AD-753 262

HUMAN FACTORS GUIDE FOR THE DESIGN OF DIVER-OPERATED HAND AND POWER TOOLS

Birger G. Andersen

Whittenburg, Vaughan Associates, Incorporated
Landover, Maryland

July 1972

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

AD753262

OI-TR-72/2-Sk

Final Technical Report
ONR Contract No. N00014-70-C-0070
Work Unit No. NR 196-095

HUMAN FACTORS GUIDE FOR THE DESIGN OF DIVER-OPERATED HAND AND POWER TOOLS

Birger G. Andersen

July 1972

Prepared for:

Office of Naval Research
Engineering Psychology Programs
Arlington, Virginia 22217

Prepared by:

Oceanautics Division
Whittenburg, Vaughan Associates, Inc.
3308 Dodge Park Road
Landover, Maryland 20785

This document has been approved for public release and sale; its distribution is unlimited

149

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) Oceanautics Division, Whittenburg Vaughan Associates, Inc. 3308 Dodge Park Road, Landover, Maryland 20785	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP

3 REPORT TITLE

HUMAN FACTORS GUIDE FOR THE DESIGN OF DIVER-OPERATED HAND AND POWER TOOLS

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report, October 1969 through June 1972

5 AUTHOR(S) (Last name, first name, initial)

Birger G. Andersen

6 REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1972	149	

8a CONTRACT OR GRANT NO. N00014-70-C-0070 b. PROJECT NO. NR 196-095 c. d	9a. ORIGINATOR'S REPORT NUMBER(S) OI-TR-72/2-Sk 9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None

10 AVAILABILITY/LIMITATION NOTICES

This document has been approved for public release and sale; its distribution is unlimited.

11 SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Office of Naval Research Engineering Psychology Programs Arlington, Virginia 22317

13 ABSTRACT

This final technical report describes the results of a research study directed toward expanding the available data base of man's ability to work underwater, by providing human factors data on man's requirements and capabilities as an undersea worker. The report is a basic human factors criteria guide for the design of diver-operated tools and work systems.

Data included were developed and compiled through evaluation of operational diver work tasks, in-the-field observation of diving operations, and survey and review of existing human factors research data.

The document is organized into five major sections: 1) Anthropometry and Biomechanics, 2) Body Restraint and Tethering Systems, 3) Underwater Visibility, 4) Control/Display Criteria, and 5) Human Engineering Considerations for Specific Underwater Tools. The Appendix contains detailed specifications for a selected number of frequently used power tools.

DD FORM 1 JAN 64 1473

UNCLASSIFIED

Security Classification

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Human Engineering Performance Measurement Underwater Tools Underwater Work Measurement Man-in-the-Sea Diver Performance						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

UNCLASSIFIED

Security Classification

OI-TR-72/2-Sk

Final Technical Report
ONR Contract No. N00014-70-C-0070
Work Unit No. NR 196-095

HUMAN FACTORS GUIDE FOR THE DESIGN OF DIVER-OPERATED HAND AND POWER TOOLS

Birger G. Andersen

July 1972

Prepared for:

Office of Naval Research
Engineering Psychology Programs
Arlington, Virginia 22217

Prepared by:

Oceanautics Division
Whittenburg, Vaughan Associates, Inc.
3308 Dodge Park Road
Landover, Maryland 20785

ACKNOWLEDGMENTS

This program of research was supported by the Engineering Psychology Programs of the Office of Naval Research. We wish to express our appreciation to Dr. James W. Miller, former Head of the Engineering Psychology Branch, who initiated the study and provided support during the first year of the program. We also wish to thank Dr. Martin Tolcott, present Director of Engineering Psychology Programs, and Mr. Gerald S. Malecki for their support, encouragement, and guidance during the latter phases of the study.

Our appreciation also goes to the many individuals and groups who have made important and material contributions to this report. While we cannot acknowledge everyone involved, we do wish to recognize the cooperation of the Naval Civil Engineering Laboratory in permitting the use of their facilities and personnel and to thank Mr. John Quirk, Mr. G. Lonn Liffick, and Mr. Frederick Barrett of NCEL for their active interest and valuable technical suggestions made during the course of this study.

A special note of indebtedness is given to Mrs. Elizabeth Richmond of Oceanautics, Inc., without whose editorial assistance this report could not have been produced.

CONTENTS

Preceding pagesblank

Section | Page

FIGURES

Preceding page blank

TABLES

Preceding page blank

FOREWORD

This final report presents the results of the work performed under ONR Contract No.N00014-70-C-0070, "Development of Human Factors Criteria for Design of Diver-Operated Underwater Equipment and Systems." The program was performed during the period from October 1969 through June 1972, and encompassed:

1. The specification of underwater tool categories and their functional requirements within the context of operational underwater construction and salvage jobs.

2. The development and compilation of human factors design criteria data applicable to specified categories of underwater tools and individual tool items.

The research program was aimed at filling a gap in current human factors literature of man's capabilities and limitations in an underwater work environment. The technical approach taken involved:

1. Evaluation of operational work tasks currently being performed by man in the sea.

2. In-the-field evaluation of actual diving operations for identifying and diagnosing human factors design deficiencies.

3. Survey and review of existing human factors research data for applicability to the problems and conditions unique to the underwater environment.

The results of this research program are described in two technical reports:

1. An annual summary report in January 1971, entitled "Human Engineering Criteria for the Design of Diver-Operated Underwater Tools." This report summarized the first year's study effort and was limited to an evaluation of underwater tools used by divers in the performance of torqueing tasks.

2. "Diver Performance and Human Engineering Tests, Salvage Equipment Program, U.S.N./Makai Range Aegir Habitat Saturation Dive," February 1972, described the results of a diver performance

evaluation program designed to obtain both quantitative and qualitative data on the capabilities and limitations of divers in operating selected underwater tools in simulated operational salvage tasks under saturation diving conditions. This report will be included as an appendix to the overall report describing the U.S.N./Makai Range Aegir Habitat Saturation Dive conducted in November 1971.

The current and final report prepared during this research program is a basic human factors design criteria guide applicable to the design and utilization of diver-operated hand and power tools. This document has been organized into five major sections: 1) Anthropometry and Biomechanics, 2) Body Restraint and Tethering Systems, 3) Underwater Visibility, 4) Control/Display Criteria, and 5) Human Engineering Considerations for Specific Underwater Tools. An appendix to the report provides detailed specifications for a selected number of power tools most frequently used in current underwater salvage and construction operations.

PURPOSE AND SCOPE

Technological advances made in the areas of diving physiology and ocean-oriented man/machine systems and the application of this technology to both military and commercial diving operations have resulted in man's penetration of the ocean to depths and tolerances previously thought impossible. Yet the number of complex work tasks performed in this hostile environment has been limited.

As new manned underwater systems and equipment are developed, divers will be called upon to perform new and increasingly demanding work tasks for which their capabilities are not clearly understood. As specialized underwater tools and equipment are developed to expand man's potential in the undersea environment, the problem of matching men and machines becomes increasingly complicated.

Over the years the human factors profession has generated a large quantity of research documentation, guidelines, and handbooks which provide human factors engineering data to assist designers and engineers in optimizing the development and utilization of man/machine systems and equipment. While these data encompass a broad range of systems and hardware, they are, for the most part, not applicable to the requirements of the underwater environment.

This research program was undertaken to expand the data base concerning man's ability to work underwater and to develop and compile this material into a human factors guide relating to man's requirements and capabilities as an undersea worker.

To insure the achievement of this goal within the context of the operational diving community, a technical approach was taken that would:

1. Concentrate on the operational work tasks currently being performed by man-in-the-sea, provide for realistic environmental conditions, and include the major categories of tools in current usage.

2. Emphasize in-the-field evaluation and diagnosis of design deficiencies and validate proposed human factors criteria via the evaluation of both operational and prototype equipment designs.

3. Utilize existing human factors data, where applicable, to

the specific capabilities and requirements of the equipment and its users.

In organizing the human factors guide, a format was selected that would emphasize factual information expressed in graphic and/or tabular form.

Section I contains that information which relates to the structure of the human body and its biomechanical capabilities. Included are both static and dynamic body dimensions, range of movement, and strength characteristics.

The operation of tools in a tractionless environment is clearly most efficient when a means of traction or control of body position is provided for a diver. Section II reviews the design features and characteristics of various restraints and tethering systems that can be applied to a wide range of underwater work situations.

Section III consists of data relating to the problems of underwater visibility. The basic physics of underwater visibility are described, along with the problems of visual resolution, stereoscopic acuity, size and distance judgment, and color visibility.

Section IV provides a compilation of human engineering control/display criteria and recommendations for the design and modification of tools for underwater applications.

Section V contains a detailed human engineering evaluation of selected underwater tool items currently employed in underwater construction and salvage operations by military and commercial diving organizations.

The specified nature and infrequent use of some tools employed by divers in underwater work have resulted in limited and/or inadequate performance and human factors data. Evaluation of these tool items has not been incorporated in this report.

Anthropometric and biomechanical data for divers were found to be extremely limited, which required the use of data from other population groups and work environments only approximating undersea conditions. Clearly, the limited amount of quantitative research data available, regarding the physical characteristics and capabilities of working divers, must be expanded in order to determine accurately how well a proposed

underwater tool will accommodate the anticipated user population with respect to such characteristics as the various body dimensions, strength, reach, and endurance. It is hoped that these shortcomings can be corrected by future research efforts.

I. ANTHROPOMETRY AND BIOMECHANICS

A. Introduction

Data relating to the structure of the human body and its biomechanical capabilities constitute an important variable for the design of underwater tools. Such data include both static and dynamic body dimensions, range of movement, and muscle strength. The general criteria for determination and selection of appropriate tool dimensions and control requirements must take into consideration the size and capabilities of the general diver user population. For most effective work output and personal safety, an underwater tool system should match the range of the physical size and strength capabilities of the user population.

Tool configurations and dimensions should be determined and specified, based on the following considerations:

1. The physical measurements of man himself, his size, shape, and biomechanical capabilities.

2. Increase in body size, movement constraints, and other reductions in work capability which result from specific diving apparel and life support systems.

3. The general body position which a diver must maintain during execution of an underwater work task.

4. Mobility requirements of the diver while handling the tool item or system.

5. The nature, frequency, difficulty, and duration of the work task for which the tool was designed.

B. Human Body Measurements and Factors Affecting Biomechanical Capabilities

1. Physical Measurements of Man

Man, unlike inert material, varies significantly with respect to physical size and biomechanical capabilities as the result of a variety of factors, biological, environmental, and occupational. Two kinds of anthropometric dimensions, static and dynamic, are generally applied to the problems of equipment design.

Static human body dimensions are based on measurements of nude subjects in rigid and artificially erect positions. As such, these measurements are not representative of the positions the human body assumes in the performance of work or in the operation of tools. Further complications arise from static body measurements, since additional allowances must be made for clothing and other personal equipment worn under the full range of environmental conditions in which the operator will be working.

Dynamic body dimensions include those measurements that vary with body movements. These dimensions are measured with subjects in various working positions. Since most dynamic dimensions result from altered body movements, they are complex and difficult to measure.

A problem that will confront the designer of underwater tools is the fact that available anthropometric literature is devoted entirely to men working on land or in the air. The data are also heavily weighted toward military populations. Ideally, the designer of underwater equipment and tools snould identify the user population and seek reliable data on its dimensions and capabilities. However, since no comprehensive anthropometric data exist for the diving population, caution must be exercised in applying the existing data to underwater tool design. The anthropometric data presented in this report have been selected from existing literature as appearing most applicable to the underwater environment.

2. Diver Apparel and Equipment

Equipment and tools designed for underwater applications should suit the diver, as he will use this equipment under actual operating conditions. While the typical underwater worker's environment may vary with temperature, visibility, and depth, the primary factors affecting his performance will be his wearing apparel and life support equipment. Three types of diving dress can be identified as those worn by the working diver:

Deep-Sea Diving Dress consists of a spun-copper helmet with fittings and breastplate, and diving suit that encloses the entire body with the exception of head and hands and, when worn with diving helmet and gloves, provides the diver with a complete, watertight covering. Weighted belt and shoes are used to overcome the positive buoyancy gained by the volume of the helmet and inflated dress. Air is supplied by hose from the surface to the diving helmet.

Lightweight Diving Outfit consists of dress, mask or lightweight fiberglass helmet, hose, safety line, weight belt, and shoes. The one-piece dress, with hood cemented to the body part, is made of rubberized fabric and covers the entire body with the exception of the face and hands. Because air enters and exhausts directly into the face mask or light helmet without entering the lightweight dress, there is no excess buoyancy with this outfit. The weights provided can, therefore, be much lighter than those used with the deep-sea dress.

Wetsuit and Scuba consist of a cellular, neoprene, two-piece dress usually fabricated with a protective nylon coating. Wetsuits are available in various thicknesses, depending on the degree of thermal protection required. Supplemental wetsuit apparel includes hood, gloves, and boots. Life support is provided by diver-worn air bottles connected to a scuba regulator and mouthpiece.

Each of these types of diving apparel and its associated personal equipment affects human body dimensions and restricts the diver's movement and strength to varying degrees. Further variations in equipment result in added movement restriction and changes in overall dimensions. Additional equipment resulting in increased size and bulk may include hot-water-heated wetsuits, closed and semi-closed breathing apparatus requiring chest-mounted breathing bags, and specialized mixed-gas diving helmets.

The bulkiest diving apparel is the deep-sea dress. It imposes the greatest constraint on the diver's body movements and mobility. The weighted shoes and bulky helmet of this outfit severely restrict the positions in which the diver can effectively work. The primary advantage of this outfit is that the diver is fully enclosed and is therefore able to achieve a high degree of thermal protection. The deep-diving helmet also allows the most reliable and intelligible voice communications between the diver and the surface support personnel. For underwater operations utilizing diver-operated welding and torch cutting equipment, reliable voice communication is considered desirable.

Some relief from bulk and movement constraints can be obtained with the less cumbersome lightweight diving outfit. Though the diver can wear fins and swim in this outfit, normal usage of this diving apparel includes weighted shoes and either a full face mask or a lightweight fiberglass helmet with air supplied from the surface. The thermal protection provided by this outfit is less than that of the standard deep-sea dress. It has, therefore, found its greatest use in areas where the water temperature is relatively warm or where only short dive durations are required. Voice communication is possible with the lightweight diving outfit; however, intelligibility is reduced considerably because of the smaller air cavity of the lightweight helmet and the full face mask.

The wetsuit and scuba outfit is considered by many to be the most versatile diving apparel in operation today. Divers are unencumbered by surface air hoses and have nearly complete freedom of movement. The thickness of the neoprene foam material governs the thermal insulating properties of a wetsuit. Suit material is offered in thicknesses of 1/8, 3/16, 1/4, and 3/8 inches. While the thicker materials afford more insulation, they also impose some restrictions in movement due to the additional bulk. However, even with the thickest wetsuit, the water pressure at depths over 100 feet will compress the suit to the point where not only is the bulk of the suit reduced but also its thermal properties. For this reason the wetsuit and its inherent advantages must be restricted to shallow depths. Recent developments in the use of hot-water-heated wetsuits have overcome the depth limitations and thermal insulating inadequacies of the standard wetsuit. However, the freedom of movement attributed to the wetsuit is severely reduced by the increased bulk of the heated suit and the hot-water hoses which must be employed to pump heated water to the diver.

With the wide range and combinations of diving apparel currently used

by working divers, it can readily be seen that variations in overall diver size and restrictions in diver movements resulting from his apparel will be significant. The anthropometric and biomechanical data presented in this guide have been selected from existing literature as being representative of the anthropometric variables important to the design of diver-operated equipment. Since most of these data represent dimensions and capabilities of men operating in a space of 1-G surface environment, caution must be used in applying the data to the diver work situation. Where dimensions and measurements permit, data will be adjusted to represent a specific diving dress and/or underwater work situation.

3. Underwater Work Positions and Mobility

The body positions that a diver must assume and maintain while operating tools underwater are significantly different from the seated, standing, kneeling, and prone positions which are standard for the surface operator. Based on performance measurements of divers operating various types of tools underwater and direct observation of divers working in a wide range of operational situations, a number of factors which influence and limit underwater working positions can be identified:

Diver apparel and equipment--The working positions available to a diver are closely related to his apparel and personal equipment, since most dynamic dimensions are altered by restrictions in body movements. The diver outfitted in deep-sea dress is most severely hampered in the working positions he can assume and maintain. While the overall bulk of the deep-dive dress offers some resistance to body movement and position, the primary effect on his working position results from his weighted shoes and diving helmet. The weighted shoes make it almost mandatory that a diver work in a vertical position either in a negatively buoyant state with feet firmly planted on the ocean floor, or in a semi-buoyant state suspended from his life line. He is also limited by the size and bulk of the deep-sea diving helmet which further restricts his movement and overall mobility.

The working positions within the capability of a diver are considerably increased by the use of a lightweight diving outfit. When this outfit is used in conjunction with a full face mask or lightweight fiberglass diving helmet, and swim fins, the diver can assume other working positions than the vertical stand-up position. While the mobility obtained with the lightweight outfit does provide the diver with the potential for increased flexibility, the diving industry normally uses ankle weights or weighted shoes, thereby limiting the diver's working position to the standing one. The wetsuit-outfitted diver clearly has the greatest mobility underwater, since he is unencumbered by weighted shoes or bulky diving helmet and is able to maintain himself in a state of near-neutral buoyancy. This degree of flexibility allows the diver to work in an infinite number of positions not possible to the deep-sea-dressed diver.

Work surface orientation -- The orientation of the surface on which a diver is working will influence and limit the diver's working position requirements. Work surfaces applicable to underwater work are classified as being overhead, vertical, or deck. To work effectively in any of these planes, the diver must be able to fulfill certain basic requirements. First, he must orient his body in a position that will allow him to see the work surface. Second, he must be able to operate the tool item from this position so that effective biomechanical forces can be applied.

Diver performance research (Barrett and Quirk, 1969) has shown that the time required to perform hand tool operations underwater will vary depending on the work surface orientation. The orientation which allows a diver to assume the most comfortable working position and also to gain the maximum mechanical advantage is the deck position. This is especially true when operating heavy tools such as most hydraulic-powered hand tools. The diver assumes a crouched standing position and lets his tool rest against the work surface, thereby reducing a great deal of energy expenditure which would otherwise be used in supporting the weight of the tool over the work surface. The deck surface also lets the diver operate in a comfortable, crouched, standing or kneeling position. However, the diver must assume the weight of his tool while operating on a vertical surface, thereby increasing his energy expenditure, expecially when heavy tool systems are involved. The overhead work surface is the most inefficient for the diver to work on, since it is difficult to assume a comfortable working position and achieve an effective mechanical advantage when operating tools that require the application of force against the work surface.

Tool handling -- The handling characteristics and the physical configuration of a tool play an important role in determining a diver's working position. A tool weighing in excess of 10 pounds will require a diver to use both hands in operating and guiding it. Therefore, in order to maintain his body and the tool in a proper relationship to his work surface, he must be able to place his feet on a firm horizontal surface and operate the tool from a standing position. An alternative method for operating heavy hand tools is the use of body restraints to anchor the diver in a fixed position in relation to the work surface. Tools that are light in weight or near neutral in buoyancy provide the diver with a greater latitude of working positions in which he can operate effectively.

Bulky tools can also severely constrain the working position of a diver, especially since the bulkiest tools are the heaviest. Such tools are usually operated from a fixed position and are rigidly supported in relation to the work surface, or else lifting devices must be employed, thereby enabling the diver to readily position and move the tool from one work surface to another. In order to effectively operate bulky tools that require movement over any distance, maximum mobility and freedom of movement must be available to the diver.

Visibility -- Underwater visibility and its relation to a diver's work position is a function of two major factors. One concerns the physical qualities of the water and the ways in which they influence the diver's ability to see the work surface in relation to his underwater tool. The variables included here are water clarity or transmissivity, depth, and size distortion. The diver has little, if any, control over these variables, other than his limited ability to adapt to the size distortion encountered underwater and his ability to distinguish objects under conditions of reduced light levels. The second factor involving underwater visibility and the diver's work position is the effect that the face mask lens or helmet viewports have on the overall visual field. This factor is largely an equipment design feature involving the size and shape of the viewing plate, the thickness and type of material used in fabrication, and the distance from the eye to the lens plane of the face plate. Whether the factors influencing underwater visibility result from environmental variables or limitations in the diver's equipment, the problems of reduced and restricted visibility underwater will require a diver to position himself closer to the work surface than would be required under atmospheric conditions. The visual requirements of the diver under conditions of reduced and/or restricted visibility may therefore necessitate him to work in positions that will reduce his effectiveness as an operator.

C. Anthropometric Guidelines

As the science of external human body measurements, anthropometry includes static and dynamic body dimensions, range of body movements, and muscle strength. Such measurements are an important segment in the development of human engineering design criteria as a means of determining to what extent a proposed tool or equipment item is able to accommodate the user diver population, in regard to such physical characteristics as the various body dimensions, strength, and reach.

Anthropometric measurements are usually expressed in percentiles. In human engineering, two percentiles of body dimensions are typically used and are the most useful to the equipment designer: the 5th and 95th percentile measures. These values permit the designer to select dimensions that are appropriate to specific equipment requirements. The designer should design according to the concept of "design limits" or "range of accommodation" for the anticipated user population. The range from the 5th to the 95th percentile encompasses 90 percent of a given sample population; therefore, a measure at the 95th percentile would mean that, of the total group measured, 95 percent were below and 5 percent exceeded the measured value. By proper analysis of the data available for the user population, the designer can efficiently provide precisely the adjustability needed for any desired segment of the group.

General rules for the use of body dimension data are:

Gross Dimensions (accesses, safety clearances): Areas and enclosures which must accommodate passage of the body or body parts should be based on the 95th percentile values. The requirement here is to accommodate the largest personnel expected to operate the equipment .

Limiting Dimensions (reaching distances, displays, control movements): Dimensions which involve reaching or extension of body parts should be based on 5th dimension values. The requirement here is to accommodate the smallest personnel.

Adjustable Dimensions (restraint belts, diving masks): These should adjust to accommodate the range of 5th through 95th percentile personnel. The requirement here is to accommodate both the largest and smallest personnel.

Available anthropometric data have been compiled on numerous population subgroups, including military, civilian, and industrial groups. These data represent a broad range of measurements applicable to nearly every conceivable work task. However, the problem facing the designer of diver-operated tools and equipment is whether the available anthropometric data are directly applicable to the work situations and wearing apparel of the diver group. Where existing anthropometric data are not applicable to a specific underwater problem, the following procedure should be followed (Morgan, et al., 1963):

1. Obtain data on the physiques of the intended user population. Although human beings vary widely in size and shape, their variability follows certain patterns. However, the limits of the desired percentile range must be determined by actual measurement of samples of the group to be accommodated, since the measurement values of divers may differ significantly from those groups for which measurements are available.

2. Select and measure a small group of representative divers. Select subjects representing both ends (around the 5th and 95th percentiles) of the height and weight distribution of the divers to be accommodated. This will give reasonable assurance that the range of other dimensions will be approximated. Ideally, divers should be measured in the detail desired for the operator group. For example, in order to determine a control handle size that will accommodate 90 percent of the expected user population, it would be more exact to determine such a design feature from hand measurements than from height and weight alone.

3. Outfit divers used as test subjects in the widest range of diving apparel and life support equipment that might be worn while operating the tool. All operational aspects of the tool should accommodate 90 percent of the anticipated user group in the full range of the diving apparel used when operating the tool.

4. Have the diver test subjects operate the tool underwater under environmental conditions (depth, water temperature, and visibility) expected in an operational setting. The tool operators should perform all the motions normally required in an operational work setting. The test performance should last as long as an actual work task. Make sure the diver can operate the tool on all normal work surface orientations (deck, vertical, and overhead).

5. Note the difficulties encountered by the test divers with respect to handling ease, personal comfort, quality and quantity of work output, vision, and safety hazards caused by body size and operator

capability.

6. Relate the deficiencies and problems resulting from design to the percentiles of the operator population and recommend redesign accordingly. Operator percentile can be estimated for the appropriate anthropometric dimension by comparing the dimensions of the test diver with known percentile ranks contained in existing anthropometric data sources.

D. Basic Body Dimension Data

Anthropometric data required for the design of underwater tools and tool systems involve the basic body components and body positions used in the performance of underwater work tasks by divers outfitted in the most commonly used diving apparel.

The tables and figures presented in this section will enable designers and engineers to determine dimensions to account for various percentages or percentiles of the population. From these dimensions, equipment configurations, sizing, and weights can be designed to accommodate a large percentage of the population.

Unfortunately, only very limited anthropometric studies have been made of either military or commercial divers, and it is not known if divers as a group differ significantly in body type from the general population or sub-groups for which detailed anthropometric data have been developed. In a preliminary survey of diver anthropometrics (Beatty, et al., 1971), measurements of 19 parameters required for custom-made wetsuits were obtained from 41 male divers at the Navy Experimental Diving Unit in Washington, D.C. The interrelationships between the various measures were also calculated and are presented in a correlation matrix. Data were obtained on hand measurements of 12 divers, for bare hand, 3-finger 1/4-inch wetsuit gloves, and 5-finger 1/4-inch wetsuit gloves (Andersen and Swider, 1971).

