly negative buoyancy. Also, difficulty was found in draining the clear water from the box prior to removing it from the water. Due to the weight of the water in the box, and its rather fragile construction, it was necessary to thoroughly drain this



box before attempting to lift it. In any future use of such a system, a more effective drainout means should be provided. However, for the main purpose, which was to allow observation and photography under water, this device performed very well.

C. Other Field Trials Of The CAVIJET Method (14, 15, 16)

During the time period in which this program has been active, a number of related field trials of the CAVIJET method have been performed. Although these trials were not a part of the funded program supported by MARAD, it is of interest to include a brief description here of these other field experiences for reference purposes.

The first trial (14), held during April, 1978, was motivated by an interest in improved methods for removing fouling from offshore oil rigs, in preparation for nondestructive testing of these facilities. The field trial of the CAVIJET method, however, was performed against the seawall of a lock in Holland, in order to provide a comparison with traditional wet sandblasting, and conventional high pressure jet blasting. A single 2.2 mm (0.086 in.) orifice diameter CAVIJET was used in this trial. The nozzle was mounted upon a conventional hand-held lance, such as is used during in-air cleaning. Because this cleaning lance was not provided with any type of counter-thrusting mechanism, it was difficult for the



diver in these underwater trials to control either the CAVIJET or either of the other two devices. However, by bracing himself among the rocks in the shallow water adjacent to the wall of the lock, cleaning trials were nevertheless performed. Operating at a pressure of 15.2 MPa (2,200 psi), the CAVIJET nozzle provided a more thorough cleaning in comparison to a conventional 2.2 mm nozzle also run at 15.2 MPa (2,200 psi). The wet sandblasting in these trials was, as expected, much more effective in removing not only the fouling, but also the severe rust on this steel wall and providing a white metal finish. However, with regard to the sole objective of fouling removal, the CAVIJET was sufficiently effective.

The second series of trials of the CAVIJET method for underwater cleaning, also utilizing a diver held unit, was begun in July of 1978 (15). These trials have resulted in a preliminary license agreement between HYDRONAUTICS and a private company based in the State of Hawaii. This application is underwater cleaning of commercial and Navy ship and submarine propellers and other appendages which cannot be cleaned with the large multibrush equipment such as the SCAMP\*, or BRUSH-KART\*\* systems. As of this time, several ships and submarines have been cleaned utilizing the CAVIJET method, at

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\* Is a registered trademark of Butterworth Systems, Inc.

\*\* Is a registered trademark of U.S. Phosmarine, Inc.

cleaning rates as high as three to five times faster than those achieved by conventional approaches for cleaning propellers. These conventional approaches include the use of small hand-held brushes as well as various types of scrapers. Because of the importance of avoiding damage to these Navy propellers, the CAVIJET, which can be controlled by means of the driving pressure at the pump, provides an excellent alternative to these very slow and difficult scraping and brushing procedures. For instance, in a trial conducted on twin propellers and other underwater appendages in September, 1978 at Pearl Harbor (15), a single CAVIJET nozzle with an orifice diameter of 2.5 mm (0.10 in.) operating at a pressure of 13.8 MPa (2,000 psi) was capable of cleaning both propellers on this ship in only five man hours. A subsequent hand polishing was performed which required an additional three hours. The comparable cleaning time required using the conventional methods was at least 20 man hours. Water intake gratings were also cleaned in these trials. See, for instance, the before and after photographs of one of these water intakes as shown in Figure 40a and 40b. (15).

