PROCEDURES AND DEVICES FOR UNDERWATER CLEANING OF CIVIL WORKS STRUCTURES

by

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GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

For example, Technical Report REMR-CS-8 is the eighth report published under the Concrete and Steel Structures problem area.

COVER PHOTOS:

TOP—Whirl Away Rotary cleaning tool.

BOTTOM—Jetin high pressure, high flow waterjet tool.
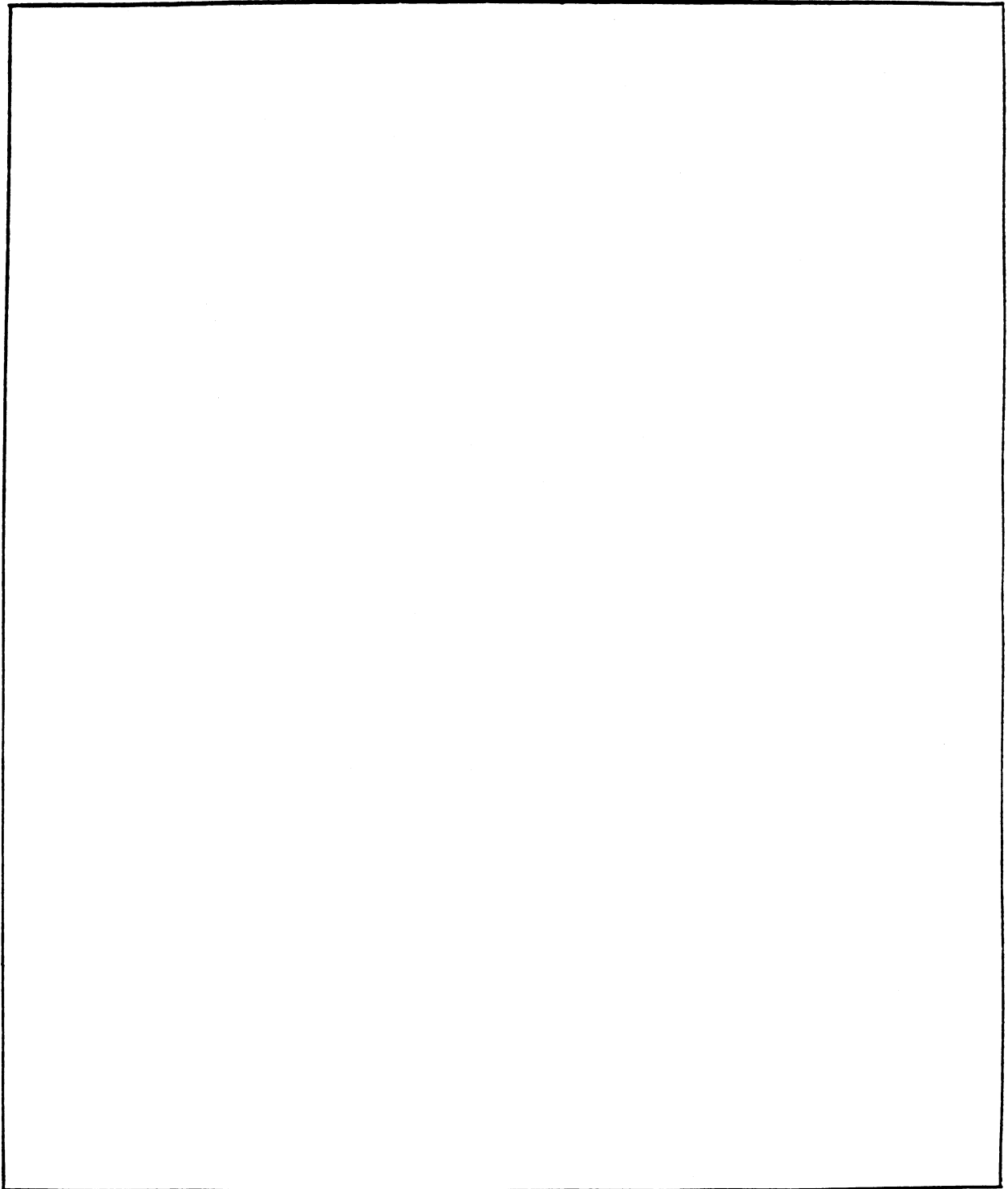
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Civil works structures must be continually evaluated for structural safety, stability, and operational adequacy. Proper inspection and evaluation of them to identify deficiencies will usually require some type of cleaning of the structure. A wide variety of underwater cleaning tools and methodologies have been developed and are currently in use in the off-shore oil industry and by the US Navy. These tools range from hand-held scrapers to powered tools and high-pressure waterjets. Several tools have been specifically designed for removal of underwater debris. These tools include jet eductors, dredges, and air lifts.

This report summarizes underwater cleaning procedures and devices that are appropriate for use on civil works structures. The application, advantages, disadvantages, and operation of each type of equipment are discussed, along with recommendations for those tools best suited for specific conditions.

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PREFACE

The study reported herein was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), under Civil Works Research Unit 32270, "Underwater Surveying," for which Mr. Henry T. Thornton, Jr., Concrete Technology Division (CTD), Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES), is principal investigator. This work is part of the Concrete and Steel Structures problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The Overview Committee of HQUSACE for the REMR Research Program consists of Mr. John R. Mikel, Mr. Bruce L. McCartney, and Dr. Tony C. Liu. Technical Monitor for this study was Dr. Liu.

The study was performed by the Naval Civil Engineering Laboratory (NCEL) under Intra-Army Order for Reimbursable Services No. WESCW 85-173. This report was prepared by Ms. Carmela A. Keeney, NCEL. The study was monitored by Mr. Thornton under the general supervision of Mr. Bryant Mather, Chief, SL, and Mr. John M. Scanlon, Chief, CTD. Program Manager for the REMR Research Program is Mr. William F. McCleese, CTD. Problem Area Leader for the Concrete and Steel Structures problem area is Mr. James E. McDonald, CTD.

COL Dwayne G. Lee, CE, is the Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet per second	0.028316846	cubic metres per second
cubic yards per hour	0.7646	cubic metres per hour
feet per second	0.3048	metres per second
gallons per minute	0.003785	cubic metres per minute
inches	0.0254	metres
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.02	kilograms per cubic metre
square feet	0.09290304	square metres
square feet per minute	0.09290304	squre metres per minute

PROCEDURES AND DEVICES FOR UNDERWATER
CLEANING OF CIVIL WORKS STRUCTURES

PART I: INTRODUCTION

Background

1. The U.S. Army Engineer Waterways Experiment Station (WES) began an
investigation into the maintenance and preservation of concrete civil works
structures in 1977. This study was later expanded to other types of civil
works structures through the Repair, Evaluation, Maintenance, and Rehabilita-
tion (REMR) Research Program (Scanlon et al 1983). The overall objective of
REMR is to identify and develop effective and affordable technology for main-
taining and extending the service life of existing water-resources projects.
These include flood control and multipurpose dams, navigational locks and
dams, powerhouses and appurtenant structures, pumping stations, bridges, and
coastal structures such as piers, seawalls, and bulkheads.

2. Engineer Regulation (ER) 1100-2-100 requires that "completed Civil
Works structures be periodically inspected and continuously evaluated to
ensure their structural safety and operational ability." Underwater struc-
tures sustain varying amounts of damage and need to be monitored to assure the
integrity of the structure is not compromised. Accomplishment of proper
inspection and evaluation procedures to identify deficiencies will usually
require some type of cleaning of the structure. This report provides infor-
mation on equipment and procedures which may be applicable to underwater
cleaning of civil works structures.

3. A wide variety of underwater cleaning tools and methodologies have
been developed and are currently in use in the offshore oil industry and by
the U.S. Navy. These tools have been designed specifically for cleaning the
submerged portions of underwater structures. They range from hand held
scrapers to powered tools and high pressure waterjets. Several tools specif-
ically designed for the removal of underwater debris are also available.
These tools include jet eductors, dredges, and air lifts.

Objective

4. The objective of this effort is to survey underwater cleaning techniques and devices for possible application to Army Corps of Engineers civil works structures. Underwater cleaning is required to facilitate the inspection, maintenance, and repair of the submerged portion of dams, locks, bridges, seawalls, piers, and other similar structures.

Scope

5. This report summarizes underwater cleaning procedures and devices that are appropriate to use on civil works structures. The report was prepared by the Naval Civil Engineering Laboratory, which has conducted extensive tests and evaluations of underwater cleaning techniques for waterfront structures. The cleaning systems evaluated encompassed several different types that are characteristic of those that are commercially available. The application, advantages, disadvantages, and operation of each type of equipment are discussed, along with recommendations for those tools best suited for specific conditions.

PART II: UNDERWATER CLEANING CONSIDERATIONS

6. Underwater cleaning is required to remove fouling (marine growth), corrosion, and debris from the submerged portions of structures to facilitate inspection, maintenance, and repair operations. Surfaces must be free of all fouling and debris to allow a thorough visual examination and accurate condition assessment of the structure. Cleaning is also required before most forms of nondestructive evaluation can be conducted.

7. There are many types of fouling that must be removed from underwater structures. These fall primarily into two categories: marine and freshwater fouling. Marine fouling is generally more severe than freshwater fouling and includes several types of shellgrowth, plant growth, and corrosion. Marine growth includes seaweed, kelp, grass, barnacles, tubeworms, and anemones. Marine growth six inches thick is common on structures in certain environments. Freshwater fouling is usually less extensive and easier to remove than marine fouling. This is because of the lack of freshwater organisms that produce calcareous deposits. The most common types of freshwater fouling include slime and algae. Other types of material that must be removed from underwater structures in both freshwater and marine environments include mud, silt, rust, corrosion, and other debris.

8. Different types of fouling and structures will require different types of cleaning techniques and equipment. Typically the construction material and the type of fouling serve as selection criteria for the cleaning system. Construction materials include concrete, steel, and timber although concrete and steel are the most common in Civil Works structures. The accessibility of the surface to be cleaned also influences the cleaning techniques and types of equipment that are used.

9. The performance of the equipment, in terms of cleaning effectiveness or cleaning rates, depends upon many factors. These factors include:

- the physical and operational characteristics of the cleaning device

- the amount and type of fouling

- the construction material

- the operator experience

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- the underwater working conditions

- the surface accessibility

This report addresses each of these factors, although the focus is on the physical and operational characteristics of the various cleaning systems.

PART III: UNDERWATER CLEANING TOOLS

10. There are three general types of cleaning tools: hand tools; powered hand tools; and self-propelled cleaning vehicles. Hand tools include conventional devices such as scrapers, chisels, and wire brushes. Powered hand tools include rotary brushes, abrasive discs, and waterjet systems. Although waterjet devices can be considered powered hand tools, they are covered in a separate section since they are quite different from other powered hand tools. Self-propelled cleaning vehicles are large brush systems that travel along the work surface on wheels. Each tool has its own advantages and disadvantages. These advantages and disadvantages are discussed in detail in the following sections.

Conventional Hand Tools

11. Hand tools include conventional cleaning devices, such as scrapers, wire brushes, and chippers. These tools are not powered and are capable of removing light fouling and marine growth from most structures. These tools are most effective when a diver must be highly mobile and when only small spot cleaning is required. Hand tools are small, lightweight, and highly portable. They also are the least hazardous types of cleaning device to operate in an underwater environment.

12. The major disadvantage associated with using hand tools is their low cleaning efficiency. The highest cleaning rate that can be expected is on the order of one square foot per minute. Cleaning rates as low as 0.2 to 0.3 ft^2/min are typical in heavily fouled areas. Because of their low cleaning rates, hand tools are not well suited for cleaning large areas or for removing heavy fouling, particularly from concrete structures.

13. The most common type of conventional hand tool used for underwater cleaning is the scraper. Scrapers are made from many different materials, including steel, wood, and acrylic. Wood and acrylic scrapers are not as effective as steel scrapers and are typically used on sensitive surfaces where it is important not to mar the surface while removing the fouling. Figure 1 shows several different types of scrapers.
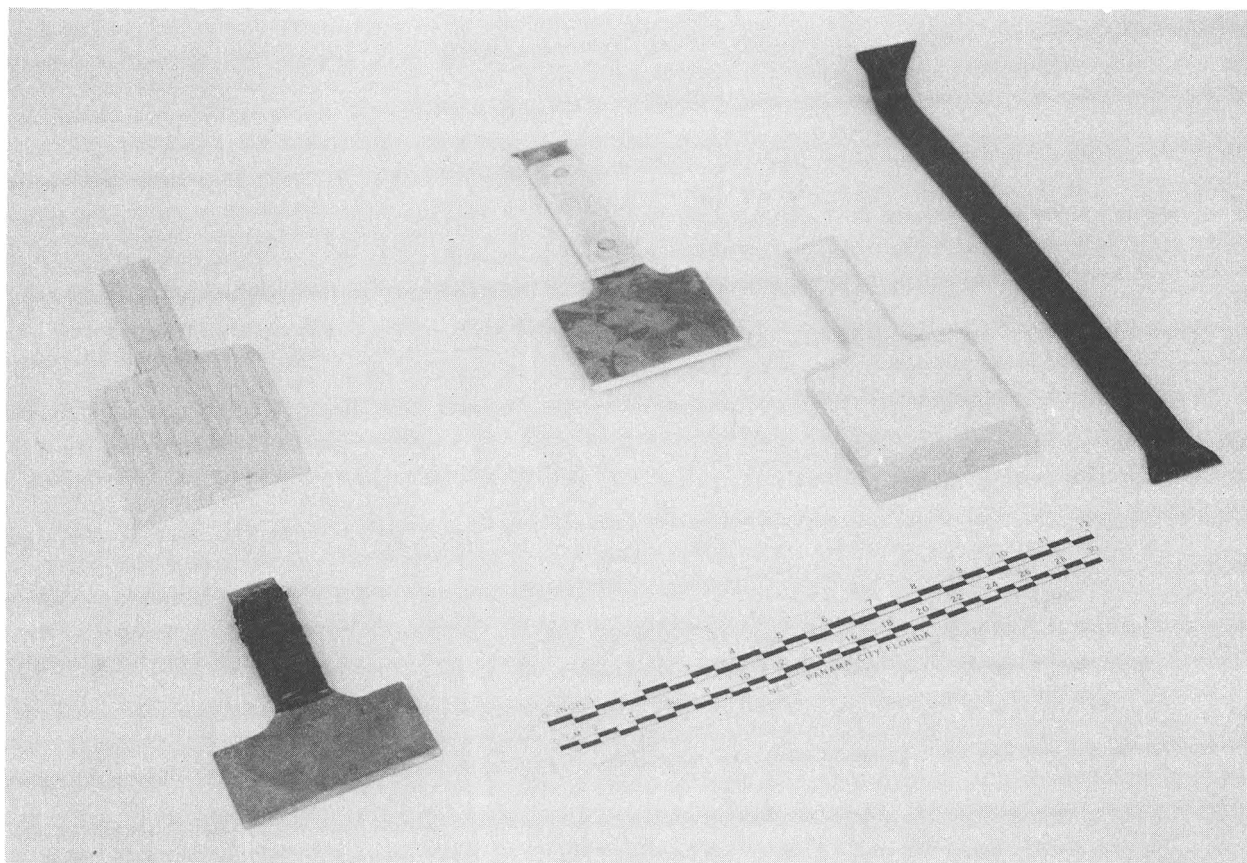
Figure 1. Hand held scrapers.

