AD-A133 640 DIVER-OPERATED SEDIMENT EXCAVATION TOOL(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA H THOMSON SEP 83 NCEL-TN-1677 1/1

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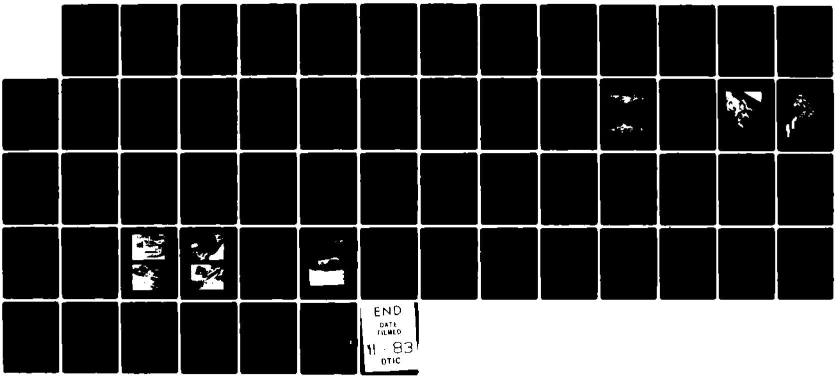

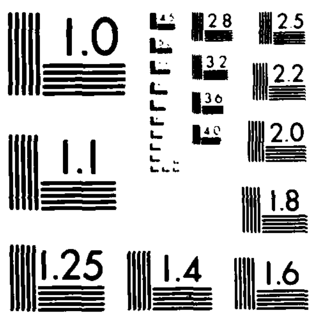

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TITLE: DIVER-OPERATED SEDIMENT EXCAVATION TOOL

AUTHOR: Hugh Thomson

DATE: September 1983

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NOTE

NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

METRIC CONVERSION FACTORS

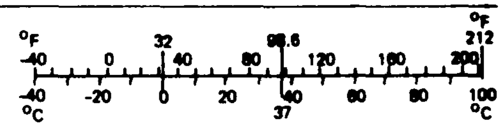
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Underwater construction tasks frequently require the removal of seafloor sand and sediment. An experimental sediment excavation tool was fabricated from commerically available and specially designed components. The diver-operated tool combined a jet-eductor, a jet nozzle, and a hydraulically powered sump pump into a jet-dredge tool to increase excavation rates, reduce reaction forces, and improve water visibility in jetting operations. A later version included multi-jet nozzles rather than a single jet nozzle. Engineering tests of the

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Underwater construction tasks frequently require the removal of seafloor sand and sediment. An experimental sediment excavation tool was fabricated from commercially available and specially designed components. The diver-operated tool combined a jet-eductor, a jet nozzle, and a hydraulically powered sump pump into a jet-dredge tool to increase excavation rates, reduce reaction forces, and improve water visibility in jetting operations. A later version included multi-jet nozzles rather than a single jet nozzle. Engineering tests of the experimental tool and all candidate components were conducted. The test results are presented in this document and show that the tool is effective. The next step in development is suitable engineering design for use by Fleet units.

CONTENTS

INTRODUCTION

Under sponsorship of the Naval Facilities Engineering Command (NAVFAC), the Naval Civil Engineering Laboratory (NCEL) is developing tool systems for Naval Underwater Construction Teams. Many construction tasks require removal of seafloor sand and sediment. The emplacement, inspection, and repair of pier pilings, pipelines, and cable systems are examples of tasks where sediment excavation is frequently required. To improve the capabilities of the Underwater Construction Teams to perform these tasks, NCEL has developed a diver-operated sediment excavation tool. This report describes the development and presents design criteria for this tool.

BACKGROUND

Prior to the development of the Sediment Excavation Tool, diver techniques for transporting and removing seafloor sediment were limited to jetting with low pressure, high flow water; dredging with hydraulic powered sump pumps; or dredging with water injected jet eductors.

Sediment removal utilizing a water jet is inefficient. The jet stream easily fluidizes the sand sediment, but with no mechanism for further transport these sediment particles eventually settle in the same area. In addition, this technique requires the diver to contend with large diameter, stiff water hoses, large reaction forces, and poor visibility at the work site.

A force-balanced nozzle, called the Falcon nozzle, does exist; however, previous experience* has shown that this does not provide adequate thrust balancing and the wash from the back thrust is potentially dangerous to scuba divers.

Hydraulic-powered sump pumps are not well-suited to dredging operations because they rely on a revolving impeller to pump fluids. In pumping abrasive sand-sediment slurries, sump pumps frequently can become clogged, pass only small-sized particles, and incur internal as well as impeller damage.

Jet eductors have no mechanism for fluidizing unconsolidated silts or clays. They utilize injected water and a venturi for pumping fluids. In the past,** jet eductors have been successful in transporting sand;

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*Naval Civil Engineering Laboratory. Letter Report: "Evaluation of seafloor tunneling and excavating equipment for salvage operations", by K. D. Vaudrey, Port Hueneme, Calif., Feb 1972.

**Naval Coastal Systems Center. Technical Memorandum No. 229-78: Underwater jetting and a jet/dredge tool for diver use", by C. Smith, and J. Mittleman, Panama City, Fla., Aug 1978.

however, divers must first breakup and fluidize the sediment material in front of the suction tube. In addition, this technique has the disadvantages of the use of large-diameter, stiff water hoses, of only moderate reaction forces, and of frequent clogging (eductors can easily become clogged if the diver gets the suction end buried in sand).

It is recognized that while the use of these components individually poses significant operational difficulties, a combination of these components could minimize or even eliminate their individual shortcomings. For instance, by adding a jet to an eductor, reaction forces could be balanced, visibility could be improved, and performance could be improved. By adding a pump to power this combination, handling stiff water hoses could be eliminated and drag forces from current acting on hoses extending to the surface could be reduced.

In 1977, NCEL tasked the Naval Coastal Systems Center (NCSC) with testing and evaluating underwater jetting and dredging components. A further task was fabrication of an experimental diver-operated combination jet nozzle - jet eductor - sump pump tool (see Figure 1). The resulting tool is composed of a Gold Divers jet eductor, a 1/2-in. diam jet nozzle and a Stanley Tools hydraulic-powered sump pump model no. SM22. The tool weighs approximately 65 pounds, has an overall length of about 4 feet, and is powered hydraulically at 9 gpm and 1,500 psi.

Results of the NCSC study* showed that, in comparison to the performance of the individual jet and dredge components, the combination tool increases excavation rates, reduces reaction forces, and improves water visibility in jetting operations.

With the preliminary design concept validated, a test program was conducted at NCEL to:

- test and evaluate the NCSC experimental tool
- test and evaluate other candidate components for use with the combination tool
- develop an optimized design of the experimental tool
- fabricate a prototype jet/dredge tool

PRELIMINARY TESTS

Three series of preliminary tests were conducted to evaluate the diver jet dredge tool. The objective of these tests was to develop information concerning tool performance, human factor considerations, and safety. All tests were conducted with Navy-qualified scuba divers.

Tool Performance and Human Factors Evaluation

Underwater Construction Team Two personnel conducted the first series of tests in the harbor at Port Hueneme, Calif., to gain familiarity with the operation of the NCSC prototype jet dredge tool. Figure 2

*NCSC Technical Memorandum 229-78.

illustrates the test rigging, with the jet dredge buoyed up with a tethered flotation bag. The tool was hydraulically powered at 9 gpm and 1,550 psi.

These tests showed the following results:

- Reaction forces are minimal - proper flow adjustment (made by adjustment of the dual butterfly valve) to the nozzle and jet eductor results in a force-balanced operation of the tool.

- Proper safety features are absent - there is no mechanism for quickly shutting the tool off in the event of a mishap incurred by the diver.

- Handling of the tool is difficult - there are no clearly defined areas or positions for gripping or holding the tool. In addition, diver handling of the tool with the tethered buoyancy balloon proved unwieldy.

- Visibility is poor at the diver work site - the tool generated heavy loads of silt and sediment resulting in near zero visibility at the test site.

Multiple Jetting Nozzle and Pump Configuration Evaluation

The objectives of this series of tests were to determine whether the pump should remain an integral part of the tool and to test a new concept of jetting with multiple jet nozzles. These tests were conducted with NCEL Diving Locker personnel in the harbor at Port Hueneme.

Sump Pump. To determine whether the Stanley submersible pump should be located directly on the jet-dredge tool or remotely, tests emphasizing diver comfort and safety were conducted with the tool in both configurations. The tool was operated first with the sump pump remote from the jet dredge combination. Fifty feet of 3-in. diam fire hose was used to connect the output flow of the pump to the inlet of the dredge unit. The sump pump was then suspended in the water while being powered at approximately 9 gpm and 1,500 psi.

After approximately 20 minutes of operation, the tool was reconfigured with the sump pump mounted directly on the tool. The tool was then deployed with the same divers to compare the handling characteristics of the two configurations.

Although the configuration of the tool with the pump attached appears to be bulky and awkward, the divers preferred this configuration because handling of the hydraulic lines to the tool was easier than handling the fire hose to the dredge unit. The fire hose becomes very stiff at high volume flow (approximately 200 gpm) and is easily kinked, since the bend radius before kinking is only about 8 feet.

Multiple Nozzles. The concept of multi-jetting in this application is to engulf the area to be excavated with an envelope of converging jet streams, thereby dislodging and suspending sediment particles in a direction and area more local to the suction tube of the dredge. To determine the feasibility of this concept, a multi-jetting apparatus was fabricated from schedule 40 PVC pipe. The jetting fixture is shown with the tool in Figure 3. The outlets are directed inward with a "focal" distance (distance between the plane of the nozzles to the point where the jet streams converge) of roughly 2 feet. The nozzles consist of end caps with 3/8-in. diam holes drilled and threaded to accept end plugs. The end plugs were used so that performance with fewer than eight jets in different positions around the ring could be evaluated.

Two jetting combinations (four and eight jets) of the multi-jetting apparatus were tested and compared to the single-jet nozzle. Excavation data are presented in Table 1. In general, excavation rates appear to be very low, ranging from 0.27 to 0.45 ft^3/min. No measurable differences in excavation rates were found for the single-, four-, or eight-jet systems. However, the divers reported that the visibility was greatly enhanced with both the four- and eight-jet systems. These tests indicate that the multi-jetting approach to fluidizing sediment results in improved visibility at the diver work site.

Excavation Rate Tests

The objective of this series of tests was to measure the excavation rates of different jet nozzle assemblies. These tests were conducted offshore from the beach at Port Hueneme, Calif., and off the west jetty of the Naval Construction Battalion Center (NCBC), Port Hueneme.

With the concept of multi-jetting validated, the jetting apparatus discussed in the previous section was replaced with a more sturdy fixture, called the plenum. Figure 4 shows the fixture attached to the tool. The plenum, constructed of aluminum and attached to the eductor with four threaded rods, functions as both a distributor and support foundation for the jet nozzles. It is designed specifically to provide versatility in adapting to different jetting combinations.

Four types of jet nozzles were purchased from Spraying Systems Company, Wheaton, Ill. Table 2 lists the model numbers, orifice sizes, and spray angles. These nozzles were selected from the manufacturer's literature based on their advertised flow-pressure performance. The direction of each jet stream, and thus the focal distance, can be varied by an adjustable ball fitting. The radial distance between each nozzle and the centerline of the plenum (same line as the major diameter of the eductor) can be varied by changing the length of the pipe nipple connecting the nozzle to the plenum.

A standardized test procedure, outlined below, was developed to evaluate the different jet nozzle assemblies.

1. The diver positioned the tool such that it rested upright on the ocean floor (major axis of the eductor suction/exhaust tube perpendicular to the seafloor).

2. With some horizontal support from the divers the tool was turned on for 3 minutes and allowed to sink into the soil.

3. The depth and diameter of the resulting hole was then recorded.

Results of these tests are presented in Tables 3 and 4 for the Hueneme Beach and west jetty test sites, respectively. Tests 1 through 4 of Table 3 compare the excavation rate of the tool with two different jetting geometries. These data show that the jetting assembly with a focal length of 16 inches and an annulus radius of 4.5 inches has a higher excavation rate than the assembly with a focal length of 21 inches and annulus radius of 7.5 inches. Examination of the remaining tests in Table 3 shows the following average excavation rates for the different nozzles used with the 16-inch focal length and 4.5-inch annulus radius configuration:

Nozzle Number	Number of Nozzles	Average Excavation Rate (ft^3/min)
H1/2U00150	4	2.87
H1/4U1570	8	2.40
H1/4U0050	8	3.30
H1/4U0070	8	2.65

Data taken from the west jetty site are presented in Table 4. Excavation rates are very small, ranging from 0.2 to 0.6 ft^3/min. The limited performance is due to extensive clogging of both the jet nozzles and the eductor venturi with sand and pebble sediment. This clogging occurred because loose sediment was passed through the pump and into the eductor and plenum. Although the pump inlet has a screen (0.081-in.-diam, 8 holes/in. perforations), it is clear that this too may become clogged for smaller sized screen meshes. Clogging was not observed in the previous tests at Hueneme Beach, but this is probably because the smaller sand grains of the Hueneme Beach area could more easily pass through the restricted areas of the tool.

COMPONENT STUDY

To optimize the performance of the tool, basic hydraulic data describing the performance of the various jet dredge system components were needed. A series of tests gathering these data was conducted in the Shallow Water Ocean Simulation Facility at NCEL. These tests are grouped into the following categories:

- Submersible Hydraulic Pump Tests
- Jet Eductor Tests
- Jetting Nozzle Tests

Submersible Hydraulic Pump Tests

Two submersible hydraulic pumps were selected for test and evaluation: the Stanley Caisson pump (SM21) and the Stanley Dewatering pump (SM22). Both are centrifugal pumps that rely on a revolving impeller to pump fluids. Earlier studies on the SM22* and previous experience with the SM21 indicated that both pumps were likely candidates for application to the tool.

The objectives of these tests were to characterize the performance of these pumps, including:

- pressure versus flowrate curves for various hydraulic inputs
- efficiency versus output flowrate curves for various hydraulic input

Although some performance data from the manufacturer do exist, data based on Mil-H-5606C hydraulic oil were necessary because oil viscosity is different from that used by the manufacturer to determine performance characteristics. The test arrangement for the acquisition of these data is shown in Figure 5.