The most recent field trial of the CAVIJET method involved an application also motivated by interest in supporting non-destructive testing of offshore oil rigs (16). These trials were performed within a large tank at the facilities of a diving and salvage company. In these trials a hand-held CAVIJET unit with



a. BEFORE CLEANING: fouling on  
water-intake grating



b. AFTER CLEANING

FIGURE 40 - RESULTS FROM DIVER-HELD CAVIJET® UNDERWATER  
CLEANING: Using 2.5-mm (0.10-in.) NOZZLE AT  
13.8 MPa (2,000 psi). (Photographs courtesy of  
SEACO, Inc., Kailua, Hawaii)



thrust compensation was utilized which was comparable to the device used in the Hawaii underwater ship cleaning trials. The diver was able to clean both fouling and rust from a severely corroded and fouled steel structure which had rested on the bottom of the Gulf of Mexico for an extended period. A shiny metal surface was achieved with a single 2.2-mm (0.086-in.) diameter CAVIJET nozzle operated at pressures up to only 5,000 psi. This should be compared with the 10,000 psi required to produce a comparable white metal finish, albeit at slower cleaning rates, with a more conventionally contoured high pressure nozzle during the same trials.

Thus these diver-held trials of the CAVIJET method, which were motivated by various industrial interest becoming aware of the CAVIJET technique through information arising from both the prior MARAD supported program (1) as well as the existing program, have served to further validate the effectiveness of the CAVIJET method as an alternative to conventional underwater cleaning techniques.

Perhaps the most attractive feature in the use of CAVIJET nozzles for underwater cleaning relates to the safety inherent in this technology. For instance, fouling can be effectively removed at pressures of only about 13.8 MPa (2,000 psi). This pressure minimizes the probability of injury, as shown by several accidental

momentary exposures of the jet to a diver's gloved hands wherein no injury or damage occurred. If, however, this jet had been operated at 10,000 psi, it is quite certain that there would have been serious injury. In addition, the cleaning path provided by the CAVIJET nozzles is substantially wider than that provided by conventional high pressure water jets, which results in a proportionally more rapid rate of cleaning. For instance, the CAVIJET nozzles utilized in the Hawaii underwater field trials were providing clear path widths of up to 7.6 cm (3 in.) or more when swept across the propeller blades as rapidly as the diver could move them. Path widths well under 2.5 cm (1 in.) are typically observed with the conventional nozzles.

VI. CONCEPTUAL DESIGN OF CAVIJET<sup>®</sup> CAVITATING  
WATER JET HULL CLEANING SYSTEMS

In this chapter design concepts and parameters will be summarized for hull cleaning systems, employing the CAVIJET method, which are suitable for use in dry dock and for underwater ship hull cleaning. We will also provide some comparisons of the potentials of these systems versus other competing hull cleaning methods. Some indication of potential cost benefits will also be provided.

A. Dry Dock CAVIJET Cleaning System

An artist's concept of a prototype system which might be used to clean ship hulls in dry dock is shown in Figure 41. The concept of utilizing a pair of small maneuverable units, controlled by a single operator, was originated during this program. It is of interest to note, however, that a similar system, although utilizing conventional high pressure water jets, has been developed by a company in Europe. This company, Paul Hammelmann Maschinenfabrik GmbH & Co. KG of West Germany has developed a system, entitled the "Dock Master", which incorporates essentially the same maneuverability features shown by our concept in Figure 41. Each wheel should be steerable to allow movement amongst the keel blocks and other obstructions present on the dry dock floor. In addition, the units must be small enough to



fit within the confined spaces often found in drydocks between the wingwalls and the keel blocks. An arrangement as shown in Figure 41 suggests that a separate power and pumping unit might be utilized. This unit could be parked at a convenient location with hoses connected to the moving operational unit. Then periodically the operational unit might return to tow the pump and power unit to a new location further along in the dry dock. A "cherry picker" concept is provided for positioning the cleaning head so that, with a small rotation of the carriage, a large lateral motion could be achieved at the end of the extended boom. In the inset in Figure 41, it is suggested that the cleaning head might contain a means to rotate a set of nozzles, if such repeated sweeping is found to be effective in increasing the overall rate of cleaning. An alternative design might involve an automatic up-and-down oscillating action for the nozzles within the cleaning head, to be performed in conjunction with a left-to-right sweeping action provided to the entire cleaning head by the operator.