Brushes and Abrasive Devices

14. Powered hand tools are quite useful for removing fouling and marine growth because they are faster and usually more effective than conventional hand tools (NCEL 1984). These tools are primarily power brushes and abrasive discs, but can also include small powered chipping hammers and scrapers. The tools are diver operated and use a variety of cleaning attachments designed to remove different types of fouling or to clean different types of material.

15. Powered hand tools are easy to operate and to maintain. However, the brush bristles and disc abrasives on the cleaning attachments may tend to wear quickly, particularly when removing heavy or hard, calcareous fouling.

16. A typical powered hand tool cleaning system consists of the following components: an oil-hydraulic power source; a hand held rotary power tool; at least one type of cleaning attachment; and interconnecting supply lines and connectors. Pneumatic tools can be used to operate the cleaning attachment; however, hydraulic tools are preferred, since they provide consistent closed-cycle power, are not depth limited, and are easier and safer to operate underwater. Electric power tools are also available, but are seldom used in the underwater environment because of the potential shock hazard to the diver.

17. Most hydraulic hand tools operate at 1,000 to 3,000 pounds per square inch (psi) pressure and 5 to 10 gallons per minute (gpm) flows. A typical hydraulic rotary power tool is the Stanley Hydraulic Grinder, model GR 24 (Figure 2). The Stanley grinder operates at 2,000 psi and 7 to 9 gpm. It weighs 11 pounds in air and runs at 4,500 rpm at 9 gpm. This hydraulic grinder can be used to power most rotary cleaning attachments.

18. Wyman and Pemberton (1983) identified the following important physical parameters that affect the cleaning performance of powered hand tools and scrapers:

    a. Hardness of the cleaning edge

    b. Stiffness of the member holding the cleaning edge in contact with the work surface

    c. Size of the cleaning element, i.e. abrasive grit size, bristle dimension, scraper width
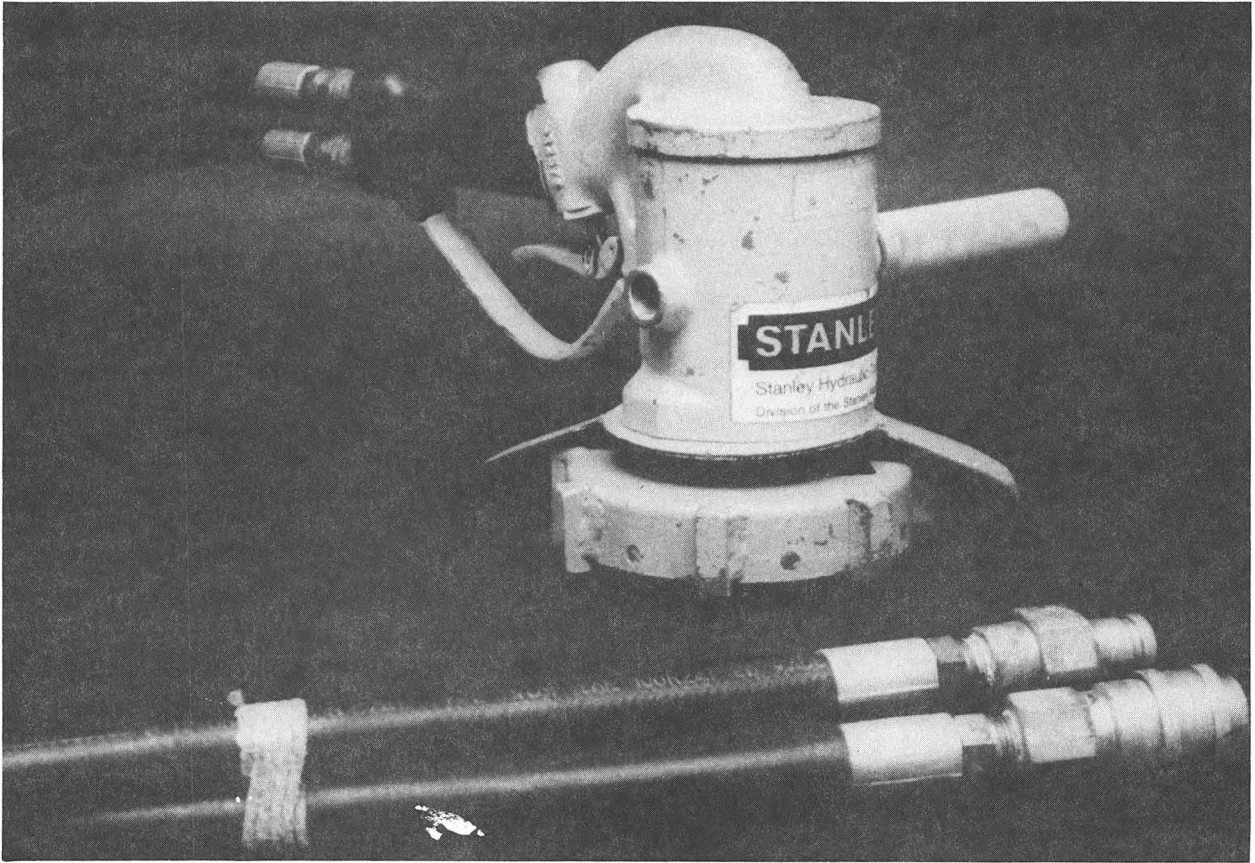
Figure 2. Stanley hydraulic grinder.

d. Velocity of the cleaning edge with respect to the work surface

19. In order to be effective, the cleaning edge must be harder than the material to be removed. This is particularly important when removing calcareous fouling such as barnacles and tubeworms. The only common cleaning materials that are harder than barnacles and tubeworms are aluminum oxide and silicon carbide abrasives and steel wires.

20. The stiffness of the cleaning edge in relation to the work surface is also an important factor that affects cleaning effectiveness. The stiffer the bristle or the material holding the abrasive, the more aggressive the cleaning. Round wire brushes should be stiffened by plastic impregnation of the bristles to ensure the effective removal of hard fouling.

21. The size of the cleaning element is also an important factor that influences cleaning performance. When using abrasives, the larger grit sizes result in more aggressive abrasion and coarser finishes. The stiffness of a brush bristle decreases with bristle length. The width of a scraper edge affects the power density or cleaning intensity. A narrow scraper edge is more effective on heavy, hard fouling than a wider edge which can more effectively remove light fouling.

22. Cleaning efficiency is also related to the velocity of the cleaning edge with respect to the work surface. The faster the cleaning edge moves across the surface the more effective it is. For rotary power tools, greater rim speeds result in improved cleaning ability. Tests conducted at the Naval Coastal Systems Center (NCSC), Panama City, FL., using abrasive tools indicated that rim speeds on the order of 100 feet per second were required to remove the basal plate material of calcareous marine growth. Two rotary power tools that have high rim speeds are the Stanley and Fairmont grinders. The Stanley Grinder, model Gr 24, has a maximum rim speed of approximately 108 ft/sec. The Fairmont Peanut Grinder has a maximum rim speed of 92 ft/sec.

23. Nylon or polypropylene bristle brushes are adequate for cleaning light and loose fouling found on steel and concrete surfaces in most freshwater environments. Abrasive disc cleaning attachments are designed primarily to clean steel surfaces. However, these devices can also scratch and mar the protective coatings or the paint found on many underwater steel surfaces.

24. The following are types of abrasive discs and brushes which can effectively clean underwater steel surfaces. Figure 3 shows typical configurations. They are listed in order of cleaning aggressiveness (Wyman and Pemberton 1983):

a. Six-inch diameter Clean 'N' Strip Cup Wheel, silicon carbide abrasive, manufactured by 3M Company, St. Paul, Minnesota.

b. Seven-inch diameter Bradex brush, 0.060/46 grit, silicon carbide imbedded in nylon bristles, manufactured by AB Tex Corp., Rochester, New York.

c. Seven- or eight-inch diameter Metal Conditioning Discs, coarse, aluminum oxide abrasive, manufactured by 3M Company, St. Paul, Minnesota.

d. Seven- or eight-inch diameter Blend 'N' Finish disc, medium, aluminum oxide abrasive, manufactured by 3M Company, St. Paul, Minnesota.

e. Seven-inch diameter Bradex Brushes, either 0.040/80 grit or 0.022/120 grit, silicon carbide imbedded in nylon bristles, manufactured by AB Tex Corp., Rochester, New York.

25. To remove heavy, calcareous fouling effectively from concrete surfaces, the "Barnacle Buster" or Whirl Away rotary cleaning tool is recommended. This tool is available from R.C. Collins, Inc., Miami, Florida. The Whirl Away (Figure 4) is a rotary cleaning tool that attaches directly to the drive shaft of most standard hydraulic grinders, disc sanders, and polishers. The attachment consists of seven sets of hardened steel cutters that rotate on their axles while the shaft of the hydraulic tool is rotating in the opposite direction. The flow of water passing through the tool keeps the rotating cutters free of debris and fouling. Seven bars attached to the perimeter of the outside housing of the tool break away the heavy shellgrowth and fouling while the 49 rotating cutter wheels remove the balance of the remaining material.

26. The Whirl Away, model #637-MA, weighs 4-1/2 pounds in air and is seven inches in diameter. Because of its size, this model has the fastest concrete cleaning rate, but cannot clean in limited access areas. There are smaller models available in 3-1/4-, 4-1/2-, and 6-inch diameter sizes. These
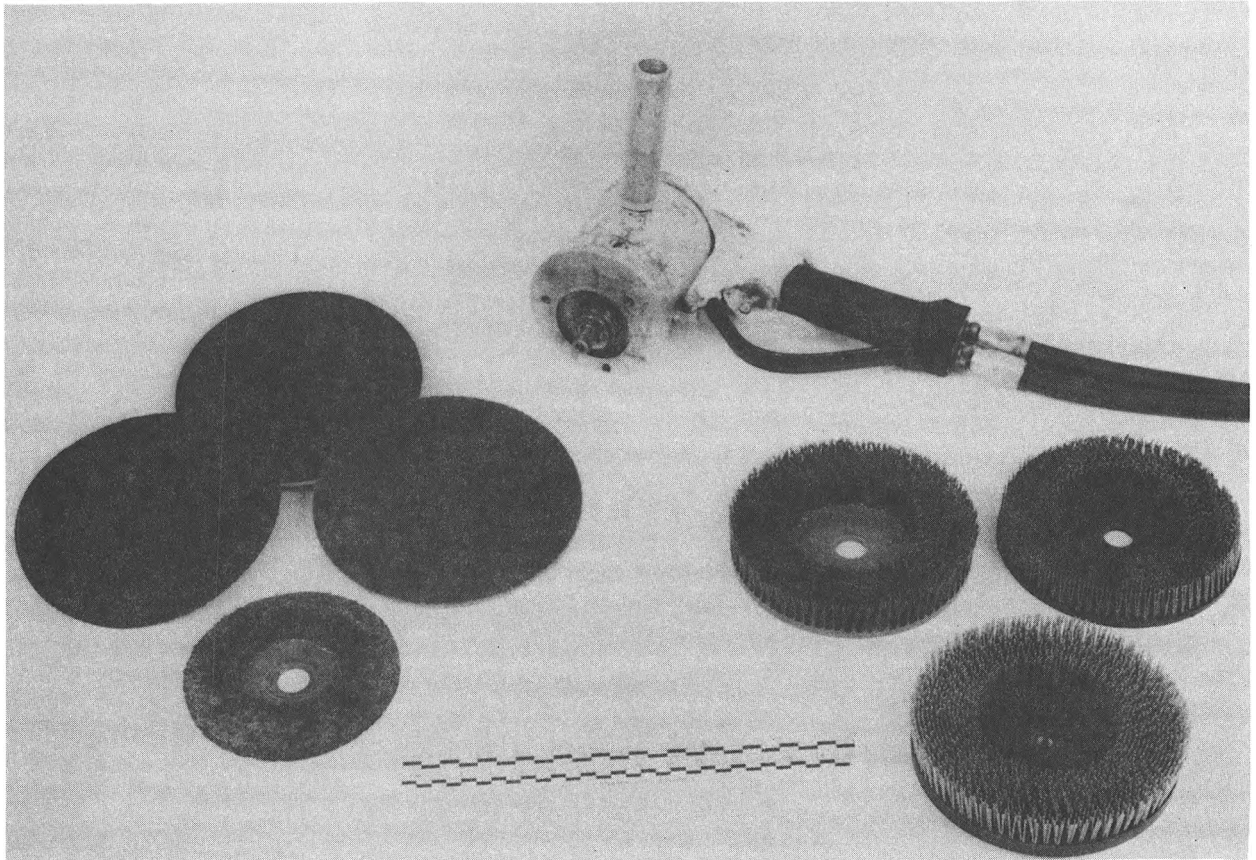
Figure 3. Brushes and abrasive discs.

Figure 4. The Whirl Away Rotary cleaning tool.

smaller Whirl Away models cannot remove heavy fouling effectively and should be used only to remove fouling of less than two to three inches thick in limited access areas.

27. The Whirl Away is a significant improvement over conventional unpowered hand tools, particularly on concrete surfaces. More than three inches of hard shell growth and six inches of sea growth can be removed at cleaning rates of three to six square feet per minute. The steel rotating cutter edges may wear and become dull when removing hard shellgrowth. Replacement cutters are available in sets of 49.