The diver anthropometric data were not considered sufficient in detail to meet all the requirements necessary for equipment design and are therefore supplemented by data for other military personnel sub-groups. The supplementary data are presented for nude adults of a specified population sub-group, such as army infantrymen, air force pilots, and astronauts. The data contained in Tables 1 through 5 have been compiled from available dimensions for these subgroups. In utilizing these data, it would be convenient to use a single data source more representative of the total population. For this reason averages were calculated for the groups indicated. A complete listing of all body dimensions was not considered appropriate to this design guide; therefore, only the most widely used general body measurements are included. Sufficient dimensions have been given to enable the designer to estimate the percentile range to which selected diver test personnel belong. Since the major interest of this report is tool design, hand measurements, which are

Preceding page blank

considered of primary importance in the design of underwater tools, are included in the greatest possible detail.

Table 1. Basic Diver Anthropometric Measurements.

Sample: 41 male divers from the Navy Experimental Diving Unit, Washington, D.C. (Beatty, Berghage, and Chandler, 1971).

Measurement	Mean (inches)	Standard Deviation (inches)	Percentile (inches) 5th	Percentile (inches) 95th
Weight (lbs.)	187.88	27.83	142.10	233.66
Height (stature)	71.16	3.60	65.24	77.08
Chest Circumference	40.46	3.17	35.24	45.68
Waist Circumference	35.98	3.59	30.07	41.88
Hip Circumference	40.95	3.17	35.79	46.10
Thigh Circumference	22.05	1.99	18.78	25.33
Shoulder-Waist Distance	18.35	2.37	14.45	22.24
Center Back-Waist Distance	28.51	1.88	25.42	31.60
Wrist-Axilla Distance	20.56	1.43	18.21	22.91
Ankle-Crotch Distance	28.76	2.54	24.58	32.94
Ankle-Waist Distance	39.40	2.77	34.58	43.95
Neck Circumference	15.60	0.90	14.11	17.09
Biceps Circumference	13.12	1.24	11.07	15.16
Elbow Circumference	11.12	0.93	9.59	12.65
Wrist Circumference	7.18	0.46	6.43	7.94
Knee Circumference	15.43	1.20	13.46	17.39
Calf Circumference	15.38	1.45	13.00	17.76

Table 2. Correlation Matrix from Table 1, Basic Diver Anthropometric Measurements. (Beatty, Berghage, and Chandler, 1971)

	Variable	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1.	Weight	52*	80	81	82	58	24	39	18	52	54	65	64	80	47	69	76
2.	Height (Stature)		35	30	38	21	48	61	64	76	67	28	22	38	-03	33	21
3.	Chest Circumference			80	78	65	30	29	02	37	37	71	75	81	51	60	69
4.	Waist Circumference				85	52	09	23	01	32	41	64	62	70	46	57	70
5.	Hip Circumference					65	14	40	19	36	42	69	67	78	43	78	82
6.	Thigh Circumference						26	13	-04	26	14	66	52	69	38	65	54
7.	Shoulder-Waist Distance							-01	07	25	-11	29	18	24	22	29	02
8.	Center Back-Waist Distance								81	68	72	21	19	32	-18	29	23
9.	Wrist-Axilla Distance									64	60	-03	-07	12	-37	12	06
10.	Ankle-Crotch Distance										86	18	09	42	01	25	19
11.	Ankle-Waist Distance											16	17	37	-03	22	29
12.	Neck Circumference												55	71	82	68	66
13.	Biceps Circumference													76	41	55	70
14.	Elbow Circumference														54	73	79
15.	Wrist Circumference															37	51
16.	Knee Circumference																80
17.	Calf Circumference																

*Decimal point omitted

Table 3. Basic Anthropometric Measurements for Three Population Groups.

Measurement	Percentile[1] (inches)		Percentile[2] (inches)		Percentile[3] (inches)		Average Percentile (inches)	
	5th	95th	5th	95th	5th	95th	5th	95th
A. Weight (lbs.)	124.0	192.0	133.0	201.0	140.0	188.0	132.33	193.67
B. Standing								
1. Stature	64.3	72.6	65.2	73.1	67.1	72.4	65.53	72.70
2. Eye Height	59.9	68.1	60.8	68.6	61.2	68.0	60.63	68.23
3. Shoulder Height	52.0	59.8	52.8	60.2	54.6	59.5	53.13	59.83
4. Chest Depth	7.2	9.6	8.0	10.4	8.4	10.5	7.87	10.17
5. Waist Depth	6.7	9.4	6.7	9.5	7.2	9.4	6.87	9.43
6. Chest Breadth	9.9	12.4	10.8	13.4	11.4	14.1	10.70	13.30
7. Waist Breadth	9.4	12.3	--	--	10.9	13.0	10.15	12.65
8. Hip Breadth (standing)	12.1	14.5	12.1	14.4	12.5	14.8	12.23	14.57
9. Elbow Height	40.6	46.4	40.6	46.4	39.4	44.5	40.20	45.77
10. Shoulder Breadth	16.4	19.6	16.5	19.4	16.3	21.2	16.40	20.07
C. Reach								
1. Functional Reach from Wall	29.4	34.9	29.7	35.0	--	--	29.55	34.95
2. Arm Reach	31.9	37.2	31.9	37.3	--	--	31.90	37.25
3. Maximum Reach from Wall	35.4	41.7	--	--	--	--	35.40	41.70
4. Span	65.0	75.2	65.9	75.6	68.1	74.0	66.33	74.93
5. Functional Arm Reach Overhead	--	--	76.8	88.5	--	--	76.80	88.50

(1) Hedgcock and Chaillet, 1964 (Army)
(2) Hertzberg, et al., 1954 (Air Force)
(3) NASA, 1968 (U.S. Astronauts)

Table 3. Basic Anthropometric Measurements for Three Population Groups (continued).

Measurement	Percentile[1] (inches) 5th	Percentile[1] (inches) 95th	Percentile[2] (inches) 5th	Percentile[2] (inches) 95th	Percentile[3] (inches) 5th	Percentile[3] (inches) 95th	Average Percentile (inches) 5th	Average Percentile (inches) 95th
D. Head								
1. Biocular	3.3	4.0	--	--	--	--	3.30	4.00
2. Interpupillary Distance	2.3	2.7	2.3	2.8	2.3	2.7	2.30	2.75
3. Interocular Diameter	1.1	1.5	--	--	--	--	1.10	1.50
4. Head Breadth	5.6	6.4	5.7	6.4	5.8	6.5	5.70	6.43
5. Minimum Frontal Diameter	3.9	4.7	--	--	--	--	3.90	4.70
6. Maximum Frontal Diameter	4.4	5.1	--	--	--	--	4.40	5.10
7. Breadth of Face	5.1	5.9	--	--	--	--	5.10	5.90
8. Head Length	7.2	8.1	7.3	8.2	7.5	8.2	7.33	8.17
E. Foot								
1. Foot Breadth	3.5	4.3	3.5	4.1	3.3	4.2	3.43	4.20
2. Foot Length	9.7	11.2	9.8	11.3	9.7	11.1	9.73	11.20

(1) Hedgecock and Chaillet, 1964 (Army)
(2) Hertzberg, et al., 1954 (Air Force)
(3) NASA, 1968 (U.S. Astronauts)

Table 4. Anthropometric Measurements for Diver Hands. Sample: 13 male divers from the Navy Special Warfare Group, San Diego, California. (Andersen and Swider, 1971).

Measurement	Mean (inches)	Standard Deviation (inches)	Percentile (inches)		Differences of Means (in.)	
			5th	95th	Bare Hand and 5-Finger Gloves	Bare Hand and 3-Finger Gloves
Hand Length - maximally stretched hand:					+0.17	+0.17
. Bare hand	7.61	0.38	6.98	8.24		
. 5-finger glove	7.78	0.40	7.12	8.44		
. 3-finger glove	7.76	0.39	7.12	8.40		
Hand Length: thumb and forefinger touching:					+0.42	+0.69
. Bare hand	4.94	0.60	3.95	5.93		
. 5-finger glove	5.36	0.63	4.32	6.40		
. 3-finger glove	5.63	0.66	4.54	6.72		
Straight Hand Breadth - metacarpal:					+0.32	+0.26
. Bare hand	3.65	0.34	3.09	4.21		
. 5-finger glove	3.97	0.12	3.77	4.17		
. 3-finger glove	3.91	0.11	3.73	4.09		
Hand Breadth - metacarpal minimum:					+0.19	+0.19
. Bare hand	3.68	0.40	3.02	4.34		
. 5-finger glove	3.87	0.14	3.64	4.10		
. 3-finger glove	3.87	0.16	3.61	4.13		

Table 4. Anthropometric Measurements for Diver Hands (continued).

Measurement	Mean (inches)	Standard Deviation (inches)	Percentile (inches)		Differences of Means (in.)	
			5th	95th	Bare Hand and 5-Finger Gloves	Bare Hand and 3-Finger Gloves
Grip Breadth - outside:					+0.34	+0.30
. Bare hand	3.50	0.25	3.09	3.91		
. 5-finger glove	3.84	0.24	3.45	4.23		
. 3-finger glove	3.80	0.17	3.52	4.08		
Grip Breadth - inside:					-0.10	-0.16
. Bare hand	1.99	0.11	1.81	2.14		
. 5-finger glove	1.89	0.12	1.66	2.12		
. 3-finger glove	1.83	0.13	1.62	2.04		
Hand Thickness:					+0.34	+0.39
. Bare hand	1.38	0.16	1.12	1.64		
. 5-finger glove	1.72	0.13	1.51	1.93		
. 3-finger glove	1.77	0.18	1.47	2.07		
Hand Circumference - thumb and forefinger touching:					+1.36	+1.90
. Bare hand	10.64	0.47	9.87	11.41		
. 5-finger glove	12.00	0.36	11.41	12.59		
. 3-finger glove	12.42	0.29	11.94	12.90		

Table 4. Anthropometric Measurements for Diver Hands (continued).

Measurement	Mean (inches)	Standard Deviation (inches)	Percentile (inches)		Differences of Means (in.)	
			5th	95th	Bare Hand and 5-Finger Gloves	Bare Hand and 3-Finger Gloves
<u>Hand Circumference - metacarpal:</u>					+1.10	+1.40
. Bare hand	8.34	0.27	7.90	8.78		
. 5-finger glove	9.44	0.17	9.16	9.72		
. 3-finger glove	9.74	0.25	9.33	10.15		
<u>Fist Circumference</u>:					+1.50	+1.82
. Bare hand	11.23	0.39	10.59	11.87		
. 5-finger glove	12.73	0.38	12.10	13.36		
. 3-finger glove	13.05	0.25	12.64	13.46		
<u>Wrist Circumference:</u>					+1.15	+1.06
. Bare hand	6.93	0.35	6.35	7.51		
. 5-finger glove	8.08	0.25	7.67	8.49		
. 3-finger glove	7.99	0.31	7.48	8.50		

Table 5. **Bare Hand Characteristics.**

Measurement -- Length, Maximally-Stretched Hand

Description -- **Subject's hand is extended, palm up. With the bar of a sliding caliper lying along the palm, the distance from the wrist crease to the end of the longest finger is measured.**

Human Engineering Applications

1. Access of the entire hand into a receptacle.
2. Location of fingertip controls in depth of receptacle.

Source	Percentile (inches)	
	5th	95th
Garrett (1968); Hertzberg, et al. (1964)	6.98	8.37
Chaillet (1965)	6.90	8.20
Hertzberg, et al. (1954)	6.40	7.50
Randall, et al. (1946)	7.10	8.20
Daniels, et al.	6.90	8.20
Newman and White (1951)	7.00	8.20
USA (1946)	7.30	8.70
McFarland, et al. (1958)	7.10	8.10
Mean Values	6.96	8.18

Table 5. Bare Hand Characteristics (continued).

Measurement -- Length, Thumb and Forefinger Touching

Description -- Subject's hand is extended with the tips of the thumb and forefinger lightly touching. Holding the bar of the sliding caliper parallel to the long axis of the thumb, measurement is made from the wrist crease to the farthest point of the second digit.

Human Engineering Applications --

1. Effective length of the hand for grasping operations.

2. Determination of length of hand support for those controls which require precise positioning.

3. Location of controls within an aperture.

Source	Percentile (inches)	
	5th	95th
Garrett (1968); Hertzberg, et al. (1964)	3.97	5.39

Table 5. Bare Hand Characteristics (continued).

Measurement -- Hand Breadth at Metacarpal, Maximum

Description -- Subject's hand is extended, palm up. With the bar of the sliding caliper lying across the back of the hand, measurement is made of the maximum breadth across the distal ends of the metac

Human Engineering
Applications -- 1. Access of the flattened hand through an aperture.

2. Minimum length of handgrips and/or handles.

Source	Percentile (inches)	
	5th	95th
Garrett (1968); Hertzberg, et al. (1964)	3.14	3.82
Garrett (1971)	3.28	3.82
Hertzberg, et al. (1954)	3.20	3.70
Randall, et al. (1946)	3.10	3.70
Daniels, et al. (1953)	3.20	3.70
Newman and White (1951)	3.10	3.80
U.S.A. (1946)	3.20	3.80
McFarland, et al. (1958)	3.20	3.80
Mean Values	3.18	3.77

Table 5. Bare Hand Characteristics (continued).

Measurement -- Grip Breadth, Outside

Description -- Subject holds a cone at the largest circumference that he can grasp with his thumb and middle finger just touching. Breadth measurement is made with the bar of the sliding calipers across the maximum breadth of the hand.

Human Engineering Application -- Minimum size of an aperture that will accept a man's hand when enclosed around a handle.

Source	Percentile (inches) 5th	95th
Garrett (1971)	3.67	4.65
Chaillet (1965)	3.70	4.44
Mean Values	3.69	4.55

Table 5. Bare Hand Characteristics (continued).

Measurement -- Grip Breadth, Inside

Description -- Subject holds a cone at the largest circumference that can be grasped with thumb and middle finger just touching. Diameter of cone corresponding to this maximum circumference is recorded.

Human Engineering Application -- Determination of the maximum diameter of a cylindrical handgrip that can be completely enclosed with fingers of one hand.

Source	Percentile (inches)	
	5th	95th
Garrett (1968); Hertzberg, et al. (1964)	1.70	2.19
Garrett (1971)	1.66	2.18
Chaillet (1965)	1.60	2.10
Mean Values	1.65	2.16

Table 5. Bare Hand Characteristics (continued).

Measurement -- Circumference, Thumb and Forefinger Touching

Description -- Subject's hand is extended with the tips of the thumb and forefinger lightly touching. Circumference measurement is made with the tape passing over the distal ends of the metacarpals (knuckles) of all five digits.

Human Engineering Applications --

1. Determination of the dimensions of apertures and workspace areas designed for occupation by a man's hand in the tip position.

2. Location of certain types of controls (toggles, rotary switches, etc.) in depth of receptacle.

Source	Percentile (inches)	
	5th	95th
Garrett (1968); Hertzberg, et al. (1964)	9.51	12.19
Garrett (1971)	9.62	11.92
Mean Values	9.57	12.06

Table 5. Bare Hand Characteristics (continued).

Measurement -- Fist Circumference

Description -- Subject makes tight fist with thumb positioned outside other fingers. Measurement is made with the tape passing over the distal ends of the metacarpals (knuckles) of all five digits.

Human Engineering Application -- Determination of the minimum dimensions of apertures and workspace designed to accept a man's hand.

Source	Percentile (inches)	
	5th	95th
Garrett (1968); Hertzberg, et al. (1964)	10.25	12.64
Chaillet (1965)	10.70	12.40
Garrett (1971)	10.76	12.54
Mean Values	10.57	12.53

E. Biomechanical Capabilities

Design criteria relative to tool operation underwater require detailed data for various arm and hand movements, along with the force emission capabilities and limitations of the operator. A diver's strength varies with his buoyancy and diving dress, the position of his body and limbs while exerting a required force, the direction of the force emission, and the mechanical advantage of the body's lever system.

The maximum amount of force required for a given tool operation (control, torqueing, lifting) should be determined with respect to the strength of the weakest operator. Performance at or near the limits of the diver's physical abilities will result in increased energy expenditure and fatigue which could physiologically endanger the operator.

Critical to the operator/tool interface in performing underwater work tasks is the requirement to exert force in different directions and amounts, and for different periods of time. Such data are required by tool designers to determine maximum and optimum control resistances, forces required in tool handling and operation, and specification of optimum tool weights for safe, efficient lifting, positioning, and carrying.

Tables 6, 7, and 8 contain force and torque emission data for various body and limb positions. The measurement values indicated should be used as limits wherever applicalbe. The biomechanical research data obtained in underwater environments for diver work applications is extremely limited. Much of the material contained in this section has therefore been adapted from the aerospace human engineering literature for zero-G simulation performed underwater. While these data were not obtained for subjects outfitted in working diver apparel, every effort was made to select data specifically relevant to the diver's work and environmental requirements.

Table 6. Hand Torque Values.

Measurement - Maximum Bare-Hand Torque, Supination and Pronation

Description - Subject grasps metal T-handle of force receiver with the shank between digits 2 and 3. His thumb touches the fingertips. Subject exerts maximum force in turning the handle to the left. Task is repeated, turning handle to the right. Force data are read from torque wrench.

Human Engineering Application

- 1. Determination of the maximum resistance allowable on a rotary hand control.
- 2. Determination of the maximum torque for hand-tightened bolts and fasteners.
- 3. Limitation of man's capacity for torque around an axis in or near his forearm.

Source		Percentile (inch-pounds)	
		5th	95th
Garrett (1968)	Pronation	79.32	100.44
	Supination	58.08	83.30
Hunsicker & Greey (1957)	Pronation	30.00	125.00
	Supination	32.50	90.50
Garrett (1971)	Pronation	79.83	227.95
	Supination	71.93	171.03
Mean Values	Pronation	63.05	151.13
	Supination	54.17	114.94

Table 6. Hand Torque Values (continued).

Measurement - Hand Torque Values for Three Rotary Force Handle Types (Pierce, 1963).

Description - Measurements were obtained for pressure-suited subjects to determine manual dexterity of force capabilities for man-in-space activities. Three types of handle were investigated. The first type, representing a typical screwdriver handle, was 4.25 inches in length and 1 inch in diameter, with longitudinal grooves 0.25 inch in width and 0.0625 inch in depth. The second handle was a globe, 2 inches in diameter. The third handle was a circular knob, 3.25 inches in mean diameter, with 8 sinusoidal finger-grip indentations, 0.25 inch in diameter. Measurements were obtained for both pronation (downward turning of the palm) and supination (upward turning of the palm). Since no appreciable differences were found, averages for these data are presented as a single hand torque value.

Test Apparel	Hand Torque Value (inch-pounds)		
	Screwdriver	2" Ball	3-1/4"Knob
Bare Handed	63.34	79.58	117.92
Full-Pressure-Suit Glove(unpressurized	54.17	72.08	129.75
Full-Pressure-Suit Glove(pressurized)	50.16	58.80	105.67

Note: Measurements were not obtained underwater; however, considering the relatively small torque values involved, it is predicted that these force values would not differ significantly underwater.

Table 6. Hand Torque Values (continued).

Measurement - Sustained and Impulse Hand Torque Values (G.E.)

Description - Measurements were obtained to evaluate man's ability to generate impulse and sustained torque emissions under various conditions of restraint, type of suit, and force receiver location. The two types of forces are defined as follows:

<u>Sustained</u> - Subject exerts maximum force that he can sustain for 4 seconds.

<u>Impulse</u> - Subject exerts maximum possible instantaneous force upon receipt of cue-signal.

Two different handles were used for torque emissions. One was an L-handle wrench which allowed the subject to exert a true torqueing force. The other was a T-handle wrench which required the subject to exert a torsion-like motion. Restraint systems consisted of waist, shoe, and combined waist-and shoe. Each system freed both hands for use at the work site. Measurements were made underwater at a pool facility, with subjects neutrally buoyed. Suit conditions consisted of the Litton Advanced Extravehicular Suit and shirtsleeve, utilizing standard scuba.

Variables		Torque (inch-pounds)	
		Sustained	Impulse
Mode	- Underwater Neutral Buoyancy Simulation	212.5	369.3
Suits	- Shirtsleeve (Scuba)	218.3	334.7
	- Advanced Extravehicular Suit	220.3	344.6
Restraints	- Waist	140.9	298.7
	- Shoes	231.4	347.0
	- Waist and Shoes	228.7	329.8
Tools	- L-Handle	283.9	470.9
	- T-Handle	148.2	194.8

Table 7. Sustained Pushing Force Values for Restrained Divers.

Measurement - One and Two Arm Sustained Pushing Force Values for Restrained Divers in Three Working Positions (Barrett and Quirk, 1969).

Description - Measurements were obtained for divers working on vertical, overhead, and deck surfaces where no natural handholds or footholds existed. Waist-tethering equipment was used for diver restraint during two-arm measurements. Measurements were made using a hand dynamometer.

Mean Pushing Force for Divers

Work Surface	No. of Arms Used	Diver Force (lbs)-Duration of:			Mean Diver Force (lbs)	
		6 minutes	3 minutes	1 minute	Each Arm	Both Arms
Overhead	One	18.8	21.4	29.0	23.1	35.5
	Two	32.3	38.9	72.9	48.0	
Vertical	One	21.8	23.6	34.5	26.6	36.6
	Two	35.7	41.4	62.6	46.6	
Deck	One	17.5	18.4	35.4	23.8	39.6
	Two	42.2	44.0	80.4	55.5	
Mean	One	19.3	21.1	32.9	24.5	--
	Two	36.7	41.4	71.9	50.0	--
	Combined	28.0	31.2	52.4	--	37.2

Force Measurement Range Based on Individual Diver Mean Scores

No. of Arms Used	Test Range	Diver Force (pounds) for Duration of:		
		6 minutes	3 minutes	1 minute
Two	High	50.0	61.3	102.5
	Low	13.0	22.7	28.3
One	High	32.3	33.3	54.0
	Low	8.8	12.0	20.8

Table 8. Hand Grip Strength.

Measurement - Hand Grip Strength

Description - Subject grasps hand dynamometer, fully extends arm, and squeezes instrument. Force emission value is read from instrument.

Human Engineering Application - 1. Determination of the amount of force loading on double-handled squeeze controls.

- 2. Limits of a man's hand to grip an object against a force.

Source	Percentile (pounds)	
	5th	95th
Garrett (1968)	67.10	128.28
Taylor (1954)	63.68	116.32
Clarke (1945)	104.39	163.61
Mean Value	78.39	136.07

II. BODY RESTRAINT AND TETHERING SYSTEMS

A. Introduction

The extent to which a diver is able to maintain himself in a fixed relation to his work site plays an important role in specifying his strength and force emission capabilities. It has been estimated that the applied forces resulting from the use of restraining support for the diver are approximately double that of the unrestrained free-swimming diver (Barrett and Quirk, 1969). Clearly, the operation of tools in a tractionless underwater environment is most efficient when some means of traction or control of body position is provided. The form of diver restraint or traction is a function of the following (Trout and Bruchey, 1969):

- The amount and direction of the forces required to perform the tool operation.
- The body position that the diver must assume to operate the tool.
- The size, weight, and general configuration of the tool system being operated.
- The duration of the work task.
- The degree of dexterity required to successfully complete the work task.

The operation of tools requiring only the application of small forces can, in most cases, be effectively performed from a neutrally-buoyant, free-floating state. Screwdrivers and other tools requiring only small rotational forces of the wrist and lower arm can be operated by an untethered diver. The unrestrained diver has the advantage of complete freedom of movement allowing him to move unencumbered about his work site. He is also able to correct his body orientation to the most comfortable and effective work position.

For tools requiring large and/or sustained forces, the need for some form of diver restraint becomes mandatory. For example, hand wrenches, requiring a large degree of mechanical leverage to operate, cannot impart sufficient torque unless the diver is provided with traction. Without traction, the diver's body merely rotates about the torqueing axis and none of the torque is imparted to the object being tightened.

The purpose of this section is not to design or develop a diver restraint and tethering system, but to review the design features and characteristics of an optimum restraint and tethering system that could be applied over a broad range of underwater work situations. A number of tethering and restraint devices have been tested and used, or have been proposed for use in underwater applications. Some of these are the result of techniques developed by the aerospace industry to deal with the problems of working in the zero-gravity environment of space (O'Neil, 1969; Trout and Bruchey, 1969). Others have been developed specifically for diver applications (Barrett and Quirk, 1969).

B. General Requirements

The diversity of structures that divers are called to work on, along with the numerous modes of diver apparel, make it difficult, if not impossible, to specify a single tethering and restraint system suitable to all applications. However, general requirements can be specified, along with design features that provide a system readily adaptable to a wide range of underwater work applications. The following requirements have been identified as the most desirable design features for positioning and restraining a free-swimming diver. Many of these requirements also reflect the needs of an astronaut working in the weightlessness of space.