Also suggested in this concept in Figure 41 is a method for capturing and recirculating the effluent water with the entrained particles of fouling and paint. This concept seems very desirable for several reasons. First, increasingly stringent environmental protection regulations may soon make the recovery and suitable

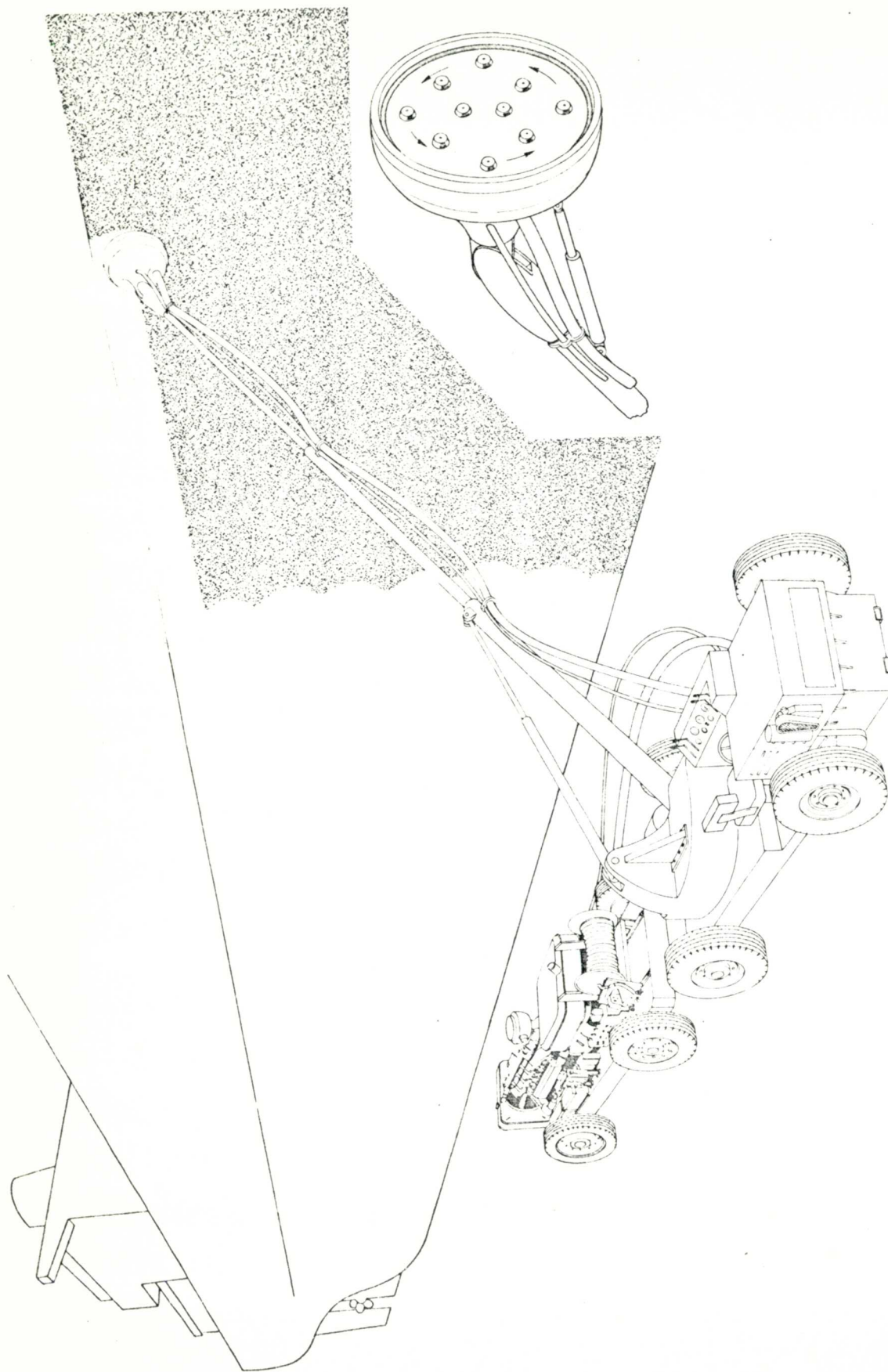


FIGURE 41 - ARTIST'S CONCEPT OF CAVIJET® HULL CLEANER FOR DRYDOCK USE

disposal of such effluents mandatory. Thus, recapturing and filtering to remove pollutants could be a more economical alternative to cleanup of the dry dock floor. A second motivation for the recapture of the effluent and its recirculation relates to the use of such a water cleaning system in the northern portions of the U.S.A. Formation of ice during such a cleaning operation would probably totally negate its potential benefits. Thus, the introduction of an antifreeze to the system would be required, but this additive would be prohibitively expensive unless the working water could be recirculated, filtered, and reused. In addition, for those situations wherein cleaning to bare metal would be desired, a rust-inhibitor might also be added to the working fluid. Indeed, consideration of a working fluid other than water might very well turn out to be a practical alternative.

The cleaning head for this dry dock CAVIJET system should contain about six to ten CAVIJET nozzles. Based on the results achieved in the current program, the six nozzle array can achieve a cleaning rate in excess of  $500 \text{ m}^2/\text{hr}$  ( $5,400 \text{ ft}^2/\text{hr}$ ). Thus, by extrapolation, we might expect the rate for a ten CAVIJET nozzle array to be about  $840 \text{ m}^2/\text{hr}$  ( $9,000 \text{ ft}^2/\text{hr}$ ). (See Table 14) The total flow required for a six nozzle array, each nozzle having an orifice diameter of 3.0 mm (0.120 in.) is 4.4 l/s (70 gpm) if the system is operated at the pressure of 13.8 MPa (2,000 psi) which we have found to be adequate during our dry dock hull cleaning trials. In addition the water required for the six dynamic sheathing devices corresponds to a flow of about 5.7 l/s (90 gpm). Hence the total flow for this system,