28. Plastic barnacle busters are rotary abrading devices that use plastic edges, rather than steel edges, to knock off the fouling. These devices work well on steel structures with light to moderate fouling. The advantage of using a plastic barnacle buster on steel surfaces is that it does not damage the surface coating material; however, the plastic cutters do wear rapidly when removing hard fouling. A combination plastic barnacle buster and silicon carbide imbedded nylon bristle brush was manufactured by AB Tex Corp., Rochester, New York for NCSC, Panama City, Fl. (Wyman and Pemberton 1983). During a preliminary evaluation this tool was found to quickly remove most types of light to moderate fouling from steel surfaces. However, additional development work was necessary to reduce the rapid wear of the plastic edges.

Waterjet Cleaning Tools

29. High-pressure waterjet cleaning tools provide a quick and effective means of removing fouling and corrosion from underwater surfaces. These tools produce some of the highest cleaning rates. However, a high-pressure waterjet is a potential hazard and must be handled with extreme care. There are many commercially available waterjet tools designed for underwater use. A waterjet cleaning system is comprised of the following components: a pump and power source, a waterjet tool, and interconnecting hardware such as high pressure hoses and connectors. A minimum of two people are required to operate waterjet cleaning systems. A trained and qualified scuba diver is required to operate the underwater tool. Another person is required topside to operate and monitor the performance of the power source. Most high-pressure waterjet cleaning systems require a freshwater source to supply the pump.

30. The force required to overcome the shear strength of the fouling material is proportional to the pressure. Once that threshold pressure is obtained there is no advantage in increasing the pressure further, except to increase the waterflow (Odds 1978). Therefore, to increase the cleaning rate once the optimum pressure has been determined, the volume of water must be increased by using a larger nozzle, which will increase the flow (at optimum pressure). One parameter which can affect the cleaning efficiency is the ability of the diver to exert pressure via the cleaning tool onto the cleaning surface. Three methods have been used during tests of cleaning tools to allow the diver to exert pressure via the cleaning tool onto the surface being cleaned. If minimal cleaning is to be done, the diver can often generate sufficient force for short periods of time by using his fins to propel him toward the structure. For more extensive cleaning, the diver either holds onto the pile if the configuration of the pile allows, or a tether is used to secure the diver to the pile. If a tether is used, the diver must be fitted with a harness containing D-rings to allow rapid release of the tether in the event that problems arise during the diving operation.

31. Waterjet cleaning systems generally fall into one of two categories: high-flow devices and low-flow devices. Most high-flow tools require a retrojet to counter the reaction force generated by the cleaning jet. The retrojet is a reverse facing nozzle that develops a thrust of equivalent magnitude that acts in the opposite direction of the cleaning jet. This results in a "reactionless" cleaning tool, which is easy to operate. A system that uses a retrojet requires twice the power of a single jet system. Flows are generally on the order of 20 gpm, with 10 gpm out of both the forward and reverse nozzles. To increase the efficiency of counterthrusted devices, some systems have an educted retrojet. Eductors create additional flow from the surrounding water environment with a venturi effect that decreases the pump horsepower required to negate the reaction force (Figure 5). Low-flow tools do not develop enough backthrust to require a retrojet. Flows in the range of 2 to 4 gpm are common, with corresponding reaction forces of approximately 5 to 10 pounds.

32. The reaction force of the water jet is created at the nozzle by the pressure and flow combination. The reaction force is related only to changes in momentum and is dependent upon the flow rate and the nozzle orifice size.
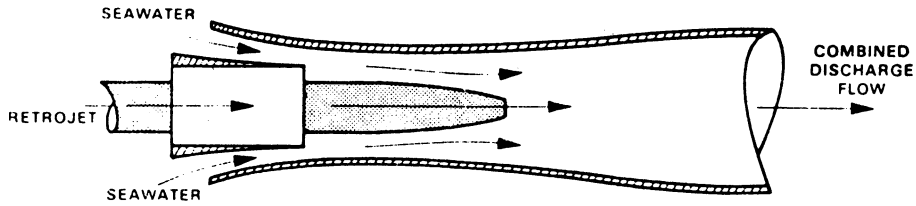
SEAWATER

RETROJET

SEAWATER

COMBINED
DISCHARGE
FLOW

Figure 5. Educted retrojet.

The reaction force can be obtained from the following equation:

$$ F = \frac{d(mV)}{dt} = \frac{Vdm}{dt} = V(pVA) = \frac{pQ^2}{A} $$

where   F = force (pounds)

          m = mass (lb-mass)

          V = velocity (ft/sec)

          p = density (lb-mass/ft^3)

          Q = flow rate (ft^3/sec)

          A = orifice area (ft^2)

33. Most waterjet cleaning systems have interchangable fan- and
straight-jet nozzles. Fan-jet nozzles clean a wider path, where straight jet
nozzles have a greater cleaning intensity. According to research conducted by
Daedalean Associates, Inc. (Parker, et. al 1979), the nozzle orifice size that
has proved to be the most effective in removing marine fouling is the orifice
design of 0.031 inch diameter. Although under equivalent operating conditions
the peak intensity of a straight-jet nozzle exceeds that of a fan-jet nozzle,
fan jets have been found to clean an area up to 10 times faster than typical
straight jets. However, fan-jet intensity dissipates rapidly with the dis-
tance from the work surface (Figure 6).

34. Some systems use the phenomenon of cavitation erosion to aid in the
removal of fouling and corrosion. Cavitation is the formation and collapse of
vapor-filled cavities or bubbles and results from flow-induced pressure
reductions in a fluid. At pressures of 10,000 psi or more, standard sized
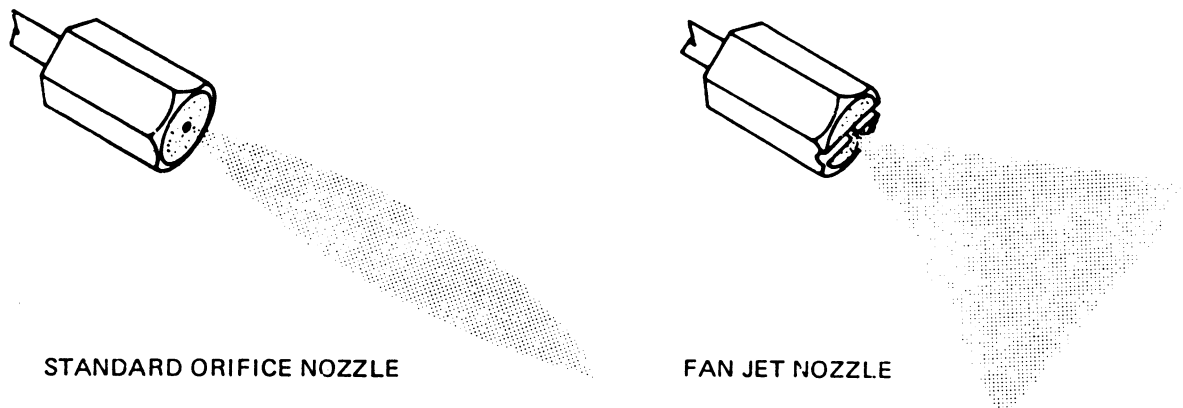waterjet nozzles will cavitate. A "cavitation nozzle" will accelerate the

STANDARD ORIFICE NOZZLE   FAN JET NOZZLE

Figure 6. Fan and straight jet nozzles.

flow and decrease the pressure below the vapor pressure of water. This cre-
ates cavitation bubbles, which are entrained in the flow. The cavitation
bubbles begin to flatten and deform as the jet nears the work surface and the
pressure gradients increase. Cavity implosion results and causes an extreme
local pressure in the immediate region of the collapsed bubble. "Cavitation
nozzles" use these high local pressures to remove fouling material from under-
water surfaces. The collapse of the cavitation bubbles occurs just beyond the
nozzle. To obtain the full benefit of the cavitation it is therefore impor-
tant to maintain the proper standoff distance. Generally, the optimum stand-
off range for cavitation fan jet nozzles is 12 to 100 times the orifice size,
or 1/2 to 1-1/2 inches.

     35. Whenever the trigger is released, a means for relieving the pres-
sure and flow in the supply lines must be provided to prevent the supply lines
and fittings from bursting. Some waterjet tools use a dump valve to exhaust
the flow at a low and harmless pressure whenever the trigger is released. If
the tool does not have a dump valve (that is, it uses a direct shutoff valve)
then a means for unloading and recirculating the flow at the pump is required.
During tests conducted at NCEL, it was determined that divers preferred a
pilot-operated direct shut-off valve over a dump valve (Keeney 1981). High
pressure water flow through a pilot-operated valve is controlled by differential
pressure on a poppet (Figure 7). The small diameter pilot valve is manually
controlled by the trigger lever. Depressing the trigger forces the pilot
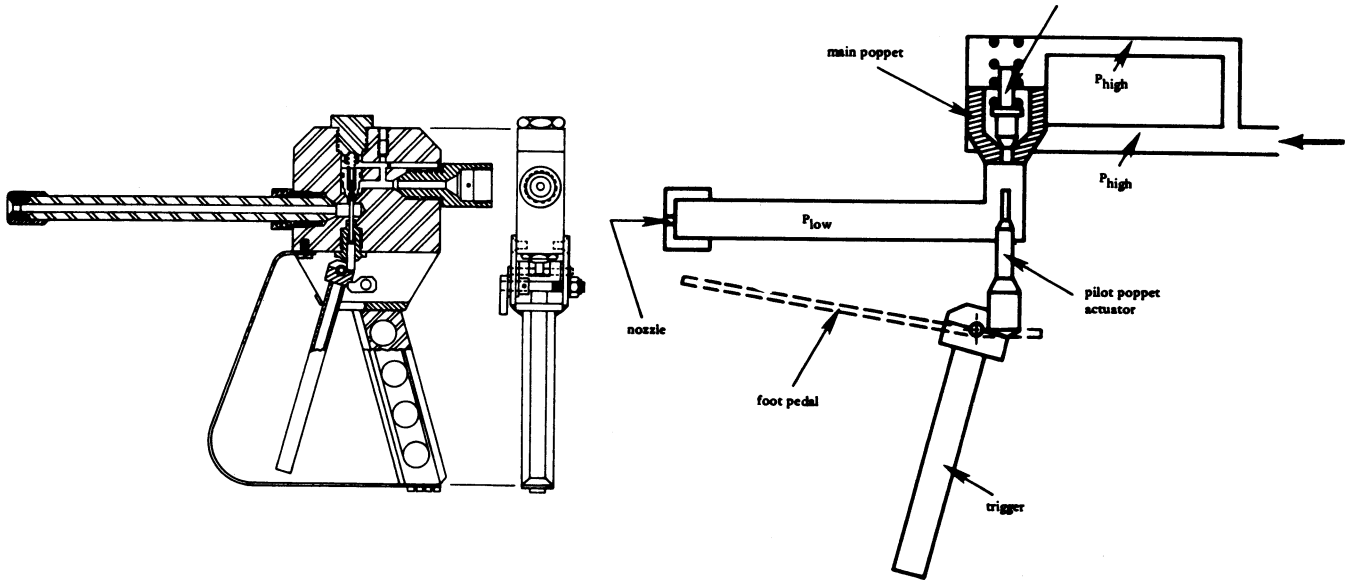
19

Figure 7. Waterjet pistol with pilot operated trigger valve.

valve from its seat and allows high pressure water to flow to the nozzle and balance the pressure on the main trigger valve. Hydrodynamic forces further open the main trigger valve to allow full flow of high-pressure water to the nozzle. This decreases the amount of force the diver must exert to maintain the valve in a fully opened position. Releasing the trigger allows the pilot poppet spring to reseat the now balanced main trigger. Differential pressure then seals the trigger valve as the downstream barrel section drains to lower ambient pressure through the nozzle.

36. The hydraulic horsepower required to develop the proper flow rates and pressures at the nozzle is directly proportional to the product of the pressure and volumetric flow at the nozzle. This hydraulic horsepower does not take into account any losses due to fluid transmission or pump inefficiency. The power required at the pump/power source can be up to 25% more than the calculated hydraulic nozzle power. The major transmission losses are a function of the flow rate, hose diameter, and hose length. The pressure or head loss varies directly as the square of the flow rate and inversely as the fifth power of the hose diameter:

$$h_L = \frac{fV^2L}{2gD} = \frac{f}{2g}\left(\frac{4Q}{\pi D^2}\right)^2 \frac{L}{D} = \frac{2fL}{\pi g} \cdot \frac{Q^2}{D^5}$$

20

where h_L = pressure or head loss (lb/in^2)

f = friction factor

g = gravitational acceleration (in/sec^2)

V = water velocity or Q/A = flow rate/cross-sectional area (in/sec)

L = hose length (in)

D = hose diameter (in)

To prevent high-pressure losses, it is desirable to use large diameter delivery lines. However, large diameter lines are fairly rigid and have a limited bending radius, which makes them very difficult for a diver to manuever. Therefore, at the cost of some power losses, highly flexible, small diameter delivery lines are recommended, since they are easy to operate and maneuver and do not cause the diver to fatigue as rapidly.

37. During tests conducted with several commercially available waterjet cleaning systems (Keeney 1981), the cleaning performance was found to depend primarily upon four factors: degree of fouling, operator technique, diver experience with the equipment, and equipment capabilities. As expected, heavy marine fouling was the most time consuming material to remove. Operator technique, such as the distance from the work surface, the angle between the surface and the waterjet, and the rate of translation over the surface are other important factors that influenced the cleaning rates. It was determined that the best general operating technique included a standoff distance of 1/2 inch to 3 inches, an impingement angle of 40° to 90°, and a quick and agitated translation. Each tool has an optimum operating technique that should be established prior to any actual cleaning. Divers with experience in handling high-pressure waterjets achieved the highest cleaning rates.

38. The equipment design and capabilities also affected the cleaning rates. Heavier and larger equipment, including the high-pressure supply hoses, were more difficult to maneuver and handle underwater. It is recommended that at least one 50 foot length of small diameter, lightweight and flexible high pressure hose be used to connect the cleaning tool to the main supply line when high flow rates are required. The tools without retrojets and without pilot-operated trigger mechanisms caused early diver fatigue, especially in the hands and arms.

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39. High-Flow Waterjets. Diver operated high pressure, high-flow cleaning systems operate at approximately 4,000 to 12,000 psi and 12 to 25 gpm. The waterjet tool is large enough to require two handed operation. There is no reaction force because of the retrojet which uses half of the flow. Interchangeable fan and straight nozzles are available.

