

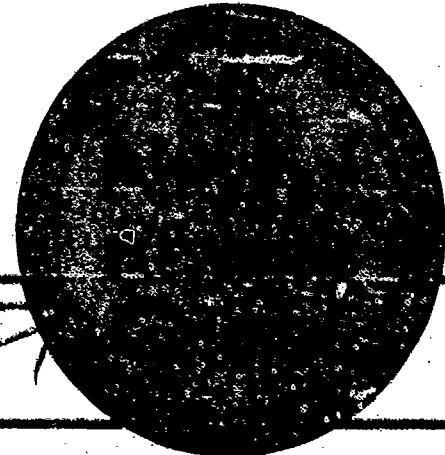
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# Underwater Electrical Safety Practices

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**Underwater  
 Electrical  
 Safety Practices,**

11/1976

This is a report prepared by the Panel on Underwater  
 Electrical Safety Practices of the Marine  
 Board, Assembly of Engineering, National Research Council

12/155p.

15 N00014-67-A-0244-0002

National Academy of Sciences  
 Washington, D.C. 1976

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NOTICE:

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by the Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

✓ This report represents work supported by Contract N00014-67-A-0244-0002 between the Office of Naval Research and the National Academy of Sciences.

Printed in the United States

## PREFACE

This report deals with underwater electrical safety, with particular emphasis on the hazards surrounding Navy and commercial divers engaged in cutting and welding operations. It records a study undertaken at the request of the Office of Naval Research (ONR) in 1974 by the Marine Board of the Assembly of Engineering, National Research Council. The purpose was to study the degree of divergence, if any, between Navy and commercial safety practices in underwater electrical work, to determine whether the safety practices used by the Navy are unnecessarily restrictive, and, once this was done, to recommend any technical investigations or corrective actions that are considered necessary.

The study proceeded through a series of formal and informal meetings by a panel organized under the Marine Board. Members conducted examinations of various aspects of underwater electrical safety practices. In addition, a special survey of industrial practices was made by members of the staff of the Naval Coastal Systems Laboratory (NCSL) at Panama City, Florida.

Experts from the Navy, industry, and academia appeared before the panel to discuss particular practices, perceived problems, and potential needs. The panel wishes to acknowledge the contributions of these participants: A.B. Behnke, Jr., Richard Brereton, F. Busbi, Henry Croull, William Culpepper, Charles Dalziel, C.E. Grubbs, Don Hackman, K.R. Haigh, Max Lippitt, Jr., F. Marrone, W.J. Mullaly, Bud Nuquist, R.E. Sargent, David Saveker, Charles Shilling, and Scott Stevenson.



SUMMARY

Initial development of underwater electrical cutting and welding techniques occurred in the early 1930's. One of the first successful repairs using electrical cutting and welding techniques under water was carried out on a damaged ship in 1939. Since then, the jobs connected with ocean salvage, construction, maintenance, and pipelaying have increased considerably electrical operations conducted under water. While advances continue in developing new and more effective underwater electrical equipment, the Navy is concerned that its underwater electrical safety practices with regard to cutting and welding may be unnecessarily restrictive, and thus frequently ignored in practice.

The principles of cutting and welding are about the same in the water as in air. However, underwater operations impose certain hazards and limitations on the use of electrical equipment and techniques. As a result of this study, the panel found that the principal underwater electrical hazard facing divers engaged in welding and cutting is non-lethal electric shock. This hazard exists when a diver wearing inadequate protective dress is in close proximity to a relatively high-powered source of electricity.

Both Navy and commercial divers tend to be undeterred by risks and difficulties. Some commercial divers, who do considerably more cutting than Navy divers, become used to electric shocks while cutting and welding. Electric current above shock levels passing through human tissue is known to alter, temporarily, the physiological function of cells. The long-term effects, if any, are unknown. Much greater current levels can cause thermal burns. Severe shocks could conceivably result in respiratory or cardiac arrest in divers. Therefore, electric shocks should not be tolerated in underwater operations, even though no physiological damage may be immediately apparent.