which would be the burden on any recirculation and filtration components, is about 10.1 l/s (160 gpm). The hydraulic power for this six nozzle CAVIJET array is about 61 kw (82 hp).

A ten nozzle CAVIJET cleaning head, operated at the same 13.8 MPa (2,000 psi) pump pressure, would require a total flow of about 7.4 l/s (117 gpm). Add to this the required flow for ten dynamic sheathing devices, namely 9.5 l/s (150 gpm) and one finds a total flow requirement for this case of about 16.9 l/s (267 gpm). The hydraulic power for this ten CAVIJET nozzle cleaning head is about 102 kw (136 hp). The optimum size for this cleaning head would require a trade-off evaluation of the labor costs associated with this system versus the increased capital costs, as well as the associated dry docking costs, and the time restraints on the duration wherein the ship to be cleaned can remain in dry dock. The current technique, as described in Chapter I of this report might typically utilize a total of 15 men in three sandsweeping teams. These teams can achieve in one shift a total cleaning of about 4,650 m<sup>2</sup> (50,000 ft<sup>2</sup>). This total amount of cleaned area could readily be achieved, in an eight hour shift, with the use of two systems each with a six CAVIJET cleaning head array. Depending on the size of the ship to be cleaned, a larger, and hence more rapid cleaning might be desirable.

Although an optimum system might be indeed of the configuration suggested in Figure 41, that is, with total recapture and recirculation of the working fluid, it is conceivable that certain shipyards would not require such refinements. For instance in the southern part of this country freezing would not be a problem. Thus, in situations where the majority of the cleaning is of a "sweeping" nature, so that a rust-inhibitor would not be required, it may not be necessary to utilize the closed recirculation system envisioned here. In this case one might examine the alternative of pumping back the effluent which falls to the floor of the dry dock, with a filtration of this water, followed either by routing into a convenient holding tank or to disposal overboard. Thus, the specific needs of a particular yard would certainly be the prime factor in the final design decisions of a dry dock CAVIJET cleaning system.