40. The Jetin high-flow waterjet cleaning system operates at 4,000 to 10,000 psi and 12 to 26 gpm (Figure 8). During tests conducted at the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, Ca. this tool demonstrated cleaning rates as high as 7 ft^2/min, and achieved an average cleaning rate of 4 ft^2/min on both concrete and steel surfaces (Keeney 1981). The waterjet gun uses a pilot-operated, direct shutoff trigger mechanism, which significantly reduces diver hand and arm fatigue. There is no dump valve on the waterjet gun. The flow is recirculated at the power source when an unloader relief valve detects a pressure buildup in the delivery lines. The waterjet gun is reactionless, that is, it diverts 50% of the flow through a retrojet nozzle for thrust compensation. The retrojet is shrouded with a diffuser for safety purposes. The diffuser, a hollow tube with slots in it, produces a venturi effect and draws water into the barrel through the slots to increase the mass flow and reduce the penetrating effect of the retrojet to a safe level. The diffuser is an important safety device for counterthrusted systems since it prevents injury by inadvertantly passing the retrojet in front of the operator or an observer. The diffuser is effective only underwater. The retrojet is still very hazardous if operated in air.

41. Another high-pressure, high-flow system is available from Seaco, Inc. This system operates at 3,000 psi and 18 (Model 1B) or 22 gpm (Model 1A) and uses cavitation nozzles (Figure 9). The 18 gpm cleaning tool, Model 1B, has an adjustable educted retrojet that enables the diver to vary the retrojet flow and control the amount of thrust into or away from the work surface. The educted retrojet requires less than half the flow to counterbalance the 11 gpm cleaning nozzle. The 22-gpm tool, Model 1A, does not use an educted retrojet. It is shorter in length and is therefore easier to maneuver. The flow through the retrojet on this tool is also adjustable, which allows the diver to vary the thrust to counteract currents or imbalances in the jet forces. During tests conducted at NCEL these tools achieved average cleaning rates on concrete and steel surfaces of one to two square feet per minute, respectively. A maximum cleaning rate of 3 ft^2/min was achieved on steel surfaces.
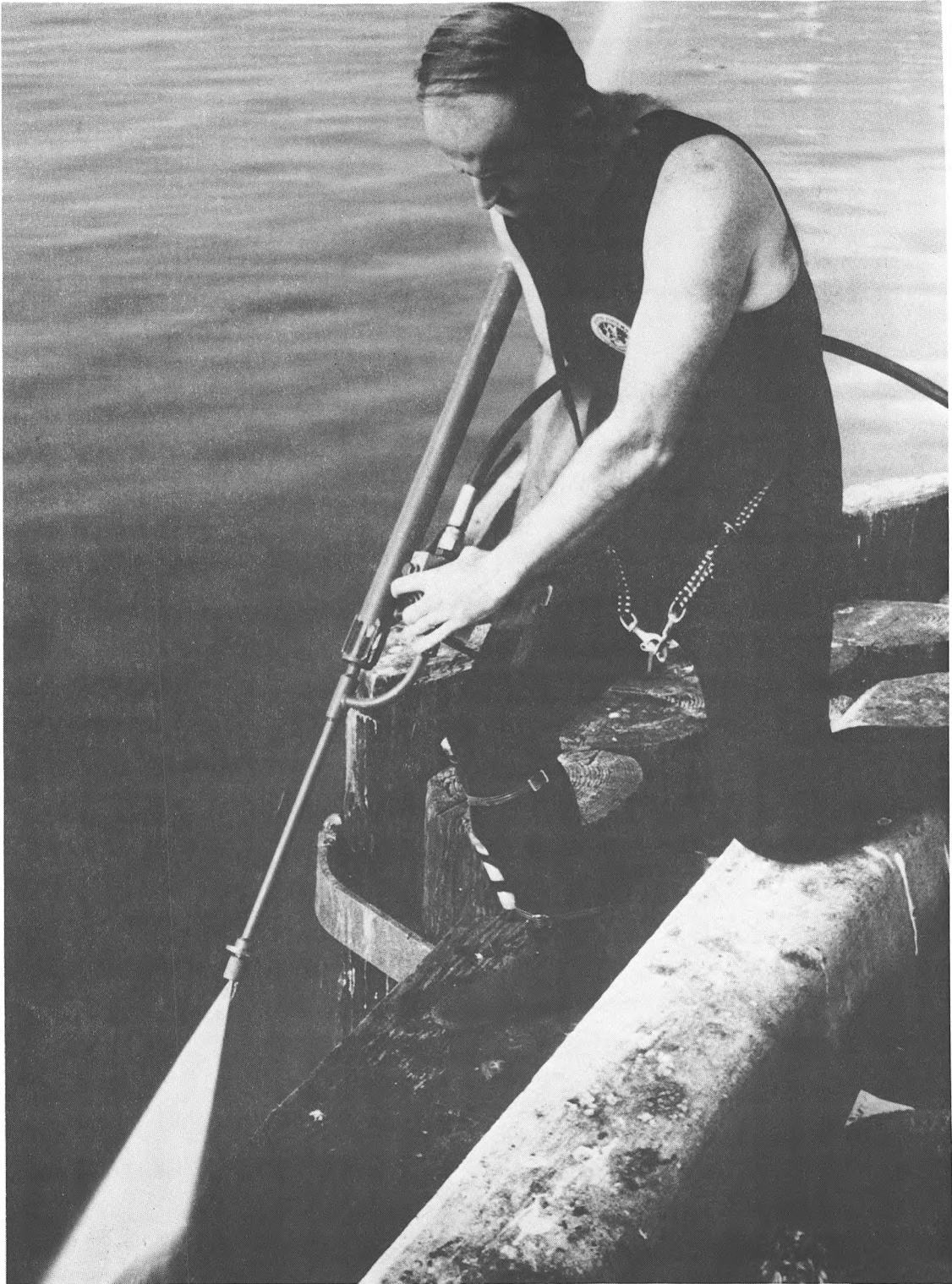
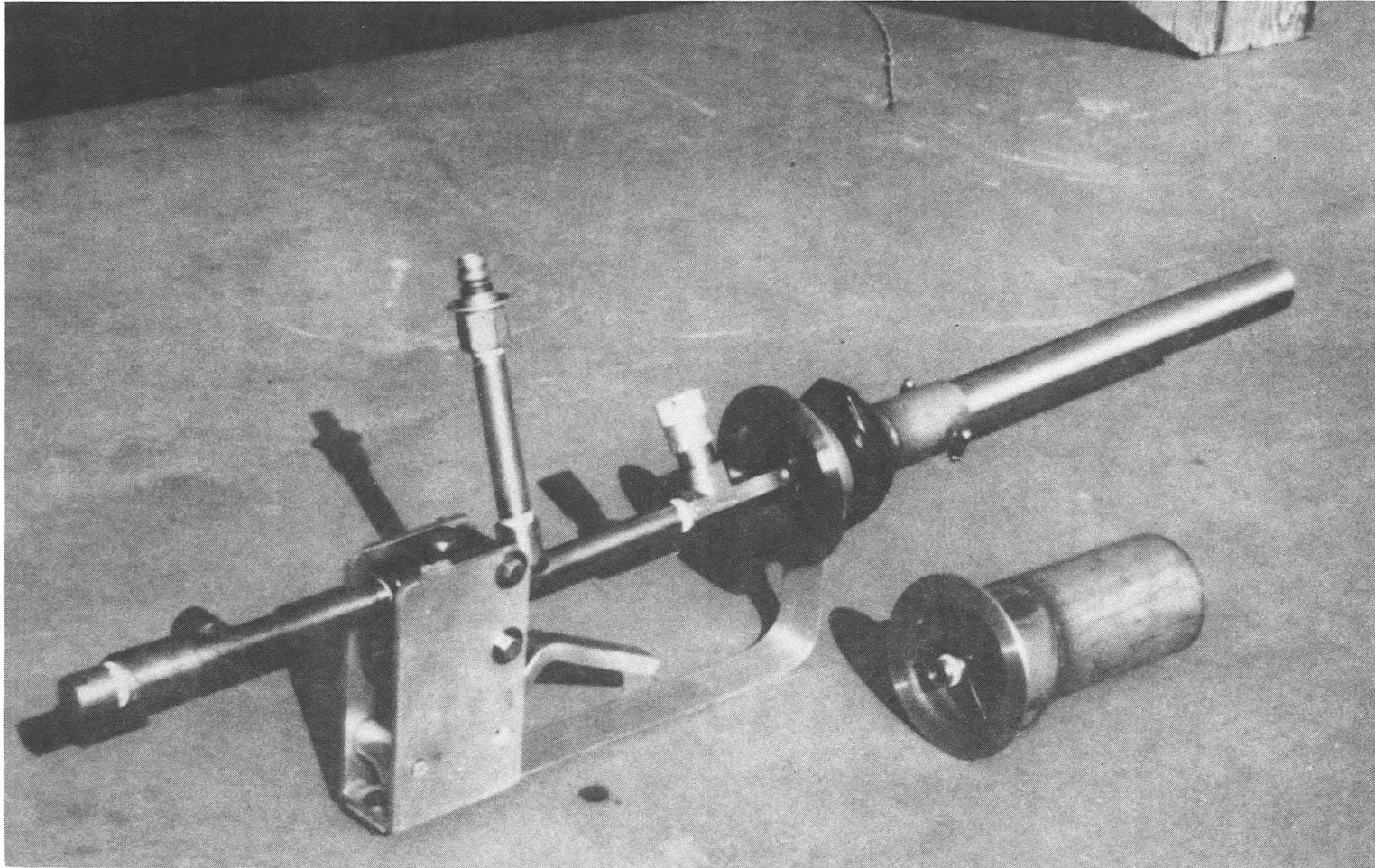Figure 8. Jetin high pressure, high flow waterjet tool.

Figure 9. Seaco counterthrusted waterjet with eductor.
Non-educted retrojet in foreground.

42. _Low-Flow Waterjets_. Diver operated high pressure, low flow cleaning systems operate at approximately 10,000 psi and 2 to 5 gpm. The pistol-like waterjet tool can be operated with one hand. Because of the low flow rates, these tools do not develop enough backthrust to require a retrojet for compensation. A shoulder stock can be used to help support the diver against the backthrust if needed. Low-flow waterjet tools develop a 5 to 10 pound reaction force depending upon the size and type of nozzle used. Interchangeable fan and straight jet nozzles are available. Since these waterjet tools are relatively small and lightweight, they can be used to clean in limited access areas that are difficult to reach by any other means.

43. A high-pressure, low-flow cleaning system was developed by Flow Industries, Inc., Kent, WA., for the U.S. Navy under contract to NCEL (Keeney 1984). This system (Figure 10) was developed for routine cleaning of underwater structures, particularly in limited access areas. Components include a small, hand held waterjet pistol (five pounds in air); interchangeable cavitating fan and straight jet nozzles; a pilot-operated trigger valve with automatic safety lock; flexible, small-diameter high-pressure supply hoses; a foot-actuated shut-off valve; and a high pressure swivel. The power source delivers up to 5 gpm at 12,000 psi, is driven by a diesel engine and includes a double acting pressure intensifier and variable displacement hydraulic pump. The power unit can operate on either freshwater or seawater, eliminating the need for a fresh water supply in marine applications. The power source is also capable of supplying hydraulic powered hand tools. Cleaning rates of up to 6 ft^2/min can be achieved, depending upon fouling amount, construction material, and operator experience.

Abrasive Waterjets

44. Diver-operated waterjet systems that use abrasives are effective for removing fouling, corrosion, and paint from metal surfaces. Abrasive waterjet cleaning typically is required to obtain a bare metal finish before certain maintenance and repair operations, such as welding and painting, can be performed. Cleaning rates of 4 ft^2/min can be obtained (Keeney 1981).