To obtain the desired data format, the input hydraulic flowrate was held constant while the input pressure, output pressure, and output flowrate of the pump were recorded. The output flowrate, and thus input and output pressures, were varied by adjustment of the ball valve in the assembly. The output pressure was monitored with a gage located immediately downstream of the pump; the output flowrate was monitored with a turbine flowmeter. The hydraulic input was monitored with the pressure gage and flowmeter of the hydraulic power source.

Figures 6 and 7 show a family of pressure versus flowrate curves for various input flowrates to the SM21 and SM22 pumps, respectively. The manufacturer's advertised performance curves are shown in the top right-hand corner of each figure. These data show that for a given input flowrate the SM22 has a slightly larger output flowrate and pressure than the SM21 pump. Also, the output flowrate and pressure of both pumps is slightly lower than the manufacturer's advertised performance level. Since the grade of hydraulic oil used in the manufacturer's tests is not known, some difference was expected due to differences in oil viscosity.

Pump efficiency data are presented in Figure 8 for the SM21 pump and Figure 9 for the SM22 pump. These data are plotted as efficiency versus output flowrate for different hydraulic inputs. The data show peak efficiencies of approximately 28% and 38% for the SM21 and SM22 pumps, respectively.

Eductors

These tests were designed to obtain performance data on the couple-jet by Gold Divers. The jet pump (see schematic in Figure 10) relies on the venturi effect created by injecting water at a high velocity into a mixing chamber. The high velocity creates a lower than ambient pressure in the mixing chamber, resulting in entraining the fluid mixture at the inlet into the mixing chamber and out the discharge. The venturi orifice size can be adjusted by sliding the inlet suction tube inside the housing with a set screw adjustment.

*NCSC Technical Memorandum 229-78.

The performance of the jet pump can be characterized in terms of efficiency, the dimensionless head ratio, and the dimensionless discharge ratio for a family of venturi orifice sizes. The efficiency is defined as the work done divided by the work exerted. The rate of work done by the system is that performed in transporting the fluid at an entrained flowrate Q_e through the increased static pressure P between the point of entrainment ($P = H_e$) to the pump discharge ($P = H_d$). The total workrate ($\dot{W}_{out}$) then becomes:

$$\dot{W}_{out} = \rho g \, (H_d - H_e) \, Q_e$$

where ρ is the fluid density and g is the acceleration of gravity.

The rate of work exerted by the system is the power expended in moving the injected fluid at a flowrate of Q_I through the pressure drop across the venturi gap. The total workrate ($\dot{W}_{in}$) expended then becomes:

$$\dot{W}_{in} = \rho g \, (H_I - H_e) \, Q_I$$

Thus, the efficiency (k) can now be written as:

$$k = \frac{\rho g(H_d - H_e) \, Q_e}{\rho g(H_I - H_e) \, Q_I}$$

or

$$k = R_H R_Q$$

where $R_H = (H_d - H_e)/(H_I - H_e)$ is the dimensionless head ratio

$R_Q = Q_e/Q_I$ is the dimensionless discharge ratio

The equipment configuration for these tests is shown in Figure 11. To obtain the desired data format, the injection flowrate was varied at a specified venturi gap while the entrained flowrate (Q_e), entrained pressure (H_e), and injected pressure (H_I) were monitored. The injected flowrate (Q_I) was calculated using the data obtained in the previous section. The discharge flowrate was calculated by summing the injection flowrate and the entrained flowrate. The discharge pressure (H_d) was assumed to be ambient pressure.

Table 5 shows the venturi gap setting used in the eductor tests. For convenience, these gaps are denoted by a "set position." Performance data are presented in Figures 12 through 15.

Figure 12 is a plot of efficiency as a function of injection flowrate for set positions 1 through 4. These data show a trend of higher efficiencies with both smaller gap sizes and increased injection flowrates. Efficiencies range from 6% to 16%.

Figure 13 is a plot of the head ratio versus discharge ratio. The most notable feature of these data is the large increase in the discharge ratio with decreasing gap size. By comparison to the gap size, the head ratio has little apparent effect on the discharge ratio.

Figure 14 is a plot of the discharge ratio as a function of the injection flowrate. These data also show the increase in discharge ratio with decreasing gap size, as well as a nearly linear relationship between the injection and entrained flowrates.

Although it is clear that the smaller venturi gap settings yield higher discharge ratios, they may not be the most optimum setting to use with a centrifugal pump. This point is illustrated in Figure 15, which shows the induced flowrate as a function of the eductor set position for a family of input hydraulic flowrates to the SM21 pump. Figure 15 clearly shows the largest induced flowrate occurring at Set Position 2.

Jetting Nozzles

The nozzle tests were designed to obtain pressure and flowrate data for four different sized Spraying Systems Company nozzles in various jetting combinations. They range in size from 1/4-inch to 1/2-inch nozzle diameter with all of the nozzles having a spray angle of either zero or 15 degrees. The jetting combinations tested are shown in Table 6.

The test setup is shown in Figure 16. The flowrate to the nozzle assembly was varied by adjustment of the ball valve. This flowrate was monitored with a turbine flowmeter. The pressure was monitored with a gage located at one of the exit ports of the plenum.

The data are presented in Figures 17 through 20 with pressure as a function of flowrate. These data were acquired primarily for use in the systems integration analysis.

SYSTEMS INTEGRATION ANALYSIS

Given the multitude of component setting combinations possible for operation of the present experimental tool, a systems integration analysis was conducted to analyze operating trends as component parameters vary and to identify optimum operating conditions. This analysis utilized a Hewlett Packard HP-85 computer in conjunction with all the component study data obtained previously.

The following two initial conditions for steady state operation are assumed.

$$P_{\text{pump output}} = P_{\text{eductor input}} = P_{\substack{\text{nozzle plenum} \\ \text{input}}} = P_{\text{system}} \qquad (1)$$

and

$$Q_{\text{pump output}} = Q_{\text{eductor input}} + Q_{\substack{\text{nozzle plenum} \\ \text{input}}} \qquad (2)$$

where P is pressure and Q is flow.

Equation 1 assumes incompressible flow with no head loss between the pump outlet and the eductor and nozzle plenum inlets. Equation 2 is simply a statement of conservation of mass.

With flow as a function of pressure for each component expressed in the form of second order polynomial best-fit equations, Equation 2 may be solved for the pressure of the system using the quadratic formula. By virtue of Equation 1, the operating point of each component can be calculated.

Appendix A shows the tool operating characteristics for all combinations of pumps, nozzle assemblies, pump input, and eductor settings. System pressure is found by solving Equation 2 for pressure. Nozzle jet stream velocity is calculated from the following equation:

$$\text{nozzle velocity} = \frac{(Q_{\text{nozzle plenum input}})}{(\text{no. of nozzles in plenum})(\text{nozzle cross-sectional area})}$$

The stagnation pressure of the jet stream is calculated from:

$$P_{\text{stagnation}} = P_{\text{system}} + 1/2\rho v^2_{\text{nozzle}}$$

where ρ is fluid density.

For the set of conditions described by Equations 1 and 2, the entrained flowrate into the eductor, the eductor efficiency, and the pump efficiency are all known from the data obtained previously. The calculation of the tool reaction force is detailed in Appendix B.

The data in Appendix A show the following:

- Eductor setting no. 2 results in the largest entrained flowrate through the eductor
- The nozzle stagnation pressures increase with decreasing venturi gap sizes
- Eductor efficiencies increase with decreasing venturi gap sizes
- Pump efficiencies increase with increasing venturi gap sizes

The optimum operating position is defined as that position that has both relatively high nozzle stagnation pressures and entrained flowrates through the eductor, combined with relatively low reaction forces. Four optimum positions are identified in Appendix A with a star symbol. These positions all have nozzle stagnation pressures larger than 50 psi, a minimum eductor entrained flowrate of 150 gpm, and reaction forces lower than 6 pounds.

PROTOTYPE JET/DREDGE TOOL

Based upon the results and experience gained during the initial phase of the project, the following changes were incorporated into the experimental tool:

- on/off "dead-man" switch
- debris ejector device
- directly attached buoyancy package
- lengthened suction tube

The dead man switch is embodied in a handle fixture for the tool; the handle-switch assembly, shown in Figure 21, is manufactured by Stanley Hydraulic Tools. A spring-loaded four-way tandem center spool valve provides the mechanism for on/off operation. The handle was modified by changing the porting configuration on the pressure (or tool) side of the handle. A bracket to firmly fix the handle to the tool was also incorporated.

As previously mentioned, sand and pebble sediment can clog the venturi of the jet eductor. To eliminate this clogging, a debris ejector device was developed to flush accumulated sediment out the venturi system. The ejector device, shown in Figure 22, attaches to both the eductor housing and the suction tube of the eductor. The lever arm action positions the tube relative to the eductor. By pulling the tube outward, the venturi gap widens, enabling large particles to be flushed out. The tube can then be pulled back to maintain the desired gap width and performance of the eductor.

The buoyancy package is made of a porous, closed-cell urethane foam (CPR 739 series), manufactured by the UpJohn Company in Torrance, Calif. The low viscosity of the components (consistency of a 30-weight motor oil) and long reaction time (approximately 20 minutes) allows for intimate molding of the foam around the tool. From the manufacturer's literature, the cured product has the following properties:

Property	Measurements
Density	20 lb/ft^3
Compressive Strength	1,150 psi
Tensile Strength	630 psi
Shear Strength	500 psi

The buoyancy package, shown in Figure 23, is molded into two removable shells for easy access to the tool components. The in-water weight of the entire tool with buoyancy is approximately 8 pounds.

Figure 24 shows the tool with the longer length (2-3/4 feet long) suction tube. The buoyant pack is designed to be positioned under the diver's arm against his side. By holding the tool in this manner and angling the front end downward, the diver can more easily place the jet nozzles and suction end of the tool on the seafloor with the longer suction tube. This helps minimize the amount of bending and crouching required of the diver and, hence, allows the diver to work longer periods before becoming fatigued.

OCEAN TESTS

Ocean tests of the prototype jet/dredge tool were conducted in 35 to 40 feet of water offshore from Anacapa Island, Calif. These tests were conducted to:

- Obtain excavation data for the tool with two different "optimum" component setting combinations
- Verify the operation and performance of the debris ejector system
- Evaluate the handling characteristics of the tool in the ocean

As previously discussed, many component setting combinations are possible for operation of the tool. The systems integrations analysis identified potential optimum component setting combinations. Two promising candidates are listed below:

Pump	Nozzle Configuration	Eductor Setting
SM22	H1/2U00150 - 4 nozzles	2
SM22	H1/4U0070 - 8 nozzles	2

Data for the tool with these two setting combinations are presented in Figure 25. These data are plotted as volume excavated versus time and show an average excavation rate of 15 ft^3/min for the four-jet system. The eight-jet system has an average excavation rate of 7.6 ft^3/min. Examination of the tool following these tests showed some clogging of the smaller (H1/4U0070) nozzles. The relatively low excavation rates of the eight-nozzle system is attributed to this clogging.

Operation of the debris ejector system was reported to be simple and fast by the divers. Clearing the venturi system was done periodically while conducting excavation tests. Examination of the jet eductor following these tests showed no clogging of the venturi, even though the smaller nozzles had clogged.

Handling of the tool was also reported to be very good. Figure 26 shows the tool in operation. The divers reported that the light in-water weight (8 pounds) and long suction tube greatly improved the handling of the tool. Minimal reaction forces, ranging from none to a very light pull in the forward direction, were reported.

CONCLUSIONS

1. Average excavation rates of 15 ft^3/min can be obtained with the jet/dredge tool. However, variations in excavation performance should be expected at different sites due to differences in soil characteristics.

2. In comparison to the single-jet nozzle, the multi-jetting approach to fluidizing sediment results in substantially improved visibility at the work site.

3. Handling of the tool by divers is greatly enhanced by the addition of a fixed buoyancy pack and a longer suction tube to the tool.

4. The debris ejector system provides clog-free operation of the jet eductor.

5. The jetting assembly should employ the larger-sized nozzles (H1/2U00150 - four-jet system) to minimize clogging with sand and pebble sediment.

RECOMMENDATIONS

The diver jet/dredge tool should be transitioned into an advanced development program to provide a tool suitably engineered for use by Fleet units.

Table 1. Excavation Data Taken at the Port Hueneme Harbor

Jetting Configuration	Number of Jets	Nozzle Diameter (in.)	Time Interval of Jetting (min)	Dimensions of Hole		Excavation Rate (ft^3/min)
				Depth (in.)	Diameter (in.)	
Hollow Annulus of 16 in. dia.	[illegible]	5/16	app. 2	12	18	0.44
Hollow Annulus of 16 in. dia.	8	5/16	1.25	8	16	0.27
Hollow Annulus of 16 in. dia.	8	5/16	3	15	20	0.45
Hollow Annulus of 16 in. dia.	4	3/8	3	15	20	0.45
Single 3/4 in. jet nozzle	1	3/4	3	18	18	0.44
Single 3/4 in. jet nozzle	1	3/4	3	25	15	0.43

Table 2. Jet Nozzles from Spray Systems Company

Model Number	Orifice Size (in.)	Spray Angle (deg)
H1/2U00150	19/64	0
H1/4U1570	13/64	15
H1/4U0050	11/64	0
H1/4U0070	13/64	0

Table 3. Hueneme Beach Test Results

[Soil Description: Medium grade sand]

Test No.	Submersible Pump			Nozzle Description			No. of Nozzles	Jetting Geometry		Excavation			
	Type	Hydraulic Input		VeeJet	Orifice Diameter (in.)	Spray Angle		Focal Length (in.)	Annulus Radius (in.)	Depth (in.)	Diameter (in.)	Time (min)	Rate (ft^3/min)
		Flowrate (gpm)	Pressure (psi)										
1	SM21	8	2,050	H1/40070	13/64	0 deg	8	16	4.5	37	34	3	3.3
2	SM21	8	2,050	H1/40070			8	16	4.5	60	21	3	2.0
3	SM21	8	1,950	H1/4U0070	13/64	0 deg	8	21	7.5	26	22	3	1
4	SM21	8	1,950	H1/4U0070	13/64	0 deg	8	21	7.5	24	22	2	1.4
5	SM21	8	2,050	H1/2U00150	19/64	0 deg	4	16	4.5	42	32	3	3.3
6	SM21	8	2,050	H1/2U00150			4	16	4.5	42	25	3	2.0
7	SM21	8	2,050	H1/2U00150			4	16	4.5	39	28	3	2.3
8	SM21	8	2,050	H1/4U1570	13/64	15 deg	8	16	4.5	44	28	3	2.6
9	SM21	8	2,050	H1/4U1570			8	16	4.5	49	24	3	2.2
10	SM21	8	2,050	H1/4U0050	13/64	0 deg	8	16	4.5	58	29	3	3.7
11	SM21	8	2,050	H1/4U0050			8	16	4.5	42	30	3	2.9