1. A restraint system must be flexible enough to provide a diver with a wide degree of freedom to position his body with respect to his work surface. The system must provide the diver with a selection of restraint points that will fit the multiple or variable body positions that may be required.

2. The basic restraint equipment must be usable with all standard forms of diver apparel and life support systems. These will include both hard-hat deep-dive dress and wetsuit scuba, self-contained life support backpacks, and surface-supported air hose and mixed-gas systems.

3. The diver must be able to enter and exit a restraint device with and without gloved hands and without the assistance of support or tender divers.

4. The limited visual field of diving helmet faceplates requires that the restraint system release and adjustment mechanisms be operable under "no-sight" conditions. In addition, all mechanisms must be operable with gloved hands.

5. A restraint system should be readily transportable between work sites by a diver. Any portion of the restraint system worn should not encumber the diver or affect his buoyancy underwater.

A survey was made of the research literature pertaining to restraint systems used for force applications both in underwater simulation of zero gravity for space environments and in systems designed specifically for underwater tool work. These studies indicate a number of design approaches that will meet the requirements of a diver operating in a tractionless environment. A research program sponsored by the National Aeronautics and Space Administration (Norman, 1969; General Electric Space Systems Organization) utilized underwater zero-gravity simulation techniques to develop basic force exertion data under various conditions of personnel restraints, work site geometry, and type and direction of forces to be exerted. Three types of restraint were tested for their ability to effectively provide an energy sink and stabilizer in resisting the effects of forces exerted by subjects in any given direction. The restraints selected for these tasks appeared to be representative of the most effective types in a space environment and included:

> No Restraint -- In this condition, the subject maintained contact with the force receiver handle with his right hand only.
>
> Handhold Only -- The handhold restraint was located 19 inches forward of the subject's left shoulder, with its center at the same height as the center of the force receiver handle.
>
> Waist Only -- The waist restraint consisted of a wide fabric belt attached to telescoping metal bars extending from the sides of the support structure. The telescoping bars permitted the positioning of the swivel plates against the sides of the subject's waist to prevent rotation around the sagittal axis (yaw). The swivel plates permitted the subject to pitch freely, fore and aft, around the axis formed by the support bars of the test platform. The height of the waist restraint was adjusted for each subject so that the center of the force receiver handle was level with the subject's chest.
>
> Shoes Only -- The shoe restraint used in this study was the Gemini Dutch Shoes. These shoes effectively immobilized the subject against up-and-down movement and provided a pivot point for left right, push, and pull forces.

The remaining restraint conditions consisted of all possible combinations of the three primary restraints described above, resulting in four combinations: handhold-waist, handhold-shoes, waist-shoes, and handhold-waist-shoes.

Since force-producing capability varies greatly with the intended direction of force application, subjects were required to generate forces in both directions of the three orthogonal axes defining the location of the force receiver. The directions of force application were:

- Push
- Pull
- Left
- Right
- Up
- Down

Two types of data concerning force-emission capability were obtained, the impulse force and sustained force, with the former defined as the peak force exerted during a 1-second interval and the latter as the maximum force maintainable during a 4-second interval. Quantitative data regarding these two types of force emission provide the equipment designer with specific data regarding the peak force which an operator can be depended upon to produce in a given restraint condition combination, and also what force the operator can maintain for a reasonable amount of time. The results of mean forces across restraint systems are shown in Table 9.

These data provide the following implications with respect to the effects of restraint on force application. First, a sustained force cannot be applied in a no-restraint, tractionless environment. Second, the single-point restraints (handhold, waist, and shoes) have differential values for different force directions. For sustained forces, the waist restraint was best for push/pull forces, the shoes were best for up/down, and the hand-hold was best for left directions. In addition, all single-point restraints were about equal in their inability to permit significant right direction forces. The handhold-waist-shoes restraint combination resulted in the largest push/pull forces, with the waist-shoes combination a very close second. The handhold-shoes combination resulted in the largest mean sustained force for the up/down and right/left directions.

A study conducted by the McDonnell Douglas Corporation (O'Neil, 1969) discusses various special equipment and restraint techniques for enhanc-

Table 9. Mean Sustained and Impulse Forces (pounds) as a Function of Restraint Systems (Norman, 1969).

Direction	Restraints																	
	None		Hand		Waist		Shoes		Hand and Waist		Hand and Shoes		Waist and Shoes		Hand, Waist and Shoes		Mean	
	S	I	S	I	S	I	S	I	S	I	S	I	S	I	S	I	S	I
Push	0	35	1	41	15	43	4	46	29	57	30	62	35	58	43	69	19.6	51.4
Pull	0	43	2	43	22	46	4	48	31	51	33	61	37	57	38	61	20.9	51.3
Up	0	19	5	21	10	23	17	28	14	23	18	31	17	28	17	29	12.3	25.3
Down	2	23	9	26	10	23	21	33	16	26	26	37	19	30	21	32	15.5	28.8
Right	0	18	10	22	12	22	9	22	15	25	16	28	14	23	16	27	11.5	23.4
Left	0	18	17	29	12	22	8	23	17	28	21	34	15	25	19	30	13.6	26.1
Mean	0.3	26.0	7.3	30.3	13.5	29.8	10.5	33.3	20.2	35.0	24.0	42.2	22.8	36.8	25.7	41.3		

S = Sustained Force (4-second interval)

I = Impulse Force (1-second interval)

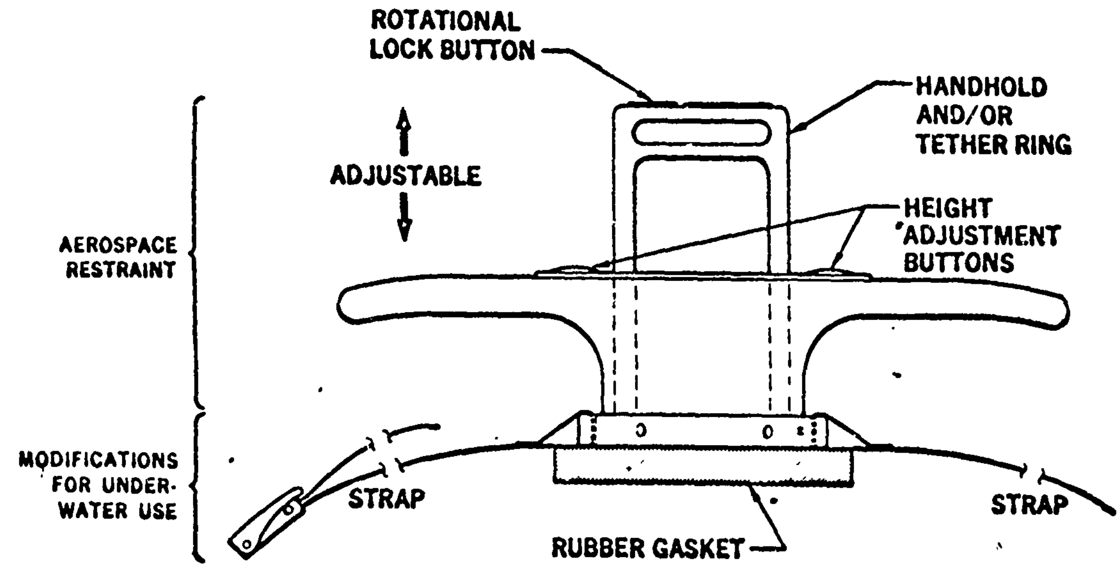
ing performance in the zero-gravity environment of space and the application of these techniques to the hydrospace industry. One such restraint system is the lower-leg restraint, developed for manned space vehicle applications and intended for use both in a pressure-suited mode outside a space vehicle and in a shirtsleeve environment inside the vehicle. The configuration of the lower-leg restraint, illustrated in Figure 1, can readily be adapted for certain underwater applications by the addition of straps to secure the device to underwater pilings, pipelines, and other structures. In its primary mode of operation, the essential restraining pressure points are at the feet and knees, as well as behind the calves. For an alternate, this device can be used as a tether ring in conjunction with a waist tether, thus providing the user with a different kind of mobility/flexibility with greater distance from the work surface. The device can also be utilized as a handhold or partial foot restraint. The basic advantages suggested for the lower-leg restraint device for underwater applications are listed below:

Restraint Flexibility -- The device can enhance the diver's force application. The degrees of restraint available to the diver are a function of his leg strength and the frictioned forces generated by the knees and feet pressing against the anchoring surface of the device. Simple muscle tension can be used to vary the degree of restraint. Frictional forces generated by the knees and feet pressing against the anchoring surface can be considered as components of the resultant restraining force.

Body Mobility -- The lower-leg restraint provides excellent body mobility while the diver is restrained, since the diver's natural movement above the knee is not constrained. The diver can also obtain multiple restraint points by positioning the restraint anywhere along his calves from ankles to knees.

Fixity -- The rotational (swivel) capability of the device enables the user to lock the restraint at multiple angles. Locking is accomplished by pushing a button that inserts a pin through an upper rotating flange into prepositioned holes in the base fixed flange.

Adjustability -- The lower-leg restraint is adjustable to various leg thicknesses by the height adjustment which can easily be operated with or without gloved hands.



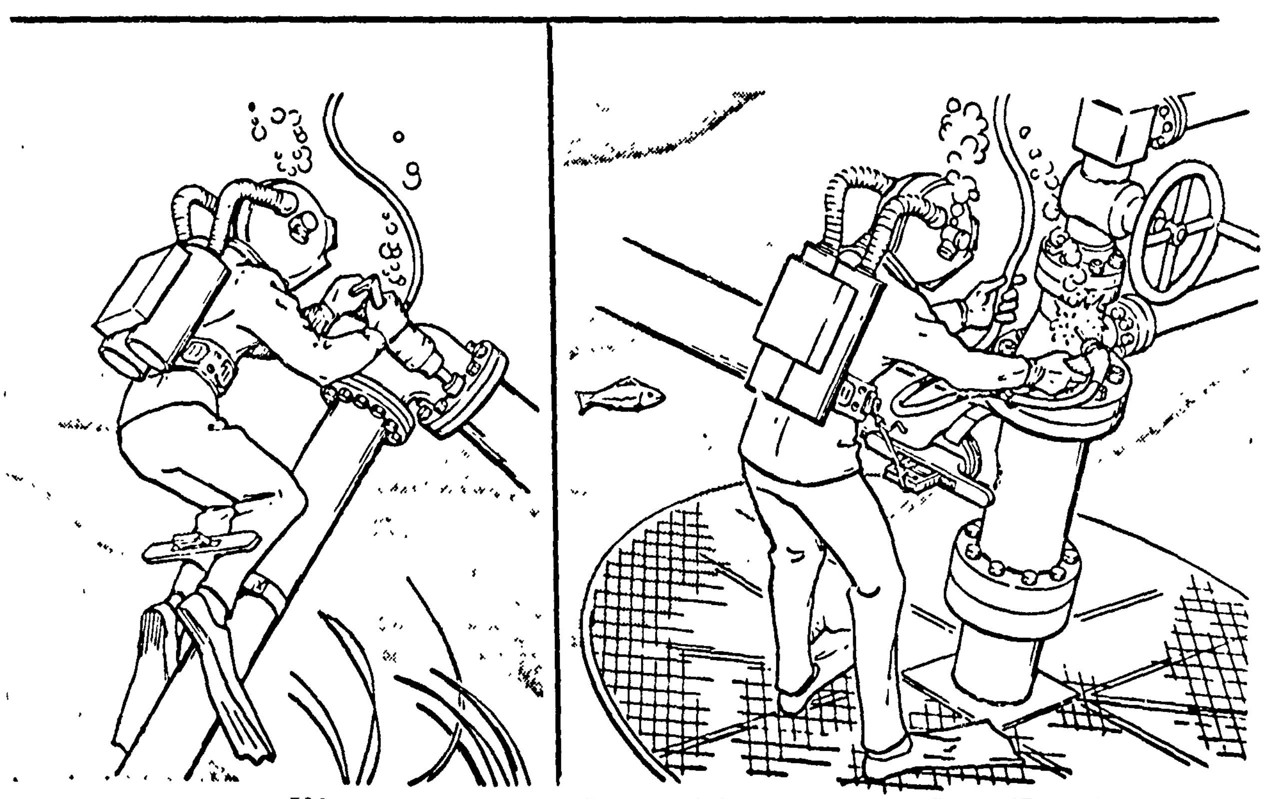


Figure 1. Lower Leg Restraint Modified for Diver Application (O'Neil, 1969).

Transportability -- The restraint is easily transported and can be worn around the diver's waist without encumbrance. There is no need for any portion of the restraint to be attached to the diver while working, an important safety consideration.

Work Surface Interface -- The restraint device has a minimum of structural interface problems. The adjustability straps allow the device to be fitted to various sizes of pipes and/or pilings (roughly 6 to 24 inches in diameter). No special modifications are required on the work surface or support structure; however, the structure must permit the restraint strap to wrap completely around it.

Another type of restraint developed for space use, which has underwater application, is the rigid waist restraint. This device offers a different type of fixity and reach envelope than the lower-leg restraint and generally requires that the diver be negatively buoyant or provided with a supplementary foot restraint. Figure 2 illustrates a rigid, telescoping-arm, waist restraint for maintaining a fixed, but adjustable, distance between the diver and his work surface. The primary disadvantage of waist restraint systems is the need for some sort of attachment point at the work surface.

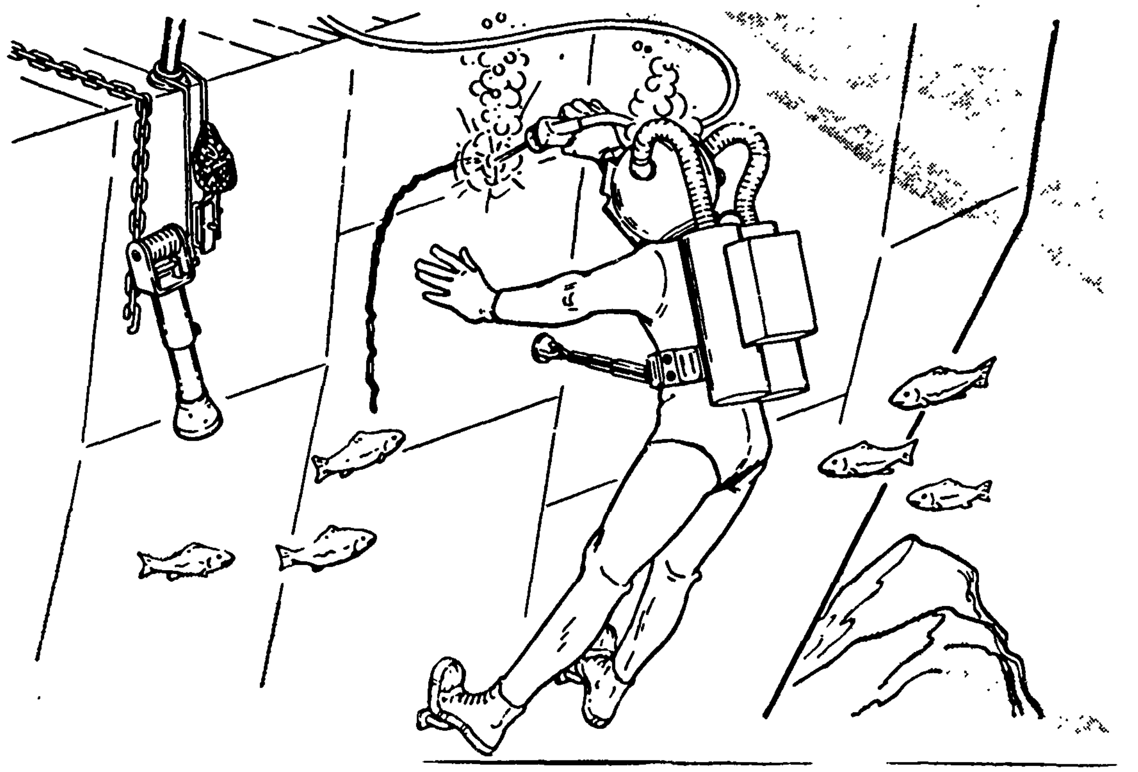


Figure 2. Rigid Telescoping Waist Restraint (O'Neil, 1969).

III. VISIBILITY

A. Introduction

Most underwater work requiring the use of diver-operated tools is carried out under conditions or at depths where visibility is poor. The underwater worker is very dependent upon water conditions to identify and locate his work site or work surface, view the progress of his work output, identify and select his tools and tool components, and visually identify tool controls and displays.

Natural water is not very transparent. In addition to its absorption of light as a function of color, water nearly always contains mineral and organic particles in suspension, which result in scattering of light. Thus it is difficult to see very far through water. While it is not necessary to be an expert on the physics of light in water to identify the visual problems of the underwater worker, a general understanding of the changes in light that take place underwater will help in solving some of the practical problems encountered in designing tools for underwater use.

B. Physics of Underwater Visibility

1. Absorption and Scattering

Two phenomena which usually limit underwater vision range are scattering and absorption. Observers agree that the absorption and scattering of light in clear ocean water are essentially the same as in clear distilled water, that some dissolved matter increases absorption, and that suspended matter increases the scattering. Both absorption and scattering present difficulties when visual observations are made in water. Scattering is the more troublesome, as it not only removes useful light from the beam but also adds background illumination. Compensation for the loss of light through absorption can sometimes be made by the use of a strong artificial illumination source; however, this addition of light can also be degrading to visibility because of the increase in backscatter (Briggs and Hatchett, 1965).

Vision through suspended particles presents two problems to the viewer. First, light must traverse the space between the viewer and the object in order to illuminate the object. The light unavoidably illuminates the suspended particles in the water, which causes light to be scattered back to the observer. In addition to reducing the light available to the object, this backscatter creates a bright foreground. Thus the illumination required to provide contrast between a viewed object and the foreground is increased as a function of the backscatter, while the actual light available at the object is reduced by the same mechanism.

The background illumination caused by scattering can be reduced by keeping unnecessary light out of the water between the object being viewed and the observer. This can be accomplished by locating artificial light sources in the area of the object and by using two or three efficiently positioned, lower-powered lights rather than one high-powered light.

Objects a few yards from an underwater observer can generally be seen distinctly in open ocean waters; however, clarity is greatly reduced for distances even as small as 10 yards. In coastal or turbid waters, the distance at which an object can be viewed clearly may be reduced to as little as 1 to 2 feet.

Preceding page blank

2. Refraction and Dispersion

Man is able to see objects plainly in an air environment because the light rays coming from objects being viewed are refracted (bent) to a focus on the retina of the eye. Most of this bending or refraction of light occurs at the corneal surface in accordance with Snellen's Law of Refraction. This law states that oblique light rays, when passing from a medium of lesser density (air) to a medium of greater density (the cornea), will be refracted toward the perpendicular. They will be bent away from the perpendicular when passing from a denser to a less dense medium. Since water has the same optical density as the cornea of the eye, the rays of light coming from an object underwater are not bent to a focus on the back part of the eye. The result is that visual acuity is reduced from 20/20 (normal) to less than 20/1200.

For man to see clearly underwater, an airspace must be placed in front of his eyes. For the diver, this is accomplished by the use of a face mask or the viewing plate of a diving helmet. With this aid, the rays of light from an underwater object strike the glass surface, pass into the airspace, strike the cornea obliquely, and are bent (refracted) to a focus on the retina.

Placing an airspace in front of the eyes is not without a number of deleterious effects, however. When viewing an object in water through an airspace, the refraction of light rays causes focus error, magnification error, and reduced visual field.

a. Focus Error

Since the refractive index of water relative to air is 4/3, all objects viewed underwater appear to be 25 percent closer than they actually are. For example, an object that is 20 feet away appears to be only 15 feet.

b. Magnification Error

Refraction of light rays passing from water to air result in magnification of objects underwater. As the light rays are refracted on entering the diver's mask, objects underwater appear to be one-third bigger, and hence closer, than they actually are. Thus, an object that is 3 feet in size appears to be 4 feet.

c. Reduced Visual Field

Where the diver's faceplate is a flat, glass surface, there is a narrowing of the visual field by approximately 25 percent, due to the incident light rays being refracted away from the normal perpendicular. At 49^{o}, which is the critical angle, light rays are totally reflected from the water-air interface. This phenomenon of total internal reflection sets a limit to the cone of vision (peripheral vision) which can be obtained through a plane or flat surface in any underwater visual aid.

C. Visual Resolution Underwater

Visual acuity or resolution is usually described by the Snellen Fraction, wherein the numerator of the fraction indicates the distance of the observation and the denominator indicates letter size where size is related to distance in such a manner that for "normal" vision the ability to resolve letter detail subtending one minute of arc at the observing eye's nodal point is required. Visual acuity may also be expressed as the reciprocal of the Snellen Fraction (e.e., $\frac{1}{20/20}$ = 1.00). This decimal defines the letter detail in minutes of arc subtended at the observers eye.

An investigation of visual resolution underwater (Kent and Weissman, 1966) indicated that, under conditions of clear water and good illumination, visual resolution of the image of an underwater test object, as seen through a scuba mask, is better than if the object was observed in air at the same physical distance and with the same apparent illumination. A summary of experimental results is shown in Table 10.

Table 10. Comparative Visibility of Landolt Rings in Air and Underwater Using a Scuba Mask (from Kent and Weissman, 1966).

	Binocular		Right		Left	
	Air	Water	Air	Water	Air	Water
Mean	1.79	1.65	2.26	1.86	2.07	1.83
Median	1.12	0.87	1.11	1.01	1.04	1.00

Note: Comparison of Landolt Rings target sizes was at the 50 percent frequency of seeing intercept. Sizes are noted as the angular subtense of the gaps in the rings in minutes of arc at the nodal point. Test distance was 16 feet. A scuba mask was worn for both underwater and surface testing. (N = 20).

The conclusion made by Kent and Weissman was that, given clear water and good illumination, visual resolution of the image of an underwater

Preceding page blank

object as seen through a scuba face mask is better than if the object was observed in air at the same physical distance and with the same apparent illumination. However, the improvement is, on an average, less than would be predicted on the basis of image magnification.

D. Stereoscopic Acuity Underwater

Experimental research has shown that while, under optimal conditions, visual acuity improves underwater (Kent and Weissman, 1966), the ability of divers to judge which of two objects is closer or farther (stereoacuity) is degraded in water (Ross, 1966; Luria, 1968). There are a number of reasons why stereoacuity is degraded in water:

- Fogged or dirty faceplate.

- Decrease in level of illumination with depth or water clarity. Both monocular acuity and stereoacuity begin to decline when background luminance drops below about 10 mL (Mueller and Lloyd, 1948).

- Acuity deteriorates with increased viewing distance underwater as the result of decreased brightness contrast between the object and its background. As the result of the absorption and scattering characteristics of light underwater, objects become invisible when their contrast is reduced to about 2 percent.

- Non-optical factors such as anxiety, cold, and nitrogen narcosis may impair a diver's visual efficiency (Baddeley, 1965).

Experiments conducted by Luria (1968) also showed that stereoacuity is degraded as a function of decreased water clarity. The results of these tests are shown in Table 11.

Table 11. Stereo Thresholds in Seconds of Arc as a Function of Water Clarity (from Luria, 1968).

	Transmission of Water			
	80%	32%	19%	10%
Mean - positive error group (N=5)	+9.82	+4.91	+23.60	+32.60
Mean - negative error group (N=2)	+9.14	+0.57	-10.00	-24.28
Standard Deviation	±4.30	±8.15	±17.35	±40.68

It is suggested that a main cause of the drop in stereoacuity with decreasing water clarity is the decrease in object-background contrast. It was also found that stereoacuity decreases in air when there is a loss of peripheral cues in water is a significant cause of the drop in stereoacuity underwater.

E. Size and Distance Judgment Underwater

Overestimation of size underwater is generally attributed to the fact that objects viewed in water are optically nearer, due to the refraction of light passing from water to the airspace within the diver's face mask. However, since the perceived size of an object is determined by its angular size in conjunction with its perceived distance, object size should be judged with a fair degree of accuracy underwater, provided the object is seen to be at its optical distance (3/4 physical distance).

Experimental studies of size judgment underwater (Ross, 1965) for objects ranging from 5.5 to 10 inches in diameter have shown that underwater sizes are considerably overestimated with marked variability as a function of the observation distance; the greatest overestimates occur for the farthest observation distance.

Distance judgment was found to be underestimated underwater. Object size affected underwater distance judgments beyond 30 feet, with the smaller objects judged more distant.

Size judgments did not bear the geometrically correct relation to distance judgments. The ratio of judged to true size was always found to be considerably greater than the ratio of judged to optical distance, whereas the ratios should be the same. If they were the same, the ratio of underwater to land size judgments would be the same as the ratio of underwater distance judgments to 3/4 of land distance judgments. Ross (1965) found that this correspondence did occur, but that the size ratios were displaced in the direction of the true rather than the optical distance ratios. It is suggested that this occurred as the result of divers learning to compensate for the underwater optical effect.