45. Abrasive waterjet cleaning systems require more hardware and personnel to operate than waterjet-only cleaning systems. This is due to the additional grit handling and mixing equipment that is needed to inject the abrasives into the waterjet stream. Care must be taken during the operation
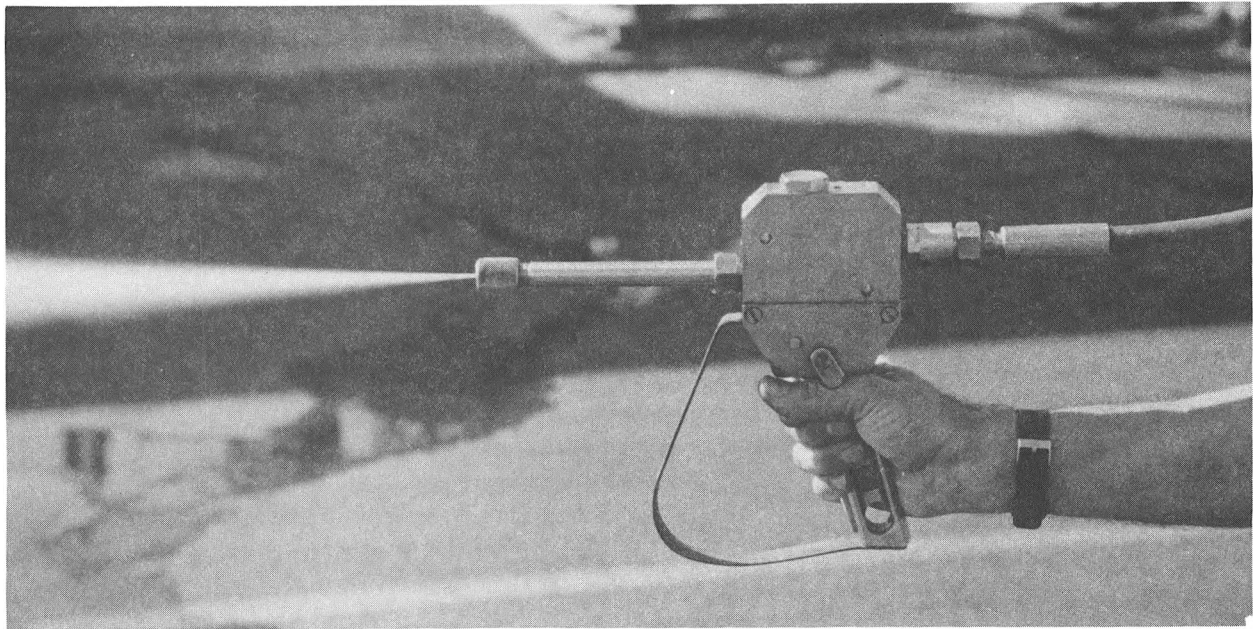
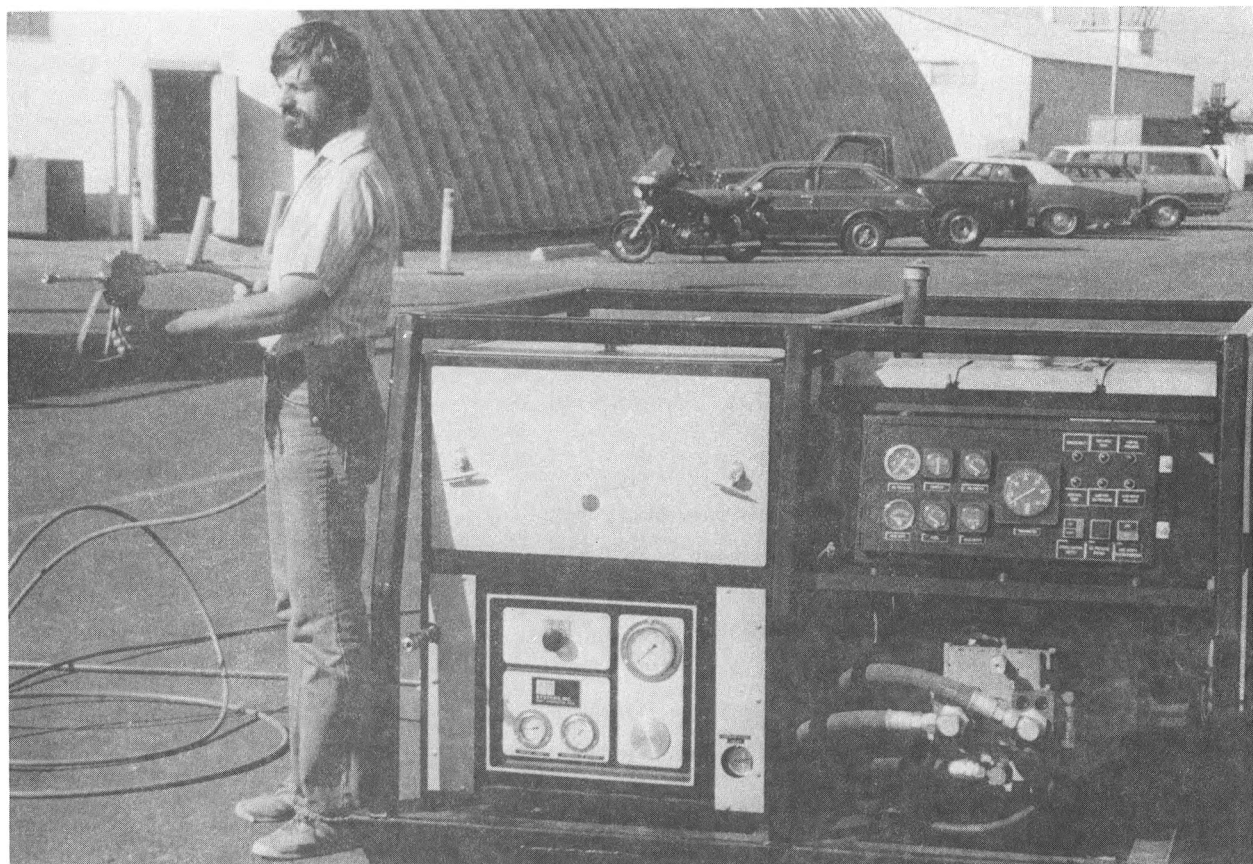Figure 10a. Flow Industries high pressure, low flow cleaning tool.

Figure 10b. Flow Industries waterjet cleaning system.

of the system to prevent water from entering the abrasive supply lines and becoming clogged.

46. The components in an abrasive waterjet cleaning system include a pump/power source, a waterjet tool, a sand or grit hopper, an air/grit pump, and interconnecting hardware such as hoses and fittings. Two types of abrasive waterjet systems are commercially available: a slurry system and a dry grit system. In a slurry system (Figure 11), the grit and pressurized water are mixed topside and delivered to the nozzle in a slurry mixture. This system requires a special mixing device to create the slurry at the power control unit. The slurry can either be pumped to the gun at a low pressure or the venturi effect of the nozzle can form a suction. In some abrasive waterjet systems the slurry is obtained from a submerged sand hopper that is lowered to the underwater working level. Other systems, deliver a slurry that has been mixed on the surface. The primary disadvantage of a submerged hopper is that the hopper must be lowered by crane and returned to the surface for filling.

47. In a dry-grit waterjet system (Figure 12), the abrasive is delivered to the work site in a dry line that is separate from the pressurized water line. A special mixing nozzle is used to entrain the abrasives in the waterjet stream. An additional on/off valve is required on the dry-grit tool to control the separate flow of abrasives to the work site.

48. Both the slurry and dry-grit cleaning systems are counterthrusted with a water-only retrojet nozzle. Water pressures and flow rates range from 6,000 to 10,000 psi and 14 to 22 gpm. Half of the water flow is directed out the retrojet to balance the reaction force. Commercial manufacturers include Jetin Sullair, Inc., Portland, OR and Harben, Inc., Cumming, GA. Jetin Sullair offers an Offshore Module that can be used as either a slurry or waterjet-only cleaning system.

Waterjet Safety

49. The use of high-pressure waterjets is a potentially dangerous operation. The velocity of a waterjet at 10,000 psi is over 825 miles per hour. Pressures greater than 440 psi will damage human skin after cutting through wet suit material. It is important that all personnel be aware of the hazards involved and receive proper training before underwater operation. In no instance should the operator position himself, or anyone else, between the nozzle and the work area.
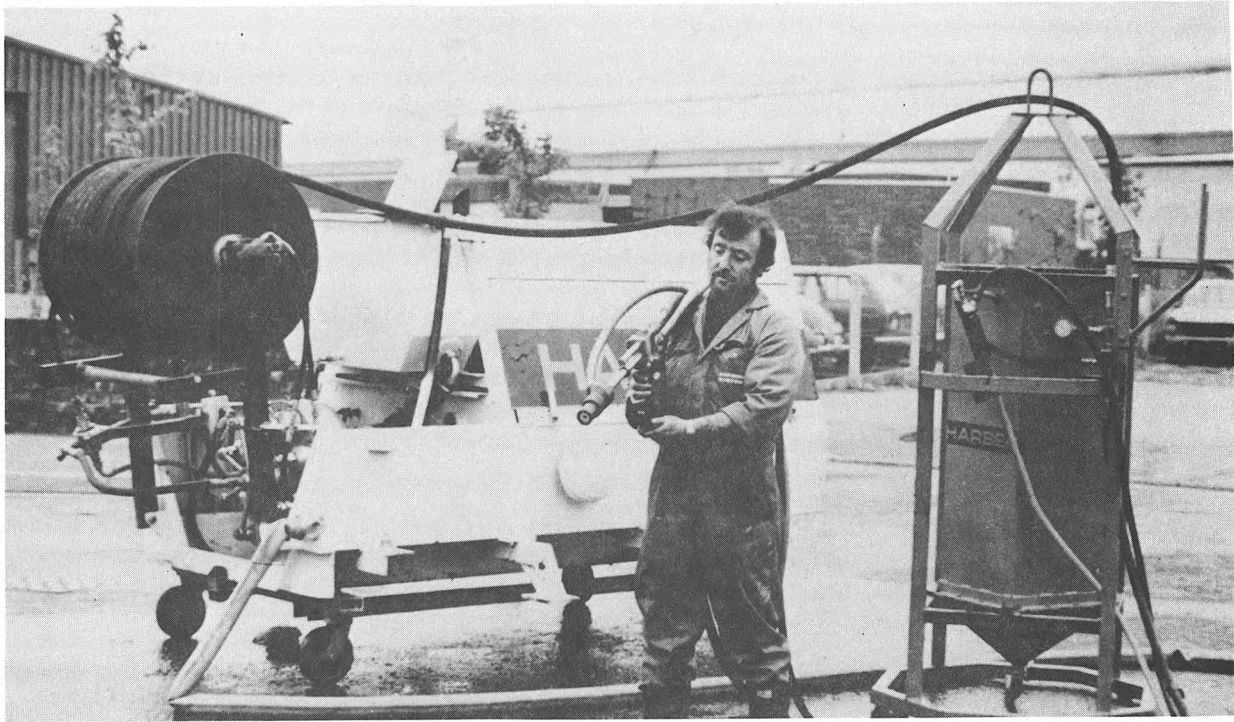
Figure 11. Harben submersible abrasive blasting system.
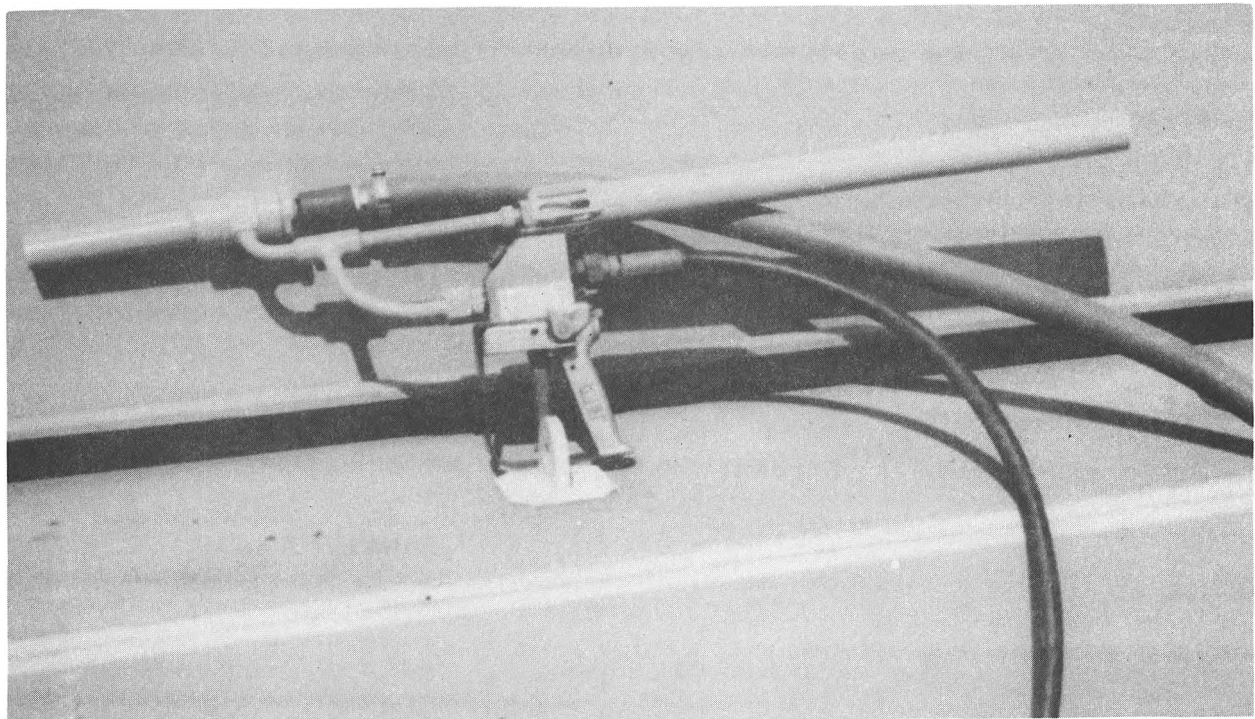

Figure 12. Jetin dry abrasive system.

50. The following waterjet system design features significantly improve diver safety:

- a trigger guard and safety lock to prevent inadvertent or accidental operation

- a topside foot activated shutoff or dump valve to stop all flow to the work area in an emergency

- pressure relief valves or blow out discs to relieve excessive pressure buildup in the event the nozzle becomes blocked or clogged

- filters on the water intake line to prevent the passage of any object large enough to block the nozzle

- for counterthrusted waterjet devices, a diffuser shroud to prevent injury from passing the retrojet in front of the diver

51. Predeployment checks for signs of visible damage and wear should be conducted before operating a high-pressure waterjet. Hoses and fittings should be checked for chafing, splitting, and leaks. An interactive diver communication system should be used during the cleaning operation. If possible, the power-source operator should be included in the diver communication system network to eliminate any misinterpretation of surface and subsurface operations. Additional safety procedures should be observed for the particular equipment in use.

52. High-pressure waterjets can produce excessive levels of noise underwater. Underwater noise exposure levels can be harmful to diver operators unless exposure time limits are imposed. The U.S. Navy has established guidelines (Appendix A) for measuring and evaluating acceptable noise exposure limits for underwater tools. U.S. Navy exposure time limits for the Flow Industries, Inc. high pressure waterjet range from 2 hours and 20 minutes to 6 hours and 27 minutes per day, depending upon the nozzle. The Whirl Away rotary abrading power tool does not have an exposure time limit, since its sound levels are below the Department of Defense damage risk criterion (OPNAVINST 1979) of 84 decibels for 8-hour exposure periods (Keeney 1984).

Self-Propelled Vehicles

53. Self-propelled cleaning vehicles can clean large underwater surfaces effectively prior to inspection, maintenance, and repair operations. These cleaning vehicles have been used to clean the hulls of Navy ships and commercial oil tankers rapidly, without the need for drydocking. Self-propelled cleaning vehicles are designed to remove fouling and corrosion from large and accessible underwater surfaces. Although they have been used primarily on steel surfaces, they can also clean concrete. The sides of lock walls and the faces of dams are two potential areas where these vehicles could be used effectively without the need for dewatering the facility.

54. A disadvantage of self-propelled cleaning vehicles is the fact that they can be used only to clean relatively flat and unobstructed areas. Additionally, the equipment is large and heavy and requires a crane or other special handling equipment for deployment and recovery. Self-propelled vehicles are more expensive than most other types of cleaning equipment.

55. However, the highest cleaning rates can be achieved with self-propelled vehicles. For large areas, self-propelled vehicles can be the most economical cleaning technique based upon cost per square feet (total area cleaned) or cost per hour (total cleaning time required). Depending upon the conditions, up to 450 square feet per minute can be cleaned.

56. Two to three people are required to operate these vehicles. A trained and qualified scuba diver is needed to position and monitor the progress of the cleaning vehicle. A crane operator is required to deploy and recover the underwater equipment. Another person may be needed to monitor a topside power source and tend the umbilical cable.