B. Underwater CAVIJET Hull Cleaning System

The multinozzle cleaning array pictured in Figure 41 would be the essential feature of any underwater CAVIJET hull cleaning system. To be competitive with the existing large multibrush systems such as the SCAMP or the BRUSH-KART, a relatively large cleaning swath must be achieved. Various alternatives are possible to provide the necessary horizontal traverse of such a multinozzle CAVIJET array. For instance the boom-controlled unit seen in Figure 41 might conceivably be adapted for operation from

either a barge, dock, or pier adjacent to the ship. The use of a barge, which would allow access to both sides of the ship, would seem to be the preferable approach for this type of system. Alternatively a diver-controlled unit, utilizing counter-thrusting jets or propellers to maintain the required position adjacent to the hull, is an optional method which is similar to that now utilized by the existing multibrush equipment.

Another consideration is the environmental protection which might be required for any underwater cleaning systems. The need to avoid release of toxic paint flakes into a harbor, as well as the excessive B.O.D. (biological oxygen demand) from the cleared fouling, suggests that capturing, filtrating, and reusing the working fluid be considered in a fashion analogous to that suggested for the dry dock system. High pressure flow and power requirements, for either a six nozzle or a ten nozzle CAVIJET cleaning head or interim sizes, would be relevant here for an underwater cleaning system, but with no dynamic sheathing flow requirement.

C. Comparison With Alternative Cleaning Systems

The most popular, and currently most practical, technique for hull cleaning in dry dock involves the use of hand-held grit blasting units. As indicated, a group of 15 men operating in three sand sweeping teams can now achieve about  $4,650 \text{ m}^2$  ( $50,000 \text{ ft}^2$ ) in a single eight hour shift. As discussed in



Chapter I, the total cost including grit, labor, power, and capital, represents a total of something over \$54 per 100 m<sup>2</sup> (\$50 per 1,000 ft<sup>2</sup>) to clean by sand sweeping. If we assume that the same 4,650 m<sup>2</sup> (50,000 ft<sup>2</sup>) is to be cleaned by utilizing one of the ten-nozzle CAVIJET cleaning systems discussed above, then the job can be done well within the single eight hour shift. The cost<sup>\*</sup> for this CAVIJET method of cleaning is estimated to be less than \$600 per day, including costs for power, depreciating a \$350,000 machine over eight years, labor to operate the machine, plus maintenance and setup. This, therefore, corresponds to a cost of about \$13 per 100 m<sup>2</sup> (\$12 per 1,000 ft<sup>2</sup>). Thus, in comparison to the sand sweeping cost of \$54 per 100 m<sup>2</sup> (\$50 per 1,000 ft<sup>2</sup>) the CAVIJET system suggests a potential savings of \$41 per 100 m<sup>2</sup> (\$38 per 1,000 ft<sup>2</sup>).

To estimate the potential yearly cost savings for the use of the CAVIJET method, compared to the conventional sand sweeping method, consider a range of wetted surface area per ship to be cleaned of from 5,000 m<sup>2</sup> to 20,000 m<sup>2</sup> (50,000 to 200,000 ft<sup>2</sup>) where the latter figure refers to large tankers. A typical yard may average about two ships per week or about 100 ships per year. For the range of ship sizes suggested, this savings in cost per ship might therefore range between \$1,900 to \$7,600 per ship. Hence, the total savings per year per yard could be estimated to be between \$190,000 to \$760,000. Thus, within about one year the

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\* See Appendix A for this cost estimation.

capital costs related to the purchase of this type of semiautomated CAVIJET equipment should be recovered.

Another relevant comparison of the CAVIJET cavitating fluid jet method was briefly mentioned in Section C of Chapter V in this report. This application related to the underwater cleaning, utilizing diver controlled equipment, for maintenance of ship components such as propellers, sea chests, control surface clearances and ballast gratings. Conventional large multibrush systems are unsuitable for cleaning such components and appendages. Therefore, the alternative approaches include high pressure water jet blasting or hand-held brushes and scrapers. Experience has demonstrated that a diver-held CAVIJET unit can clean from three to five times faster than the conventional brushing and scraping techniques. Comparably faster rates, while operating at substantially lower pump pressures, have been achieved with the CAVIJET technique. Also, as described above, the use of these lower pressures represents a considerably safer method for achieving this cleaning.