F. Visibility of Colors Underwater

Visibility of colors underwater varies with transmissivity of the water, depth, illumination, and color of the viewed object.

The use of colored paints to code tools, controls, and other underwater objects can alter their visibility and identification characteristics by increasing their contrast with respect to the underwater background surroundings. Kinney, et al. (1967) investigated the visibility characteristics of both fluorescent and non-fluorescent paints. A summary of this empirical study is provided as a guide for determining the relative underwater visibility of various-colored paints in different bodies of water.

1. Specification of Colors

Fourteen different paints were used in the Kinney study of underwater color visibility" blue, green, yellow, orange, and red in both fluorescent and non-fluorescent varieties, plus white, gray, and black. Their characteristics are listed in Table 12. The paints were chosen to be representative of commercially available items, and were varied in reflectance as well as hue.

Preceding page blank

Table 12. Specification of Color Paint Samples (from Kinney, et al., 1967).

Color	Luminance Factor % T	CIE Chromaticity Coordinates		
		x	y	z
Fluorescent:				
Blue	20.3	0.1591	0.1756	0.6653
Green	60.4	0.2625	0.6005	0.1370
Yellow-Green	111.2	0.4138	0.5472	0.0392
Yellow-Orange	95.4	0.5558	0.4183	0.0258
Orange	70.4	0.6065	0.3853	0.0082
Red-Orange	49.2	0.6323	0.3364	0.0313
Non-Fluorescent:				
Blue	12.8	0.2199	0.2085	0.5715
Green	12.3	0.2755	0.5183	0.2063
Yellow	44.4	0.5052	0.4548	0.0401
Orange	16.6	0.6024	0.3535	0.0441
Red	9.0	0.6024	0.3047	0.0929
White	81.5	0.3080	0.3188	0.3732
Gray	13.6	0.3197	0.3325	0.3477
Black	3.7	0.3058	0.3209	0.3833

2. Visibility of Colors

Underwater visibility of colors varies considerably depending on the characteristics of the body of water in which the observations are made. The results of Kinney's investigation, made in four types of water conditions, are shown in Table 13. These data present the colors that are easiest and most difficult to see at distances near the outer limit of visibility and can be used to determine what color to paint an object to make it as visible as possible.

The question of which colors to use for color coding, where multiple colors or absolute identification of colors is required, is quite different. The data in Table 14 list the true colors and the color names reported for four conditions of water visibility. Based on the colors which are often identified incorrectly or confused with other colors, combinations of colors can be selected for best absolute identification.

Table 13. Visibility of Colors and Transmissivity Characteristics for Four Types of Water Conditions (from Kinney, et al., 1967).

Description of water condition	Transmittance of sunlight by 1 m of water (%)	α	Horizontal viewing path (m)	Depth (m)	Colors of highest visibility	Colors of lowest visibility
Extremely murky, polluted	0.05	2.30	1.8	1.5	fluorescent oranges (yellow-orange, orange, and red-orange); non-fluorescent white, yellow, and orange	black, gray, blue, and green
Moderately turbid	0.50	0.70	3.4	3.7	fluorescent oranges and green; nonfluorescent yellow, orange, and white	black, gray, blue, and green
Clear	0.90	1.10	11.0	8.6	fluorescent greens and yellow-orange; non-fluorescent yellow and green	red, orange, gray, and black
Very clear	0.92	0.09	26.0	3.7	fluorescent greens; nonfluorescent blue and white	black, gray, red, orange, and fluorescent orange

Table 14. Reported Color Names in Order of Frequency (from Kinney, et al., 1967).

	True Color in Air	Reported Color under Various Water Conditions: Extremely Murky	Moderately Turbid	Clear	Very Clear
FLUORESCENT	Blue	Green Green-Blue	Blue Green	Blue	Blue
	Green	Green	Green Blue Yellow	Green Yellow	Yellow Green
	Yellow-Green	Gray White Yellow	Yellow Green White	Yellow Green White	Yellow Green White
	Yellow-Orange	Orange Red	Orange	Orange	Orange Yellow
	Orange	Orange Red	Orange Red	Orange Red	Orange
	Red-Orange	Red Orange	Orange Red	Orange Red	----
NON-FLUORESCENT	Blue	Gray Green Blue	Blue	Blue	Blue
	Green	Green	Green Gray	Green Blue	Green
	Yellow	Yellow Orange	Yellow Orange	Yellow	----
	Orange	Red Orange	Orange	----	Orange Yellow
	Red	Red Red-Orange	Orange Red	Black	Black
	White	White Yellow	Green White Yellow	White Green Blue	White Blue
	Gray	Gray	Green Black	Blue	----
	Black	Black	Black	----	----

3. Summary and Recommendations

a. The following colors are recommended for underwater viewing at the limits of visibility, with natural illumination and a water background:

- Under extremely turbid and murky conditions, fluorescent orange is the most visible. Non-fluorescent colors of good visibility are white, yellow, orange, and red.

- In coastal waters of moderate turbidity, fluorescent green and orange are superior. White, yellow, and orange are the best non-fluorescent colors.

- In clear water, fluorescent greens and white are best. With extreme clarity and increased viewing distance, the most visible colors change from yellow-green to green to blue-green.

- Fluorescent materials are superior to non-fluorescent materials of the same color in all water conditions. White is the best non-fluorescent material under all water conditions.

b. The most difficult colors to see at the limits of visibility with natural illumination and a water background are gray and black under all conditions, plus orange and red in clear water, and blue and green in murky water.

c. The number of colors which are not confused with other colors underwater is limited. Where absolute color identification is important, the following combinations are recommended:

- Green, orange, and black.

- Blue, green, orange, and black in clear water. Avoid black and red together.

- Green, yellow, red, and black in murky water. Avoid blue and black together.

G. Perceptual Narrowing

Laboratory experiments on human performance under conditions of psychological stress have produced experimental evidence that stress reduces the breadth of attention and produces perceptual narrowing. These studies have reported that a subject maintaining performance on a usually central or primary task is less able to respond to peripheral or secondary stimuli when placed under stress. The effect is a narrowing of the perceptual field.

Two experimental studies have examined the effect on visual perception activities of the risk-stress situation generally associated with ocean diving. While a diver does not anticipate drowning in the same way that a soldier anticipates injury or death when told that the crash of his aircraft is imminent, there are indications that the more diffuse type of stress associated with diving can also result in perceptual narrowing.

The first experiment investigating perceptual narrowing underwater was carried out by Weltman et al. (1966). A group of novice divers were tested through surface, tank and ocean exposures. Subjects monitored a peripheral light alone or while simultaneously performing an attention-demanding visual task. The results of these tests indicated that for novice divers, reaction time to the peripheral light progressively lengthened as subjects moved from the surface to a diving tank and to the open ocean, whereas the central task performance was not changed. These results suggested that the stress factors created by the diving environment would cause the perceptual narrowing previously seen in other stressful situations. However, in these tests the experimenters could only surmise that the affected subjects reacted to the tank and the ocean as anxiety-producing environments. It was uncertain whether the changes in peripheral response were also related to the physiological changes which accompany any submergence, and particularly submergence in cold water.

In a second study (Weltman, G., Smith, J.E., and Egstrom, G.H., 1971) the experiment was repeated in a laboratory setting which imposed no extreme environmental conditions, and consequently no inherent physiological change, and which permitted distinct measurement of anxiety. The simulation technique used employed an altitude chamber which had been refurbished to resemble a high-pressure facility with simulated pressurization to a 60-ft. depth. Preliminary exploration of the facility revealed that the chamber was an adequate simulation and experienced divers stated that the chamber closely duplicated the sights and sounds of an actual hyperbaric facility. The central task performed by subjects in the chamber was a self-paced automatic presentation of Landolt ring targets; detection of a light flash in the diving mask periphery was the criterion of perceptual narrowing. Anxiety was measured by heart rate and a questionnaire. Two groups participated; one in the chamber, the other as controls outside. Central task performance was the same for both groups; but the chamber subjects detected significantly fewer peripheral lights. The chamber group showed a significantly higher heart rate, while the anxiety test scores indicated a normal state for the controls, and a "mild" anxiety for the chamber subjects. Based on the experimental results of this study, the hypothesis of the initial study was validated and it can be safely assumed that peripheral visual performance can be degraded during situations of diffuse risk such as diving. The effects of perceptual narrowing should therefore be taken into account in the human factors design of diver's apparel and underwater tools. It should also be considered in the planning of practical diving tasks where the possibility that the diver's functional vision, already constricted by his mask or helmet, will be further constricted during periods of stress.

IV. CONTROL/DISPLAY CRITERIA

A. Introduction

Control design is concerned primarily with the extent to which an operator is effective in bringing about changes in equipment performance. This change is usually expressed as an output such as rate, quantity, or direction. A display, on the other hand, is any device that can be used to present information to an individual by visual, auditory, tactile, or other exteroceptive channels. Ordinarily, controls and displays are regarded as separate entities; however, this dichomomy is not always distinct. For example, the impact direction control on an underwater hydraulic impact wrench acts not only as a means of controlling the direction of flow of hydraulic fluid, but serves also to transmit information to the operator by its position, and is therefore a display as well.

The interrelationship between controls and displays is particularly prevalent in underwater tools and equipment where controls and displays must be designed to operate under conditions of poor visibility and restricted levels of illumination. The proper design and selection of control/display configurations for underwater tools therefore becomes an important factor affecting diver performance.

This section provides a compilation of human engineering criteria and recommendations for the design and modification of tools for underwater applications. Many of the design principles and recommendations are based on existing human engineering research findings, which have been adapted to meet the specific requirements and restrictions that result when man-machine systems are placed in an underwater environment. Other recommendations have been developed by the author from personal experience and from the experience of military and commercial divers currently engaged in working with tools underwater.

B. Control/Display Requirements

While the underwater environment creates a number of unique requirements and restrictions which limit the number and types of controls and displays that can be employed on individual tool items, the factors that must be considered in their selection and design are similar to standard surface controls. These include:

1. Functional Requirements -- The importance of the control in terms of regulating the tool output, the nature of the output that must be regulated, and the amount and direction of the output control.

2. Work Task Requirements -- The force and range of movement requirements in using the control, along with the effects of speed and precision in control movement and actuation.

3. Information Requirements -- The requirements of the operator in locating and identifying the control, determining the control position (setting), and sensing a change in control position.

4. Positioning Requirements -- The proper utilization of available space on a tool to place controls and displays, the importance of locating controls and displays where they can readily be identified and operated without interference with other controls/displays, or with the functioning or handling characteristics of the tool.

Preceding page blank

C. General Principles for Control Design

The following basic principles of human engineering design should be considered carefully in the selection and design of controls used underwater:

1. Accessibility

The following aspects of control accessibility require consideration:

Reach Distance -- Operator personnel must be able to initiate and maintain contact with the control in all body positions in which the control will be used. Activation of the control should in no manner reduce the operator's ability to support the tool accurately and maintain it positioned properly against the work surface. This requirement is especially important for power tools operated by one hand. Secondary controls should be located where access can be gained by the operator's free hand without interfering with the operation of the tool or endangering the safety of the operator. The 5th percentile dimensions are appropriate for use in meeting reach distance requirements.

Size -- The size of an individual control should be designed for easy grasping by an operator wearing gloves, mittens, or other personal equipment that might hinder control access and manipulation. Where space for locating controls is limited, the use of minimum-sized controls will not degrade performance, provided that resistance is low. Minimum control depth for fingertip grasp underwater is 3/4 inch and maximum is 1 inch. The minimum depth of 3/4 inch is 1/4 inch greater than standard human engineering recommendations (Ely, et al., 1956), as the result of experience gained from the use of neoprene foam thermal protection gloves. When control resistance is very low, the control could remain at 1/2 inch; however, the use of too low a control resistance may result in accidental or inadvertent control activation. Caution should therefore be exercised in the use of such controls.

Clearance -- Sufficient separation or clearance should be provided around a control to allow ample room for grasping and to minimize possible interference with adjacent controls. The following factors should be considered in proper control separation:

- **Requirements for simultaneous or sequential operation of controls.**

- **Size of the control and the amount of movement (displacement or rotation.**

- **Requirement for "blind" reaching (being able to reach for and grasp the control without seeing it).**

- **The effects on the tool's performance and the operator's safety of inadvertently activating the wrong control.**

- **Personal equipment that might hinder control manipulation.**

The general rule for control separation or clearance is 2 inches for controls requiring one-hand, random operation.

2. Direction

Certain stereotyped relationships have been developed between control movements and system or equipment component responses over the years. They are listed in Table 15.

Table 15. Conventional Control Movements.

Control Function or Equipment Response	Control Action or Movement
On	Up, Right, Forward, Clockwise
Off	Down, Left, Rearward, Counterclockwise
Increase	Forward, Up, Right, Clockwise
Decrease	Rearward, Down, Left, Counterclockwise
Right	Clockwise, Right
Left	Counterclockwise, Left
Raise	Up
Lower	Down
Retract	Up, Rearward
Extend	Down, Forward

Generally these accepted control movements and their related functions apply to the control of underwater tool systems. However, the fluid environment in which the diver works provides him with far greater freedom of movement than his surface counterpart. For this reason, the tool designer must be aware of a number of additional factors which could influence the performance of a diver. The direction of movement of controls operated underwater must be considered in the orientation of the diver's body in relation to his work surface and to the underwater tool and its control system. Since the tool operator may be in a state of near zero gravity (neutral buoyancy) and not restrained or tethered, any change exhibited by the tool in terms of torque or force output must also be considered in the design of control devices.

3. Resistance

The application of some degree of force by the operator is a basic requirement for control movement, and all controls must have a base resistance built-in to reduce the probability of accidental activation.

The following general factors should be considered in determining the kinds and amounts of resistance to be built into a control:

- Primary controls governing the tool's output should have sufficient elastic resistance to move the control toward a null position when the operator's hand or finger is removed (momentary-contact or "dead-man" control activation).

- Controls should have sufficient pre-loading elastic resistance to allow the operator's controlling hand to rest on the control surface without activating it.

- Controls should have sufficient resistance to protect the operator from undesired activation caused by accidental contact with the control, or by shock, G forces, or vibration.

- Controls should have enough resistance to provide the operator with feedback information ("feel") concerning control position. It should be noted that under conditions of cold-water operations, such feed-back information must be transmitted through gloves or mitts worn by divers for thermal protection.

It will be found that diver-operated underwater tools are provided almost exclusively with hand-operated and/or finger-operated controls. In general, resistance for hand-operated controls should not be less than 5 pounds, since below this resistance the pressure sensitivity of the hands is poor (Orlansky, 1948). The introduction of the operator to a cold, fluid environment will further reduce hand and finger sensitivity. The limits for maximum resistance for hand controls will depend on the type and location of controls, the frequency and duration of activation, and the direction and distance of control movement.

For finger-operated controls, resistance is usually described in terms of torque. The force that can be applied by a diver to finger-operated controls is largely a function of the "efficiency" of the diver's grasp on the control. The presence of a fluid environment and the use of protective gloves will further tend to reduce the diver's efficiency in applying torque. General guidelines for application of force to finger-operated controls are provided in Table 16.

Table 16. Resistance for Finger-Operated Controls (from Morgan, et al., 1963)

Finger-Operated Control	Resistance (ounces)	
	Minimum	Maximum
Pushbuttons (not generally recommended	10	40
Lever Controls	12	48
Rotary Selector-Switch Control	12	48
Knob Controls(continuous action)	--	4.5-6.0
Handwheels	80	*

* Depends on diver buoyancy and tethering devices empolyed. The greater the diver's ability to maintain a fixed body position, the greater the torque application that can be achieved.

4. Identification

The identification of specific controls is usually accomplished by some means of coding. Whereas for an ambient air environment controls are generally designed for easy identification by sight, this means of control identification is not well suited to underwater conditions, due to the extremely poor visibility that is normally encountered. For underwater applications, therefore, control identification must depend on other means than sight. The coding methods applied to identifying controls underwater are shape, size, and position. The crucial consideration with regard to these coding methods is the ability of the operator to tactually differentiate among controls. The following rules should be applied to the identification of controls:

a. Use a combination of several coding methods whenever possible.

b. Determine the total demands on the operator during the time when a control must be identified.

c. Consider the speed and accuracy with which a control must be identified.

d. Determine the space available for the location of controls.

e. Determine the number of controls to be coded.

f. Consider the tactual discrimination limitations of the gloved operator.

g. Consider the resistance requirement of the control.

Shape coding clearly provides one of the best means of positive identification of controls underwater. When such controls require the application of rotary force or torque, the shapes selected should provide the operator with a positive "non-slip" grip, even with gloves. In addition, standard shapes should be used and sharp edges on any part of the control should be avoided.

Since the ability to discriminate shape is relatively independent of size, size coding can be superimposed on shape coding. In selecting controls for size discrimination, the larger control should always be about 20 per-cent larger than the smaller one for controls ranging from 1/2 inch to 6 inches in diameter. The number of sizes that should be employed on a single tool is limited, and only two or three sizes should be used when the operator cannot compare the size of all controls before selecting the proper one. It should be noted that both shape and size coding are less effective if the operator wears thick gloves.

Tools requiring a limited number of controls can use position coding for control identification. By maintaining consistent control positions among tools having similar functional outputs, positive identification of controls is enhanced and inadvertent control activation will be minimized.

5. Type of Motions

The force producing characteristics of unrestrained divers have been studied under controlled conditions at shallow water depths (Streimer et al., 1968, 1971). The experimental results obtained from unrestrained divers are shown in Tables 17 and 18.

Table 17. Torque Development by Unrestrained Operators in Breakaway Impulse Mode as a Function of Task Nature Rotary Forces - 5 Foot Depth (N=4) (Streimer et al. 1968)

Task	Mean Value of Torque Produced	Standard Deviation	Recommended Value 95% Reliability
6-inch wheel	37.7 ft.-lbs.	4.4 ft.-lbs.	31 ft.-lbs.
12-inch wheel	70.5 ft.-lbs.	8.4 ft.-lbs.	57 ft.-lbs.
21-inch wheel	105.5 ft.-lbs.	9.0 ft.-lbs.	90 ft.-lbs.
2-inch shaft rotation	29.0 inch-lbs.	4.3 inch-lbs.	22 inch-lbs.
3 inch shaft rotation	33.0 inch-lbs.	5.4 inch-lbs.	25 inch-lbs.
4 inch shaft rotation	32.8 inch-lbs.	4.0 inch-lbs.	25 inch-lbs.

Table 18. Force Development by Unrestrained Operators in Breakaway Impulse Mode as a Function of Task Nature -- Linear Forces -- 5 Foot Depth N = 4 (Streimer et al. 1968)

Mode of Force Application	Mean Obtained Value	Standard Deviation	Recommended Value 95% Reliability
Push			
Two-hand	162 lbs.	8 lbs.	150 lbs.
One-hand	106 lbs.	23.8 lbs.	70 lbs.
Pull			
Two-hand			
Horizontal plane	151 lbs.	33.5 lbs.	100 lbs.
Vertical plane	224 lbs.	26.2 lbs.	185 lbs.
Pull			
One-hand			
Horizontal plane	114.6 lbs.	17.6 lbs.	90 lbs.
Vertical plane	151.0 lbs.	24.6 lbs.	115 lbs.

As can be seen from these data, significant degradations occur in the unrestrained diver s ability to produce "breakaway" forces. Degradation results from both the mode of force production, and within a given mode the type of force application.

In a later study (Streimer 1971) it was also found that the unrestrained diver's ability to produce manual power varied significantly as a function of the power production mode and, within a given power production mode as a function of the biomechanical characteristics of the man-task interaction. A summary of the results of these tests is shown in Table 19.

Table 19. Underwater Power Production by Work Mode and Configuration -- Unrestrained Operator -- Ten-Minute Effort, Five-Foot Depth, in Units of Horse Power (from Streimer 1971).

Resistance Level	Continuous Rotary Effort			Continuous Reciprocating Linear Effort
	6-Inch Radius	9-Inch Radius	12-Inch Radius	
3 lbs.	.016	.020	.021	
6 lbs.	.029	.036	.036	.016
9 lbs.	.038	.045	.045	.020
12 lbs.	-	-	-	.022

These results indicate that the productivity and efficiency of rotary repetitive work (e.g. continuous torque production) are significantly better than the productivity and efficiency with which repetitive reciprocating linear work (e.g. wobble pump operation) is produced. The 9-inch cranking radius at a 9-lb. resistance level offers the best configuration. A power output of .045 hp. is the most that can be expected (1485 ft-lbs./min.) in this configuration. This output rate can be maintained for up to 15 minutes with no fatigue indications.

Linear reciprocating work is less productive and less efficient than work obtained from rotary cranking. A power output of approximately 0.02 hp. (660 ft.lbs./min) can be anticipated from linear work involving resistance levels of up to 12 pounds. This output can be maintained for at least 15 minutes.

6. Safety

Two areas of concern exist with regard to the safe operation of a control. The first involves the possibility of personal injury to the operator during use. Such an injury could occur due to protruding or sharp edges on the control itself, or as the result of obstructions, projections, or tool outputs(cutting blades, abrasive grinding wheels, highspeed drills) that the operator may come in contact with while operating a control.

The second area of concern relates to tools having electrical power sources, where there exists the possibility of electric shock being transmitted to the operator through the control. All controls on such tools should be fabricated of nonconductive material and should be adequately grounded. Provision should also be made for safety shut-off circuits.

V. HUMAN ENGINEERING CONSIDERATIONS FOR SPECIFIC UNDERWATER TOOLS

A. Introduction

The biomechanical, anthropometric and human engineering data presented in the previous sections of this report have provided generalized design criteria applicable to the design of diver-operated tools and tool systems. These data have been drawn primarily from existing human factors literature, including generalized human engineering design guides, aerospace research findings, and the limited amount of underwater research data available.

This section provides a detailed human engineering evaluation of those underwater tool items which are currently being employed in underwater construction and salvage operations by military and commercial diving organizations. The tools selected for evaluation do not include all the various tools being used for underwater work, but represent a sample which have a high relative usage rate. These tools are all standard tools that have been applied directly to underwater use or which have been modified to meet the fluid and pressure conditions of the environment. As such, they serve as excellent examples of the types of problems experienced by divers and provide test situations for the application of human engineering design criteria input and recommendations. For each of the tool items evaluated, the following categories of human engineering data have been considered:

1. Tool size, form, and weight.
2. Controls and displays.
3. Handling characteristics.
4. Output capabilities.
5. Time required to operate.
6. Biomechanical considerations.
7. Requirements for strength and force applications.
8. Safety implications.

9. Recommendations.

The data presented are based on: 1) applicable human engineering research data; 2) results of diver performance research; 3) direct observation of underwater tool operations; and 4) interviews with commercial and military divers experienced in underwater salvage and construction work.

B. Hand Tools

1. Screwdrivers and Nutrunners

a. General

Standard screwdriver and nutrunner type tools designed for land use are, in general, well adapted for underwater work. However, their application to underwater work is limited, since most salvage and construction tasks requiring dismantling or assembly by a diver utilize large and more sturdy fastening systems. Such equipment usually requires a level of torque application beyond the capability of a hand-operated screwdriver. However, under conditions of limited access a screwdriver type tool offers distinct advantages and is the only type of tool that enables the diver to successfully performa a given work task.

b. Tool Size, Form, and Weight

Experience has shown 4-inch and 6-inch screwdrivers to be the most widely used in underwater work. These sizes are of sufficient bulk to be easily handled by a diver wearing gloves and working under most environmental conditions. The handle size and shape should be comfortable to grip and should cover the full breadth of the operator's hand, thereby allowing for maximum leverage. The following specifications are recommended:

- Handle diameter: 1.0 to 1.25 inches.
- Handle length: 4.0 to 4.5 inches.
- Handle grips: 6 longitudinal grooves from 1/4 inch to 3/8 inch in width, 1/8 inch deep.
- Material: dielectric plastic handle for safety when working electrical equipment.

The average weight of a standard 6-inch screwdriver is approximately 1/4 pound and can readily be operated by a diver for extended periods of time. Nearly all screwdrivers available on the market meet these general specifications.

An addition of a hand knob (Palm Grip) to the end of a standard screwdriver handle has been shown to increase the operator's rotary force capability, resulting in increased torque. The recommended size for such a hand knob is 2.75 to 3.25 inches in diameter. The hand knob should be designed with sinusoidal finger-grip indentations to insure positive control by the operator and to minimize hand slippage.

c. Controls and Displays

Controls and displays do not apply to screwdriver type tools with the exception of those provided with ratchet drive. These tools incorporate a single ratchet direction selector control having three positions (left ratchet, fixed drive, and right ratchet). The control consists of a small selector lever having fixed stops at each of the three positions. The control should be of sufficient size and depth to be operated by a gloved hand without interfering with the tool operations.

d. Handling Characteristics

The handling characteristics and functional capabilities of screwdrivers limit their use in the underwater environment. The amount of rotary force that can be applied to a screwdriver handle by a diver in a semi-weightless condition is limited, and, in most cases, is sufficient only to generate the required force to torque small screw or nut type fasteners. In addition, small fasteners, whether they are hex head bolts, Phillips head screws, or standard flathead machine screws, all have a number of inherent disadvantages and limitations when used underwater:

1) Small screws and bolt type fasteners are difficult to handle with a gloved hand or under cold-water conditions.