57. One underwater self-propelled vehicle that has been used for cleaning ship hulls is the SCAMP, operated by Butterworth Systems Inc., Florham Park, New Jersey. This underwater vehicle (Figure 13) is six feet in diameter and 20 inches high. It weighs approximately 1,500 pounds in air and is positively buoyant in water. It is operational to a depth of approximately 120 feet. The saucer shaped unit holds three large, rotating brushes and travels along on three traction wheels (the forward wheel provides the steering). Various cleaning brushes can be used on the vehicle, depending upon the type and amount of fouling. The SCAMP makes a five foot cleaning swath and can travel up to 90 feet per minute depending upon the degree of fouling. The maximum cleaning
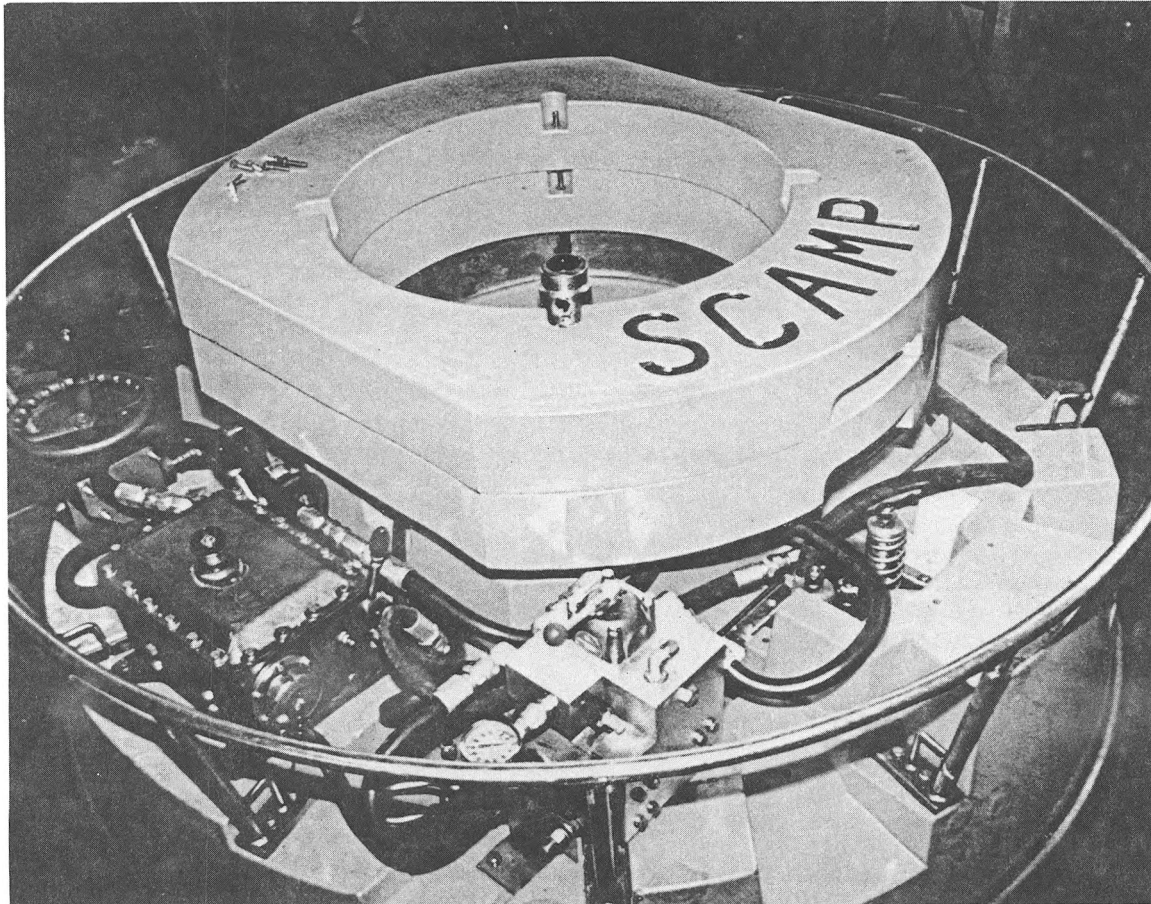
Figure 13. SCAMP self-propelled cleaning vehicle.

rate is about 450 square feet per minute. An impeller in a central duct
secures the vehicle to the work surface with a thrust of 1,000 pounds. Power
is supplied by a surface generator to a 15 horsepower submersible electric
motor that drives a duplex hydraulic pump. One of the pump units powers the
wheels and the cleaning brushes, while the second unit drives the impeller.
The vehicle, connected to a surface control console with a coaxial cable, can
be operated by remote control or directly steered by a scuba diver. The

control and display console shows the orientation of SCAMP, along with its depth and distance travelled.

58. Another self-propelled cleaning vehicle is the Brush-Kart by Phosmarin, Marseilles, France (Figure 14). This vehicle has three, large (16-inch) rotating brushes that can clean a four-foot wide strip at up to 125 feet per minute, depending upon the type and amount of fouling. This also yields a maximum cleaning rate of 450 square feet per minute. Various cleaning brushes are available, depending upon the nature and degree of fouling. The vehicle weighs 360 pounds in air and is approximately six feet long, four feet wide, and two feet high. The vehicle is slightly positively buoyant in water and is held against the work surface with a 1,400 pound thrust. The vehicle rides on four traction wheels. The front two wheels are driven by a hydraulic motor for forward motion and steering. The hydraulic pump is powered by a 52 horsepower diesel engine. A diver rides the vehicle and directs it with a steering wheel.

Excavation and Debris Removal

59. Underwater excavation and debris removal techniques are required to keep sediment and debris from accumulating in stilling basins, discharge laterals, outlet channels, etc. (McDonald 1980). Sediment and debris must be removed before many types of underwater surveys, maintenance or repairs can be carried out.

Excavation Techniques

60. The three primary methods for the excavation of accumulated material, such as mud, sand, silt, clay, and cobbles, include: air lifting, dredging, and jetting. Controlled blasting may be used to remove large obstacles such as rocks and boulders. Explosive excavation techniques are beyond the scope of this report. The interested reader is referred to the literature for information on explosive excavation procedures, authorizations, and training.

61. The best method for excavating material depends upon the following factors (NCEL 1984):
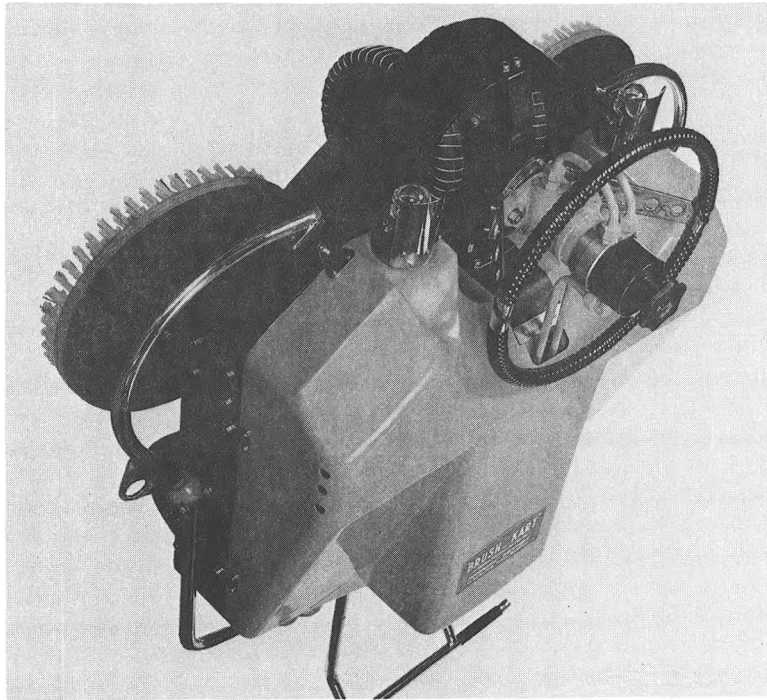
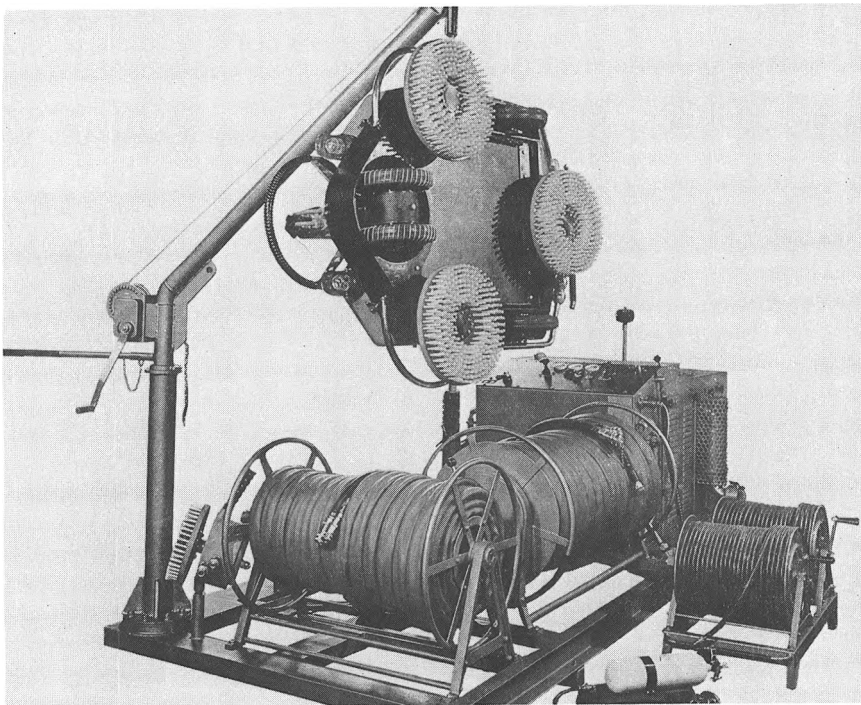Figure 14a.   Brush-Kart self-propelled
vehicle.

Figure 14b.   Brush-Kart cleaning vehicle and
deployment system.

- The nature of the material to be excavated: soft or hard, fine grained or coarse grained, and maximum size of particle.

- The horizontal distance the excavated material must be moved

- The vertical distance the excavated material must be moved

- The quantity of material to be excavated

- The operating environment, including water depth, currents, and wave action.

Table 1 provides general guidance on the suitability of the various excavation methods. Each of the techniques are discussd in more detail in the following sections.

Table 1. Guidance on Excavation Techniques

Excavation Factor	Excavation Method		
	Air Lift	Jet	Dredge
Type of seabed material	mud, sand, silt, clay, cobbles	mud, sand, silt, clay	mud, sand, silt, clay
Water depth	25 to 75 ft	unlimited	unlimited
Horizontal distance material moved	short	short	short to long
Vertical distance material moved	short to long	short	short to medium
Quantity of material excavated	small to large	small to medium	small to medium
Local current	not required	required	not required
Topside equipment required	compressor	pump	pump
Shipped space/weight	large	small	medium

62. _Air Lifting_. The air lift uses a density differential to remove accumulated bed material. Air is introduced into the lower end of a partially

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submerged pipe. The air bubbles in the pipe, create a mixture less dense than the surrounding water. A suction is caused at the inlet as the lower density mixture in the pipe rises. The amount of material lifted depends upon the size of the air lift, the submerged depth of the pipe, the air pressure and volume, and the discharge head. The size of the discharge pipe depends upon the type and amount of material to be excavated. The air lift (Figure 15) can be from 10 to 70 feet long, but it is relatively inefficient in lengths less than 30 feet.

63. The air lift has the disadvantage of discharging the material relatively close to the intake point, which may result in some of the material settling back into the excavated area. If a current exists, the discharge should be positioned down current to allow the material to be carried away from the work site.

64. Dredging. Underwater dredging is used to move large amounts of soft bed material. It is useful when the water is too shallow for an air lift to be effective and also when the dredged material does not have to be lifted too far above the intake point. A typical underwater dredging system (Figure 16) consists of a tube or pipe with a 30-degree bend near the intake end. At the center of the bend a water jet is connected. The water jet is aimed towards the discharge and creates a suction at the intake. The height of the lift will depend upon the size of the pipe and the output of the pump. For example, a 200 gpm pump with a 6-inch pipe will lift up to 60 feet above the bottom material. If the lift height is only a few feet above the bed, this system can move up to 10 cubic yards per hour of mud, sand, and loose gravel (NCEL 1984).

65. Jetting. Jetting can be used to move large quantities of silt, sand, or mud. During underwater jetting operations, a diver directs a high velocity water stream through a nozzle at the material to be moved. Jetting nozzles with balancing retrojets that reduce or eliminate the backthrust are available (Figure 17). Jetting is often used for the burial of cables and pipelines and for the installation of structural piles and instrument tubes.

66. Two different jetting techniques are used in practice. The first involves the use of a large jet to erode and displace the bed material. This technique is best suited for moderately consolidated soils such as mud, as well as some noncohesive materials like sand. The second jetting technique typically uses many small jets to fluidize and move noncohesive sandy soils.
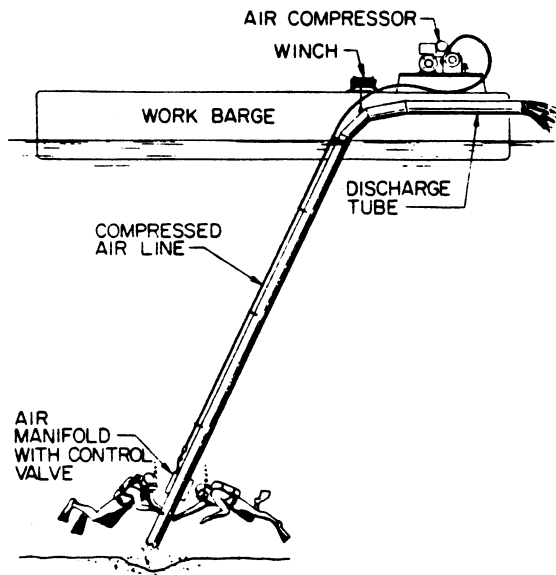
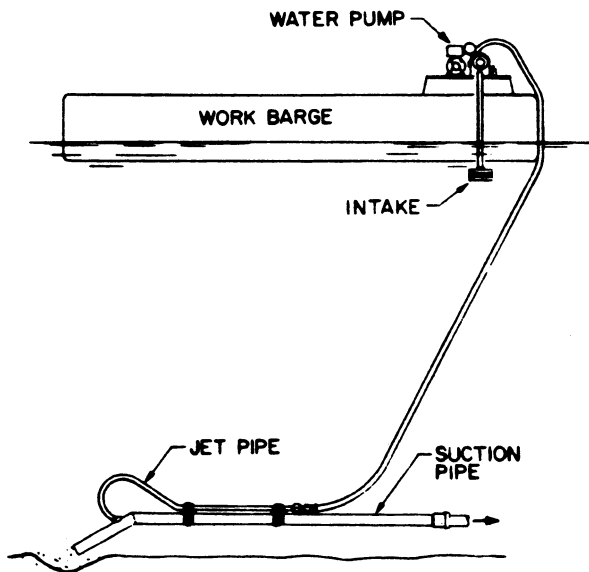Figure 15. Air lift for removing submerged fouling materials.