Such hazards notwithstanding, records of U.S. Navy diving accidents do not reveal any fatality directly attributed to electric shock other than in 1943, when a Navy student diver died while undergoing training in an indoor tank. Nevertheless, the combination of insufficient training, diver carelessness, and equipment malfunction suggests an existing and continuing possibility for fatal and non-fatal accidents for divers engaged in

underwater welding and cutting. The panel recommends specific efforts to increase the safety of present underwater electrical operations. Changes in operational requirements, operating environments, and diving equipment may require increased analysis of electrical safety, research and development, to maintain the safety record thus far achieved by the Navy.

### Overall Systems

The panel found little evidence of prior analysis of underwater electrical hazards. Comparing Navy and industry underwater cutting and welding practices, the panel noted that safety-related differences exist in diver dress, diver-to-tender communications, and training and qualification of personnel. Comparing written Navy procedures and actual field practices, safety-related differences were also found in diver dress and communications. New underwater electrical equipment have been used by divers that have potentially dangerous AC voltage levels.

Consequently, the panel recommends the use of systems-analysis techniques in evaluating the safety aspects of the several elements of the system--human physiology, equipment, procedures, and training.

### Human Physiology

Present knowledge of the physiological effects of electrical fields on humans indicates that 10 milliamperes (ma) is the safe limit for alternating current (AC) electricity applied to the diver's body. The comparable safe upper limit for direct current (DC) energy is about 60 ma.

These limits are considered sufficient, when integrated in a simple systems model consisting of the diver, the equipment, and the electric field, to protect the diver from normal lethal electrical hazards under present operating conditions. However, the panel recommends further studies to extend present knowledge concerning diver dress, equipment, and procedures.

One peculiar long-term physiological side effect apparently resulting from repeated electrical shocks is the deterioration of metallic dental fillings. This suggests that divers receive continued medical and dental surveillance to determine the extent of this problem and the possibility of other uncertain, long-term physical

complications.

Changing operational requirements, such as work at greater depths, new breathing gas mixtures, and longer time spent under water, make additional physiological information necessary. Thus, the panel recommends further study of the possible effects that changes in diving environments and operations may have on human physiological responses to electric shock.

### Equipment

AC power is more harmful at lower levels physiologically than DC power (10 ma AC is comparable to 60 ma DC). Thus a diver considered to be safe in a DC field would not be safe in a similar AC electric field unless the resulting body currents were only one-sixth as intense as in the DC field. The only case of electrocution in commercial underwater cutting or welding resulted from the failure of a rectifier in an AC-DC rectifier type welding power supply.

Where the use of AC power is required for such underwater applications as lights, hand tools, or drive power for DC generators, the AC equipment should be protected by ground-fault detection (GFD) and/or interruption (GFI) devices.

For protection against shocks, diver-support equipment for underwater cutting and welding should completely insulate the body, including the head, hands, and feet. In addition to lack of visible suit damage, current Navy regulations state that wet suits that have been worn below 50 feet cannot be reused for underwater electric welding or cutting work. The panel believes the depth restriction is unnecessarily restrictive. Instead, the panel believes that wet suits worn while cutting and welding under water should not have any worn spots, tears, holes and other indications of loss of integrity of the closed cell structure of the material.

### Procedures

In the course of day-to-day Naval operations, the amount of underwater cutting and welding required is relatively slight. Consequently, most Navy divers have difficulty maintaining their proficiency. By contrast, many commercial companies of varying size and experience are engaged in a wide range of underwater cutting and welding tasks particularly as activities increase in the offshore

extraction of oil, gas, and hard minerals.

In both the Navy and industry, sound written procedures and practices are vital for assuring the safety of divers in underwater electrical operations.

The Navy Technical Manual on Underwater Cutting and Welding,<sup>1</sup> although more stringent than comparable industry documents, suffers from ambiguities, inaccuracies, and omissions. Examples: references to obsolete equipment and procedures, such as carbon arc and Swafford Type electrodes; confusing rules for the use of AC power because of differences in wording in various paragraphs; and vague wording (see Appendix C for additional cases). The Manual should be revised and provision should be made for periodic updating to ensure that it reflects the progress made in the state of the art.

### Training

Evaluating Navy training and qualification practices against those of commercial diving firms is difficult because of the entrance skill of Navy trainees and the minimal amount of cutting and welding required of Navy divers. The need for a reassessment of the Navy's training requirements and re-evaluation of the training program is indicated.