2) Conditions of poor underwater visibility limit a diver's ability to properly position and align small screws and bolts.

3) Divers have difficulty in keeping the driver head of these tools positioned on the screw or bolt head. Experience has shown that hex head, allen head, and Phillips head driver tips are preferred over flathead tips, since these permit a more positive engagement on the screw.

4) Prolonged submersion of small fasteners,

resulting in corrosion and/or excessive marine growth, obscures the head of the fastener, making it difficult to position a screwdriver tip or socket on the fastener for removal.

Despite these limitations, screwdrivers have a number of advantages over other torqueing devices. These tools are small and lightweight; they can be carried easily by the diver and do not limit or hamper his movements underwater. Screwdriver type tools can also be operated in confined areas where wrenches and larger power tools cannot be used.

e. Time Required to Operate

Screwdriver torqueing tasks do not require extensive time to perform under normal underwater conditions. Human factors studies conducted in conjunction with the training for the Sealab III project (Bayles, 1970) showed that actual tool operating times for loosening and tightening flathead, Phillips head, and allen head screws can be accomplished in 30, 29, and 20 seconds, respectively, for six screws. Tests were conducted by NCEL (Barrett and Quirk, 1969) in which comparative task times for three types of screwdriver head did not show that any substantial gains could be obtained by the use of a particular screwdriver head and tool combination. Performance times for the removal and replacement of three types of screw head in three operator positions are shown in Table 20.

Table 20. Screwdriver Task. Comparison of Performance Times (minutes) for Three Basic Working Positions (overhead, vertical, deck) (Barrett and Quirk, 1969).

Task	Mean Time to Complete Task Operator Position: Overhead	Vertical	Deck	Mean Times for Three Positions
Remove and replace 6 1/4-inch allen screws	2.70	3.98	2.50	3.07
Remove and replace 6 1/4-inch Phillips screws	2.92	3.93	2.55	3.13
Remove and replace 6 1/4-inch flathead screws	3.23	3.50	2.23	2.98

The large discrepancy in overall performance times between the Sealab III and NCEL data can be attributed to a variation in the task procedures. The Sealab III task required that the divers only loosen and retighten the six screws, while the NCEL tests required that the six screws be completely removed and replaced.

f. Biomechanical Capabilities

The biomechanical forces required to operate screwdriver type tools include hand torqueing or rotary force application in which body movements and positions do not change rapidly. Research data involving these biomechanical capabilities for divers are not available. However, a NASA research project (Trout and Bruchey, 1969) using pressure-suited subjects in a swimming pool found that short-duration tasks requiring the application of small forces could be performed effectively from a semi-free-floating condition of the weightless environment. In an earlier study (Pierce, 1963), an investigation was made of the effects of wearing a full-pressure suit on manipulating certain types of tools requiring rotary force application. The results are shown in Table 21.

Table 21. Hand Torque Values for Three Rotary Force Handle Types (Pierce, 1963).

	Hand Torque Values (inch pounds)		
Test Apparel	Screwdriver	2" Ball	3-1/4" Knob
Without full-pressure suit	63.34	79.58	117.92
With full-pressure suit (unpressurized)	54.17	72.08	129.75
With full-pressure suit (pressurized)	50.16	58.80	105.67
Mean Values	55.89	70.15	117.78

These pressure-suit tests of the three handle types indicate an increased rotary force capability of the 3-1/4 inch knob over the standard screwdriver handle by a factor of approximately two to one. The 3-1/4 inch knob handle is similar in design to the "Palm Grip" tool series, which is comprised of a variety of driver-type tools falling under the maximum provisions of Federal Specifications GGG-W-641d, GGG-S-00122, and GGG-S-121. Each tool has a square, metal, female drive and slot, 3/8 inch across, in the handle top. The Palm Grip handle consists of a 2-3/4 inch diameter palm-fitting grip, with sinusoidal finger-grip indentations, and incorporating a four-to-one ratio, three positional, reversible, steel ratchet. The handle thickness is 1-1/8 inches, including the drive. The Palm Grip handle and driver unit are illustrated in Figure 3.

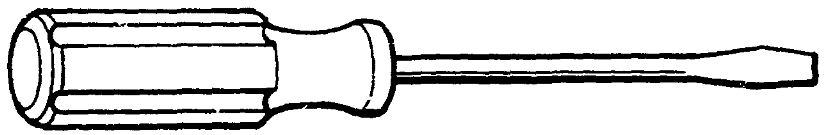
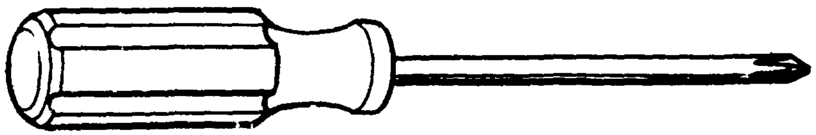
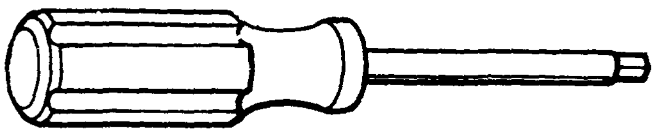
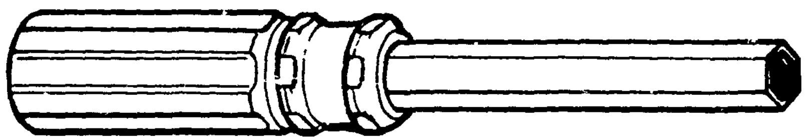
Tool Item	Name and General Specification
	1a. <u>General Purpose Flat Tip Screwdriver</u> 5/16 x 2-inch length up to 3/8 x 12-inch length
	1b. <u>Phillips Head Cross Tip Screwdriver</u> #1 x 3-inch length up tc #4 x 8-inch length
	1c. <u>Socket Driver</u> 1/4-inch and 3/8-inch drive shaft
	1d. <u>Selective-Socket Driver</u> Four nut sizes - 1/4-inch, 5/16-inch, 3/8-inch and 7/16-inch
	1e. <u>Palm Grip Handle with Ratchet</u> 2-3/4 inch diameter; 1-1/8 inch handle thickness, including drive tang

Figure 3. Palm Grip Tool System

g. Recommendations

Fixed drive versus ratchet drive -- The biomechanical techniques generally used when working with screwdrivers involve repetitive hand torque force applications. In performing the task, the operator turns the driver with a twisting motion of his hand, while maintaining a firm grip on the tool handle. He then slackens his grip and repositions his hand in preparation for the next torque application. During the repositioning phase, the operator does not have positive control of his driver tool, unless he uses his other hand to hold the shank. With the use of a ratchet drive incorporated in the tool handle, the operator can maintain a firm grip on the handle at all times, throughout the operating cycle of the tool. A ratchet drive also enables the diver to operate the tool with one hand, thereby freeing his other hand to grasp the work structure, acting as a restraining and steadying mechanism.

Handgrip design -- It has been demonstrated that the incorporation of a hand knob on the end of a standard driver handle can increase the torque capability of a driver type tool by a factor of two. The recommended size for such a hand knob is 2.75 to 3.25 inches in diameter. Hand knobs should be designed with sinusoidal finger-grip indentations to insure positive control by the operator and to minimize hand slippage.

Modular design -- The number of screwdriver tools that might be employed by a diver underwater is extensive and may include an inordinate number of driver tips and sockets. This problem can be minimized by the use of a modular tool system whereby multiple drive units can be used on one handle. Such a system should also be designed so that the driver tool can be operated in a standard screwdriver fashion or with the hand-knob, Palm Grip type, ratchet handle.

2. Hand Wrenche

a. General

Hand wrenches are recognized by both the commercial and military diving communities as being some of the diver's most important tools. Specific operations performed by divers using these tools include unbolting and removal of exterior ships' hardware, unbolting pipe flanges, making and breaking thread pipe connections, and unfastening valve bonnets.

Most types of wrenches that are used for normal surface bolting and torqueing tasks have, at one time or another, been employed in underwater work. The effectiveness of each type varies greatly with the task being performed, the environmental conditions, and the diving dress worn during the utilization. The discussion of wrenches in this section is by no means all-inclusive, but is intended to establish the relative importance of specific design features and to identify those features which are conducive to underwater applications and those which have presented problems for the diver.

A diver's standard tool kit contains crescent wrenches, open-end wrenches, box-end wrenches, a spud wrench, and a socket set with ratchet-drive handle. Each of these wrenches may well be capable of effectively performing the given task. The selection criteria, therefore, must include other facets of the tool than merely its ability to accomplish the job. The additional considerations which must be taken into account are:

1) The efficiency of the tool with respect to the time required to perform the task.

2) The ease with which the diver is able to handle the tool underwater.

3) The precision with which the tool can accomplish the specified task.

The ability of the wrenches described in this section to meet the additional selection criteria will be discussed in terms of specific design features of these tools.

b. Tool Size, Form, and Weight

All hand-operated wrenches have two basic components: a handle or "arm" by which the operator gains the necessary mechanical advantage to either torque or break loose a bolt or nut assembly, and a wrench head that is positioned over the bolt head or nut.

The wrench handle having a round or rounded-rectangle cross section may vary in length from 6 to 48 inches, depending on head size and the amount of mechanical advantage and to [illegible] imparted at the head. Clearly, the size of the handle and head combination will govern the overall weight of the tool and the access area in which the wrench can be operated effectively. A 48-inch pipe wrench, for example, weighs 30 pounds, which is considered in excess of the weight which a diver can easily operate on a repetitive basis. The maximum weight that a diver can be expected to handle over an extended period of time is about 10 pounds. This weight limits him to a wrench size of approximately 24 inches.

The wrench head designs fall into four general categories: 1) the adjustable open end, found on the crescent wrench, the spud wrench, and the special purpose "Kanta" wrench; 2) the fixed open-end wrench; 3) the box-end wrench; and 4) the socket head used on standard ratchet handles.

The adjustable open-head wrenches are extremely versatile, in that a single wrench can be used on different sized nuts and bolt heads. This feature is particularly appealing to the diver performing bolting tasks on different sized nuts or bolt heads, since he is not required to carry a large inventory of wrenches with him. The prime drawback of the adjustable wrenches is that the adjustable jaws have a tendency to slip on the nut when maximum torque is applied. This was found to be true especially for the Kanta wrench. The open end of the wrench jaws also is apt to slip off the nut during initial torqueing.

The fixed open-end wrench eliminates much of the slippage problem encountered with the adjustable-type wrenches, since the fixed-jaw open end is designed for a specific nut size. However, the open-end feature still allows the wrench head to slip off the nut unless the operator maintains the wrench securely on the nut.

The box-end wrench head eliminates the slippage problems found in the open-end wrench heads and has proved to be efficient and easy to handle underwater. The major disadvantage of this wrench is that a large inventory of wrenches is required where multiple-sized nuts and bolt heads are used. This same drawback also applies to the fixed open-end wrench head.

The three types of wrenches discussed to this point all have one additional feature in common which may cause both efficiency and handling problems. The fixed handle/head relationship of these wrenches requires that the operator reposition the wrench head on the nut after each torque application. In addition to being inefficient, this operating procedure is difficult under conditions of turbulence or poor visibility. This tool operation is also arduous where the operator does not have a restraint system to maintain a fixed body position.

Nearly all of the problems associated with operation of the fixed head/handle wrenches can be solved by a ratchet type wrench. The socket-head wrench with standard ratchet handle has been found to be well adapted to underwater use. Once the socket head is positioned on a nut, the socket does not have to be removed until the nut/bolt assembly is fully torqued. The closed design of the socket head completely eliminates slippage on the nut. A large number of bolt sizes can be accommodated with individual socket heads of the proper sizes. While the diver does not have the complete advantage of a single multi-purpose wrench, he is not encumbered by a separate wrench for each bolt size. Even where few bolt sizes are required, the socket wrench with ratchet handle is an extremely versatile tool and greatly cuts down the total number of wrenches which the diver needs to have available in his standard tool kit.

c. Controls and Displays

As with the driver tools, hand wrenches generally do not require extensive control mechanisms. Among the hand wrenches applied to underwater work tasks, only two types of controls are employed. The first is found on the adjustable open-end crescent wrench and pipe wrench, where a rotating wheel is used to adjust the size of the jaw opening. This adjustment wheel should be of sufficient size and raised far enough away from the wrench surface to allow adjustment by a gloved hand. The second type of control is furnished on ratchet handles A two-position control lever is recommended and should be of a size that can be operated with a gloved hand. A minimum 1/2-inch length and 1/4-inch depth are recommended. Where possible, both of these controls should be sealed against sand and other foreign matter.

While displays are not generally associated with hand-operated wrenches, consideration should be given to identification coding. Such coding can be especially useful where multiple wrenches of different sizes are used or when a socket wrench with various socket sizes is required.

Identification can be accomplished by the color-coding of sockets and wrench heads. Caution should be exercised in the selection of colors to ensure proper discrimination among colors. Under poor visibility conditions, additional coding may be provided by notching the sockets or wrenches for more positive size identification.

d. Handling Characteristics

The hand wrenches described in this section are almost exclusively land tools that have been brought directly into underwater use without modification. The primary problems experienced in handling these wrenches underwater result from the limited torque that can be applied in a tractionless environment. While this problem also exists with the screwdriver-type torqueing tool, the relatively small torque levels required can be achieved through short impulse actions by the diver. Applying torque with a wrench, on the other hand, requires full arm strength with elbow flexion to reach the required level of torque. This problem becomes especially acute when hand torqueing larger bolts of the 3/4-inch to 1-inch size, which may require torque applications up to 400-600 foot-pounds. Effective torqueing at these levels becomes nearly impossible without a firm, fixed structure at hand, against which the diver can brace himself, or a restraint system which the diver can use to keep his body in a fixed position.

Subjective reports from divers describing their experiences with the handling characteristics of various types of wrenches (Hedgepeth, 1967) relate the problems associated with a standard crescent wrench. The jaw-adjustment wheel on this type of wrench was found to be susceptible to jamming underwater from sand and bottom sediment. Problems were also experienced with socket wrenches underwater, in that, when removing the wrench from a nut or bolt, the socket would drop off the wrench and either sink to the bottom or remain frozen on the bolt. Underwater tests of conventional hand tools conducted by the Naval Civil Engineering Laboratory (Barrett and Quirk, 1969) showed no serious problems associated with the operation of ratchet wrenches. However, the test divers found it necessary to keep the ratchet mechanism well oiled or it soon became difficult to move the rotation direction change lever.

In underwater tests of the self-adjusting "Kanta" wrench, NCEL divers found that this wrench was considerably more difficult to operate than a standard crescent wrench. The divers had difficulty remembering or determining which way tc place the wrench to match the required direction of rotation. This wrench also had a tendency to slip over the bolt head or nut when torque was applied. A similar problem was experienced with a pipe wrench. The divers appeared to have trouble remembering which way to place the pipe wrench to match the direction of rotation, when working with a pipe nipple and coupling task. The pipe wrench also appeared to slip on a pipe slightly more then when working on land.

e. Time Required to Operate

Tests of performance times required for the operation of various hand wrenches were carried out by NCEL (Barrett and Quirk, 1969; Bayles, 1970). Hand wrench torqueing tasks were performed under three environmental conditions: open-air land, freshwater test tank (18 feet in diameter and 15 feet deep), and open-ocean salt water at a depth of 50 feet. These tests were conducted to obtain comparative data of land, test tank, and open ocean conditions and to compare three basic working positions: vertical, deck, and overhead. Task performance time results are shown in Tables 22 and 23.

For these tests, divers were equipped with full wetsuits and standard open-circuit scuba. Mean water temperature for the tank tests was 70°F, while the ocean test temperatures varied from 51° to 58°F. Tethering straps were used by the divers to maintain a fixed position with relation to their work surface.

From the data obtained, it is difficult to make an overall comparison of the four types of hand wrenches tested, because of the number of units torqued in each test and the difference in the sizes of bolts and nuts used. Only the crescent and Kanta wrench tests were performed on the same bolt sizes. The results for both environment (land, tank, and ocean) comparison and work position (overhead, vertical, and deck) comparison clearly indicate that the crescent wrench was a more efficient tool than the Kanta wrench. Test results for the three environmental conditions show the expected degradation in performance between land and water environments; however, the difference in performance times between the tank and ocean conditions is not significant. This would suggest that underwater tools can be tested reliably in the convenient tank environment where experimental controls can more readily be exercised.

Results of the hand wrench tests performed in conjunction with the

Table 22. Hand Wrench Torqueing Task (Barrett and Quirk, 1969). Comparison of Performance Times (minutes) under Three Environmental Conditions (land, tank, ocean), Vertical Work Position.

Tool Type	Task Description	Mean Time Required to Complete Task (N = 4)			Mean Times for Three Test Environments	Mean Times for Two Water Environments
		Land	Tank	Ocean		
Hand Ratchet	Loosen and retighten 9 1/4" bolts	1:62	2:47	2:15	2:08	2:32
Crescent Wrench	Loosen and retighten 1/4", 1/2", and 5/8" bolt and nut	0:97	1:38	1:37	1:23	1:38
"Kanta" Wrench	Loosen and retighten 1/4" 1/2" and 5/8" bolt and nut	1:67	2:45	2:32	2:15	2:38
Crescent Wrench	Loosen and retighten 3/4" hydraulic union	1:03	1:30	1:27	1:22	2:38
Pipe Wrench	Loosen and retighten 1" pipe nipple and coupling	0:97	1:37	1:40	1:23	1:38

Table 23. Hand Wrench Torqueing Task (Barrett and Quirk, 1969). Comparison of Performance Times (minutes) for three Basic Working Positions (overhead, vertical, and deck).

Tool Type	Task Description	Mean Time Required to Complete Task (N = 4)			Mean Times for Three Positions
		Overhead	Vertical	Deck	
Hand Ratchet	Loosen and retighten nine 1/4" bolts	2.27	2.25	3.23	2.75
Crescent Wrench	Loosen and retighten 1/4", 1/2", and 5/8" bolt and nut	2.60	1.60	1.57	1.92
"Kanta" Wrench	Loosen and retighten 1/4", 1/2", and 5/8" bolt and nut	2.57	2.53	1.75	2.28
Crescent Wrench	Loosen and retighten 3/4" hydraulic union	1.43	1.43	0.67	1.18
Pipe Wrench	Loosen and retighten 1" pipe nipple and coupling	1.08	1.67	1.07	1.27

Sealab III salvage work projects (Bayles, 1970) are shown in Table 24. The Sealab III tests were performed in an open-ocean environment and are considered representative of the results that would be obtained in an operational environment.

Additional data (Andersen and Swider, 1970) involved the torqueing of 8 bolts on an API flange by divers in a shallow test tank facility. The tools used in this test consisted of an open-ended hammer wrench and either a 4-pound or 8-pound sledgehammer. The task also required the use of a 15-inch crescent wrench as a backup wrench for holding the back nut of the stud bolt in position. Performance times were obtained for both torque and breakdown tasks of the 8 stud bolts of the flange. The results are shown in Table 25.

Comparison of performance times obtained from the two weights of sledge-hammers used in this task indicate that the divers were able to torque the bolts 29 percent faster with the 4-pound sledgehammer than with the 8-pound sledge. In the breakdown task, the 4-pound sledge had a 41 percent advantage over the 8-pound hammer. These results clearly suggest that the weight of the tool systems employed will influence performance time. The results of the two hand wrench tool systems used to perform the bolt torqueing and breaking down task also indicated a wide range of performance times among the divers. Such variability has been found in other performance tests involving divers (Andersen, 1968; Andersen, et al., 1969) and is attributed to a number of factors including diving experience, past experience in operating similar tool systems, endurance, and motivation. All of these factors may well have contributed to the diver variability found in these tasks. However, based on the experience and observations of the author, it appears that overall physical strength is the dominant factor influencing a diver's performance when working underwater with heavy tools and equipment.

f. Biomechanical Force Capabilities

The application of torque on a hand wrench requires considerably more strength than the rotary force needed for the application of force on a screwdriver. The problem of biomechanical force capabilities in divers becomes extremely complex, since the diver's ability to apply torque in an underwater environment will be governed by the type of diver dress used, state of buoyancy, body attitude with relation to work surface, and degree of body stabilization available. Thus it can be said that

Table 24. Hand Wrench Torqueing Task. Comparison of Performance Times (minutes) for Operation of Three Types of Hand Wrenches (Bayles, 1970).

Wrench Type \ Bolt Size (inches)	3/4	5/8	1/2	3/8	Means for All Sizes
Crescent Wrench	0.35	0.25	0.18	0.22	0.25
Box-End Wrench	0.25	0.32	0.15	0.12	0.21
Open-End Wrench	0.32	0.07	0.10	0.23	0.18
Total Means	0.30	0.22	0.15	0.18	0.21

Table 25. Performance Times for Torqueing and Breaking Down an 8-Stud-Bolt Flange (Andersen and Swider, 1970).

Time Measurement (minutes)		Hammer Wrench (8-pound Sledge Assist)	Hammer Wrench (4-pound sledge Assist)
Torqueing	Mean time to torque an 8-bolt flange	19.83 (range: 13.75-24.50)	13.92 (range: 6.50-28.67)
Torqueing	Mean time to torque an individual bolt	2.48	1.73
Breakdown	Mean time to break down an 8-bolt flange	7.93 (range: 7.50-8.67)	4.65 (range: 1.42-11.00)
Breakdown	Mean time to break down an individual bolt	0.98	0.58

the diver has as many "strengths" as there are different conditions of measurement, and individuals can be compared in strength only when measured under uniform conditions.

Biomechanical force tests performed underwater as part of the Sealab II performance measurement program (Bowen, Andersen, and Promisel, 1966) were carried out at a depth of 193 feet. The strength tests were performed using two reflex torque wrenches (0 to 300 foot-pounds torque capacity with overall handle lengths of 35 inches). One wrench was positioned in the horizontal plane, the other in the vertical. A "lift" test was carried out using the horizontal handle. This test consisted of lifting up on the torque wrench handle which was positioned approximately 30 inches above a platform on which the diver stood. He kept his feet firmly braced on the platform at all times. A "pull" test was carried out on the vertical handle, with the diver grasping the handle with his left hand at about shoulder height and gripping a fixed support at arm's length from the wrench handle with his right hand. In both tests the subjects were instructed to exert maximum force. Table 26 shows the mean measurements and standard deviations resulting from these tests.

Table 26. Sealab II Biomechanical Force Tests for "Lift" and "Pull" Conditions (data given in foot-pounds) (Bowen, Andersen, and Promisel, 1966).

	Pull			Lift		
	Number of Subjects	Mean	Standard Deviation	Number of Subjects	Mean	Standard Deviation
Dry Land	14	238	27.4	14	614	103.5
Sealab II	22	187	42.3	23	557	104.5
Percent Difference	21 percent			9 percent		

The results indicate that when a diver is provided with proper body bracing and positional restraints, the underwater environment has very little influence on the maximum force applicable to a torque arm. The greater loss found in the "pull" condition may be attributed in part to the diver's neutral buoyancy state. When a diver pulled between the two handgrips in the water, he was lifted off his feet and his body weight did not provide the same amount of restraining influence that it did on land.

In an underwater test of torqueing tools (Andersen and Swider, 1970), divers were required to torque 8 stud bolts on an API flange, using a 1-5/8-inch hammer wrench, a 15-inch backup crescent wrench, and either a 4-pound or an 8-pound sledgehammer. The tests of both the hammer/wrench tool combinations were performed on a 1-inch bolt size, with a recommended torque value of 475 foot-pounds. Diving dress used during the performance of the tool task consisted of standard hard-hat gear, including a nylon rubberized suit with chafing gear and a Kirby-Morgan hard hat. Standard weight belt and boots with ankle weights were used. The mean torque values achieved during these tests are shown in Table 27.

Table 27. Mean Torque Values for 1-inch Stud Bolts, Using Two Hammer/Wrench Combinations (Andersen and Swider, 1970).

Torque Measurement	Tool System	
	Hammer/Wrench 8-Pound Sledge Assist (N=4) (foot-pounds)	Hammer/Wrench 4-Pound Sledge Assist (N = 24) (foot-pounds)
Mean torque achieved	393	262
Range of torque values achieved (low-high)	(293-548)	(108-418)
Ratio of difference in torque value achieved on the lowest and highest torqued stud bolt of each API flange (mean value)	0.55	0.57

The results indicate that for neither hammer/wrench combination did the mean torque values reach the recommended torque value of 475 foot-pounds. With the use of the 8-pound sledgehammer assist, a few of the divers were able to obtain torque levels equal to, or in excess of, those recommended. However, none of the divers were able to reach the desired level of torque when using the 4-pound sledge. This can be attributed to two factors: 1) the test divers did not have the physical strength to achieve the required level of torque; or 2) the divers did not strike the hammer wrench a sufficient number of times to reach the maximum torque potential. In any event, the divers were not able to ascertain when they had reached or exceeded the required level of torque. The results presented in Table 27 also show the ratio of the lowest torque value to the highest torque value calculated for each flange assembly made up by the divers. From these data, the percentage difference between the highest and lowest torque value for each flange makeup is shown. While the exact implication of this difference is not known, it has been suggested that, for certain applications, the degree of difference obtained could be potentially dangerous. Improper seatings of the flange union and placement of excessive strain on individual stud bolts are problems resulting from unequal tightening of a flange.