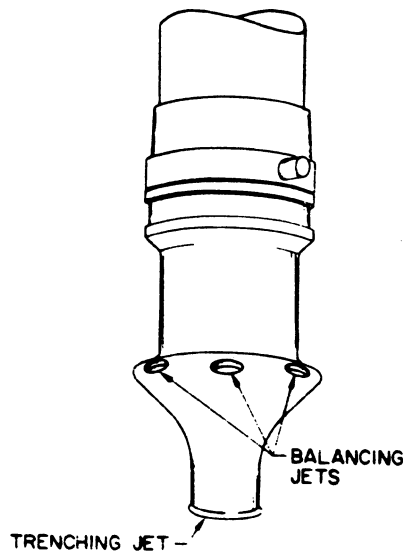Figure 16. Underwater dredging system.

Figure 17. Jetting nozzle with balancing retrojets.

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67. Sediment removal using a jetting technique is inefficient. The jet stream easily fluidizes the sediment, but with no means for further transport the sediment eventually settles back into the same area. On the other hand, dredging with water injected eductors does not provide a mechanism for fluidizing unconsolidated silts and clays. A diver is often required to first breakup and fluidize the sediment material in front of the dredge suction tube.

68. A prototype diver operated jet-dredge has been developed by the Naval Civil Engineering Laboratory that combines the benefits of a fluidizing jet and a dredging jet eductor (Thomson 1983). Tests revealed 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 (Smith and Mittleman 1978). The NCEL sediment excavation tool (Figure 18) consists of a jet-eductor, a jet nozzle, and a hydraulically powered sump pump. Multiple jets are used to fluidize the sediment and to significantly improve visibilty (over a single jet approach). Average excavation rates of 15 ft^3/min can be obtained with the jet-dredge tool, depending upon the soil characteristics and existing environment.

Debris Removal

69. A significant problem encountered in the underwater cleaning of civil works structures is the removal of accumulated debris, particularly debris from erosion damage. The primary types of debris that accumulate in civil works structures, such as stilling basins, include cobbles, sediment, and failed reinforcing steel. Cobbles and sediment can be removed using one of the excavation techniques discussed in the previous section. The removal of exposed and failed reinforcing steel often requires an underwater cutting technique to separate the reinforcing from the concrete slab or to divide the steel into sections small enough to bundle and transport to the surface. Transportation to the surface can be accomplished, without dewatering, by attaching the bundled reinforcing steel to underwater lift bags or an overhead crane. The following sections focus on several techniques that can be used to cut reinforcing steel underwater.

70. There are three general categories of underwater steel cutting techniques. The two more common techniques are mechanical and thermal.
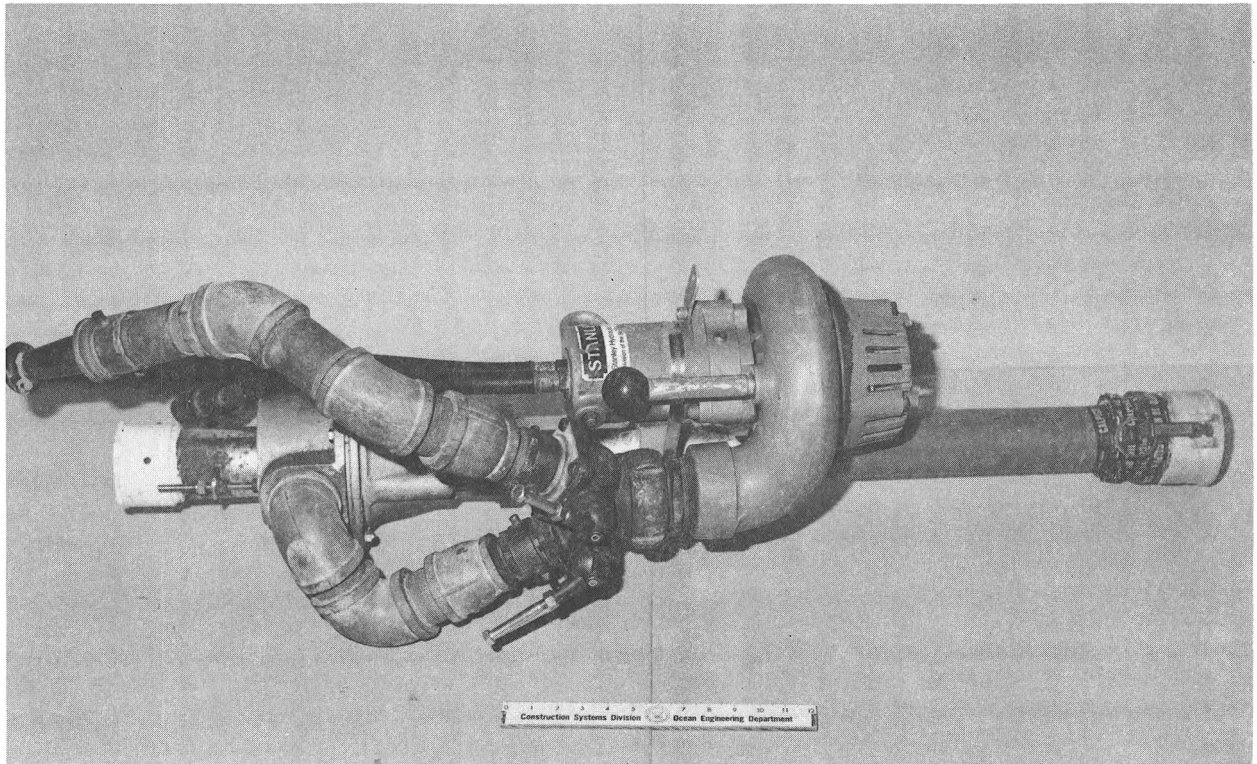
Figure 18. NCEL sediment excavation jet-dredge tool.

Another technique for underwater cutting evolving as a result of the relatively recent development of extremely high pressure abrasive waterjets.

71. <u>Mechanical Cutting</u>. The equipments used for mechanical cutting include hydraulically powered shears and band saws. Diver operated piston-actuated hydraulic shears for cutting steel cable and reinforcing are commercially available. A hydraulic barstock cutter (H.K. Porter model 1770CDX) and hydraulic cable cutter (H.K. Porter model 25662) require hydraulic oil at 10,000 and 5,000 psi respectively. These tools weigh approximately 20 pounds in water (Liffick and Barrett 1972).

72. A portable hydraulic bandsaw was developed by NCEL to allow divers to cut double-armored cable (Figure 19). The tool can be used in air or water to cut a variety of materials including steel, aluminum, wood, rope, and cable. The saw is configured to cut material up to 3-1/2 inch thick and 4-1/8 inch wide. The tool can be operated by any hydraulic power source capable of supplying 1,000 psi and 4-5 gpm.

73. <u>Thermal Cutting</u>. Three thermal techniques are recommended for underwater cutting: oxygen-arc cutting, shielded metal arc cutting and MAPP gas cutting. Oxygen cutting is the preferred technique for Navy Underwater Construction Team diver operations and is described below. A description of the other methods can be found in the U.S. Navy Underwater Cutting and Welding Manual, NAVSEA LP-000-8010. All three procedures require training and experience to ensure safety and efficient performance.

74. With oxygen-arc cutting, heat is applied with an electrode to the metal surface at the desired cut location. When the metal is sufficiently heated, a high velocity jet of pure oxygen is directed at the heated spot and the metal oxidizes or burns very rapidly. The tip of the electrode is consumed rapidly and must be replaced frequently. Two types of electrodes are used for underwater oxygen-arc cutting: the ultrathermic electrode and the steel-tubular electrode. Ultrathermic electrodes are preferred because they continue to burn after the current is switched off without loss of efficiency. They can also be used to cut nonferrous metals and some nonmetals (NCEL 1984). The ultrathermic electrode is held in a cutting torch as shown in Figure 20. Additional equipment required in an underwater oxygen-arc cutting system include: a high volume oxygen regulator; oxygen cylinders; a single pole, 400 ampere, direct current (DC) safety switch; an underwater C-type grounding clamp, a 200 ampere minimum DC welding machine; 1/0 welding cables for torch
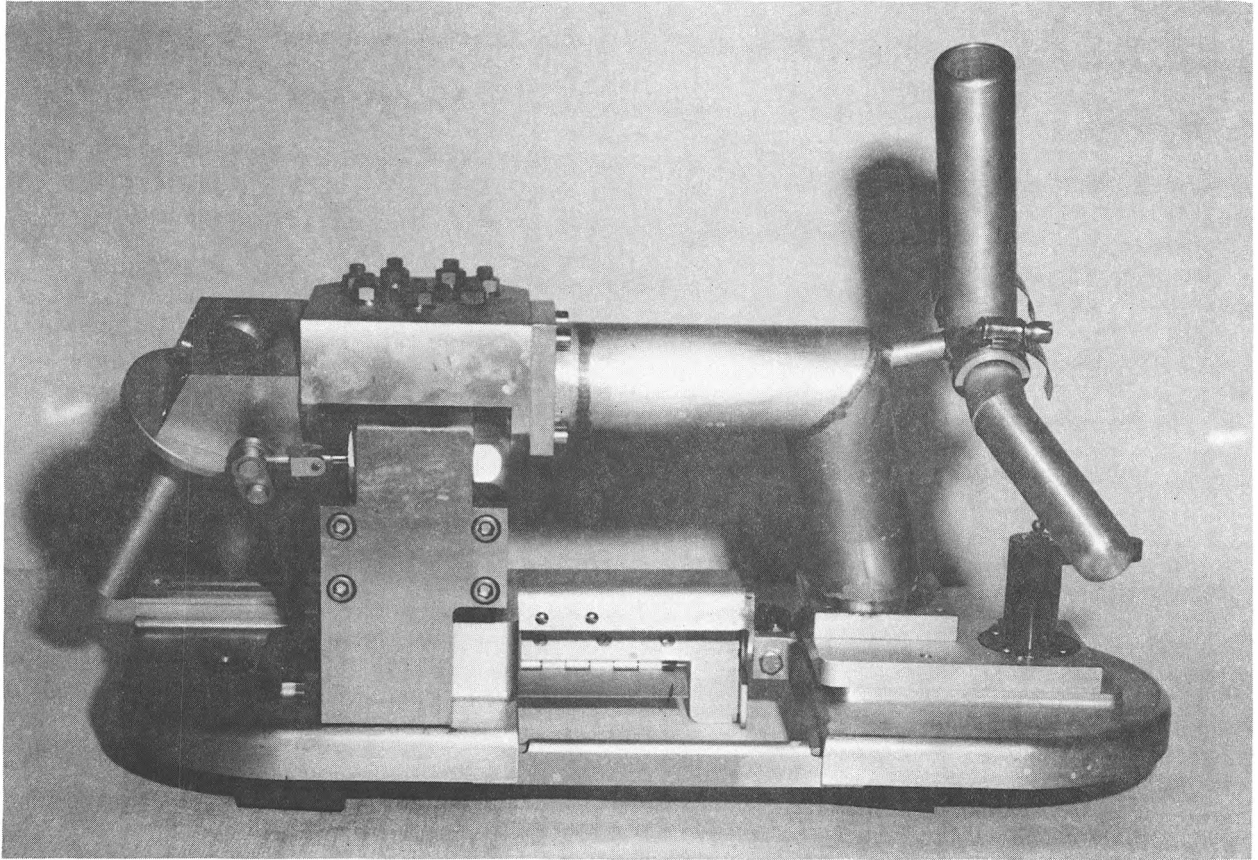
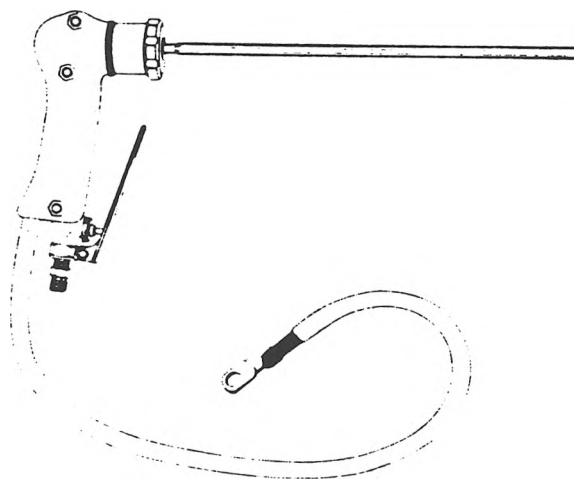Figure 19. NCEL portable hydraulic bandsaw.

Figure 20. Ultrathermic cutting torch.

and ground clamp and a 3/8-inch-ID oxygen supply hose from regulator to torch. In addition, two way diver-topside communication is strongly recommended for diver safety.

75. <u>Abrasive-Jets</u>. High-pressure waterjets have been used effectively to cut many materials, such as wood, plastics, fiberglass, paper, and cloth. The addition of abrasives to the waterjet allows many hard materials, such as steel, glass, concrete, and stone to be cut. The primary advantages of abrasive waterjets over other techniques include:

- improved safety since there is not a potential for the ignition of explosive gases

- improved safety since there is not a requirement for high electrical current or voltages

- additional capability since by turning off the abrasive feed, concrete can be cut or eroded without damaging the steel reinforcement

76. The main components of an abrasive-jet cutting system are the high-pressure pump, the waterjet, the abrasive feed system and the abrasive-jet nozzle. Pressures from 25,000 to 45,000 psi are effective in cutting even the hardest materials with abrasive waterjets. Flow rates of three gpm are typical. It is estimated that abrasive waterjets can cut through 1-inch steel at approximately 6 inches per minute. Cutting rates of slightly more than 1-inch per minute have been obtained on 10-inch thick concrete reinforced with 3/4-inch diameter steel bars (ADMAC 1984).