Table 4. West Jetty Test Results

[Soil Description: Coarse sand with small shells]

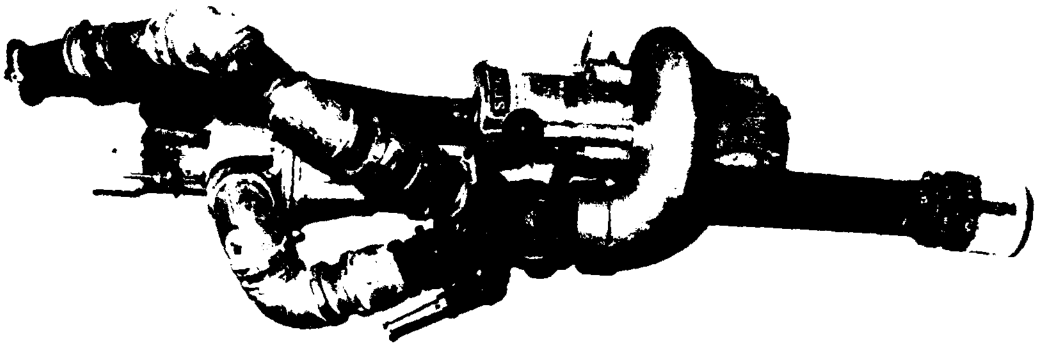
Submersible Pump			Nozzle Description			No. of Nozzles	Jet:ing Geometry		Excavation			
Type	Hydraulic Input		VeeJet	Orifice Diameter (in.)	Spray Angle		Focal Length (in.)	Annulus Radius (in.)	Depth (in.)	Diameter (in.)	Time (min)	Rate (ft^3/min)
	Flowrate (gpm)	Pressure (psi)										
SM21	8	2,000	H1/2U00150	19/64	0 deg	4	21	7.5	4	40.5	3	0.5
SM21	8	2,000	H1/2U00150	19/64	0 deg	4	21	7.5	6	19	3	0.2
SM21	8	2,000	H1/2U00150	19/64	0 deg	4	21	7.5	8	26	3	0.4
SM21	8	2,000	H1/2U00150	19/64	0 deg	4	21	7.5	18	20	3	0.6
SM21	8	2,000	H1/4U0070	13/64	0 deg	8	16	4.5	7	31	3	0.5
SM21	8	2,000	H1/4U0070	13/64	0 deg	8	16	4.5	6	32	3	0.5
SM21	8	2,000	H1/4U1570	13/64	15 deg	8	16	4.5	8	29	3	0.5
SM21	8	2,000	H1/4U1570	13/64	15 deg	8	16	4.5	5	33.5	3	0.4

Table 5. Venturi Gap Size Versus Eductor Set Position

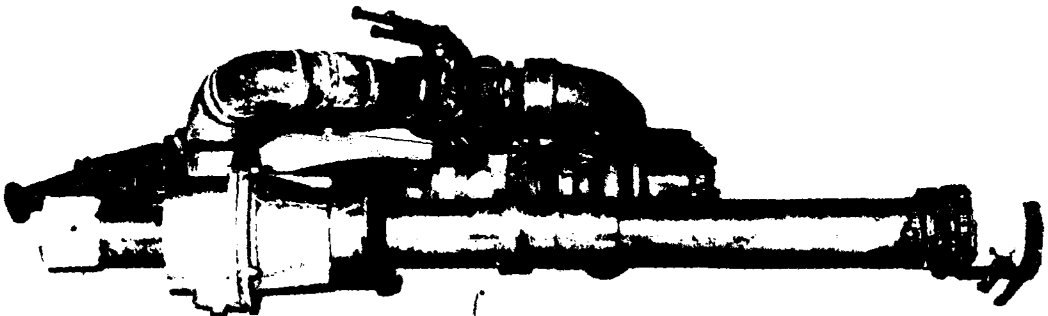
Set Position Number	Venturi Gap Size (in.)
0	0
1	1/8
2	1/4
3	3/8
4	1/2

Table 6. Jetting Combinations

Nozzle Description		Number of Nozzles
VeeJet	Spray Angle (deg)	
H1/4U0070	0	6 8 12
H1/4U1570	15	6 8 12
H1/U0050	0	6 8 12
H1/2U00150	0	4



(a) Front View



(b) Back View

Figure 1. Combination jet dredge tool developed by the Naval Coastal Systems [illegible]r.

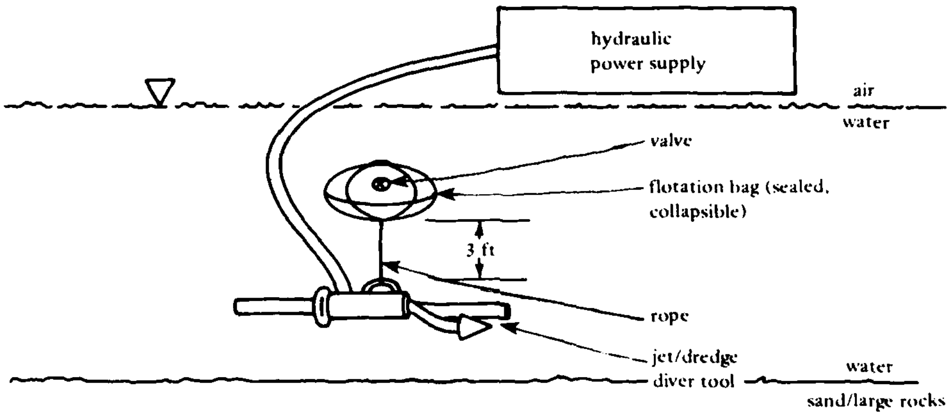


Figure 2. Test rigging for the first series test.

Figure 3. Test fixture used to validate multi-jetting concept

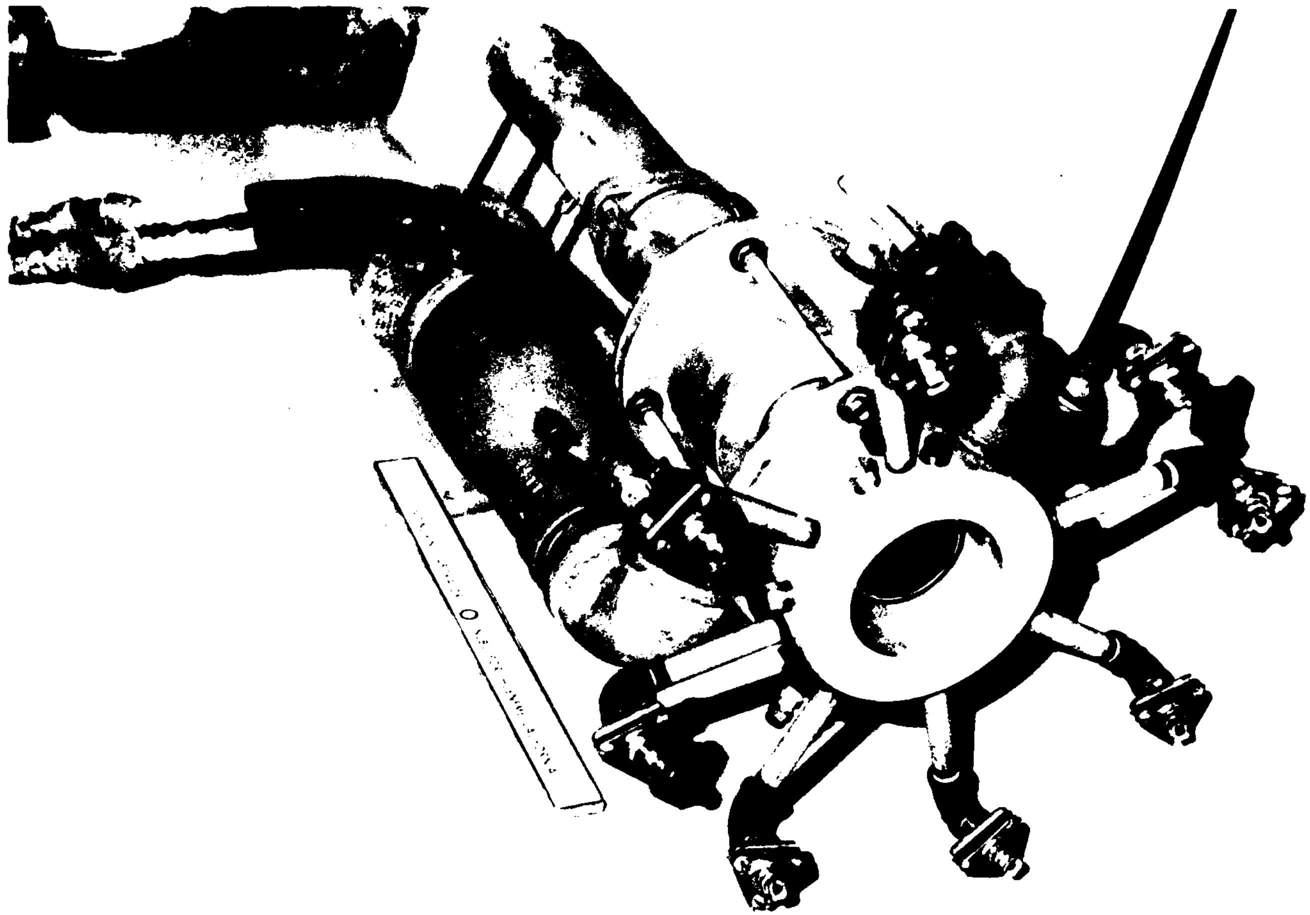


Figure 4. Jet dredge tool with attached plenum.

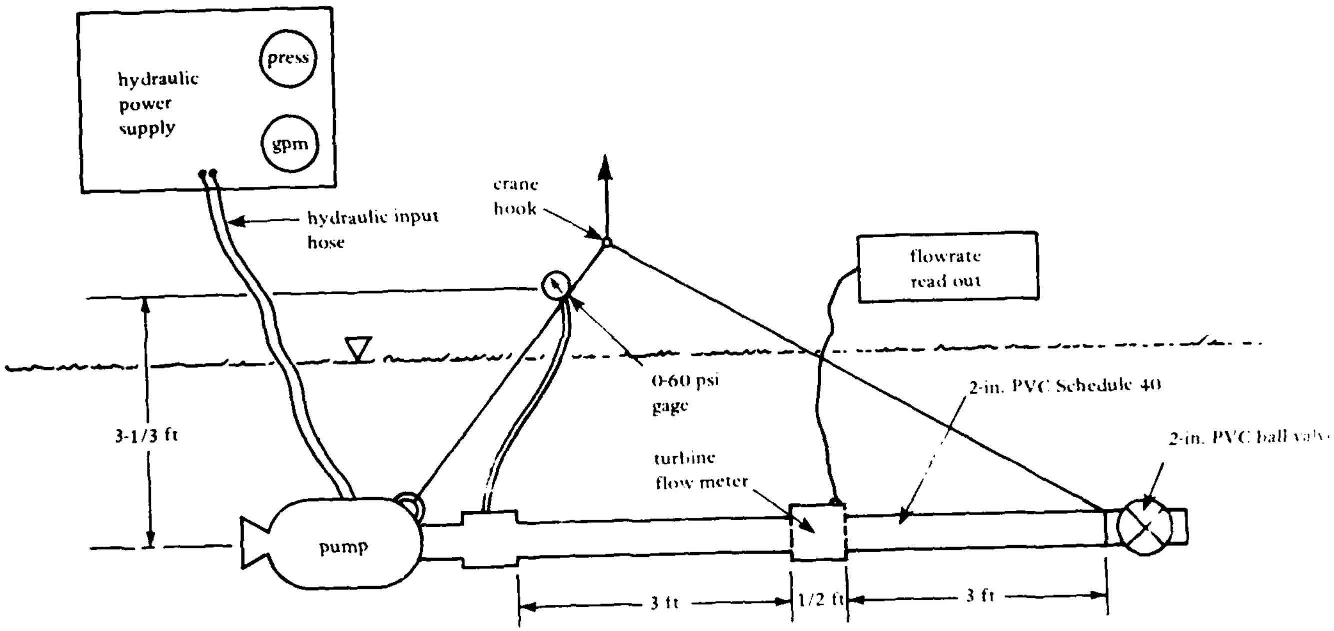


Figure 5. Test set up for the submersible hydraulic pumps.