At this time, because of the many questions related to the effective application of large multinozzle CAVIJET systems for underwater cleaning, it is not possible to provide a direct cost comparison of such an approach with the existing multibrush semiautomatic systems such as the SCAMP and the BRUSH-KART equipment.

However, the rates of cleaning achieved in our field trials under this program suggest that the CAVIJET nozzle rates of cleaning could be made competitive with these methods. For instance, Butterworth (4) claims that their SCAMP underwater hull cleaner can clean a 1.7 m (5.5 ft) path at 0.27 m/s (0.9 ft/s). This implies a cleaning rate of  $1,660 \text{ m}^2/\text{hr}$  ( $17,820 \text{ ft}^2/\text{hr}$ ). As indicated in Table 14, we might expect a ten-nozzle CAVIJET system to produce  $840 \text{ m}^2/\text{hr}$  ( $9,000 \text{ ft}^2/\text{hr}$ ) in dry dock operation. We have seen in the laboratory (see Figure 13) that CAVIJET nozzle submerged cleaning path widths are about twice those of the corresponding dynamic sheathing cleaning path widths. It is not unreasonable, therefore, to extrapolate the dry dock cleaning rate of  $840 \text{ m}^2/\text{hr}$  ( $9,000 \text{ ft}^2/\text{hr}$ ) to a underwater rate of  $1680 \text{ m}^2/\text{hr}$  ( $18,000 \text{ ft}^2/\text{hr}$ ) by suitable adjustment of the nozzle-to-nozzle spacing.



Table 14  
Specifications for CAVIJET® Dry Dock Hull Cleaning System

| Parameter                          | Six Nozzles*                       | Ten Nozzles*                       |
|------------------------------------|------------------------------------|------------------------------------|
| Flow for CAVIJET Nozzles           | 4.4 $\ell/s$ (70 gpm)              | 7.4 $\ell/s$ (117 gpm)             |
| Flow for Dynamic Sheathing         | 5.7 $\ell/s$ (90 gpm)              | 9.5 $\ell/s$ (150 gpm)             |
| Total Flow                         | 10.1 $\ell/s$ (160 gpm)            | 16.9 $\ell/s$ (267 gpm)            |
| Pump Pressure                      | 13.8 MPa (2000 psi)                | 13.8 MPa (2000 psi)                |
| Hydraulic Power at CAVIJET Nozzles | 61 kw (82 hp)                      | 102 kw (136 hp)                    |
| Estimated Rate of Cleaning         | 500 $m^2/hr$<br>(5,400 $ft^2/hr$ ) | 840 $m^2/hr$<br>(9,000 $ft^2/hr$ ) |

\*Nozzle orifice diameter: 3.0 mm (0.120 in.); plain CAVIJET nozzle configuration.

VII. CONCLUDING REMARKS

As a result of the work performed during this program the following conclusions are drawn:

- a. The use of a dynamic sheathing device can provide a significant increase of the in-air fouling removal rate for a CAVIJET cavitating fluid jet. Using about 0.95 l/s (15 gpm) of sheathing flow, an improvement equal to about one-half of the difference between in-air and submerged cleaning can be achieved with a 3.2-mm (1/8 in.) CAVIJET nozzle operated at 13.8 MPa (2,000 psi). (See Figure 13.)
- b. The cleaning rates and the area cleaning effectivenesses achieved in field trials, both during dry dock and underwater operation of a multinozzle CAVIJET array, are higher than those observed during laboratory testing. This improvement can be attributed to the greater difficulty of removing fouling from the hard epoxy coating used on the laboratory test panels relative to the same cleaning operation on softer antifoulant ship hull coatings. Thus, cleaning rates of over 500 m<sup>2</sup>/hr (5400 ft<sup>2</sup>/hr) can be achieved with a six-nozzle array of 3-mm (0.12-in.) CAVIJET nozzles, at an area cleaning effectiveness of 8.2 m<sup>2</sup>/kw-hr (65.9 ft<sup>2</sup>/hp-hr). (See Figure 35 and Table 12).