77. Abrasive waterjet systems have been used to effectively cut many hard materials, including steel and concrete, in air. There are, however, no commercially available underwater abrasive-jet cutting systems. The technology for underwater application does exist; it is a matter of producing a system that can be safely and effectively operated in an underwater environment.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

78. Several techniques and equipment for cleaning the underwater por-
tion of civil works structures have been presented. The selection of the best
system for a cleaning task depends upon the following items:

- the type of structure being cleaned

- the construction material of the structure

- the type and amount of fouling to be removed

- the environmental conditions

- the objective or purpose of the cleaning (for visual
  inspection, nondestructive evaluation, paint removal,
  maintenance, repairs,..)

79. The initial cleaning tool selection criteria are dependent upon the
type of material that must be cleaned. There are three primary types of mate-
rial used in the construction of civil works structures: concrete, steel, and
timber. Concrete is the most common material because of its relatively low
deterioration rate in marine and freshwater environments. For each construc-
tion material, the selection of the best tool depends upon the degree and
extent of fouling, the size and accessibility of the surface to be cleaned,
and the objective of the cleaning. For example, a visual inspection does not
require the level of cleaning that a nondestructive inspection technique, such
as ultrasonics, requires. The environmental conditions, such as water depth,
temperature, and visibility, also influence the final selection. Table 2
shows the types of cleaning tools recommended for different types of material,
fouling, and surface area.

Concrete Structures

80. Concrete structures in marine environments are typically the most
difficult to clean because calcareous marine fouling adheres tenaciously to
the surface. Tools that knock off hard, calcareous fouling are required in
environments where barnacles, tubeworms, and crustaceans are found. On large
and accessible concrete surfaces, a self-propelled vehicle can be used to
quickly and effectively remove light to moderate marine and freshwater

fouling. When cleaning an area that is not large enough to justify the use of a self-propelled vehicle, hydraulically powered hand tools, such as the rotary abrading Whirl Away, can efficiently remove all fouling from concrete surfaces. A high-pressure waterjet is the best tool to use in obstructed or limited access areas. A high-pressure, high-flow system can be used to remove most types of moderate to heavy fouling. A high-pressure, low-flow system may be required to clean an area that is difficult or impossible to reach with a high-flow system because of the retrojet. Hand tools should only be used when there is light fouling or spot cleaning is to be done in only a few places.

Table 2. Summary of cleaning tools for civil works structure

Fouling	Size	Material		
		Concrete	Steel	Timber
Light	Massive	Self-propelled vehicles		Waterjets
	Large	Waterjets and hand held power tools[1]		
	Limited Access	High pressure waterjets		
Moderate	Massive	Self-propelled vehicles		Waterjets/ power tools
	Large	Power tools/ waterjets	2	Power tools/ waterjets
	Limited Access	High pressure waterjets		
Heavy	Massive	Self-propelled vehicles		N/A
	Large	Power tools	Power tools/ waterjets	Power tools
	Limited Access	High pressure waterjets		

Notes:
    (1)   Hand tools for limited spot cleaning of light and loose fouling.
    (2)   Abrasive waterjets for paint removal or bare metal finish on steel structures.

Steel Structures

81. The underwater removal of fouling from steel structures tends to be less time consuming than from concrete structures. Self-propelled vehicles are recommended for cleaning most types of fouling on large and unobstructed steel structures. Although these systems are expensive, the cleaning rates achieved with self-propelled vehicles offer significant time and cost savings. For smaller areas, it is often more cost effective to use waterjets or diver-operated power hand tools. Abrasive waterjets should be used whenever paint removal and a bare metal finish is desired. As on concrete structures, hand tools should be used only for spot cleaning and for removing light fouling.

Timber Structures

82. The underwater cleaning of timber structures is a difficult task because with most commercially available underwater cleaning tools it is hard to avoid damaging the timber material. A moderate pressure (4,000 to 6,000 psi) waterjet system readily removes light fouling. High pressures and high flows remove all types of fouling, but also fray and splinter the surface. A hydraulic power brush removes light to moderate fouling without excessive damage to the timber. Hand tools can be used to remove most types of fouling, but the use can be very time consuming.

Excavation and Debris Removal

83. In addition to the removal of marine and freshwater fouling, accumulated sediment and debris must be removed from the underwater portion of civil works structures. Air lifts should be used to remove most types of sediment material in depths of 25 to 75 feet. Jetting and dredging techniques, or a combination thereof, are not depth limited. The removal of eroded steel reinforcing using mechanical, thermal, and abrasive jet underwater cutting techniques was also discussed. Abrasive-jet cutting is a promising new technique that can be used to cut steel reinforcement and concrete, but there are no commercial systems available at this time.

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APPENDIX A
UNDERWATER SOUND PRESSURE LEVEL CALCULATIONS

INTERIM GUIDANCE

In July 1982, the Bureau of Medicine and Surgery (BUMED) provided interim guidance for determining underwater noise levels that superseded the existing method of calculating exposure time limits for underwater operators. The interim guidance is in effect while BUMED completes a study and develops a comprehensive instruction on underwater noise limits. The interim guidance is as follows:

    a. Continue to use standard techniques and instrumentation developed by the underwater sound community and to thoroughly document each test and evaluation of underwater tools and equipment.

    b. Recompute the correction factor for impedance mismatch deleting the A-weighting factor. Perform the following steps for each test:

        (1) Obtain octave band levels of noise spectrum from 125 to 8,000 Hertz.

        (2) Subtract underwater hearing threshold levels at each octave frequency.

        (3) Add minimum audible field values for threshold in air.

        (4) Use combined octave band levels to compute allowable exposure time.

    c. Use the Department of Defense criterion of 84 decibels for 8-hour exposure periods with a 4-decibel trading relationship for computing allowable exposure time.

    d. Add equivalent noise dose in water to noise dose in air to obtain total daily noise dose for exposed personnel.

    e. Do NOT use correction factors for attenuation of noise by wetsuit hood or the ear canal filled with water.

    f. For noise with the preponderance of energy outside the frequency range of 125 to 8,000 Hertz or for impulse noise, consult with the Auditory Research Department, Naval Submarine Research Laboratory, New London, Conn.

    g. Conduct annual monitoring hearing tests on exposed personnel.

SAMPLE CALCULATION

An average sound pressure level spectrum for the Naval Civil Engineering Laboratory (NCEL) prototype high-pressure waterjet tool (0.031-inch straight jet nozzle) is shown in Figure A-1. A worksheet used to calculate the permissible exposure time limits is shown in Figure A-2. Across the top of the worksheet are center frequencies of the octave band levels (OBLs) from 125 to 8,000 Hertz. Vertically, along the left side of the worksheet, are numbered steps for the calculation procedure.
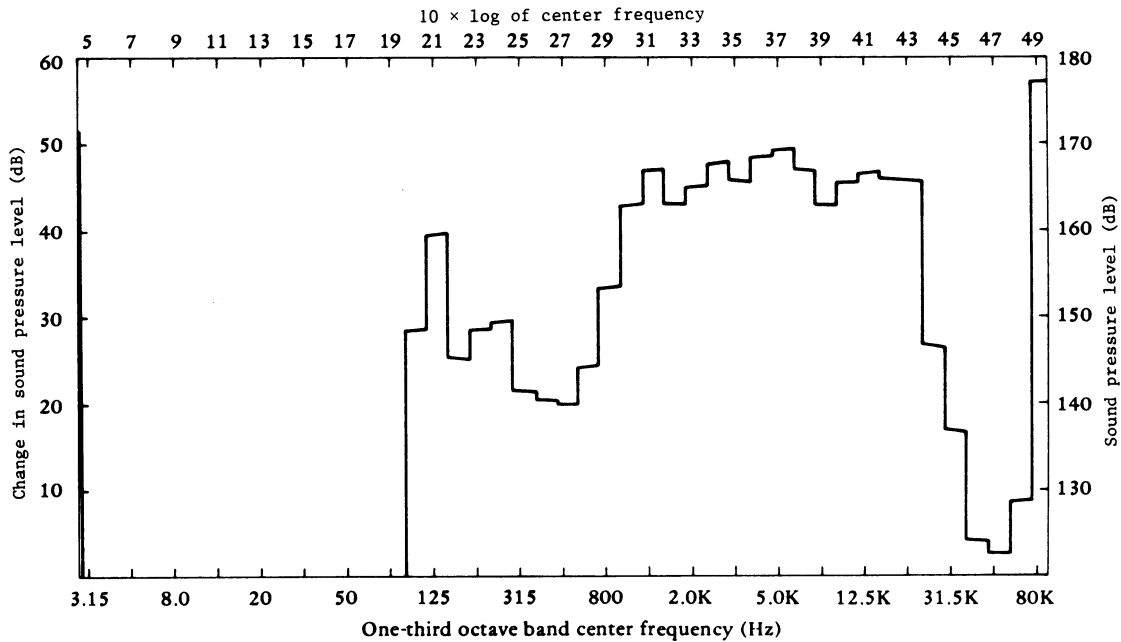
Figure A-1. Representative sound pressure level spectrum for the 0.031-inch straight jet nozzle in open water measured at the diver's ear.

In Step 1 the octave band levels of the noise spectrum (Figure A-1) are computed from the three corresponding one-third octave band levels labeled L_i. The octave band level is obtained from the equation:

$$L_{OBL} = 10 \log_{10}\left(\sum 10^{L_i/10}\right)$$

If an octave band analysis of the noise spectrum is used instead of a one-third octave band analysis, Step 1 is unnecessary and the octave band level can be read directly from the spectrum and entered as L_{OBL} on the worksheet.

Run #: _____   Nozzle: _____

Test Description: _____

Step	Center Frequency	Frequency (Hz)						
		125	250	500	1,000	2,000	4,000	8,000
1	1 2 3							
2	L_{OBL} - dB_{ref}	-26.0	-26.0	-26.0	-26.0	-26.0	-26.0	-26.0
3	-u/w correct	-70.0	-65.0	-58.0	-60.0	-66.0	-67.0	-74.0
4	BSL + MAF	+21.0	+11.0	+6.0	+4.0	+1.0	-3.0	+10.0
	L_i =							
5	$$L_c = 10 \log_{10} \left(\sum 10^{L_i/10} \right)$$							
6	$$T = 16 \div 2^{(L_c - 80)/4}$$							

where: L_{OBL} = octave band level

   dB_{ref} = correction to be in dB re 20 µPa

   u/w correct = underwater heating threshold correction

   BSL = band sensation level

   MAF = minimum audible field thresholds in air

   L_i = octave band level for equivalent air exposure

   L_c = overall or combined exposure level

   T = permissible exposure time in hours

**Figure A-2. Sound pressure level permissible
exposure time worksheet.**

A-3

In Step 2 the OBLs are adjusted, if necessary, to be in decibels reference 20 μPa (db re 20 μPa). The adjustment, called decibels reference, requires subtracting 26 decibels from the OBLs in db re 1 μPa.

In Step 3 underwater hearing threshold levels are subtracted from each octave band level (re 20 μPa). These threshold levels are as follows (OPNAVINST 6260.2):

- 70 decibels for 125 Hertz
- 65 decibels for 250 Hertz
- 58 decibels for 500 Hertz
- 60 decibels for 1,000 Hertz
- 66 decibels for 2,000 Hertz
- 67 decibels for 4,000 Hertz
- 74 decibels for 8,000 Hertz

The result, after subtracting the underwater threshold from the octave band level, is the band sensation level (BSL).

In Step 4 the minimum audible field (MAF) threshold levels in air are added to the BSLs at each center frequency. The in-air MAF threshold levels are as follows (OPNAVINST 8530.2):

- 21 decibels for 125 Hertz
- 11 decibels for 250 Hertz
- 6 decibels for 500 Hertz
- 4 decibels for 1,000 Hertz
- 1 decibel for 2,000 Hertz
- -3 decibels for 4,000 Hertz
- 10 decibels for 8,000 Hertz

The result, after subtracting the MAF threshold levels from the BSL, represents the octave band level for an equivalent exposure in air (L_i).

In Step 5 an overall or combined exposure level, L_c, is computed using the formula:

$$L_c = 10 \log_{10} \left(\sum 10^{L_i/10} \right)$$

where the L_i values are the octave band levels obtained in Step 4.

In Step 6 the permissible exposure time is calculated using the formula:

$$T = 16/2^{(L_c-80)/4}$$

where L_c is the combined or overall exposure level obtained in Step 5. The permissible exposure time, T, is expressed in hours. Figure A-3 shows the sound pressure level worksheet filled in based upon the noise spectrum in Figure A-1.

Run #: Anacapa #5   Nozzle: 0.031-inch straight jet

Test Description: in open water (free stream)
measured at the diver's ear

Step	Center Frequency	Frequency (Hz)						
		125	250	500	1,000	2,000	4,000	8,000
1	1 2 3	148.5 160.0 145.0	148.5 149.5 141.5	140.5 140.0 144.0	153.5 163.0 167.0	163.0 165.0 167.5	165.5 168.5 169.0	167.0 163.0 165.5
2	L_{OBL} $-dB_{ref}$	160.4 -26.0	152.4 -26.0	146.7 -26.0	168.6 -26.0	170.3 -26.0	172.7 -26.0	170.2 -26.0
3	-u/w correct	134.3 -70.0	126.4 -65.0	120.7 -58.0	142.6 -60.0	144.3 -66.0	146.7 -67.0	144.2 -74.0
4	BSL + MAF	64.4 +21.0	61.4 +11.0	62.7 +6.0	82.6 +4.0	78.3 +1.0	79.7 -3.0	70.2 +10.0
	L_i =	85.4	72.4	68.7	86.6	79.3	76.7	80.2
5	$$L_c = 10 \log_{10} \left(\sum 10^{L_i/10} \right) = 90.3$$							
6	$$T = 16 \div 2^{(L_c-80)/4} = 2 \text{ hr, } 40 \text{ min}$$							

where:

L_{OBL} = octave band level

dB_{ref} = correction to be in dB re 20 µPa

u/w correct = underwater heating threshold correction

BSL = band sensation level

MAF = minimum audible field thresholds in air

L_i = octave band level for equivalent air exposure

L_c = overall or combined exposure level

T = permissible exposure time in hours

Figure A-3. Completed worksheet.