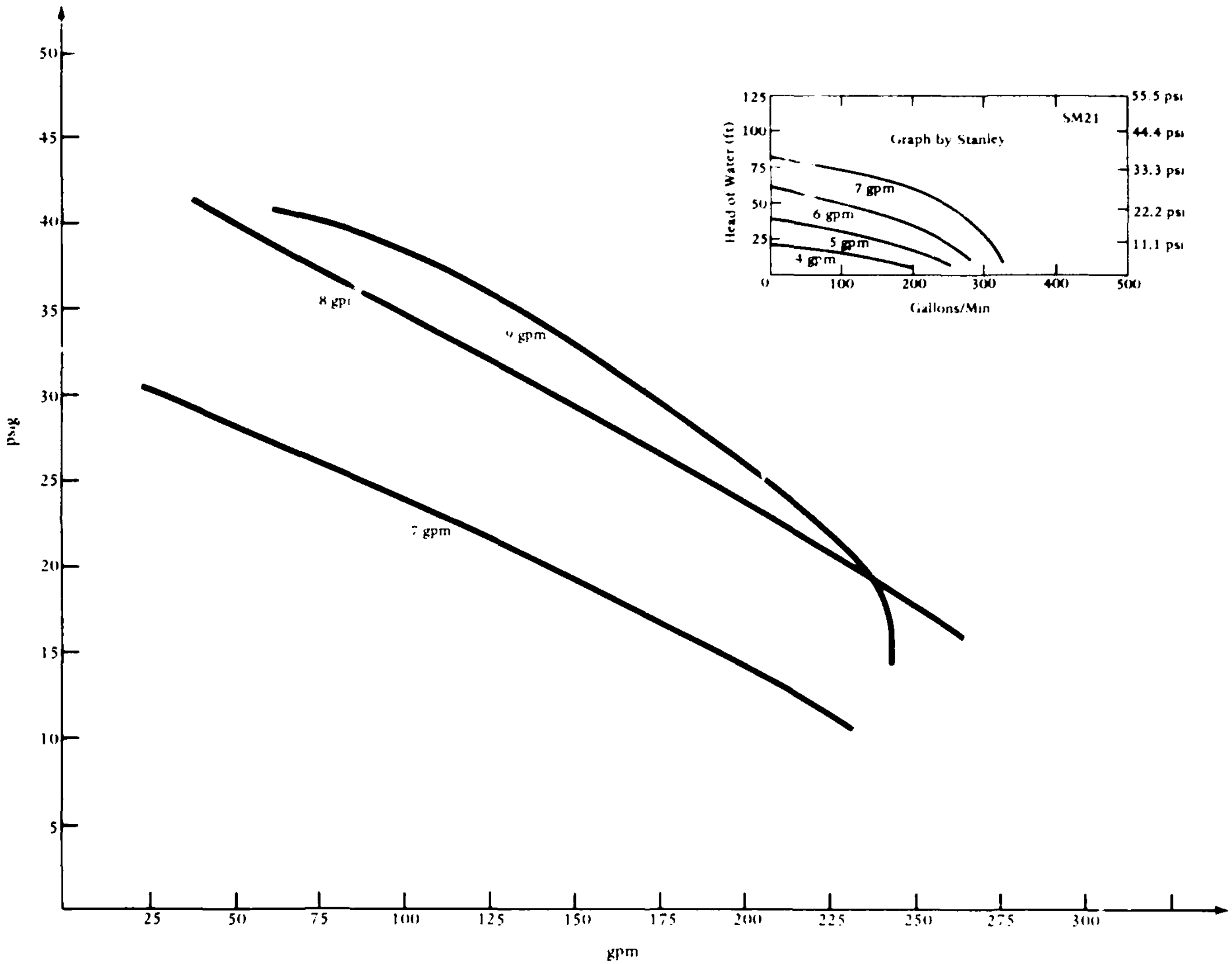


Figure 6. Stanley SM21 hydraulic pump: Water flow versus pump pressure.

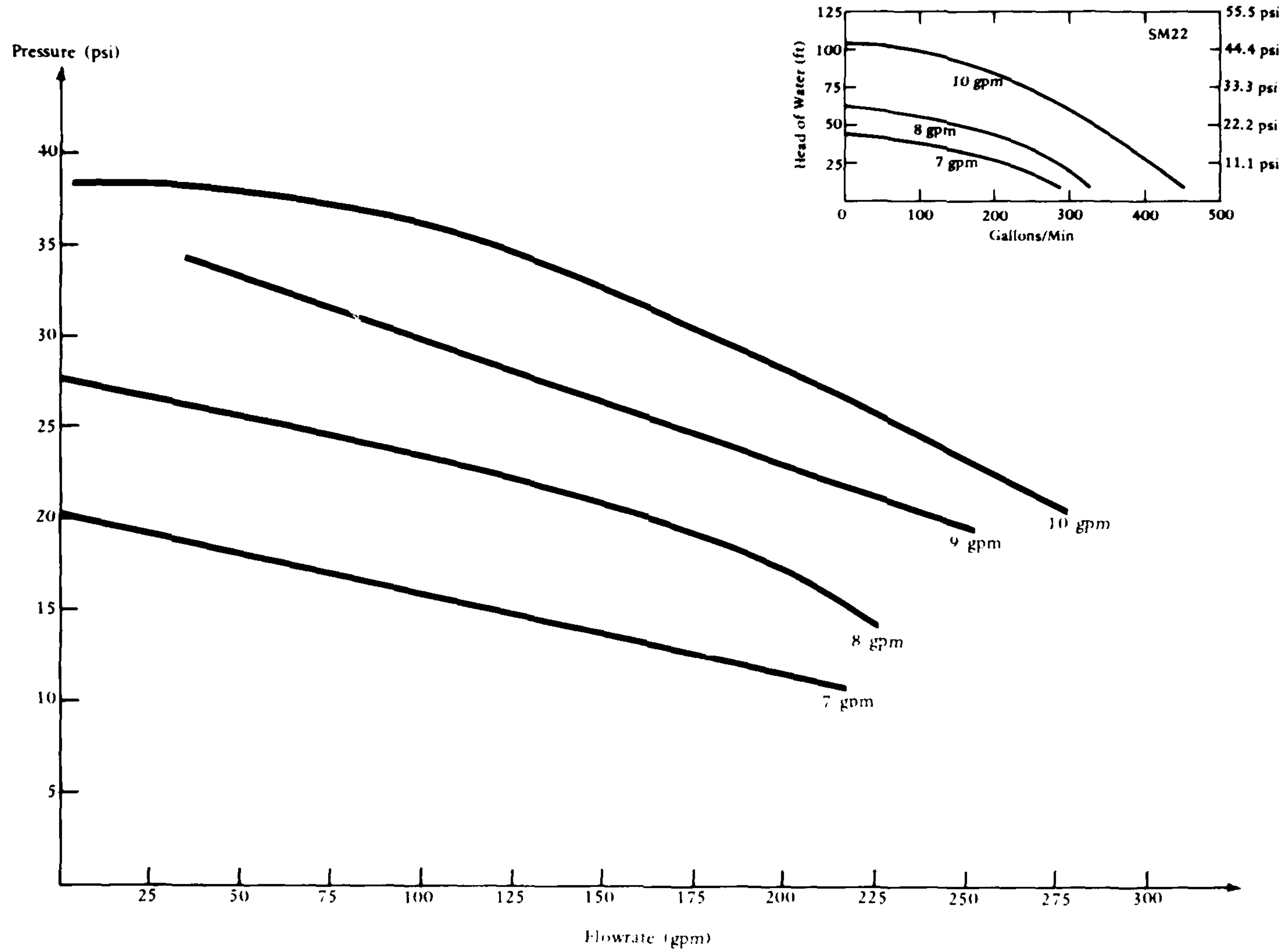


Figure 7. Stanley SM22 hydraulic pump: Water flowrate versus pump pressure.

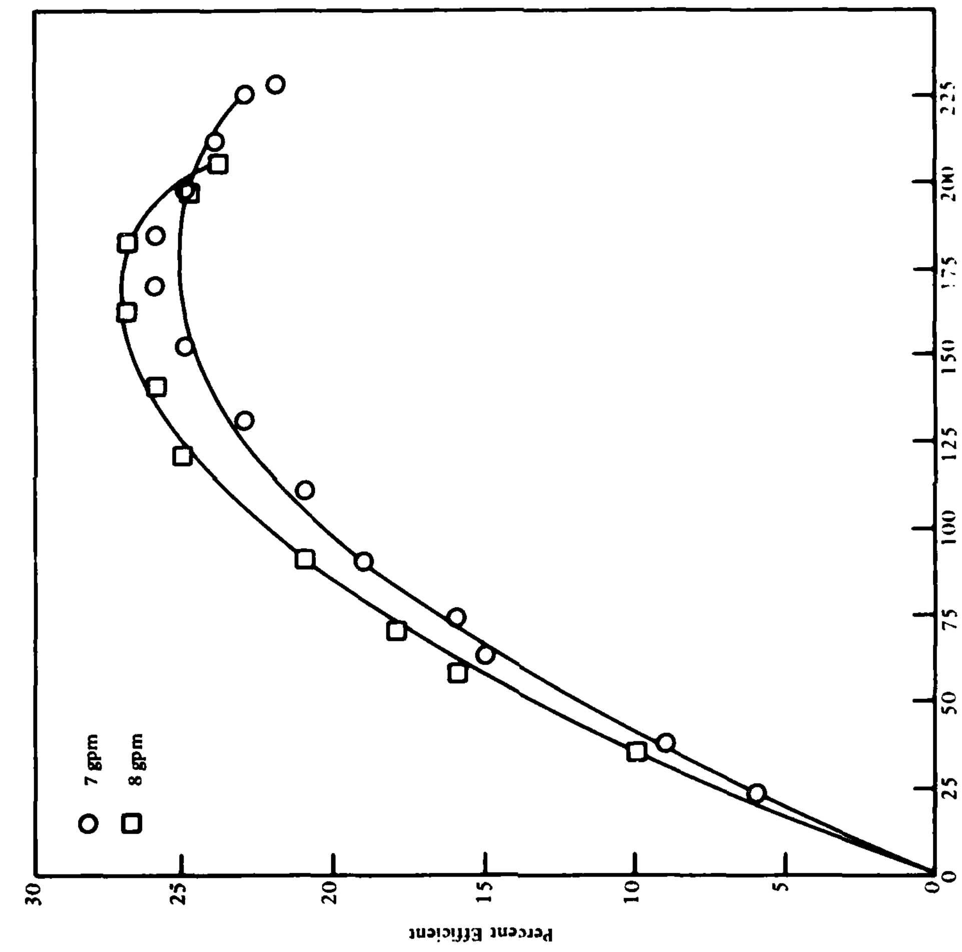


Figure 8 SM21 efficiency

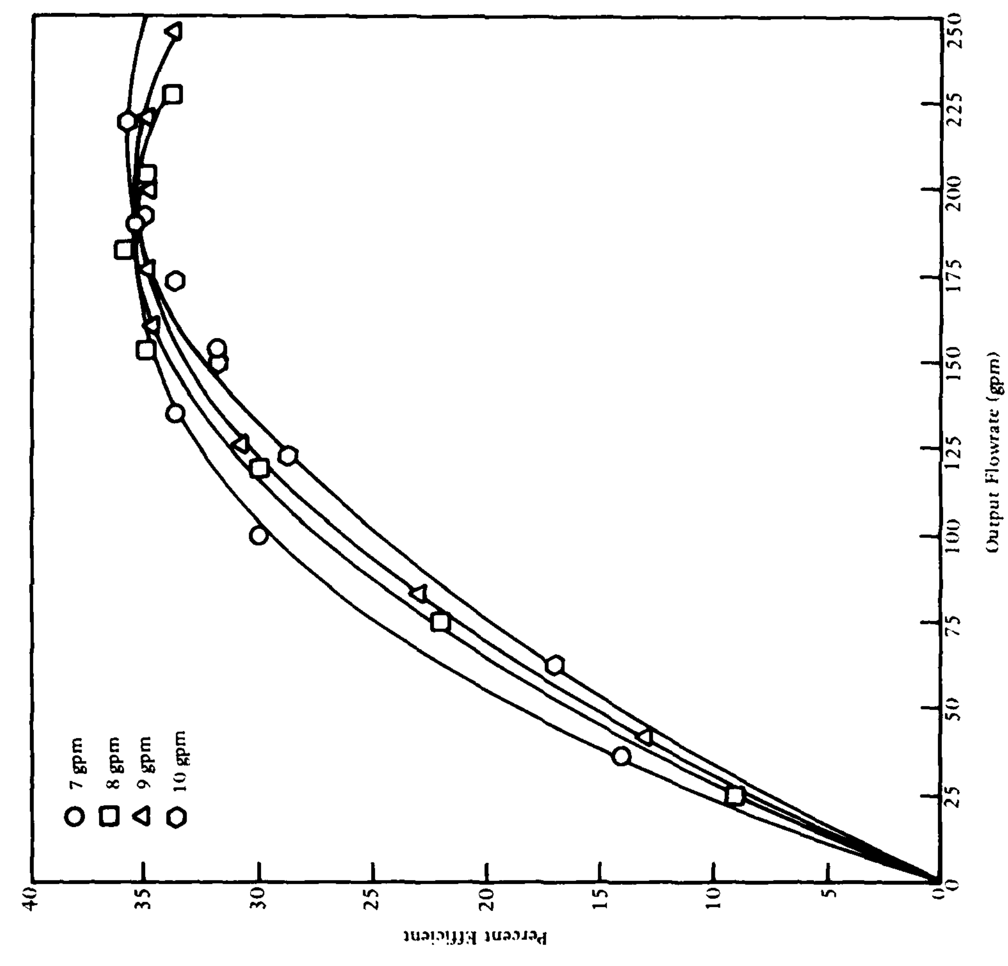


Figure 9. SM22 efficiency

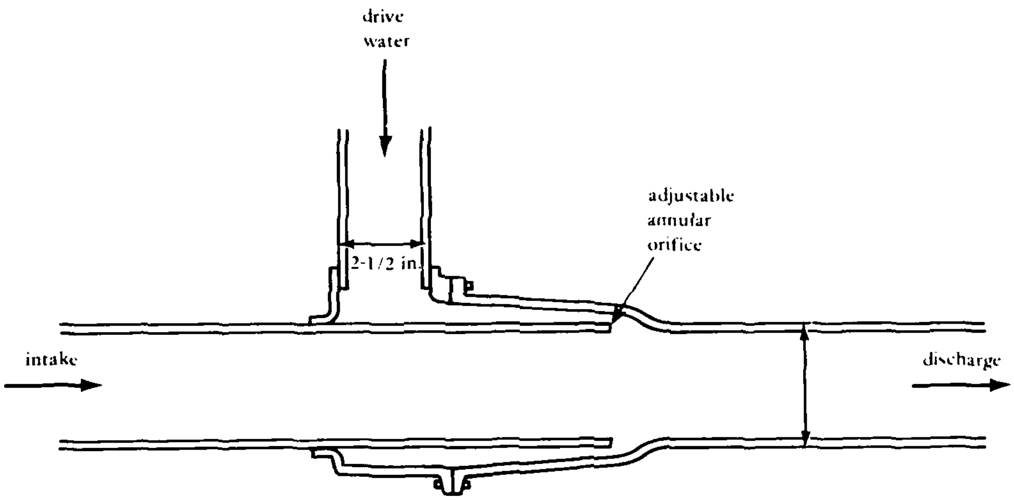


Figure 10. Gold Divers jet pump schematic.