For underwater applications where divers are required to obtain nominally equal torque values for a series of nut/bolt assemblies, or where a specified torque must be achieved, the capability to control and limit the torque output of a wrench must be developed. There is currently no technique that can provide a diver with this capability when operating a wide range of hand torqueing tools. The method presently used by divers consists of checking individual torque values with a reflex torque wrench. This technique is time-consuming, since the reflex torque wrench is difficult to handle underwater because of its size. The torque level indicator on this wrench is also difficult to read underwater from the normal position in which the diver would be operating the wrench.

A type of torque wrench that may have the capability of providing a torque-limiting function is the micrometer adjustable torque wrench. This wrench resembles a standard socket wrench, but it has a torque-limiting mechanism incorporated in the handle. By presetting a torque level on the adjustable handle, the force applied to a bolt will not exceed the torque level of the setting. The adaptability of this tool to underwater use has not been determined, nor has the accuracy of the torque-limiting mechanism been tested.

g. Recommendations

The ability to perform hand torqueing tasks underwater has come about through the direct application of existing wrenches designed for land use, or the modification of an existing wrench to meet a specific underwater task requirement. On land it is no problem to carry a large assortment of individual tools or to have on hand a wide variety of specific tool items. This convenience is difficult to accommodate underwater. With a normal assortment of wrenches alone, the weight of a working diver's standard tool kit could exceed 50 pounds. The combined weight and bulk of these individual tools cannot be handled readily by one diver, and the tools are not easily accessible or identifiable when stowed together in a tool bag. It is therefore recommended that a multi-function wrench designed for underwater use be developed. The available land tool which comes closest to meeting the requirements of such a tool is the standard socket wrench with ratchet handle. In addition to the existing design features of this wrench, the following characteristics should be incorporated to further enhance its capa'·ilities in an underwater environment:

1) Fabrication of corrosion-resistant material to ·inimize jamming and eliminate the requirement for extensive post-dive maintenance.

2) Provision for attaching handle extensions where greater mechanical advantage may be required. Extension handles should be designed with a tapered end that can be used for bolt hole aligning and prying.

3) Design of a ratchet that can be sealed against sand and other foreign matter which could jam the ratchet mechanism.

4) Incorporation of a torque-limiting mechanism that will enable a diver to control the level of torque output of the wrench.

5) Overall weight of the complete wrench system, including sockets, should not exceed 10 pounds.

C. Power Tools

1. Impacting Tools

a. General

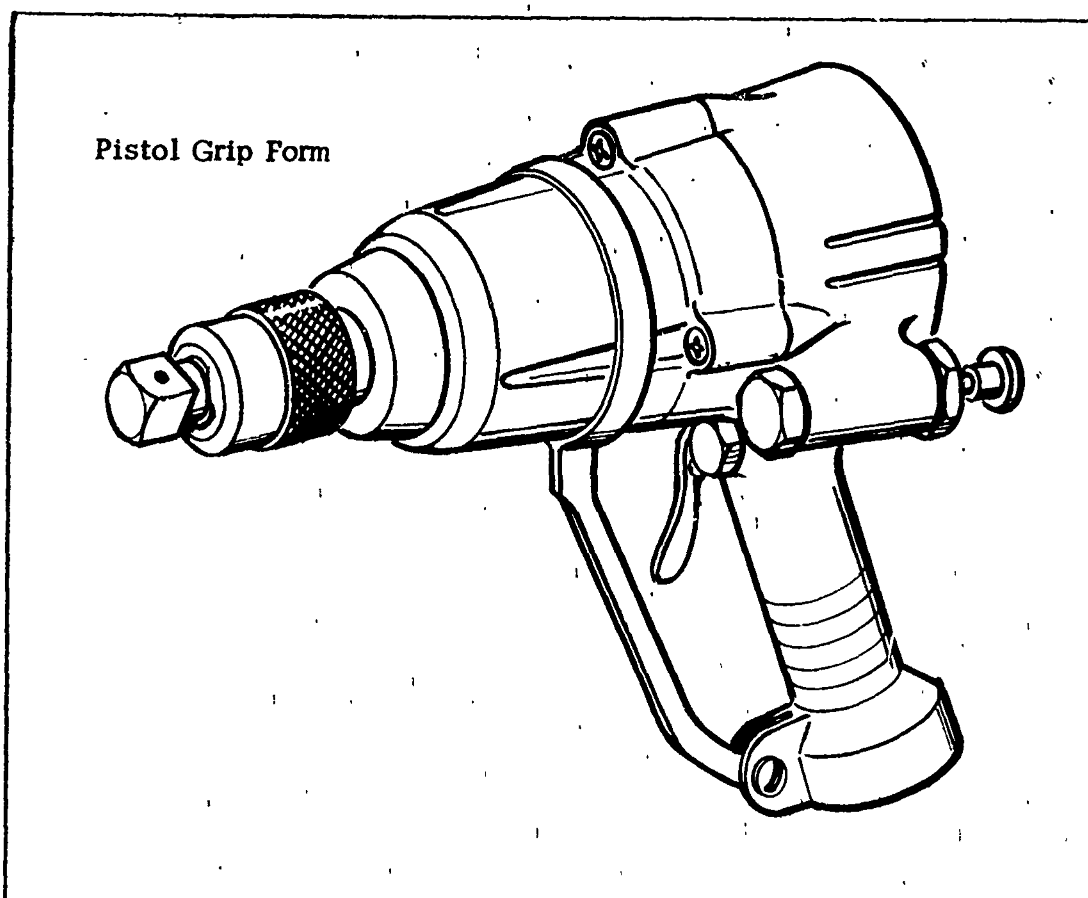
Impacting tools have been used extensively by both the Navy and commercial diving companies in performing consecutive torqueing tasks which, if performed manually, would be excessively fatiguing for the diver. Impact torqueing is also required for larger bolt sizes where the desired torque level can only be reached through power impacting. The same impacting tool employed for torqueing can also be used for drilling and tapping, and provides an excellent means for installing padeyes, eyebolts, and eyenuts.

The impacting tools presently used in underwater work are exclusively land tools which have been modified to meet the unique requirements of the underwater environment. As such, the performance limitations of the diver generally have not been considered. Even where human engineering modifications have been implemented, these changes are limited and must conform to the basic tool configuration and design.

Power sources used for impacting tools include both hydraulic and pneumatic systems. The basic tool configurations for both systems are similar and, therefore, their human engineering design considerations will be identical. Power source selection must be made in terms of operational performance requirements, including operating depths, logistics, operating costs, and power output.

b. Tool Size, Form, and Weight

Power impact tools (hydraulic and pneumatic) that have been adapted to underwater use are available in two basic design configurations: the "pistol" form and the "in-line" enclosed-handle form (Figure 4). The pistol shaped impact wrench is designed primarily for one-hand operation. A major disadvantage of this design is that application of force in the direction of the shaft orientation (pushing force) will tend to push the handle down, causing an improper alignment of the socket head with the work surface. While this problem is inherent in the pistol design, the misalignment tendency can be reduced by proper weight distribution.



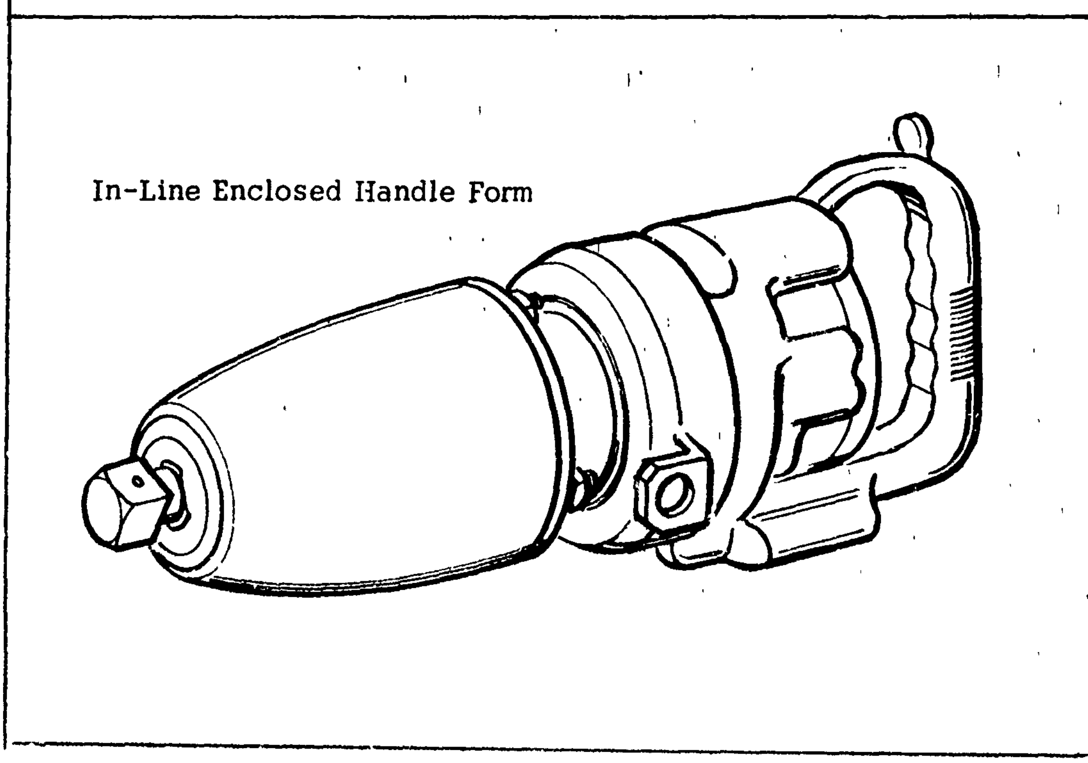


Figure 4. Power Impact Wrench Design Configurations

Lifting capabilities of a human operator have been studied by Hunsicker (1955) for various body positions and with the operator's arm positioned at various elbow angles. The data indicate that lifting capabilities are greater with the body in a vertical position, and that the lifting force decreases as the weight is moved away from the body. In the sitting position, the maximum force of 24 pounds is represented by the 120-degree elbow angle (5th percentile). Since this force represents static strength, it is not considered representative of the dynamic or sustained lifting situation encountered in tool handling. The upper weight limit recommended for the dynamic tool handling situation is estimated at one half the force values, or 12 pounds for the 5th percentile. Lifting force in the prone position appears to be reduced approximately 30 percent, which would make 8 pounds a more ideal weight for tools being operated from this body position. Subjective data have shown that double the weight of that recommended for one-hand operation is the maximum that an individual can comfortably handle with two hands over a prolonged period of time. When operation requirements imposed by the work task limit the use of the tool to one hand, tool weight should not exceed 10 pounds. Under conditions where the operator may be required to maintain the tool in a fixed position for extended periods of time, a more optimum weight of 6 pounds is recommended.

In-line impact tools weighing up to 110 pounds have been modified for underwater use but have not found wide acceptance in underwater applications. In keeping with the general weight guidelines, impact tools requiring two hands to operate should not exceed 20 pounds in overall weight, if prolonged use is necessary.

Illustrations and specifications of commercially available tools in this category are provided in the Appendix

c. Controls and Displays

Controls employed in impacting tools consist of a primary control for activating the tool and a secondary control for the selection of impact direction. Trigger hand controls of the type used to activate a pneumatic or hydraulic impact tool should offer sufficient resistance to movement to preclude inadvertent or accidental operation. However, resistance should not be so great that continued application of force will cause excessive fatigue in the operator's hand. Minimum resistance for gloved-hand operation or where limited hand sensitivity exists

Preceding page blank

should not exceed 5 pounds. Where the full weight of the operator's hand and arm is required to rest on the control without activation, a minimum resistance of 10 to 12 pounds is recommended.

The secondary control is required in the operation of both pneumatic and hydraulic impact tools. This control selects the direction of impact. Operation of the control redirects the flow of fluid within the motor mechanism and therefore requires a considerable amount of force to activate. The selection of the type of control used to perform this function should take advantage of the maximum capabilities of the operator. Since force is a major consideration, a lever selection switch is recommended. The lever length can be used to provide the operator with sufficient mechanical advantage. Maximum force required to operate the control should be 30 degrees, to allow for positive tactile position coding. The control should be readily accessible and operable without removing the impact socket from the work surface.

d. Handling Characteristics

Power impact tools modified for underwater use are primarily those having the pistol-grip design associated with electric hand drills. The normal method of using the tools relies on a one-hand operation: the tool is activated by depressing a spring-loaded trigger mechanism with the fore-finger. The ease and accuracy with which these tools can be handled underwater varies considerably with determining factors such as: 1) total tool weight and configuration, 2) force required to depress the trigger mechanism, and 3) operating ease of the direction-reversal mechanism.

The tool weight and configuration are closely related when considering handling ease. Pneumatic impact tools with a 1/2-inch drive shaft generally weigh from 4 to 6 pounds underwater. The pistol shape of these tools is operated readily with one hand and does not result in excessive fatigue for the diver, even when operated over a prolonged period of time. Hydraulic impact tools with 1/2-inch to 3/4-inch drive shafts weigh between 7 and 10 pounds. These tools also incorporate the pistol-grip configuration designed for one-hand operation. While a 10-pound pistol-grip tool can be operated with one hand, prolonged use has proved tiring to most divers. If the diver can manage to free his other hand, he will use it to relieve the weight of the tool.

Preceding page blank

Hydraulic impact wrenches with 1-inch or 1-1/2 inch drive shafts vary in shape, depending upon the manufacturer. Some have the pistol-grip design similar to the smaller tools, while others incorporate a fully enclosed handle in line with the drive shaft. Nearly all have a second handle designed to provide the operator with additional support. The weights of the larger 1-inch and 1-1/2 inch drive tools range between 20 and 27 pounds. These weights are well in excess of those which a diver can support and minipulate with one hand.

A second handling problem results from the force required to activate the trigger mechanism and to keep it depressed. While the necessary force to operate a trigger mechanism varies considerably among tools, the triggers are for the most part difficult to keep depressed for long periods of time.

Also associated with control manipulation is the problem of operating the direction-reversal mechanism. The function of the control is to reverse the direction of impacting. Two types of control have been used for this operation: a push-pull valve mechanism and a two-position control lever. In both cases the controls have been difficult to operate, due to their position and accessibility on the tool and the manual force required for operation.

The handling characteristics of impact tools are also influenced by the functional task for which they are being used. When used as an impact wrench to torque or break loose bolt/nut fastenings, relatively few problems are encountered with the operational output of the tool. The size sockets used in the impact wrench are relatively large and easy to handle. They can readily be positioned over a bolt head or nut and do not require precision alignment. Activation of the impact mechanism torques the bolt assembly until the maximum output of the impactor is reached. With the mechanism reversed, a bolt assembly can be loosened, unless the initial torque of the assembly exceeds the output capability of the impactor.

When the impact tool is used for drilling or tapping, additional care and precaution must be taken in operating the tool, in order to minimize breaking drill bits or taps. The drill bit should be maintained in a position perpendicular to the surface being drilled, and once the bit has penetrated the surface, extreme caution must be exercised to minimize movement of the tool around the axis of the bit. A steady force should be maintained on the tool to ensure continual contact by the cutting edges of the drill bit with the work surface. Best results are obtained by using medium, but steady, force against the surface being drilled. Too great or erratic pressure will chip or dull the drill bit. When tapping, intermittent application of power with minimal force applied to the tool has been found to provide the best results. To extract the tap bit, the impact direction is reversed, extracting the bit slowly while applying power.

e. Time Required to Operate

Limited tests of both pneumatic and hydraulic impact tools were conducted in conjunction with this research program (Andersen and Swider, 1970). Time measures of performance were obtained for divers torqueing and breaking down 8 stud bolts of an API flange. The results are shown in Table 28.

Table 28. Performance Times for Torqueing Using Pneumatic and Hydraulic Impact Wrenches (Andersen and Swider, 1970).

Time Measurement (minutes)	Tool System	
	Four-Pound Pneumatic Impact 1/2-inch drive (N=12)	Twenty-Pound Hydraulic Impact 3/4-inch drive (N=13)
Torqueing:		
Mean time to torque an 8-stud-bolt flange	5.13	7.98
Range (low-high)	2.50-11.03	4.43-14.50
Mean time to torque an individual stud	0.50	1.00
Breakdown		
Mean time to break down an 8-stud-bolt flange	2.18	1.38
Range (low-high)	1.13-4.00	0.67-2.22
Mean time to break down an individual stud	0.27	0.17

While the pneumatic wrench was faster than the hydraulic wrench for the torqueing task, the breakdown task resulted in greater performance times with the lighter pneumatic wrench. The reasons for these results are not clearly understood. However, it is suspected that the power output of the individual tools may have been an influential factor. Since the output of the pneumatic wrench is considerably less than that of the hydraulic wrench, it may have necessitated that the divers hold the pneumatic wrench on the nut longer before it would break loose.

Performance data was also obtained for underwater hydraulic impact tool work in connection with the salvage tool program of the Navy/Makai 1971 saturation dive (Andersen, 1971). The data was obtained during the diver training period of the program at a 40-foot depth in an open-ocean environment. The hydraulic impact tool tasks performed were observed and measured in connection with a simulated work situation involving the installation of eyebolts and padeyes in 1-inch mild steel. The results of these tests are presented in Table 29.

Table 29. Performance Times for Drilling, Tapping, and Torqueing, Using a Hydraulic Impact Wrench.

Task	Mean (minutes)	N	Standard Deviation (minutes)
Drill 3/16-inch hole through 1-inch mild steel	1.14	44	0.69
Drill 27/64-inch hole through 1-inch mild steel	1.43	28	0.56
Tap 1/2-inch NC/13 threads per inch in 1-inch mild steel	1.39	24	1.18
Tap 1/2-inch NC/13 TPI in 1-inch mild steel using combination drill/tap	0.90	12	0.43
Torque 1/2-inch bolt	0.52	22	0.25

f. Tool Output Capability

Data relating to the underwater work output of power impact tools is limited to a study conducted by Andersen and Swider (1970), comparing the torque output of a pneumatic and a hydraulic impact wrench. Divers used in this test were required to torque 8 stud bolts on an API flange. Individual bolt torques were measured with a manual torque wrench following completion of the task. The test results are shown in Table 30.

Table 30. Mean Torque Values Achieved for API Type 6B Flange, Using Hydraulic and Pneumatic Impact Wrenches.

Torque Measurement	Hydraulic Impact Wrench Weight = 20 lbs. (N = 13 ft. lbs.)	Pneumatic Impact Wrench Weight = 4 lbs. (N = 12 ft. lbs.)
Torque achieved	748.3	289.4
Range of torque achieved (low-high)	(453-900)	(191-409)
Ratio of difference in torque value achieved on the lowest and highest torqued bolts of each API flange (mean value)	0.67	0.52

For the two power impact wrenches tested, the torque values achieved were primarily determined by the tool power output, since the operator's major role in performing the task was as a controller.

The variability in the amount of torque transferred to the flange bolts was only a result of how long the operator kept the impact wrench socket positioned on the bolt head while the impact wrench was impacting. The tests using the hydraulic impact wrench were obtained on 1-1/2 inch bolts and resulted in a mean torque value of 748.3 foot-pounds, or 148.3 foot-pounds in excess of the recommended value of 600 foot-pounds for that size bolt. The operating pressure of the hydraulic power supply during these tests was 1000 psi. During later phases of the tests, the pressure was reduced to 700 psi; however, the torque levels obtained at this operating pressure were not substantially reduced.

The results using the pneumatic impact wrench were obtained on 1-1/8 inch bolts. For this tool, power was supplied from an air compressor operating at 100-120 psi. In these tests the mean torque value obtained of 289.4 foot-pounds did not reach the 600 foot-pound level of recommended torque.

g. Biomechanical Force Capabilities

Biomechanical forces required to operate power impact tools consist essentially of those forces related to the diver's ability to lift the tool and maintain it in a fixed position against a work surface, and his ability to activate the required operating controls.

Quantitative data are nonexistent on lifting capabilities of divers handling tools underwater; however, applicable information can be derived from maximum force exertion data, using a vertical handgrip developed by Hunsicker (1955). The handgrip handling position employed included various elbow angles and was very similar to that used in operating an impact tool. The data indicated that lifting capabilities are greater when the operator's body is in the veritcal position and that lifting forces decrease as the weight is moved away from the body. In the sitting position the maximum lifting force of 24 pounds was represented by a 120-degree elbow position angle (5th percentile). Since this force represents static strength, it should not be considered as representative of the dynamic or sustained lifting situation encountered in tool handling. The upper weight limit recommended for a dynamic tool handling situation is estimated at one-half the force value, or 12 pounds for the 5th percentile. Lifting force in the prone position appears to be reduced by approximately 30 percent, which would make 8 pounds a more ideal weight for tools being operated from this body position. The experience of working divers has shown that double the weight of that recommended for tools requiring one-hand operation is the maximum that an individual can comfortably lift with two hands over a sustained period of time.

The second area in biomechanical force application for impact tools relates to the resistance built into the controls used to activate the tool. These controls are trigger hand controls and therefore should offer sufficient resistance to movement to preclude inadvertent or accidental activation of the control. However, resistance should not be so great that continued application of force will cause excessive fatigue in the operator's hand. Since cold water application and the use of gloves by the operator will limit hand sensitivity, a minimum resistance somewhat greater than that normally recommended for bare-hand operation must be considered. The general guideline for minimum control resistance under such conditions is 5 pounds.

Secondary controls required for impact tools should also offer sufficient resistance to prevent activation which might be caused by accidental contact with the control, or by shock or vibration. For secondary controls the built-in resistance recommended is 10 ounces minimum and 40 ounces maximum.

h. Recommendations

Underwater tests of pneumatic and hydraulic impact tools clearly indicate a performance advantage over conventional hand tools, in terms of time savings and work output. However, the high cost of power impact tools, depth limitations, maintenance requirements, logistic support requirements, and size and weight constraints must be considered as limiting factors in their overall acceptability and general utility. The value of conventional hand tools should not, therefore, be overlooked. The tool system selected to perform an underwater work task must be matched with the output requirements of the task and with the ability of the diver performing the task.

The following specific design recommendations have been derived from underwater tool operations and related data:

1) Tool shape and weight play important roles in the work output of a diver. Impact wrenches with the pistol configuration should be limited to one-hand operation. Overall tool weight should not exceed 10 pounds. Where two-hand tool operation is required, the in-line design configuration is recommended, and tool weight should be limited to 20 pounds.

2) The torque levels that can be generated by a hydraulic impact wrench will, in many cases exceed those required by a given nut/bolt assembly. Such excess torque levels can either break the bolt or result in metal fatigue and weakening of the bolt assembly. A design feature enabling the diver to control and limit the torque output of the wrench should therefore be incorporated into the impact wrench.

3) The high costs of power impact wrenches and their logistic support requirements suggest the need for a compact and readily portable underwater power supply system. Such a system not only would reduce operational costs but would enhance performance by reducing the length and weight of power umbilical hoses required to support the diver.

2. Power Velocity Tools

a. General

Under contract to the Naval Ordnance Laboratory (NOL), Mine Safety Appliances Company has developed two velocity power underwater driver tools for use by the U.S. Navy in its salvage and emergency repair work (Lewis, 1967). These tools are portable hand-held devices designed to fire special-purpose projectiles into steel plate, either to join two sections of steel plate or to insert special-purpose threaded studs for the attachment of eyebolts or padeyes. The tools can also be used to insert hollow studs into a bulkhead for the transfer of gas or liquid. The light-duty version of the tool can be used with sheet metal, wood, and concrete, and the heavy-duty tool can be used to attach steel plate to wooden structures. Neither tool is suitable for extremely hard or brittle material.

Four different loads of solid-stud ammunition are available for the light-weight tool. All metal parts are common, but the powder charge is varied. A stud and piston constitute the projectile and are crimped into a .44-caliber, center-fire, cartridge case. The primer used is a commercial large pistol driver.

The heavy-duty tool has six types of ammunition available. These include solid studs, hollow studs, and a hole-punching projectile. Each type has a number of powder loads to accommodate various plate thicknesses. Each projectile uses the same piston-primer, block-sealing, cap assembly.

b. Tool Size, Form, and Weight

Both the light-duty and heavy-duty velocity power drivers are of an in-line design with a single handgrip and finger-operated trigger mechanism. The light-duty tool is provided with an open handgrip, while the handgrip on the heavy-duty tool is fully enclosed. The light-duty tool weighs 6 pounds and is approximately 18 inches in overall length. The heavy-duty tool weighs 17 pounds and has an overall length of approximately 20 inches. Externally, the barrel case of the tool is about 2-1/2 inches in diameter, cylindrical, and about 12 inches long, with a short flaring cone (spall guard) at the end of the barrel. The cylindrical portion contains inner barrel, body with firing pin mechanism, and etched outer barrel guide for non-slip grip. A cartridge is made up of explosive charge, piston, and stud. Both tools are constructed of aluminum except for steel barrel, trigger, and firing pin.