- c. Operation of full-scale field equipment has demonstrated that the CAVIJET method can provide an alternative to present hull cleaning techniques in dry dock, operating at equivalent or faster rates of cleaning and at substantially lower costs. For instance it is estimated that the CAVIJET method can produce a surface comparable to existing sandsweeping methods at a cost savings of about \$41 per 100 m<sup>2</sup> (\$38 per 1,000 ft<sup>2</sup>). (See Section C of Chapter VI)

Under this program, and during several small-scale diver controlled single nozzle underwater trials, the feasibility of using the CAVIJET cavitating fluid jet method for removing fouling has been demonstrated under actual field conditions. For instance, a hull cleaning system, suitable for use in dry dock and which requires no water recirculation, could now be constructed on the basis of what has presently been learned. If a more sophisticated device is required, e.g., to provide reuse of antifreeze and/or rust inhibiting additives, then it is recommended that answers should be found for questions (as listed in Appendix A) related to the recirculation problem.



APPENDIX A

Operation of a CAVIJET<sup>®</sup> Dry Dock  
Hull Cleaning System

The cost estimate of \$13 per 100 m<sup>2</sup> (\$12 per 1,000 ft<sup>2</sup>) for operating the CAVIJET system so as to clean 4,650 m<sup>2</sup> (50,000 ft<sup>2</sup>) per day was based on the following:

1. Depreciation of Capital Costs

|                                                                            |                    |
|----------------------------------------------------------------------------|--------------------|
| Cost Basis:                                                                | \$350,000.00       |
| Life:                                                                      | 8 years            |
| Method of Depreciation:                                                    | Straight line      |
| Annual Depreciation:                                                       | \$ 43,750.00       |
| Daily Depreciation (based on 250 working days per year; one shift per day) | : \$ <u>175.00</u> |

2. Labor

|                                     |                 |
|-------------------------------------|-----------------|
| a. Operator: 8 hrs @ \$22.00/hr:    | \$176.00        |
| b. Support-man: 8 hrs @ \$18.00/hr: | <u>144.00</u>   |
|                                     | <u>\$320.00</u> |

3. Power

|                                                                                                                        |                |
|------------------------------------------------------------------------------------------------------------------------|----------------|
| Operating Time: 4,650 m <sup>2</sup> ÷ 840 m <sup>2</sup> /hr<br>(50,000 ft <sup>2</sup> ÷ 9,000 ft <sup>2</sup> /hr): | 5.6 hrs        |
| Power Cost:                                                                                                            | : \$0.10/kw-hr |
| Cost: 5.6 hrs x 102 kw x \$0.10 =                                                                                      | <u>\$57.00</u> |

|                     |                 |
|---------------------|-----------------|
| 4. Miscellaneous    | <u>\$48.00</u>  |
| Total Cost per Day: | <u>\$600.00</u> |

Thus, if  $4,650 \text{ m}^2$  ( $50,000 \text{ ft}^2$ ) are cleaned within the eight-hour shift, the cost per cleaned area is: \$13 per  $100 \text{ m}^2$  (\$12 per  $1,000 \text{ ft}^2$ ).

These cost estimates were based on a system which does not utilize additives or recirculation of the working fluid. If a more sophisticated device were required, thereby providing pollution control features not presently available with the sandsweeping technique, then several aspects remain to be examined before the design of such operational equipment could be finalized. Thus, it is recommended that answers should be found to the following questions:

- a. In the design of a multinozzle enclosed cleaning head, what is the best arrangement of the CAVIJET nozzle and should these nozzles be either rotated or oscillated within the cleaning head to further increase the rates of cleaning?
- b. How should this cleaning head be designed to most effectively capture the spent water, foulants, and paint particles?
- c. What are the components required to filter and recirculate the working water?
- d. How should the sludge separated from the effluent water be handled?

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