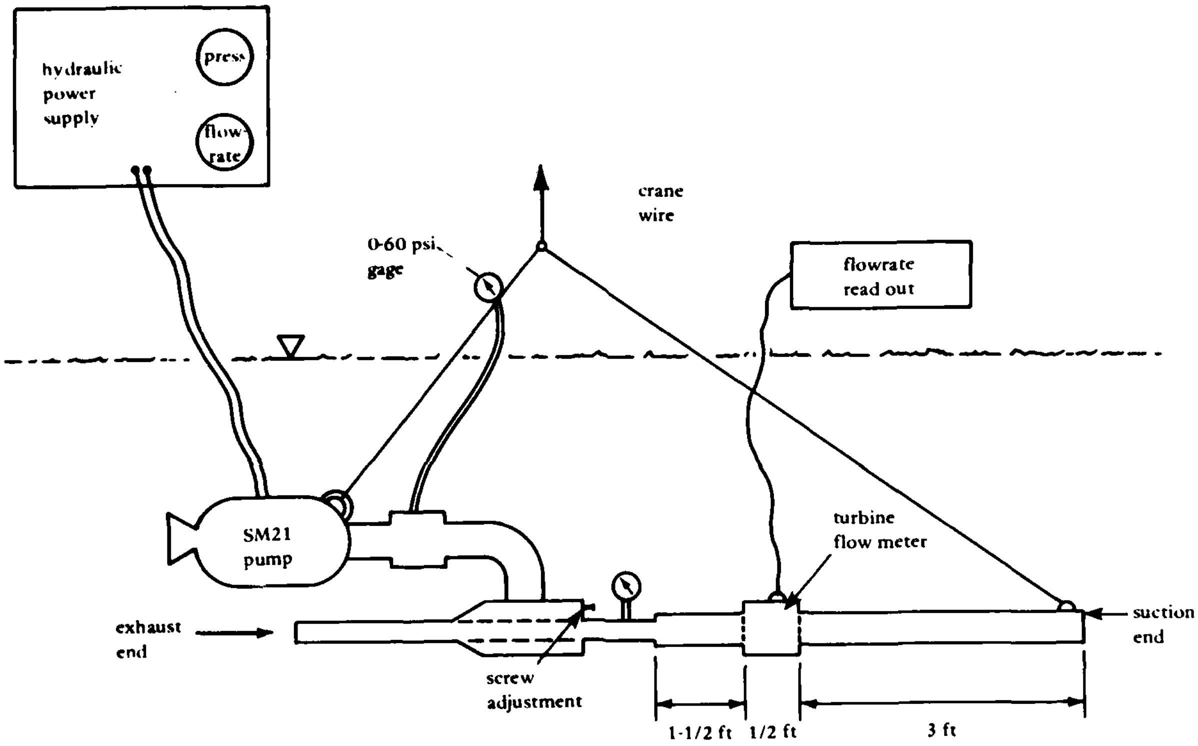


Figure 11. Eductor test set up.

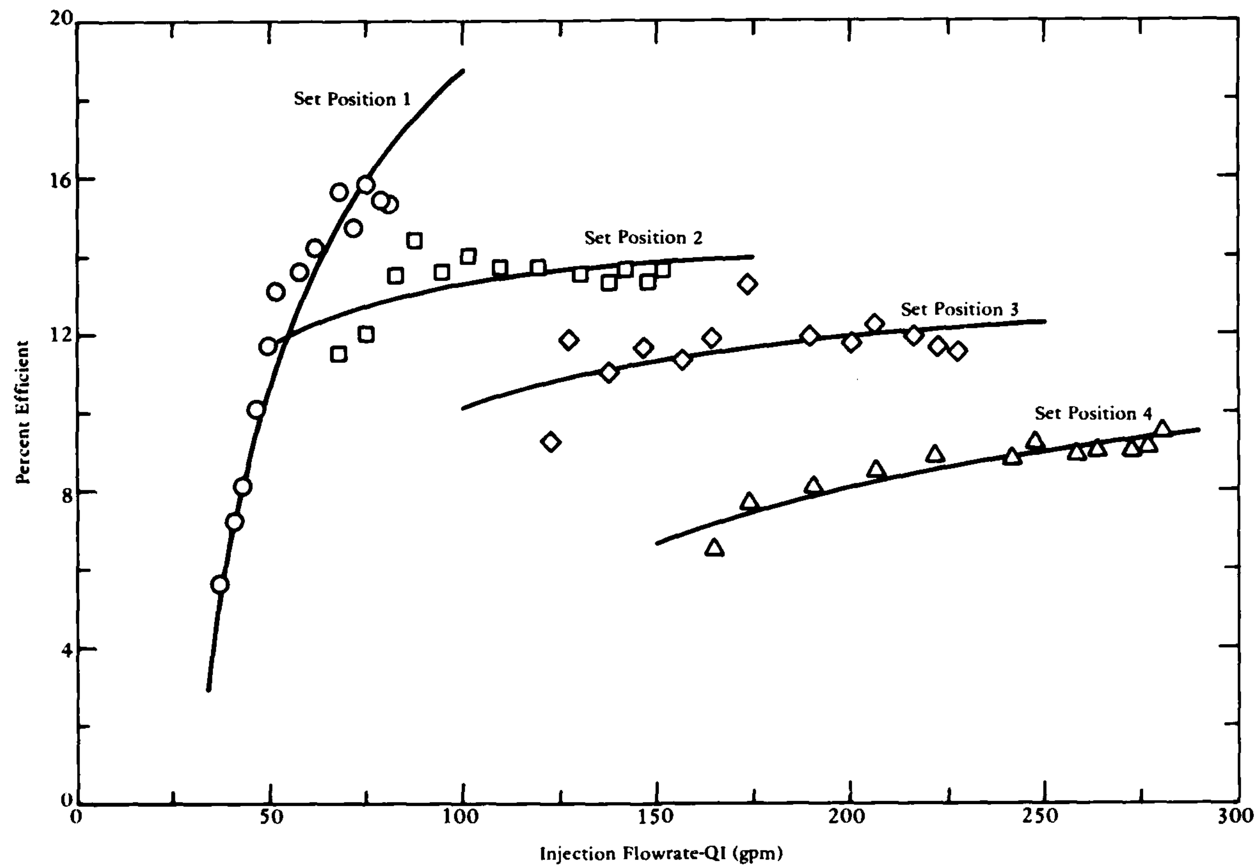


Figure 12. Eductor performance analysis: Injected flowrate versus efficiency.

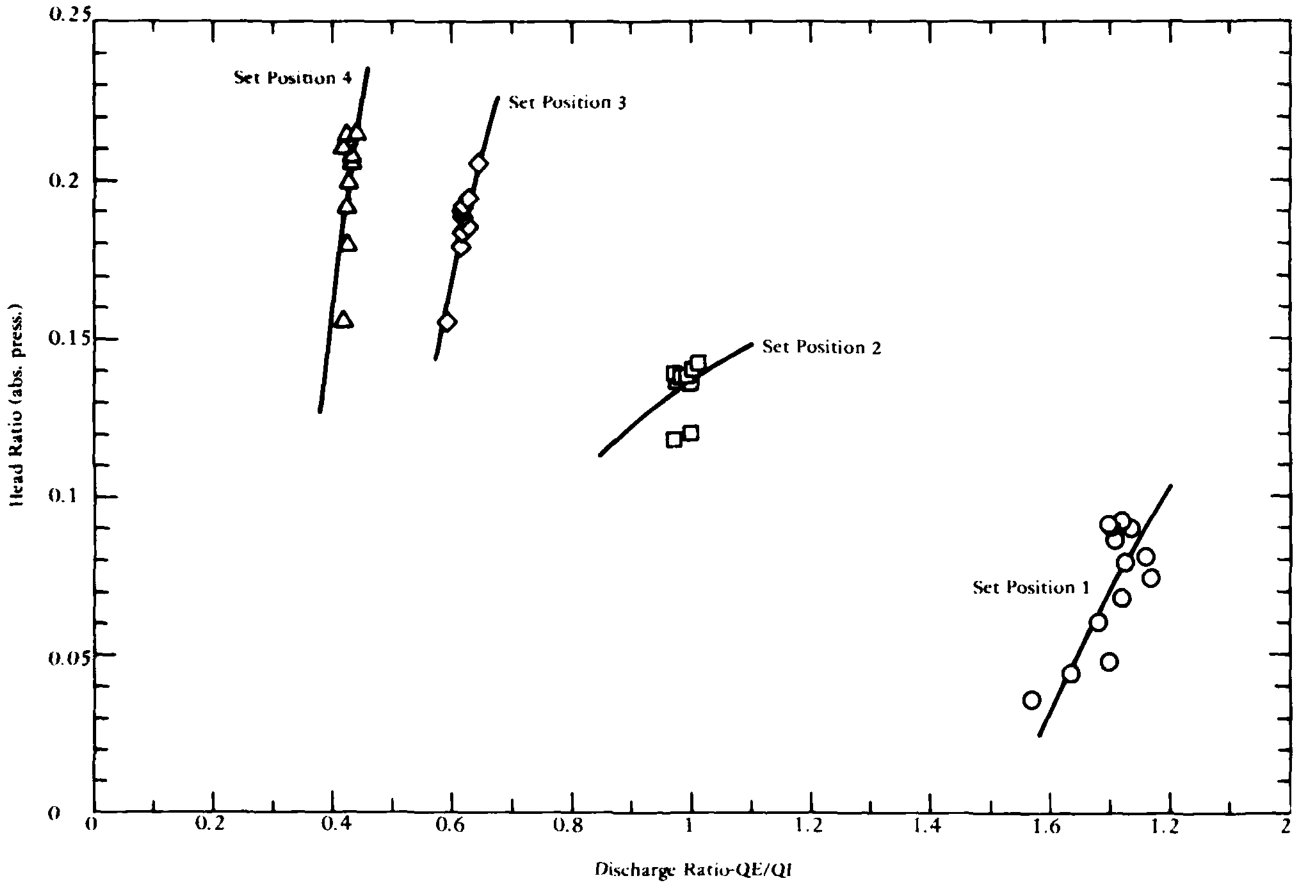


Figure 13. Eductor performance analysis: Discharge ratio versus head ratio.

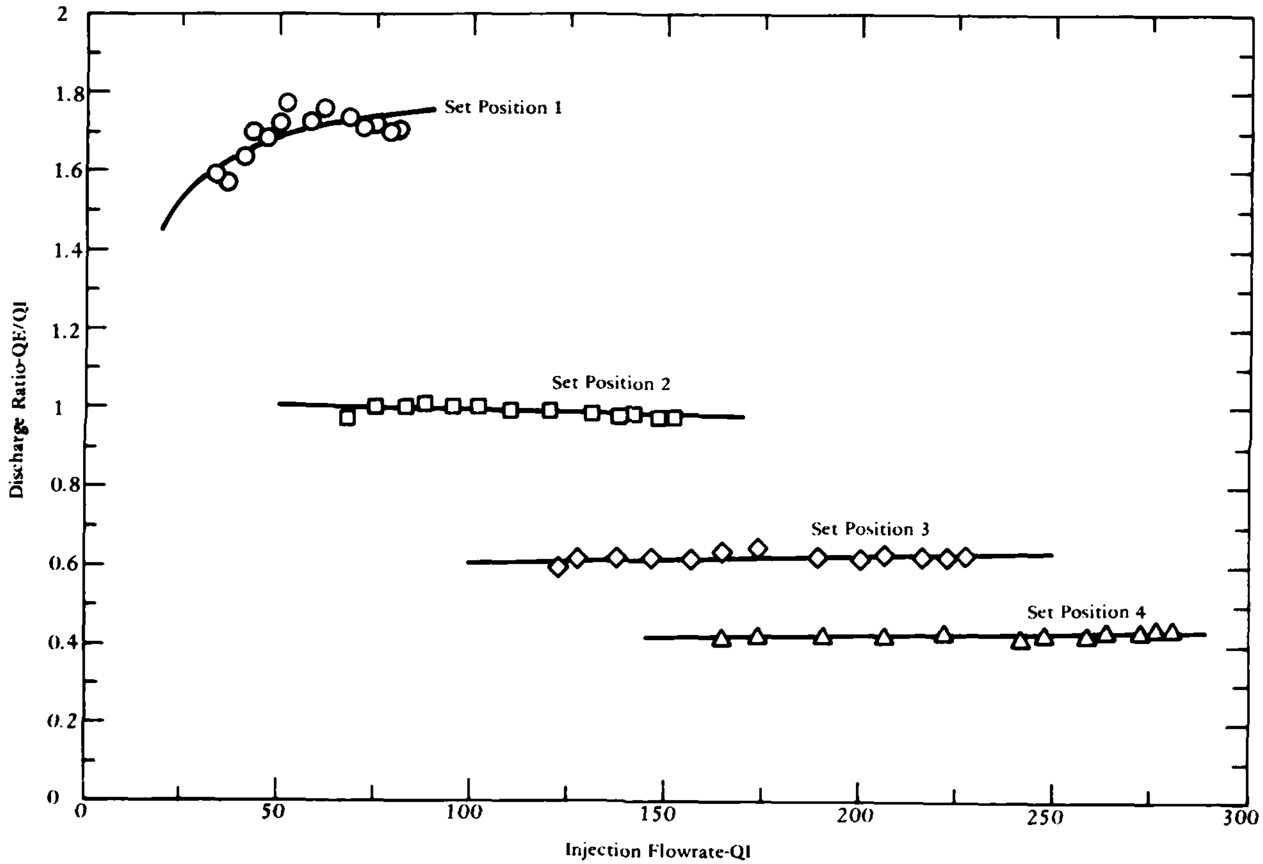


Figure 14. Eductor performance analysis: Injected flowrate versus discharge ratio.