The light-duty tool is loaded much like a shotgun that breaks in half and exposes the breech. Since the barrel of the tool is flooded, the diver can extract an expended case and reload while he is underwater. In contrast, the heavy-duty tool employs a surface pre-loaded barrel. A separate barrel is carried by the diver for each additional round required. Each barrel is sealed at both ends. An O-ring on the cartridge effects the seal at the breech end, and two copper, muzzle-sealing washers between the barrel and the arresting block, and between the arresting block and the muzzle cap, seal the muzzle end. In order to achieve the required penetration, the projectile has to accelerate in a sealed barrel. When the primer is initiated, the expanding gases cause the piston projectile assembly to separate from the primer block and sealing cap assembly. As the piston-projectile assembly approaches the muzzle, the projectile passes through the sealing washers and through the holes in the arresting block and the muzzle cap into the work. However, when the large-diameter piston reaches the arresting block and impacts against it, the piston and projectile separate at their interface and the projectile continues its travel further into the work, while the piston remains in the barrel.

Photographs and complete specifications of these two tools are provided in the Appendix.

c. Handling and Safety Characteristics

These tools require two-hand operation. One hand grips the handle, with fingers positioned around the trigger mechanism; the other hand holds the etched barrel casing to steady and align the tool against the work surface.

Both tools are designed to be convenient for divers to use and yet safe to handle and operate. Each tool is equipped with two safety devices which must be activated intentionally before the trigger can fire a projectile. In operating the light-duty tool, the barrel is normally maintained in the open position by the barrel ejector spring. If a cartridge is placed in the barrel and the barrel is aligned with the firing pin, it cannot be fired, even if the trigger is pulled, because the primer is out of range of the firing pin. In order to fire the cartridge, the tool must be pressed against the work surface, placing the cartridge primer within range of the firing pin. Unless both actions are performed, operation of the trigger will not fire the cartridge.

Firing of the heavy-duty tool requires that the barrel be rotated 22-1/2 degrees against a stop and then pushed against the work surface. When the heavy-duty tool is in a safety condition, the barrel assembly is in a forward position so that the end extends beyond the spall guard and the cartridge primer is out of range of the firing pin. When the barrel guide is rotated 22-1/2 degrees, the two spline-like components allow the barrel to move backwards until the barrel end is flush with the spall guard.

Also, these tools will fire only if they are positioned at an angle of 82 to 90 degrees to the work surface. The tools are fired by the operator pulling the trigger straight back. This action compresses the firing pin spring and then releases the firing pin. The diver must exert a pushing force of about 5 pounds against the work surface to bring the cartridge primer into range of the firing pin.

d. Time Required to Operate

Performance times required to operate the heavy-duty velocity power tool (Bayles, 1970) were in conjunction with the salvage work projects planned for the Sealab III program. The results of this test are shown in Table 31.

Table 31. Performance Times for Operation of Velocity Powered Stud Driver (Bayles, 1970).

Subtask	Performance Times (minutes)
Move gun and barrels to test platform	2.00
Fire 6 studs (for 1/2-inch penetration	5.50
Fire 6 studs (for 1-inch penetration)	2.83
Place and torque 6 nuts	3.53
Total time	21.50*

*The "total time" for this task is greater than the combined subtask times, because the time required for other factors, such as communicating and adjusting, are not listed. The total time, therefore, represents the approximate total elapsed bottom time required for the task.

Performance times for velocity power tool operations were also obtained during the training dives conducted for the 1971 Navy/Makai saturation dives (Andersen, 1971). These tests required a diver to install an eye-nut, using the heavy-duty velocity power drive to insert a threaded stud in 1-inch mild steel. The results of this test are shown in Table 32.

Table 32. Performance Times for Installation of Eyenuts Using a Velocity Power Driver.

Subtask	Performance Times (minutes)	
	Mean	Standard Deviation
Load barrel into gun	0.23	0.189
Fire stud	0.17	0.135
Screw in eyenut	0.40	0.174
Idle or rest	0.27	0.200
Total time	1.07	0.200

Percentage Time Spent on Specified Task Activities

Load barrel (Preparation)	= 21%		Preparation
Fire stud (Work)	= 16%	= 53%	Work
Screw in eyenut (Work)	= 37%		
Idle or rest	= 26%		Rest

e. Tool Output

The tool output of velocity power drivers is determined by the particular tool used, light-duty or heavy duty, and the type of cartridge employed.

Four different loads of solid-stud ammunition are available for the light-duty tool:

1) Extra-light load

- 1/2-inch plywood to 1/4-inch steel plate
- wood or light-guage metal to concrete

2) Light load

- two 1/4-inch steel plates
- 1/2-inch plywood to 1/2-inch steel plate

3) Heavy load
   - two 3/8-inch steel plates
   - 1/2-inch plywood to 5/8-inch steel plate
4) Magnum load
   - two 1/2-inch steel plates

The light-duty solid stud is 1-1/2 inches long and 3/16 inch in diameter. The stud and piston constitute the projectile and are crimped into a .44-caliber center-fire cartridge case.

The heavy-duty tool has six types of ammunition available:

1) Solid stud
   - 3/8-inch to 1-inch single or laminated plate.

2) HY-80 stud
   - 3/4-inch to 1-inch HY-80 steel plate

3) Headed deck pin
   - 1/4-inch, 3/8-inch, and 1/2-inch steel plate to wood

4) 1/2-inch hollow stud
   - 1/4-inch to 5/8-inch single-thickness plate
5) 11/16-inch hollow stud
   - 3/8-inch to 5/8-inch single-thickness plate

6) Hole-punching projectile
   - 5/8-inch diameter hole in 3/8-inch or 1/2-inch single-thickness plate

Projectiles used in the heavy-duty tool must be pre-loaded in air, thus requiring the diver to bring with him the number of charged barrels to be used for a specific job. Typical extraction forces are indicated in Table 33.

Table 33. Average Stud Extraction Forces for Velocity Power Tool Projectiles (extracted from manufacturer's specifications).

Plate Thickness (inches)	Light-Duty Tool Model NUD-38 (pounds)	Heavy-Duty Tool Model D (pounds)
1/4	3,000	---
3/8	3,500	8,000
1/2	4,000	14,000
5/8	---	16,000
3/4	---	19,000
7/8	---	22,000
1	---	25,000
1-1/8	---	29,000

f. Biomechanical Force Capabilities

The velocity power drivers tested do not place any demanding biomechanical force requirements on a diver. The trigger mechanism operates smoothly, while still offering sufficient resistance to prevent accidental activation. The designs of both tools allow them to be dropped onto a hard surface without firing. Even if the trigger is activated by a sudden impact, the secondary safety features will prevent firing.

The heavy-duty tool, though it weighs 17 pounds, can readily be handled by a diver, since prolonged positioning against a work surface is not required. As both of these tools require two-hand operation, it is recommended that, when using these tools, divers be provided with some form of body restraining device. Restraints are considered almost essential, because the operator must exert a force of about 5 pounds against the work surface to position the barrel properly.

g. **Safety Implications**

Since velocity power tools are ordnance devices and potentially dangerous to operating personnel, certain diver precautions must be exercised:

1) At no time during the firing cycle of a projectile should any part of the operator's body or that of another diver be extended beyond the plane of the work surface in which a stud is being fired. The natural tendency to place one's arm around the work surface for support must be avoided.

2) If a misfire occurs when the trigger is pulled, maintain the driver tool in its firing position against the work surface. Repeat the firing cycle three times. If the tool still misfires, keep it in position against the work surface for 30 seconds as a safeguard against the possibility of a delayed discharge, then remove and replace the cartridge or barrel. Use extreme caution in pointing a loaded misfired barrel or cartridge.

3) While handling a loaded velocity power tool, a diver must keep it pointed away from himself and other divers in the water. The tool should be treated as a loaded handgun and considered dangerous at all times.

4) In handling the velocity power tools on the surface, extreme care must be taken in handling the explosive studs during loading. Misfired stud cartridges or loaded barrels should be disposed of through proper explosive ordnance disposal means.

3. Underwater Cutting and Welding Tools

a. General

Cutting and welding tools have long been recognized as essential to the successful performance of a multitude of underwater work tasks. Metal cutting and welding torches have been used by both commercial and military divers in such varied underseas operations as rescue, salvage, construction, mining, and drilling.

An underwater burning torch is considered one of the salvage diver's most useful tools and is probably the fastest way for a diver to cut metal underwater. The major drawback in using burning tools underwater is that they require a considerable amount of skill for successful and efficient operation.

In selecting the method to be used in torch cutting underwater, consideration should be given to such factors as the complexity of the job, equipment availability, space requirements, and the supply of rods, oxygen, and fuel. For small cutting tasks at shallow depths, the oxyacetylene torch may be best; for jobs requiring a large amount of cutting, the arc-oxygen torch may be better suited and more economical. In areas where equipment supply is a problem, the light weight and slow burn-off of a ceramic rod might be preferable for the job. A primary requirement for selecting the best technique is to conduct a thorough inspection of the cutting job, examining the condition of the material to be cut, water depth, anticipated visibility conditions, and any other factors that may affect the work.

Welding has been found to be an effective method of joining metals underwater. Although welding is not used as extensively as cutting in underwater salvage and construction work, it does provide a fastening technique well suited for the attachment of padeyes and other lift points and for fastening small patches in shallow water. As with torch cutting, underwater welding requires considerable training and experience. A good underwater welder is one who is dual-rated as a diver and journeyman welder, proficient both topside and underwater.

The easiest and most commonly used method of underwater welding is the "self-consuming" technique, which requires the deposit of weld metal in a series of strings or beads. These beads, when deposited, form a fillet and result in welds having approximately the same size as the diameter of the electrode used. Fillet welding is especially adapted to underwater work since it provides a natural groove to guide the electrode. Generally, underwater welding should only be used as a temporary fastening technique for emergency repairs.

b. Tool Description

Two basic classes of cutting and welding torches have been applied to underwater burning operations: the oxygen-hydrogen torch and the arc-oxygen torch.

1) Oxy-hydrogen torch -- Until 1942, the most widely used tool for underwater cutting was the Ellsberg torch. This oxy-hydrogen torch, with only minor modifications, is representative of those manufactured by most suppliers of burning equipment. The basic design principle is the same as the standard oxy-acetylene torch, except that, in addition to the two gases for a flame, it has a third hose to supply air as a shield surrounding the torch tip. This air bubble shield stabilizes the flame and holds the water away from the surface being heated. Oxygen and hydrogen (or other fuel) hose lines connect to the torch assembly and are premixed in the torch body and spark-ignited at the torch tip. When metal cutting reaction starts, the compressed air can be shut off. The diver can then regulate the oxidant flame rate by hand levering.

The most common oxidant used in this type of torch is hydrogen, and while there are no depth limitations on the use of this gas, it burns better at moderate depths of 10 to 150 feet. The use of acetylene is also possible with the oxy-hydrogen torch but may require a special tip. Extreme caution must be exercised in the use of acetylene underwater, because it is unstable and may cause dangerous explosions at depths in excess of 25 feet. A relatively new gas which can be used in the oxy-hydrogen torch is MAPP gas (stabilized methyl-acetyl-enepropadiene). MAPP is more economical than hydrogen and is stable up to 350 psi. It will also cut through paint, rust, and laminated plate. All of the gas torches have an additional drawback in that, when used in closed or restricted areas, the residual gases may create pockets within the closed or restricted area and ignite under certain conditions.

All makes of oxy-hydrogen underwater cutting torches are of the same basic design. The operation of the torch is based on the following:

- The emission of a cylindrical envelope of compressed air which pushes the surrounding water away from the flame.
- A preheated flame produced from a mixture of hydrogen and oxygen which supplies heat to start the cut and maintain cutting temperature.

- **A central jet of oxygen which accomplishes the actual cutting by oxidizing and blowing out a narrow band of metal.**

2) Arc-oxygen torch -- Arc-oxygen torches cut by burning. The basic principles are to preheat the metal with an arc and then to combine the arc with oxygen under pressure as the oxidant cutting agent. A ceramic-coated or flux-coated electrode feeds oxygen to the work from a surface oxygen supply line. Oxygen storage bottles are generally maintained on the surface, with pressure being regulated according to the ambient pressure and the operating depth. The arc cutting torch consists of a bronze head to which an electrical leader cable is directly connected. The bronze head and collet grip the electrode securely with a full electrical contact area. Most units are secured by rotating a locknut one-quarter turn to engage or release the electrode.

The electrodes are usually made from tubular steel with oxygen delivered through the hollow center. A squeeze-type valve is used to control the flow of oxygen and a welding lead is employed to supply the current to the electrode. The second lead is closely connected to the work as a ground.

Electrodes most commonly used for cutting are 5/16 inch in diameter and 14 inches long, with an approximately 1/8-inch bore. The electrodes are manufactured with a waterproofed, extruded, flux covering, which acts as an insulation and also increases the efficiency of the cutting process. Hollow ceramic rod electrodes are also used. These rods are 8 inches long, 1/2 inch in diameter, with a 1/8-inch bore. They have a slower burn-off rate than the tubular steel rods but consume more oxygen per linear foot cut.

Arc-oxygen underwater cutting torches are still being developed and improved. The primary consideration in the design of any underwater electrode holder is to completely insulate current-carrying parts. The torch must also be light in weight, simple in construction, and incorporate some form of electrode-clamping device (collet or chuck) which will facilitate electrode changing under adverse conditions. The basic elements of an arc-oxygen cutting torch are:

- a chuck or collet for holding the tubular electrode and to permit entrance of oxygen into the tube.

- an oxygen valve.

- an electrical connection.

- a flashback arrester for use with steel tube electrodes.

- an insulating coupling installed between the valve and the chuck to safeguard the operator from electrical shock and to prevent deterioration of the oxygen valve as a result of electrolysis.

- complete insulation for all exposed current-carrying metallic parts of the torch.

Arc-oxygen torches range in length between 9.5 and 14 inches and weigh approximately 2 pounds without cable and 6 pounds with 10 feet of welding cable.

c. Controls

Arc-oxygen cutting torches require only one primary control, an oxygen valve and trigger assembly which is completely isolated from the electrical front section of the torch. The oxygen valve on most torches is designed for full 360-degree rotation to permit the operator to position the trigger for his convenience. A secondary operator-controlled component of these torches is a built-in flash-arrester cartridge and screen which may be removed with a screwdriver in 30 seconds for inspection or cleaning. If the screen has been burned out by severe flashback, it can readily be replaced in approximately 5 seconds. Another secondary control is for replacing expended electrodes, by turning a collet or chuck to engage or release the electrode. Once released, the stub of the consumed electrode may be rejected with a short blast of oxygen from the trigger valve.

The oxy-hydrogen torch requires a number of controls in addition to the basic trigger-controlled oxygen valve. These include three adjustable rotary valves usually located at the base of the torch handle. These valves function to control the flow of preheated oxygen, hydrogen gas, and compressed air. The operating pressure of each gas required will be the sum of the pressure required to operate the torch, the pressure due to depth, and the pressure required to overcome the friction in a given length of hose.

d. Handling Characteristics

Burning and welding torches, lightweight and compact in size, are easily handled by a diver underwater. Apprehension of their use underwater results primarily from the potential electrical shock hazard and discomfort to the operator. Nearly all divers who have operated oxy-arc torches have at one time or another experienced electrical shock and discomfort in their hands, lips, and teeth. The hazards of electric shock can be minimized by the use of rubber gloves and insulated dry suits. If a metal helmet is worn and AC power is used, the diver's head must be insulated from the helmet by a woolen cap or other suitable means, and the exhaust valve button should be covered with an insulating material.

Another potential handling problem which affects a diver's performance and safety results from the darkened welding lens used to protect the torch operator's vision while he is cutting or welding. Such lenses are generally permanently affixed to the diver's face mask or helmet, thereby severely hampering vision when he is not actually using the torch.

As with all underwater tools requiring power and gas umbilicals, there is a tendency for lines and hoses to become entangled. When caught on or rubbed against sharp-edged metal structures, the abrasive motion may either cut through the line or penetrate the line's insulating protective cover. In most cases, a cut or abraded line will only result in the loss of power to the tool; however, in the case of lines carrying electrical current, a break in the insulating material can result in severe injury to the diver. Extreme precautions must therefore always be exercised in the use of oxy-arc cutting and welding torches.

Recent data were obtained to determine basic diver performance capabilities with underwater cutting torches (Barrett, 1971). Cutting tasks were performed by divers outfitted in three basic types of diving apparel: standard hard-hat gear, lightweight gear using light helmets with conventional wetsuits, and conventional scuba gear with single-hose regulator and wetsuit. Burning test specimen material consisted of pipe and I beam. The pipe was 12-inch-I.D. steel with 3/8-inch wall thickness. The I beam had a flange width of 7 inches, a depth of

13 inches, and a 7/16-inch web thickness.

Miller welders were used to furnish the electrical power. They utilized 40-volt, open-circuit, line voltage with 300 to 400 amps current. Craft-shield cutting torches were used with 5/16-inch tubular, coated steel burning rods. The mean O_2 pressure was 85 psi, with a range from 70 to 100 psi. The divers used #6 welding lenses taped or mounted on the front part of their diving masks or helmets. The burning data are summarized in Table 34.

Table 34. Oxy-Arc Burning Data (from Barrett, 1971).

	Pipe (3/8" wall thickness)			I Beam (7/16" web thickness)		
	Scuba	Lightweight	Hard Hat	Scuba	Lightweight	Hard Hat
O_2 Consumed (cu.ft. @ 1 atm.)	2.8	2.8	2.5	2.9	2.9	2.7
Distance Burned (inches)	8.3	9.1	8.1	6.8	8.7	6.4
Time Required (minutes)	1.3	1.4	1.3	1.3	1.3	1.4

The test divers were able to burn slightly greater distances using lightweight diving gear, but there were no significant differences in oxygen consumption or time requirements. Generally, the test divers preferred scuba and lightweight diving gear, from the standpoint of operating ease and maneuverability. However, hard-hat gear was preferred for freedom from shock, communications ease, and buoyancy control, and was generally considered the most desirable to use for burning.

f. Tool Output

Data provided by the U.S. Navy (U.S. Navy Bureau of Ships, 1953) to assist in estimating the quantity of materials required for underwater arc-oxygen cutting have been tabulated in Table 35. The data given are based on the performance of experienced operators; therefore, allowance should be made for inexperienced personnel and for operations under adverse conditions.

Table 35. Electrode Requirements for Arc-Oxygen Cutting (U.S. Navy Bureau of Ships, 1953).

Arc-Oxygen Cutting	Unit	Number of Electrodes (approximate)	Steel plate cut in feet per box of electrodes			
			1/4"	1/2"	3/4"	1"
Commercial steel tubular electrodes	50-lb. box	167	240	170	170	160
	Tanks of O_2 (200 cu. ft.)		2.7	2.0	2.0	2.0
Ceramic tubular electrodes	6-1/2 lb. box	25	475	375	275	175
	Tanks of O_2 (200 cu. ft.) per box of electrodes		6.0	6.0	6.0	6.0

Data on quantities of electrodes needed to cut steel plate using the metallic-arc welding technique are shown in Table 36.

Table 36. Electrode Requirements for Metallic-Arc Underwater Cutting (from U.S. Navy Bureau of Ships, 1953).

Electrode Size (inches)	Unit	Number of Electrodes (approximate)	Power Source Amps	Steel plate cut in feet per box of electrodes		
				1/4"	1/2"	3/4"
1/16	50-lb. box	410	300	185	102	---
3/16		410	400	307	135	58
1/4		220	400	176	77	44

With 300-amps available for underwater cutting, 3/16-inch electrodes are recommended; 5/32-inch may be used but will result in an extremely rapid burn-off rate. With 400-amps available, 3/16-inch diameter electrodes may be used, but 1/4-inch are preferred.

Tests of welds made underwater have shown that 1 linear inch of weld has a strength of approximately 10,000 pounds, when the recommended 3/16-inch electrodes are used, and 3/16-inch fillet welds are deposited with the self-consuming technique on work held in a horizontal position. When calculating the length of a fillet weld to carry a known static load, a safety factor of 6 should be used (see Table 37).

Table 37. Typical Weld Strengths (U.S. Navy Bureau of Ships, 1953).

Electrode Size (inches)	Number of Passes	Strength (pounds per linear inch)	Strength (pounds) to be Used in Calculating (safety factor of 6)
5/32	3	12,000	2000 (1400 for padeyes)
3/16	1	10,000	1600 (1000 for padeyes)

g. Safety Considerations

The successful operation of electric cutting and welding equipment requires experienced, highly trained divers who are completely familiar with the equipment and the procedures required for its safe operation. The types of problems which generally hinder a diver in his underwater work, such as restricted visibility, currents, temperature, work position, and buoyancy, become greater potential hazards when working with electric cutting and welding torches. These hazards are even greater in seawater, which is an excellent conductor of electricity. However, with proper safeguards and reasonable care, underwater cutting and welding can be performed with comparative safety. The following basic protective measures are recommended:

1) Only experienced divers who are qualified in the use of arc-welding equipment on the surface should be permitted to operate cutting and welding equipment underwater.

2) The diver should practice cutting and welding above water before attempting underwater work. Detailed operating instructions should be followed carefully.

3) Oxygen regulators used in arc-oxygen cutting should be adequate for delivery of the required volume without freezing up. All fittings associated with oxygen regulator and torch should be clean and free of oil.

4) All current-carrying parts of the holders and torches must be insulated with nonconducting material capable of safely insulating against the maximum voltage encountered in ground. All joints in the electrical circuit should be checked at frequent intervals for current leaks.

5) A ground lead cable must be securely grounded to the work. No part of the diver's body should be in a position to become a part of the secondary circuit between the electrode and the ground.

6) The preferred diving dress recommended for use when cutting and welding is hard-hat dry gear with an insulated suit and rubber gloves. If a metal helmet is worn and AC power is used, the diver's head must be insulated from the helmet by a woolen cap or other suitable means. The exhaust valve button should also be insulated with a nonconductive material.

7) Where electric cutting and welding torches are used, reliable voice communications must be available between the diver tool operator and his surface tender. A positive operating disconnect switch must be part of the welding circuit and readily available to the surface tender, in order to safeguard the diver operator.

The current must be off at all times, except when the diver is actually cutting or welding, or when the electrode is in the cutting position.

8) After the electrode is inserted and secured into the head of the torch, the diver should position the end of the electrode at the desired starting point of the cut. He should touch the electrode to the work, open the oxygen valve by pressing the hand lever, and, at that time, signal to the surface tender for "Current On." After consuming the electrode, the diver must not attempt to remove the stub until he has signalled for "Current Off" and has had his request confirmed by the surface tender. The tender must not give his confirmation until he has actually broken the circuit and the current has been shut off.

9) Under no circumstances should the torch be held so that the electrode points toward the diver. The danger is that of a loaded gun.

REFERENCES

Andersen, B.G. Diver performance measurement: underwater navigation, depth maintenance, weight carrying capabilities. ONR Contract No. N00014-67-C-0447, Task No. NR 196-068. General Dynamics, Electric Boat Division, July 1968.

Andersen, B.G. Human engineering criteria for the design of diver-operated underwater tools. TR OI-TR-71/1-Sk, ONR Contract N00014-70-C-0070. San Diego, California: Oceanautics Division, Whittenburg, Vaughan Associates, Inc., January 1971.

Andersen, B.G. and Swider, J.S. Operational capabilities of power impact wrenches and conventional wrenches in an underwater environment. ONR Contract No. N00014-70-C-0070. Alexandria, Virginia: Whittenburg, Vaughan Associates, Inc., April 1970.

Andersen, B.G., Allen, F.L., and Lamb, J.C. Diver performance measurement: transporting neutrally buoyant objects, manual movement of heavy objects. TR U417-69-066, ONR Contract No. N00014-67-C-0447. Groton, Connecticut: General Dynamics, Electric Boat Division, July 1969.

Andersen, B.G. and Swider, J.S. Unpublished data. San Diego, California: Oceanautics, Inc., June 1971.

Baddeley, A. The relative efficiency at depth of divers breathing air and oxy-helium. Symposium of the Underwater Association for Malta, 1965.

Barrett, F.B. A comparison of underwater burning using three types of diving gear. Report No. ITP-71-10. Point Mugu, California: Human Factors Engineering Branch, Naval Missile Center, March 1971.

Barrett, F.B. and Quirk, J. Diver performance using handtools and hand-held pneumatic tools. TR R-653. Port Hueneme, California: Naval Civil Engineering Laboratory, December 1969.

Preceding page blank

Bayles, J.J. Salvage work projects -- Sealab III. TR R-684. Port Hueneme, California: Naval Civil Engineering Laboratory, June 1970.