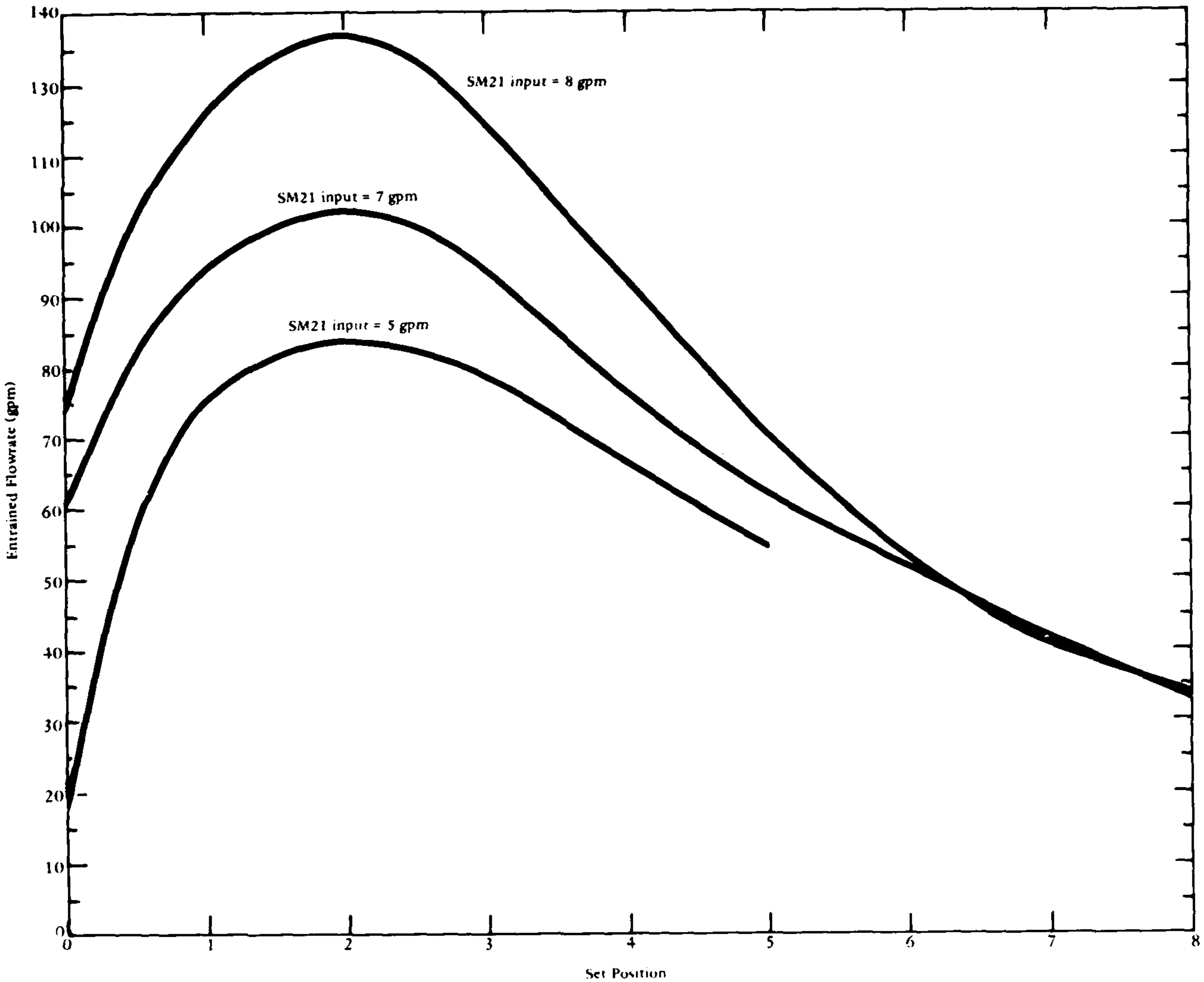


Figure 15. Eductor performance analysis: Set position versus entrained flowrate.

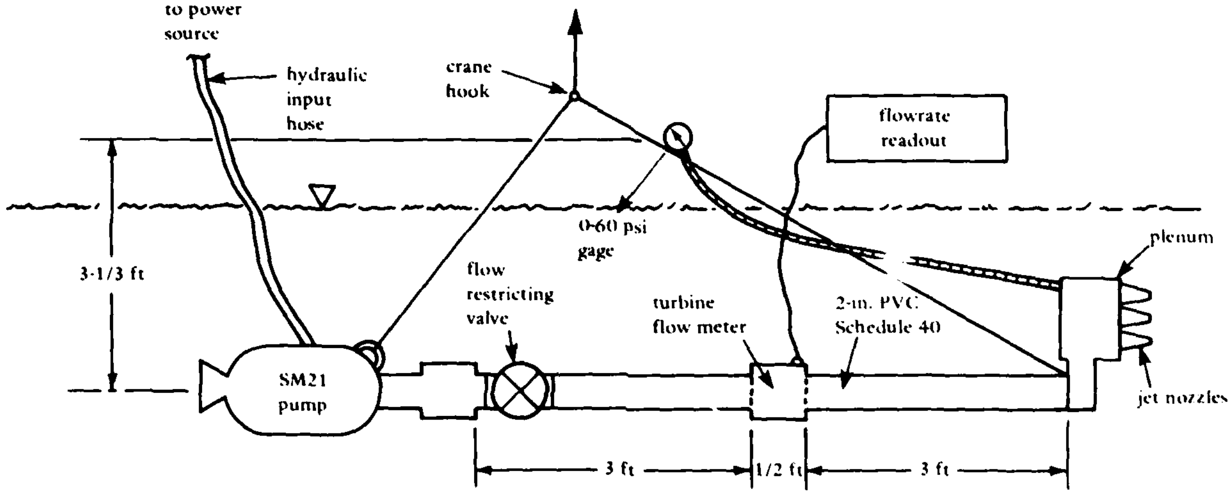


Figure 16. Test set up for jet nozzle assemblies.

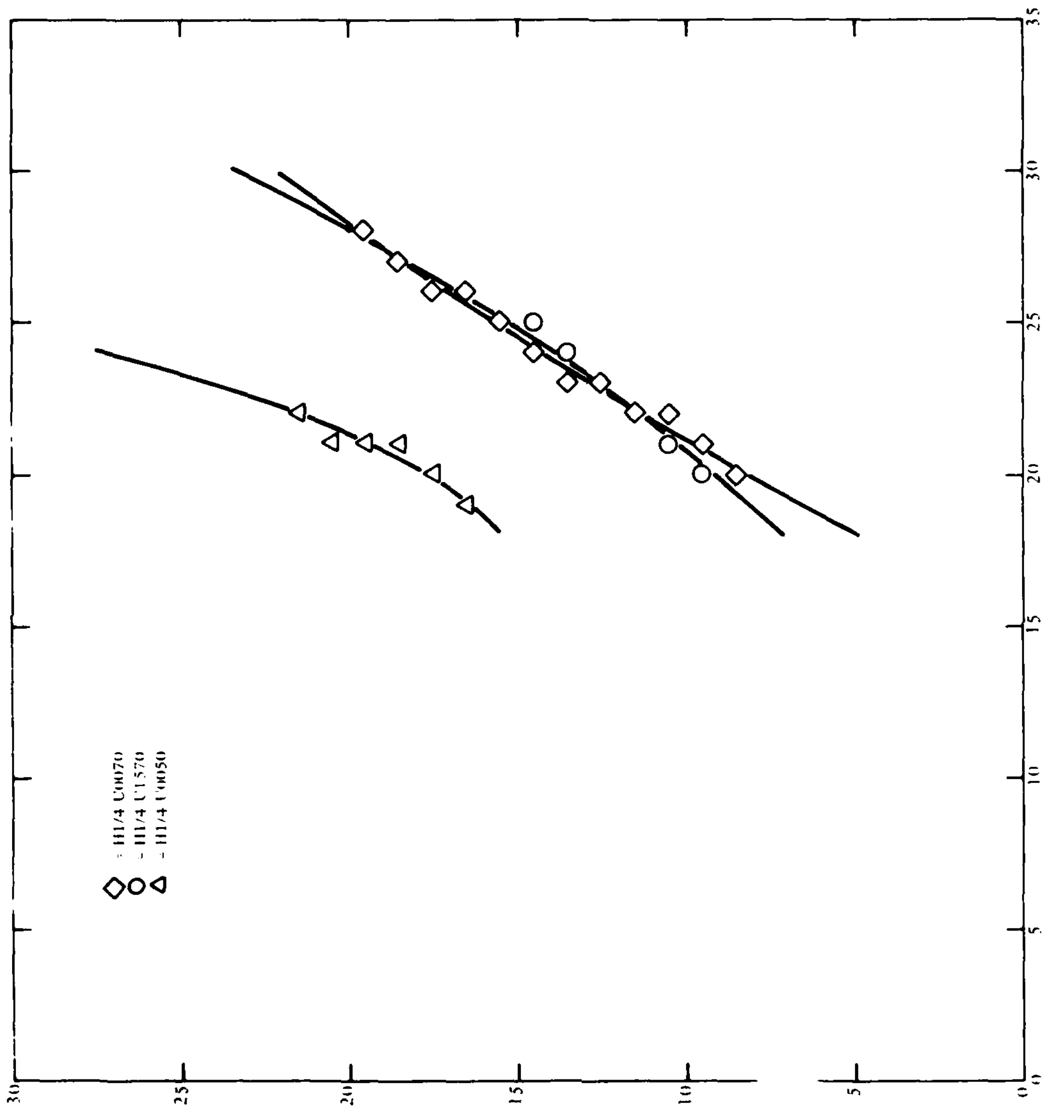


Figure 17. Veejet nozzle characteristics: 6 jets.

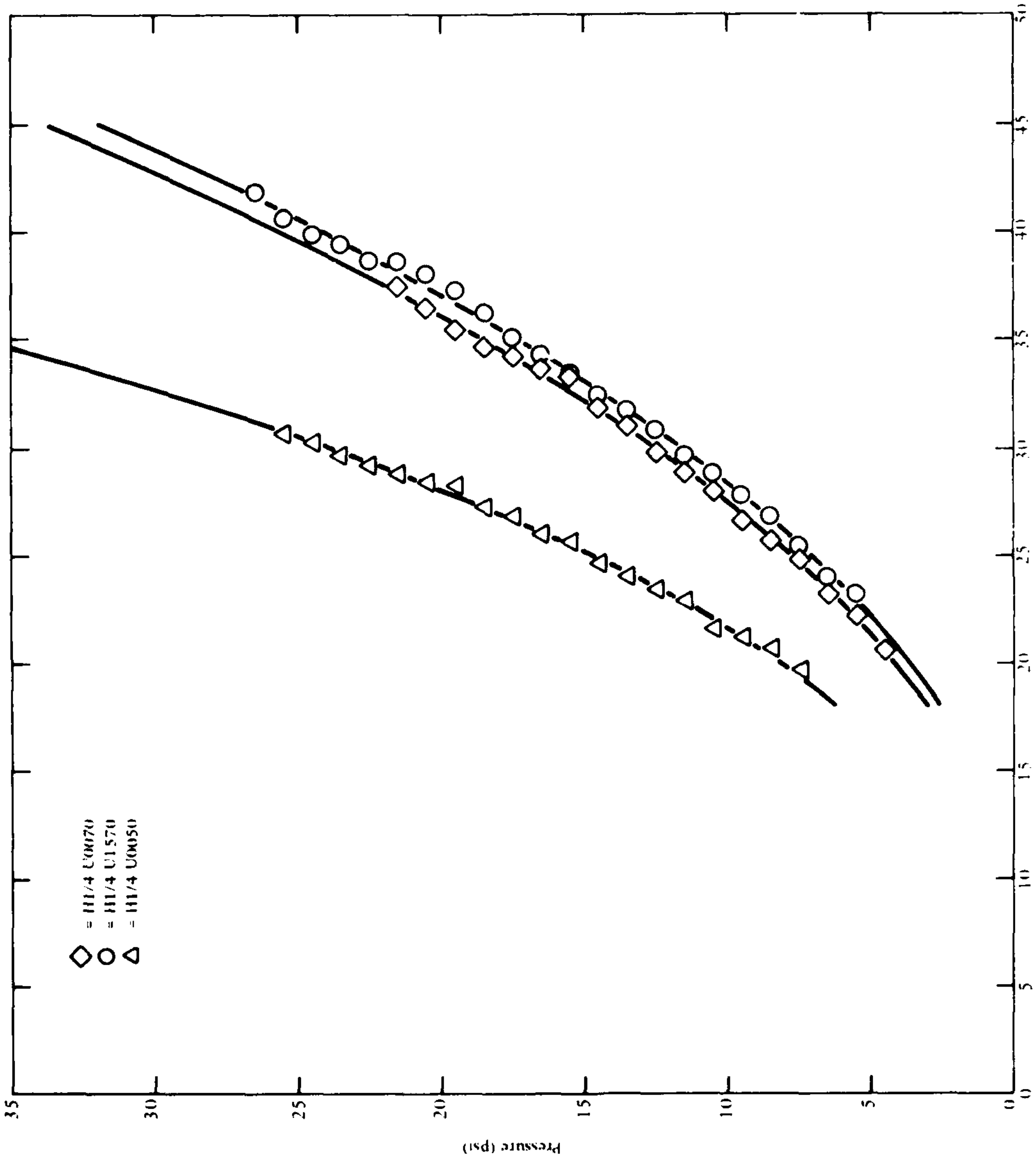


Figure 18 Veejet nozzle characteristics 8 jets

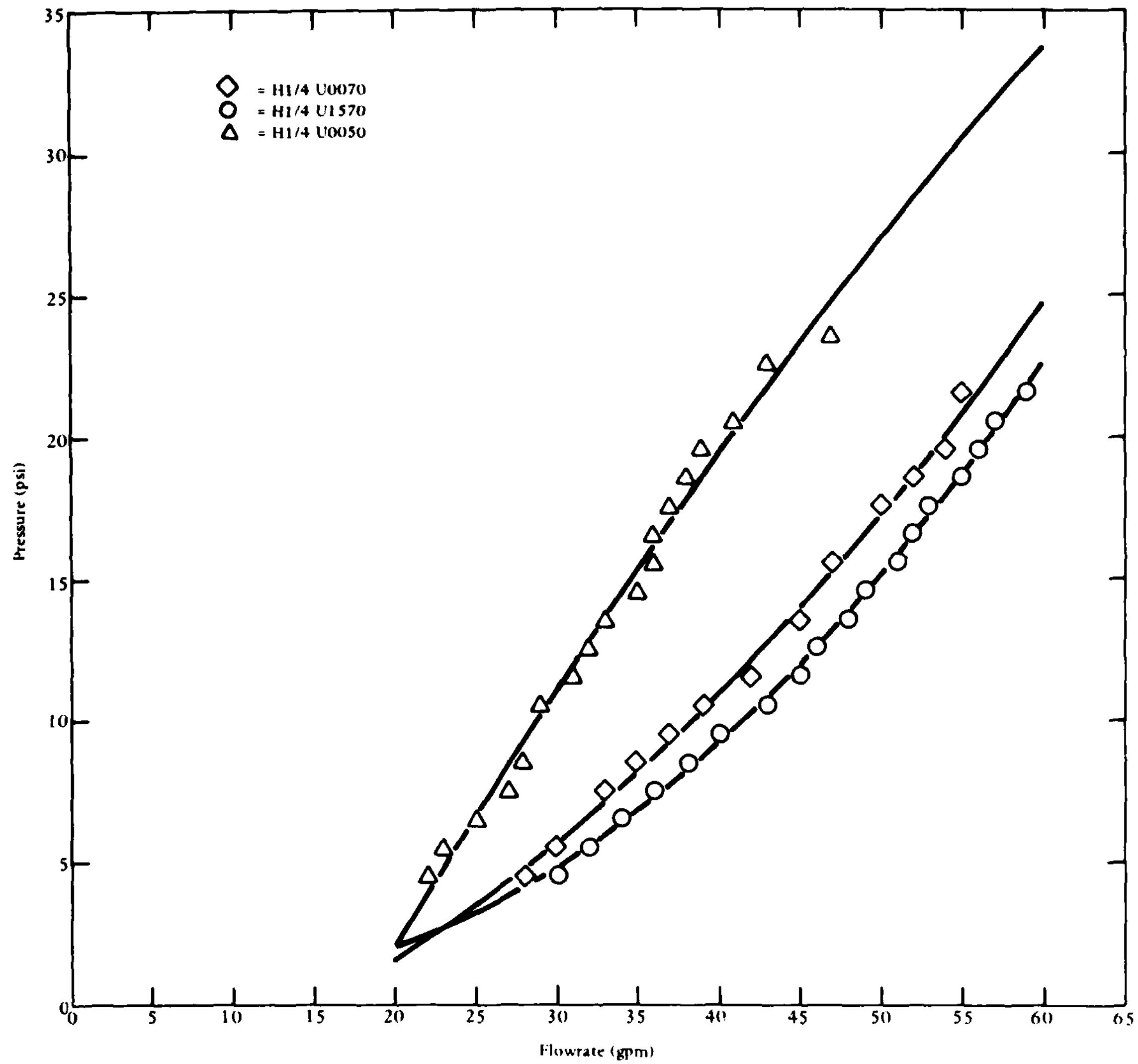


Figure 19. Veejet nozzle characteristics: 12 jets.

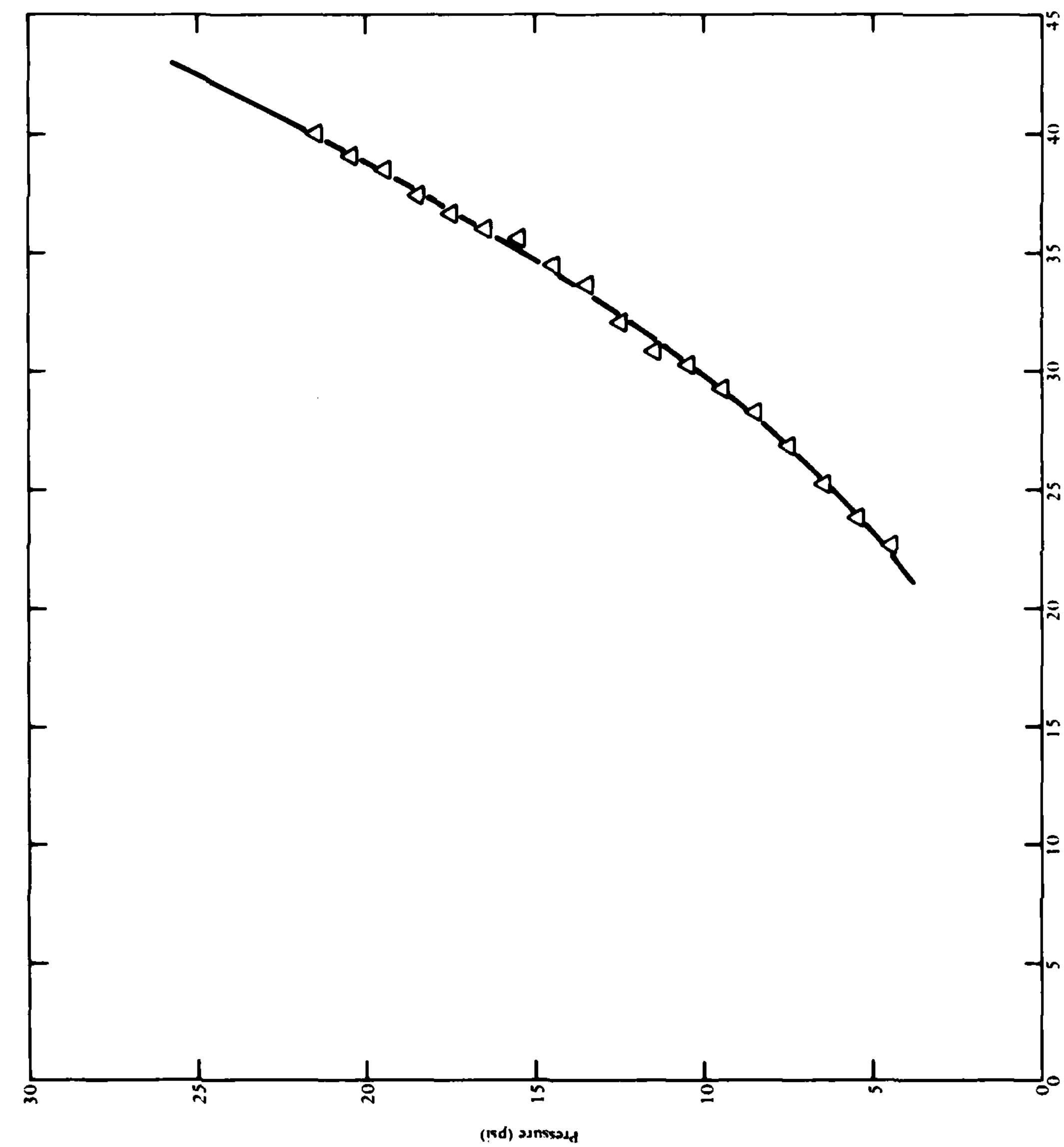


Figure 20. Veejet nozzle (H1/2 U00150) characteristics: 4 jets.

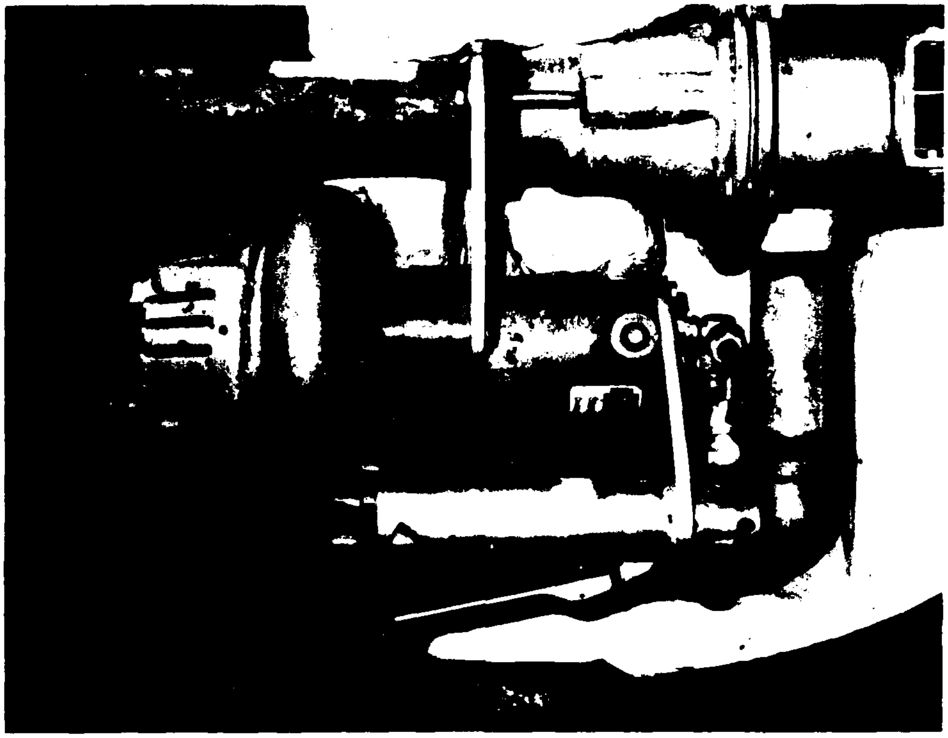


Figure 21. Handle-switch assembly.

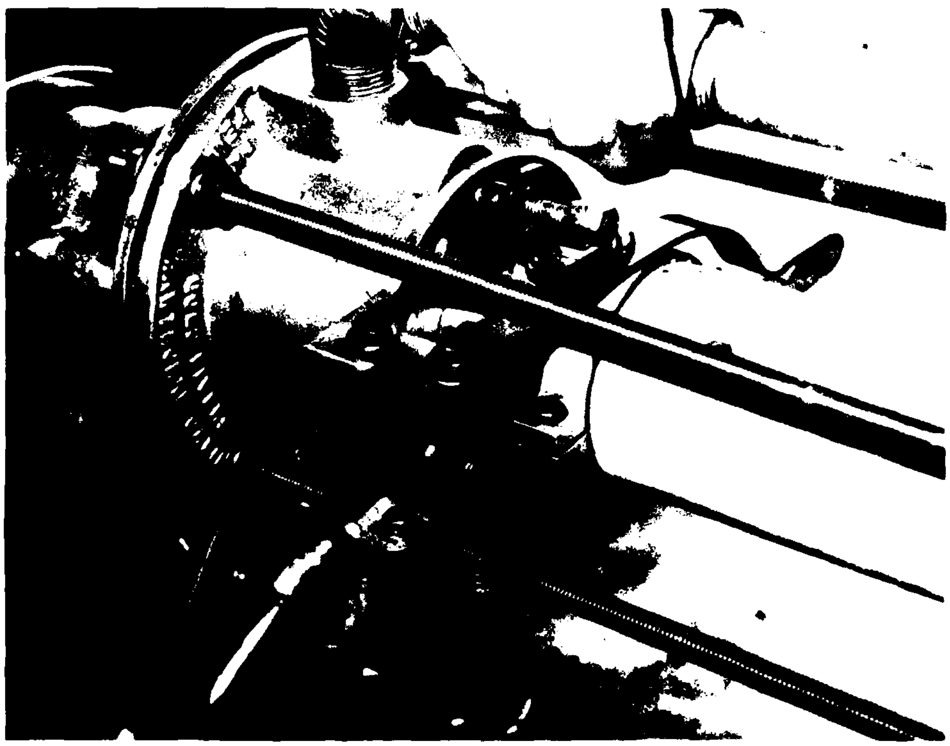


Figure 22. Debris ejector.

Figure 23. Buoyancy package.

Figure 24. Tool with long front end.

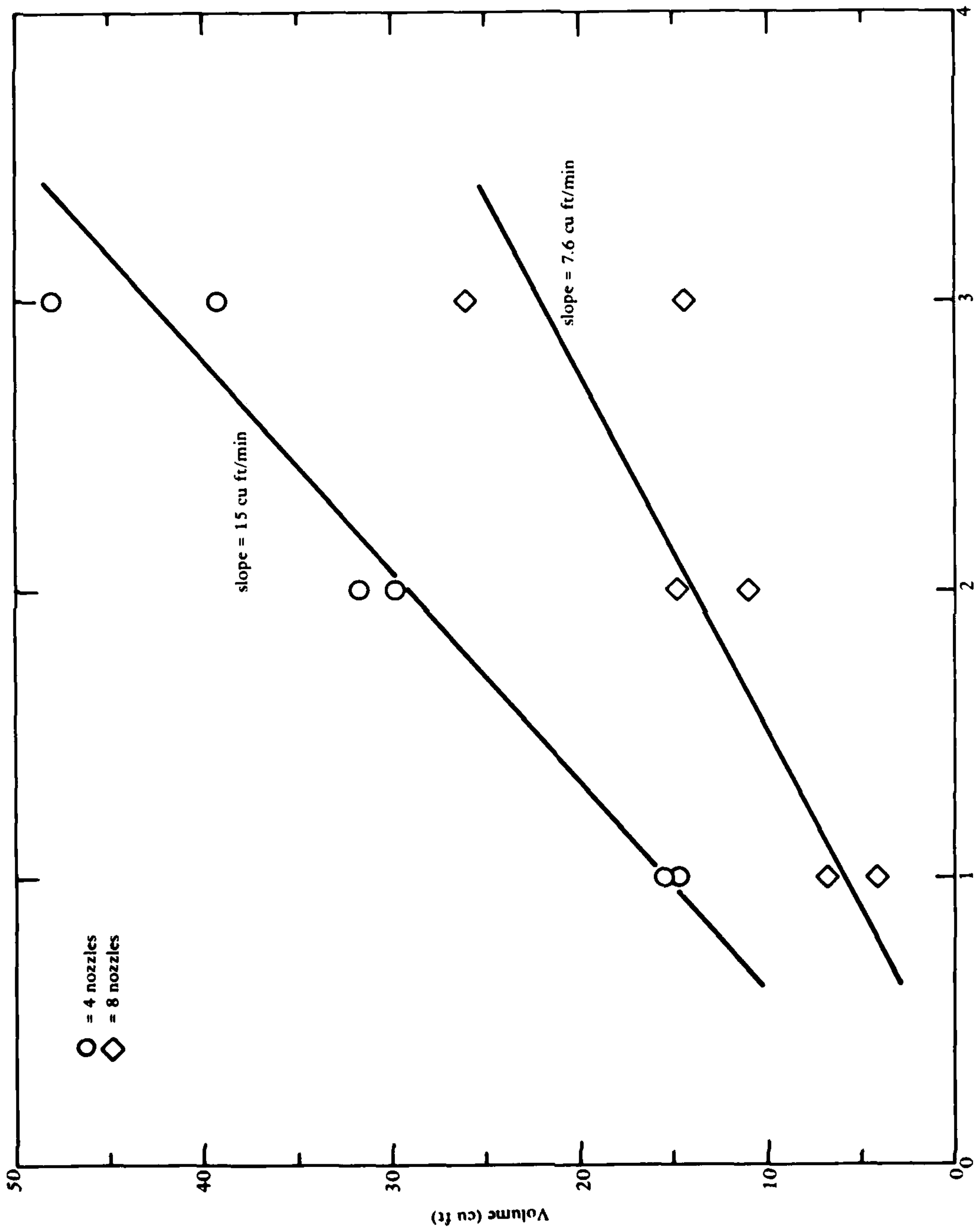


Figure 25. Excavation test at Anacapa Island.