Beatty, H. T., Berghage, T.E., and Chandler, D.R. Preliminary survey of diver anthropometrics. RR 7-71. Washington: Navy Experimental Diving Unit, Washington Navy Yark, June 1971.

Bowen, H.M., Andersen, B.G., and Promisel, D. Studies of divers' performance during the Sealab II project. Contract No. Nonr-4930 (00). Darien, Connecticut: Dunlap and Associates, Inc., March 1966.

Briggs, R.O. and Hatchett, G.L. Techniques for improving underwater visibility with video equipment. Marine Technology Society/American Society of Limnology and Oceanography, Ocean Science and Ocean Engineering, Vol. 2, 1965.

Chaillet, R.F. Human factors engineering design standard for missile systems and related equipment. HEL Standard S-3-65. Aberdeen Proving Ground, Maryland: U.S. Army Engineering Laboratories, September 1965.

Clarke, H.H. Analysis of physical fitness index test scores of aircrew students at the close of a physical conditioning program. Research Quarterly, 16, 192-195, 1945.

Daniels, G.S., et al. Anthropometry of male basic trainees. WADC-TR-53-49. Wright-Patterson AFB, Ohio: Aero Medical Laboratory, Wright Air Development Center, 1953.

Ely, J.H., Thomson, R.M., and Orlansky, J. Layout of workplaces. WADC-TR-56-171. Wright-Patterson AFB, Ohio: Aero Medical Laboratory, Wright Air Development Center, September 1956.

Garrett, J.W. Clearances and performance values for the bare-handed and the pressure-gloved operator. AMRL-TR-68-24, American Research Laboratories, 1968.

Garrett, J.W. The adult human hand; some anthropometric and biomechanical considerations. Human Factors, 13(2), 117-131, 1971.

General Electric Space Systems Organization. Astronaut zero gravity performance evaluation program. Final Study Report, Vol. 1: Summary Technical Report, Contract No. NAS 9-8640. Philadelphia, Pennsylvania, 1968.

Hedgcock, R.E. and Chaillet, R.F. Human factors engineering design standard for vehicle fighting compartments. HEL Standard S-6-66. Aberdeen Proving Ground, Maryland: U.S. Army Human Engineering Laboratories, May 1964.

Hedgepeth, C. Problems in deep water tool utilization. Symposium proceedings, Underwater Welding, Cutting and Hand Tools, Marine Technology Society, October 1967.

Hertzberg, H.T.E., et al. Anthropometry of flying personnel. WADC-TR-52-321. Wright-Patterson AFB, Ohio: Aero Medical Laboratory, Wright Air Development Center, 1954.

Hertzberg, H.T.E. and Clauser, C.E. Size and motion. In P. Webb (Ed.) Bioastronautics data book, Section 14. NASA SP-3006. Washington: NASA, 1964.

Hunsicker, P.A. Arm strength at selected degrees of elbow flexion. WADC-TR-54-548. Wright-Patterson AFB, Ohio: Aero Medical Laboratory, Wright Air Development Center, August 1955.

Hunsicker, P.A. and Greey, G. Studies in human strength. Research Quarterly, 28, 109, 1957.

Kent, P.R. and Weissman, S. Visual resolution underwater. Report No. 476. Groton, Connecticut: U.S. Naval Submarine Medical Center, May 1966.

Kinney, J.A.S., Luria, S.M., and Weitzman, D.O. The visibility of colors underwater. SubMedResLab, SubMedCen Report No. 503. Groton, Connecticut: Naval Submarine Medical Center, October 1967.

Lewis, C.A. Velocity power tools. Symposium proceedings, Underwater Welding, Cutting and Hand Tools, Marine Technology Society, October 1967.

Luria, S.M. Stereoscopic acuity under water. Report No. 510. Groton, Connecticut: U.S. Naval Submarine Center, February 1968.

McFarland, R.A., et al. Anthropometry in the design of the driver's work-space. American Journal of Physical Anthropology, 16, 1, 1958.

Morgan, C.T., Chapanis, A., Cook, J.S., and Lund, M.W. (Eds.) Human engineering guide to equipment design. New York: McGraw-Hill, 1963.

Mueller, C.G. and Lloyd, V.V. Stereoscopic acuity for various levels of illumination. Proceedings, National Academy of Science, 34, 1948.

NASA. Compendium of human responses to the aerospace environment. NASA CR-1205 (III), Vol. III. Houston, Texas: NASA, MSC, November 1968.

Newman, R.W. and White, R.M. Reference anthropometry of army men. Report No. 180. Natick, Massachusetts: Environmental Protection Branch, U.S. Army Quartermaster Research and Development Center, 1951.

Norman, D.G. Force application in simulated zero gravity. Human Factors, 11(5), 489-506, October 1969.

O'Neil, G.W., Jr. Astronaut restraints for the aquanaut. MDAC paper Wd-1133. Paper presented at the 7th National Survival and Flight Equipment Symposium, October 1969.

Orlansky, J. The human factor in the design of stick and rudder controls for aircraft. Report SPECDEVCEN-151-1-8. Port Washington, New York: U.S. Naval Training Devices Center, 1948.

Pierce, B.F. Effects of wearing a full-pressure suit on manual dexterity and tool manipulation. Human Factors, (5), 479-484, October 1963.

Randall, F.E., et al. Human body size in military aircraft and personal equipment. AF-TR-5501. Wright-Patterson AFB, Ohio: Aero Medical Laboratory, Wright Air Development Center, 1946.

Ross, Helen E. Size and distance judgments under water and on land. Symposium of the Underwater Association for Malta, 1965.

Ross, Helen E. Stereoscopic acuity under water. Sympsoium of the Underwater Association for Malta, 1966.

Streimer, I., Turner, D.P.W. and Volkmer, K. Task accomplishment times in underwater work. J. Marine Technology Society, Vol. 2, No. 2, April 1968, 22-26.

Streimer, I., et al. Experimental study of diver performance in manual and mental tasks at 66 feet. ONR Contract No. N00014-70-C-0189, Work Unit NR 196-070, Man Factors Inc., MFI 71-115, September 1971.

Taylor, C.L. The biomechanics of the normal and of the amputated upper extremity. In P.E. Klopsteg and P.D. Wilson (Ed.) Human limbs and their substitutes. New York: McGraw-Hill, 1954.

Trout, O.F. Jr. and Bruchey, W.J., Jr. Water immersion reduced-gravity simulation. Human Factors, 11(5), 473-488, 1969.

United States Army. Unpublished data. Natick, Massachusetts: Environmental Protection Branch, U.S. Army Quarterma Research and Development Center, 1946.

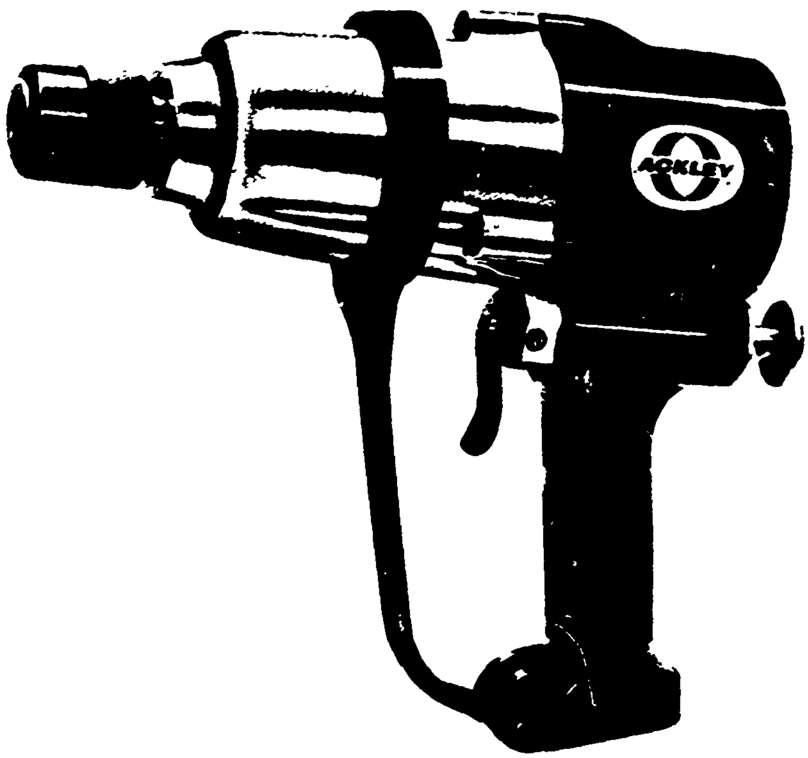
United States Navy Bureau of Ships. Underwater cutting and welding manual. Washington: Navy Department, October 1953.

Weltman, G., Smith, E.J. Perceptual narrowing during simulated pressure chamber exposure. Human Factors, Vol. 13, No. 2, April 1971.

Weltman, G., Egstrom, G. Perceptual narrowing in novice divers. Human Factors, Vol. 8, No. 6, December 1966.

APPENDIX

Manufacturer's specifications for six underwater hydraulic impact wrenches and two velocity power underwater drivers. Photographs and commercial data are included with the permission of the manufacturers.



ACKLEY MANUFACTURING COMPANY, Clackamus, Oregon

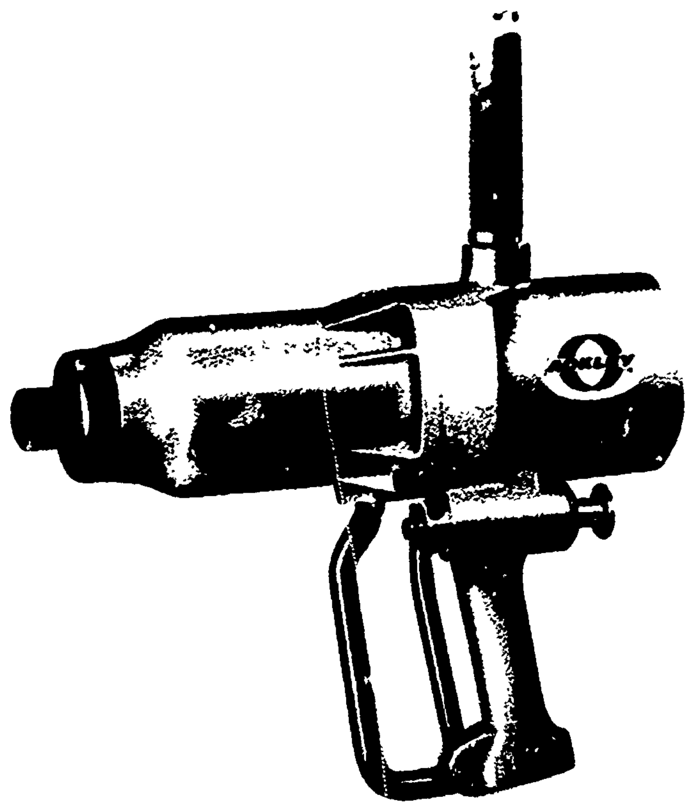
Model 6HS-O.C./C.C. Underwater Hydraulic Impact Wrench

Hydraulic System: Open or closed center.
Weight: 10.5 pounds.
Dimensions: 11-1/4 inches long; 1-11/16 inches side to center.
Drive: 5/8 inch to 3/4 inch.
Drive Options: Square drive or quick-change hex drive.
Bolt Size: 5/8 inch to 3/4 inch.
Chuck RPM: 850 at 6 gpm.
Impact Frequency (per hammer revolution): 2.
Operating Pressure: 1000 to 2000 psi.
Gallonage: 4 to 7 gpm.
Porting: 3/8 inch NPT.

ACKLEY MANUFACTURING COMPANY, Clackamus, Oregon

Model 13HS-O.C./C.C. Underwater Hydraulic Impact Wrench

Hydraulic System: Open or closed center.
Weight: 13.0 pounds.
Dimensions: 11-1/4 inches long; 1-11/16 inches side to center.
Drive: 3/4 inch.
Drive Option: Square drive.
Bolt Sizes: 3/4 inch to 1 inch.
Chuck RPM: 1080 at 4 gpm.
Impact Frequency (per hammer revolution): 2.
Operating Pressure: 1000 to 2000 psi.
Gallonage: 4 to 4.5 gpm.
Porting: 3/8 inch NPT, or 3/8 inch pressure, 1/2 inch return.



ACKLEY MANUFACTURING COMPANY, Clackamus, Oregon

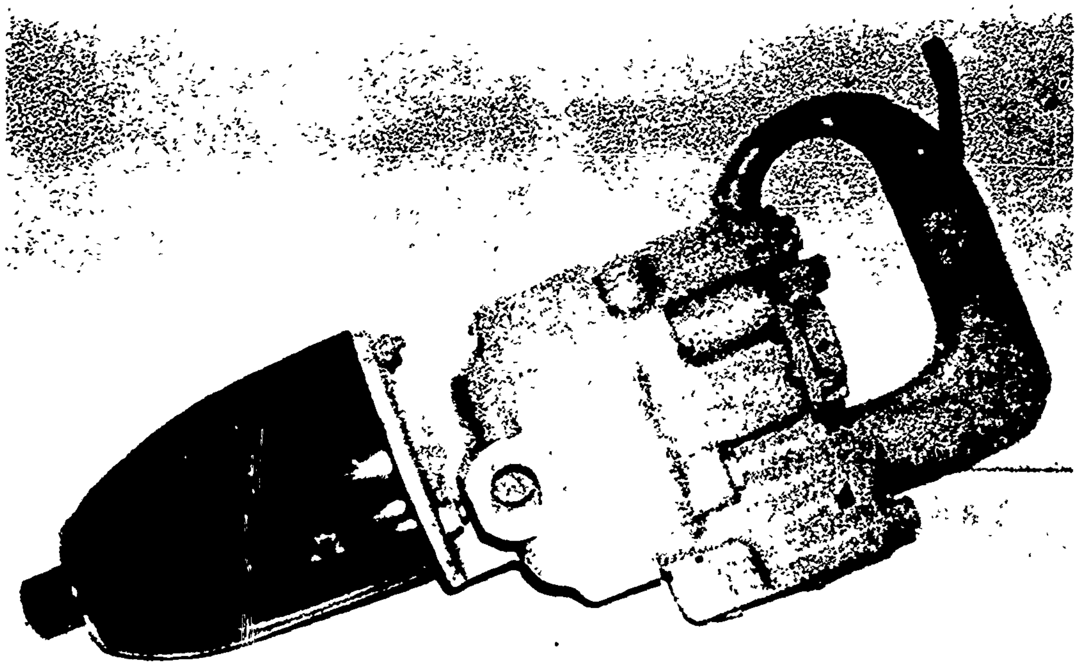
Model 22HS-O.C./C.C. Underwater Hydraulic Impact Wrench

Hydraulic System: Open or closed center.
Weight: 26.0 pounds.
Dimensions: 16 inches long; 2 inches side to center.
Drive: 1 inch.
Drive Option: Square drive.
Bolt Sizes: 3/4 inch to 1-1/4 inch.
Chuck RPM: 700 at 8 gpm.
Impact Frequency (per hammer revolution): 2.
Operating Pressure: 1000 to 2000 psi.
Gallonage: 7 to 10 gpm.
Porting: 3/8 inch NPT.

FAIRMONT HYDRAULICS, Fairmont, Minnesota

Model H6500 Hydraulic Impact Wrench and Drill (may be sealed for underwater use)

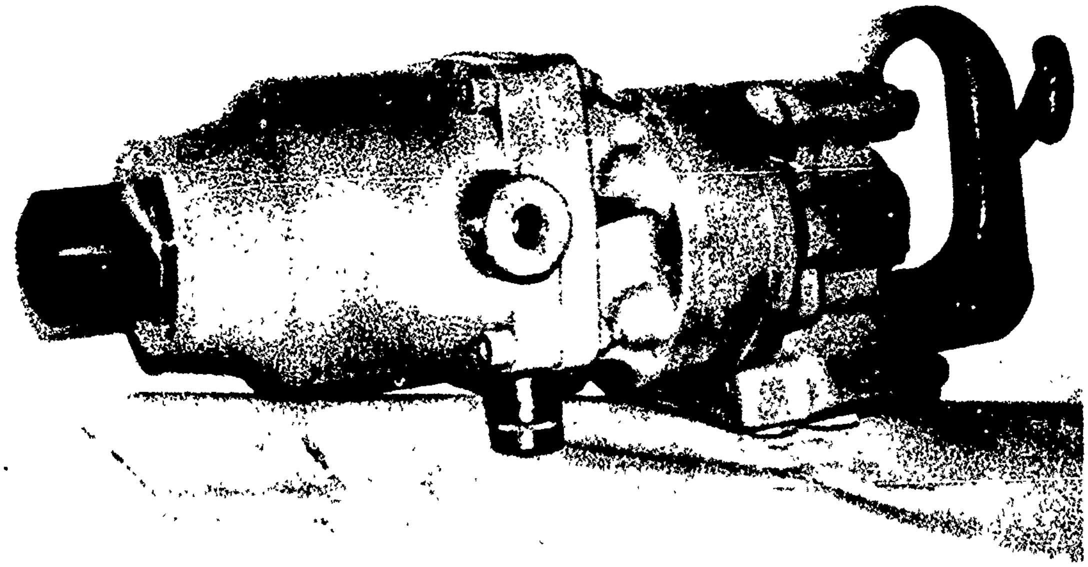
Hydraulic System: Open center or closed center (H6500-1).
Weight (less hose couplers): 6-1/4 pounds.
Dimensions: Length (over quick-change chuck) 9 inches; height (less hose couplers) 9 inches.
Quick-Change Chuck (shank size): 7/16 inch hex.
Socket Adapter (drive shank size): 1/2 inch square.
Speed (rpm): Open center, 4760 at 4 gpm; closed center, 4460 at 5 gpm.
Torque: Open center, 140 foot-pounds at 4 gpm; closed center, 140 foot-pounds at 5 gpm.
Operating Pressure: Average, 700 psi; maximum recommended, 2000 psi.
Back Pressure: Maximum recommended, 150 psi.
Impacts per Minute: Open center, 2380 at 4 gpm; closed center, 2230 at 5 gpm.
Oil Flow: Open center, minimum 3.8 gpm, maximum 4.4 gpm; closed center, minimum 4.8 gpm, maximum 5.3 gpm.



J & J MACHINE & WELDING, INC., Pasadena, Texas

Model 51W Underwater Hydraulic Impact Wrench

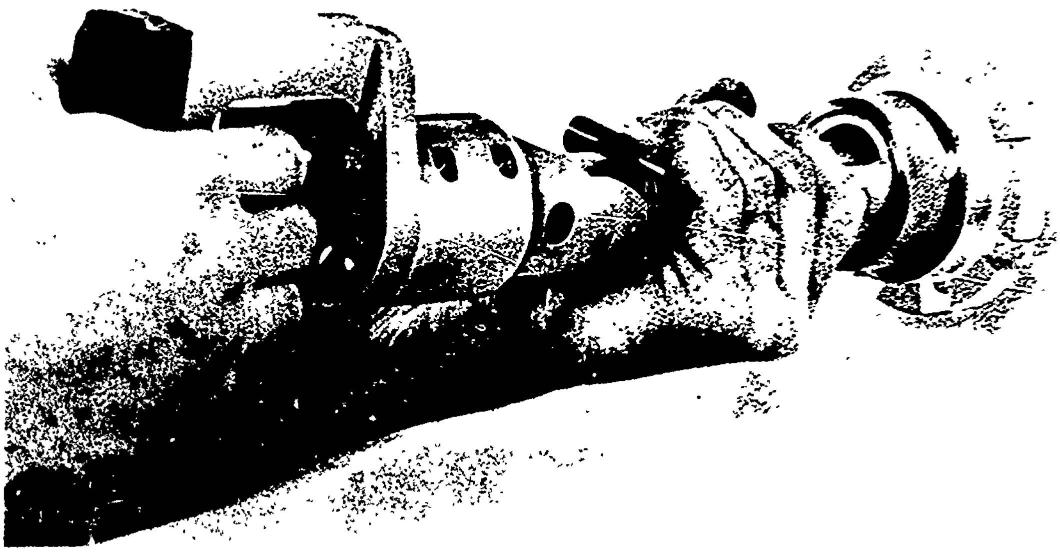
Hydraulic System: Open or closed center.
Weight: 27-1/2 pounds.
Length: 17 inches.
Drive: 3/4 inch square.
Bolt Size: 1 inch.
Speed: Variable, 1500 rpm maximum.
Torque: Up to 900 foot-pounds on 1 inch bolt.
Operating Pressure: Normal, 800 psi; maximum 2000 psi.
Gallonage: Maximum, 5.0 gpm.
Porting: Inlet, 3/8 inch NPTF; outlet, 1/2 inch NPTF.
Fluid: SAE 10, non-detergent, MIL-L-2104 Grade 10, MIL-L-10295, MIL-H-6083.



J & J MACHINE & WELDING, INC., Pasadena, Texas

Model 84W Underwater Hydraulic Impact Wrench

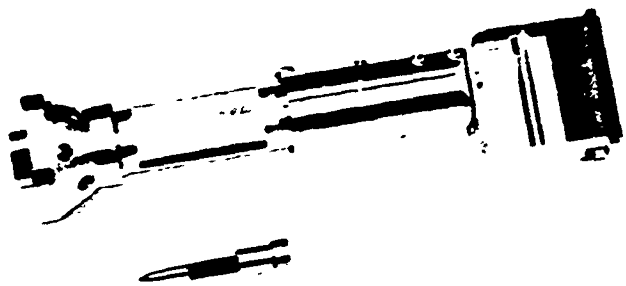
Hydraulic System: Open or closed center.
Weight: 33 pounds.
Length: 20 inches.
Drive: 1-1/4 and 1-1/2 inches square, 1-5/8 inches spline.
Bolt Size: 2 inches.
Speed: Variable, maximum 950 rpm.
Torque: Up to 5500 foot-pounds.
Operating Pressure: Normal, 1000 psi; maximum, 2000 psi.
Gallonage: Maximum, 6.0 gpm.
Porting: Inlet, 9/16 inch 18 SAE straight thread, "O" ring.
Outlet, 3/4 inch 16 SAE straight thread, "O" ring.
Fluid: SAE 10 non-detergent, MIL-L-2104 Grade 10,
MIL-L-10295, MIL-H-6083.

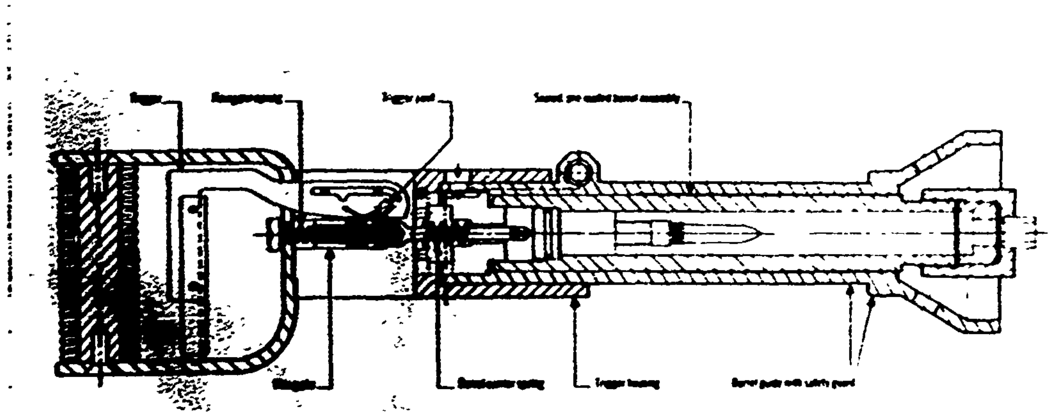


MINE SAFETY APPLIANCES COMPANY, VELOCITY POWER DIVISION
Pittsburgh, Pennsylvania

Model NUD-38 Velocity Power Underwater Driver

Operating Depth: To 300 feet maximum.
Weight: 8 pounds in air, 7 pounds in water.
Size: Overall length 17-1/2 inches; handle height 5 inches; barrel 1-1/2 inches in diameter.
Construction: Aluminum, except for steel barrel, trigger, and firing pin.
Cartridge: .44 caliber (stud and piston constitute the projectile and are crimped into a .44 caliber, center fire cartridge case).
Safety: Barrel must be aligned with the firing pin and then pushed against the work surface before trigger can fire the cartridge.





MINE SAFETY APPLIANCES COMPANY, VELOCITY POWER DIVISION
Pittsburgh, Pennsylvania

Model D Heavy Duty Velocity Power Underwater Driver

Operating Depth: To 1000 feet maximum.
Weight: 17 pounds in air, 15 pounds in water.
Size: Overall length 20 inches; handle height 4-1/2 inches; barrel casing 2-1/2 inches in diameter, cylindrical, about 12 inches long.
Construction: Aluminum, except for steel barrel, trigger, and firing pin.
Cartridge: .44 caliber in pre-loaded barrel.
Safety: Three separate functions must be performed, in sequence, before firing: 1) rotate handle, 2) push handle forward, 3) pull trigger. Driver will not fire with unsealed barrel assembly.