Figure 26. Diver using tool under water.

Appendix A

SYSTEM INTEGRATION TEST RESULTS

PUMP: SM21
NOZZLE ASSEMBLY: H 1/4 U0050- 12 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	23.5	52.1	42.4	116	13	24	7.2
	2	18.4	46.1	33.2	127	12	27	3.6
	3	12.3	37.6	22.1	116	12	24	1.1
8	1	29.4	58.2	52.9	128	14	23	9.1
	2	22.5	50.9	40.5	135	13	25	4.6
	3	14.7	41.2	26.5	126	12	22	1.4
9	1	34.5	63.0	62.1	136	14		10.9
	2	26.8	55.6	48.2	146	12		5.6
	3	15.9	42.8	28.6	131	12		1.4

PUMP: SM22
NOZZLE ASSEMBLY: H 1/4 U0050- 12 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	16.7	43.9	30.1	98	11	28	5.0
	2	14.3	40.6	25.8	109	12	34	2.7
	3	9.9	33.8	17.8	103	12	34	.9
8	1	22.9	51.4	41.3	114	13	30	7.0
	2	19.6	47.5	35.3	127	12	35	3.9
	3	13.7	39.7	24.7	122	12	34	1.1
9	1	28.5	57.3	51.3	126	14	30	8.8
	2	24.0	52.6	43.3	139	13	36	5.0
	3	16.6	43.7	29.9	134	12	33	1.6
10	1	33.2	61.8	59.8	134	14	30	10.5
	2	28.6	57.4	51.5	150	12	36	6.1
	3	18.7	46.4	33.7	141	12	35	2.0

PUMP: SM21
NOZZLE ASSEMBLY: H 1/4 U0050- 8 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	24.6	55.5	46.0	118	13	23	2.6
	2	19.3	49.1	36.1	126	12	27	-1.0
	3	12.9	40.2	24.2	119	12	24	-3.1
8	1	30.9	62.2	57.7	131	14	22	3.5
	2	23.7	54.4	44.3	138	13	25	-1.0
	3	15.5	44.0	29.0	129	12	22	-3.6
9	1	35.9	67.0	67.1	139	14		4.4
	2	28.2	59.4	52.7	149	12		-1.0
	3	17.0	46.1	31.8	135	12		-3.9

PUMP: SM22
NOZZLE ASSEMBLY: H 1/4 U0050- 8 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	17.1	46.2	31.9	99	11	26	1.8
	2	14.8	43.0	27.6	111	12	33	-.9
	3	10.5	36.3	19.7	107	12	34	-2.5
[illegible]	1	23.5	54.2	43.9	116	13	27	2.5
	2	20.3	50.3	37.8	129	12	35	-1.0
	3	14.4	42.5	27.0	125	12	34	-3.4
[illegible]	1	29.3	60.5	54.7	128	14	28	3.3
	2	24.9	55.8	46.5	141	12	35	-1.0
	3	17.5	46.8	32.7	137	12	33	-3.9
10	1	34.0	65.2	63.5	136	14	28	4.1
	* 2	29.5	60.7	55.1	152	12	35	-.9
	3	20.3	50.4	37.9	146	11	35	-4.3

PUMP: SM21
NOZZLE ASSEMBLY: H 1/4 U0070- 12 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	22.5	47.8	38.4	113	13	25	10.9
	2	17.6	42.3	30.0	120	12	27	7.4
	3	11.7	34.5	19.9	113	12	23	4.7
8	1	28.0	53.3	47.7	125	14	24	13.7
	2	21.4	46.6	36.5	132	13	25	9.2
	3	14.0	37.7	23.9	123	12	21	5.6
9	1	33.0	57.9	56.3	134	14		16.3
	2	25.3	50.7	43.1	142	12		11.1
	3	14.7	38.6	25.1	126	12		5.9

PUMP: SM22
NOZZLE ASSEMBLY: H 1/4 U0070- 12 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	16.3	40.6	27.7	96	10	30	7.9
	2	13.9	37.6	23.7	108	12	34	5.8
	3	9.3	30.7	15.9	100	12	34	3.7
8	1	22.3	47.6	38.0	113	13	31	10.8
	2	18.9	43.8	32.3	125	12	36	8.1
	3	12.8	36.0	21.8	118	12	34	5.1
9	1	27.7	53.0	47.2	125	14	32	13.5
	2	23.2	48.5	39.6	137	13	36	10.0
	3	15.6	39.8	26.6	130	12	33	6.3
10	1	32.4	57.3	55.2	133	14	32	16.0
	2	27.6	52.9	47.1	148	12	36	12.3
	3	16.8	41.3	28.6	134	12	35	6.8

PUMP: SM21
NOZZLE ASSEMBLY: H 1/4 U1570- 12 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	22.2	50.7	40.1	113	12	25	13.0
	2	17.3	44.8	31.2	119	12	26	9.4
	3	11.5	36.6	20.8	112	12	23	6.2
8	1	27.6	56.6	49.8	124	14	24	16.2
	2	21.1	49.5	38.1	131	12	25	11.5
	3	13.8	40.0	24.9	122	12	21	7.4
9	1	32.6	61.5	58.8	133	14		19.4
	2	24.9	53.7	44.9	141	12		13.8
	3	14.4	40.9	26.0	125	12		7.7

PUMP: SM22
NOZZLE ASSEMBLY: H 1/4 U1570- 12 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	16.1	43.2	29.1	96	10	30	9.5
	2	13.7	39.9	24.8	107	12	34	7.4
	3	9.1	32.5	16.4	99	12	34	4.9
8	1	22.1	50.7	40.0	112	13	32	12.9
	2	18.7	46.6	33.8	124	12	36	10.2
	3	12.6	38.2	22.7	117	12	34	6.7
9	1	27.4	56.4	49.5	124	14	33	16.2
	2	22.9	51.5	41.3	136	13	36	12.6
	3	15.4	42.3	27.8	129	12	32	8.2
10	1	32.1	61.0	58.0	133	14	32	19.1
	2	27.3	56.3	49.3	147	12	36	15.3
	3	16.2	43.3	29.2	132	12	35	8.8

PUMP: SM21
NOZZLE ASSEMBLY: H 1/2 U00150- 4 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	[illegible]	52.0	42.4	116	13	24	7.0
	2	18.5	46.0	33.2	123	12	27	3.4
	3	[illegible]	37.6	22.1	116	12	24	1.0
8	1	29.5	58.1	53.0	128	14	23	8.9
	2	[illegible]	50.9	40.6	135	13	25	4.3
	3	14.8	41.2	26.6	127	12	22	1.1
9	1	34.5	62.9	62.0	136	14		10.7
	2	26.8	55.4	48.1	146	12		5.4
	3	15.9	42.7	28.6	131	12		1.3

PUMP: SM22
NOZZLE ASSEMBLY: H 1/2 U00150- 4 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	16.7	43.7	30.0	98	11	[illegible]	4.9
	2	14.4	40.6	25.8	109	12	[illegible]	
	3	9.9	33.7	17.8	104	12	[illegible]	.8
8	1	22.9	51.3	41.2	114	[illegible]	[illegible]	[illegible]
	2	19.6	47.4	35.2	127	12		[illegible]
	3	13.7	39.6	24.6	122	12		1.0
9	1	28.5	57.2	51.2	126	14	30	6.6
	2	24.1	52.6	43.3	139	13	[illegible]	.7
	3	16.6	43.6	29.8	134	12		[illegible]
10	1	33.2	61.7	59.7	134	14		10.3
	* 2	28.6	57.3	51.4	150	12		[illegible]
	3	18.8	46.4	33.8	141	12		[illegible]

PUMP: SM21
NOZZLE ASSEMBLY: H 1/4 U1570- 8 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	23.8	51.9	42.5	116	13	24	5.9
	2	18.7	46.0	33.4	124	12	27	2.7
	3	12.5	37.6	22.3	117	12	24	-.1
8	1	29.8	58.1	53.3	129	14	23	7.6
	2	22.8	50.8	40.7	136	13	25	3.1
	3	14.9	41.1	26.6	127	12	22	.1
9	1	34.8	62.8	62.2	137	14		9.2
	2	27.1	55.4	48.4	146	12		3.9
	3	16.1	42.7	28.8	132	12		.1

PUMP: SM22
NOZZLE ASSEMBLY: H 1/4 U1570- 8 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-lb
7	1	16.8	43.6	30.0	98	11	27	4.1
	2	14.5	40.5	25.8	110	12	34	1.7
	3	10.1	33.8	18.1	105	12	34	-.0
8	1	23.1	51.2	41.3	115	13	29	5.7
	2	19.8	47.4	35.4	127	12	35	2.5
	3	13.9	39.7	24.8	123	12	34	-.1
9	1	28.7	57.0	51.3	127	14	30	7.3
	2	24.3	52.5	43.4	140	13	35	3.3
	3	16.8	43.6	30.0	134	12	33	.2
10	1	33.4	61.5	59.7	135	14	30	8.7
	* 2	28.8	57.1	51.5	150	12	36	4.3
	3	19.1	46.5	34.1	142	11	35	.4

PUMP: SM21
NOZZLE ASSEMBLY: H 1/4 U0070- 8 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-1b
7	1	23.8	51.6	42.3	116	13	24	5.8
	2	18.7	45.8	33.2	124	12	27	2.2
	3	12.5	37.4	22.2	117	12	24	-.2
8	1	29.8	57.8	53.0	129	14	23	7.4
	2	22.9	50.6	40.7	136	13	25	2.8
	3	14.9	40.9	26.5	127	12	22	-.0
9	1	34.8	62.4	61.9	137	14		9.0
	2	27.1	55.1	48.2	146	12		3.7
	3	16.2	42.6	28.8	132	12		-.1

PUMP: SM22
NOZZLE ASSEMBLY: H 1/4 U0070- 8 NOZZLES

GPM INPUT	EDUCT SETNG	SYSTEM PSI	NOZZLE VEL-ft/s	STAGN PSI	ENTRAINED FLOW-GPM	EDUCTOR % EFF.	PUMP % EFF.	REACTION FORCE-1b
7	1	16.8	43.4	29.9	98	11	27	4.0
	2	14.5	40.3	25.8	110	12	34	1.6
	3	10.1	33.6	18.0	105	12	34	-.1
8	1	23.1	50.9	41.1	115	13	29	5.6
	2	19.8	47.1	35.2	127	12	35	2.4
	3	13.9	39.5	24.7	123	12	34	-.2
9	1	28.7	56.7	51.0	127	14	30	7.1
	2	24.3	52.2	43.2	140	13	35	3.1
	3	16.8	43.4	29.9	134	12	33	.1
10	1	33.4	61.2	59.4	135	14	30	8.5
	* 2	28.8	56.8	51.2	150	12	36	4.1
	3	19.2	46.4	34.1	143	11	35	.2

Appendix B

REACTION FORCE ANALYSIS

Figure B-1 presents a diagram of the reaction force.

Momentum Equation for Inertial Control Volume:

$$\overline{F} = \overline{F}_s + \overline{F}_B = \frac{\partial}{\partial t}\int_{CV} \overline{V}\rho d\forall + \int_{CS} \overline{V}\rho\overline{V}\cdot d\overline{A}$$

($\overline{F}_B$ = 0 (in X direction); $\frac{\partial}{\partial t}\int_{CV}$ = 0 (steady flow))

where F_s = surface forces

F_B = body forces

V = fluid velocity

ρ = fluid density

∀ = control volume

A = control surface area

CV = control volume

CS = control surface

The X-component of the Momentum Equation reduces to:

$$R_x = \int_{cc} V\rho\overline{V}\cdot d\overline{A}$$

$$= \int_{A_1} V\rho\overline{V}\cdot d\overline{A} + \int_{A_2} V\rho\overline{V}\cdot d\overline{A} + \int_{A_3} V\rho\overline{V}\cdot d\overline{A} \int_{A_4} V\rho\overline{V}\cdot d\overline{A}$$

now $\overline{V}\cdot d\overline{A}$ is negative at 1

$\overline{V}\cdot d\overline{A}$ is positive at 2

$\overline{V}\cdot d\overline{A}$ is negative at 3

$\overline{V}\cdot d\overline{A}$ is positive at 4

Hence,

$$R_x = -V_1 \,/\, \rho VA \,/_1 + V_2 \,/\, \rho VA \,/_2 - V_3 \,/\, \rho VA \,/_3 + V_4 \,/\, \rho VA \,/_4 .$$

or,

$$R_x = -V_1 \,/\, \rho Q \,/_1 + V_2 \,/\, \rho Q \,/_2 - V_3 \,/\, \rho Q \,/_3 + V_4 \,/\, \rho Q \,/_4$$

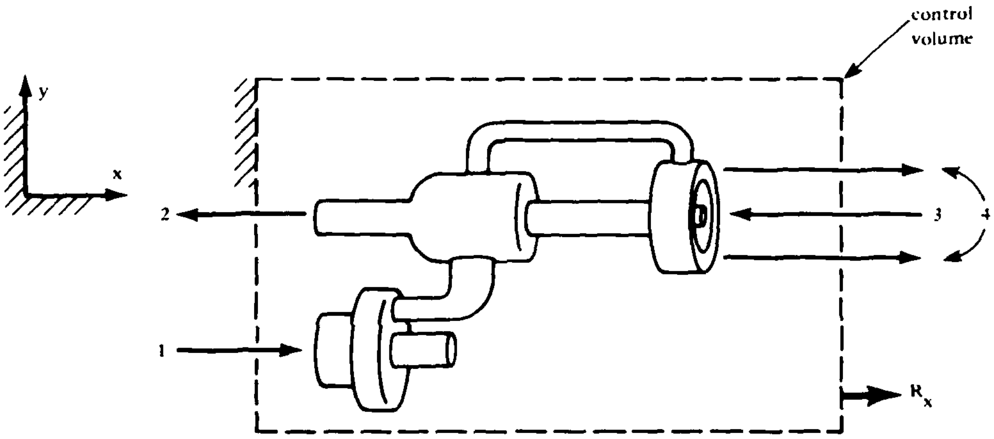


Figure B-1. Reaction force diagram.

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