Commercial diving companies recognize that underwater electrical cutting and welding is dangerous. Yet, current practices indicate that they consider the hazards of cutting and welding to be no greater than any other hazards related to diving.

An overall comparison of Navy and industry practices, written and actual, is presented in Table VI. The major safety-related differences noted are:

- . Navy fleet divers do not receive adequate training and retraining to provide and maintain proficiency in underwater cutting and welding.
- . Reverse polarity is not recommended by the Navy manual, and is not used by Navy divers, but is used by commercial divers.
- . Diver-to-tender voice communications and fully insulated diver dress are considered mandatory by the Navy manual, but are not

always used by Navy fleet divers and commercial divers.

- . The Navy manual prohibits cutting and welding in wet suits that have been compressed to depths greater than 50 feet, but Navy fleet divers appear to ignore the rule and follow the commercial practice.

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Oil Filled Pressure --  
Balanced Connector

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CHAPTER I  
INTRODUCTION

Description

Underwater cutting and welding involves a source of electrical power, mounted on a ship, barge, or other platform at the water's surface and under the control of a person called a "tender," and a diver who performs the work in the water. The diver uses an insulated electrode holder (torch) that is connected by insulated cable to one pole of the surface power source through a normally open safety switch. The other pole of the power source is connected to the metal that is to be cut or welded (the workpiece) either by an electrical cable or by the conductive path through the water from the ship or barge hull to which the power is grounded. When the diver is ready to begin cutting or welding, the electrode is touched to the workpiece and a signal given to the tender to close the safety switch. This initiates the current flow through the system and enables the diver to strike or initiate the arc by a slight withdrawal of the electrode from the workpiece.

In such a system, the electrical hazard results from the possibility of the diver directly contacting the electrode or workpiece so that his body forms a conductive path between the electrode and the workpiece when the arc is interrupted either by motion or by variations in the electrical current (AC or AC-to-DC rectified).

The primary system elements in the welding and cutting process, then, are:

- Human physiology (electrical effects on the body);
- Equipment (sources of electrical power and insulation);
- Procedures (coordination between diver and tender); and
- Training (knowledge of the other three elements).

Navy Accident History

In an examination of Navy records and discussions with veteran Navy divers, no injuries or deaths were found to be due to electric shock in underwater cutting operations, and only one fatality could be attributed to the use of welding equipment under water. The accident occurred in a 10-foot deep, open training tank at the Deep Sea Diving School, Washington, D.C., in December 1943. The victim was a diving student engaged in underwater welding. He wore a Navy

Mark V deep-sea helmet adapted for shallow-water diving, a swimsuit, and new rubber gloves, but no footwear. Shortly after requesting that the top-side safety switch be closed, so that the current would start flowing, the student diver collapsed. Although he was hauled quickly to the surface and treated by a doctor almost immediately, all attempts at resuscitation failed.

In testimony before a Board of Investigation, witnesses stated that in preparing to strike an arc the victim's bare knee had inadvertently touched the grounded metal work bench at the same time that his breastplate or helmet touched the live electrode. A thorough examination of the equipment revealed no stray circuits or grounds. The board concluded: "death by electrocution."<sup>2</sup>

Reviewing this accident 32 years later with the knowledge that both Navy and commercial divers had spent thousands of hours cutting and welding underwater wearing no more insulative protection than the victim, and with no report of fatal accidents, the panel concludes that the particular circumstances that caused this death were rare.

Shortly afterward, new regulations were issued requiring that divers wear a full deep-sea dress while welding or cutting underwater, to insure electrical insulation and to provide adequate voice communication between the diver and tender via the telephone.<sup>3</sup>

Most fleet divers, which includes all enlisted and commissioned Navy divers ashore and afloat (but not Naval Shipyard Civil Service divers) interviewed by panel members reported occasional minor shocks, especially when the safety switch was being opened or closed, but dismissed the shocks as minor irritants.

Also, most fleet divers reported no ill effects and no increase in the frequency or intensity of minor shocks when working in warm waters wearing a shallow-water mask (without voice communications), rubber gloves, swim fins, or tennis shoes, or while clothed only in swim trunks.

#### Industrial Accident History

No central registry of information on industrial underwater electrical accidents exists. The panel inquired about accidents at every opportunity during its contacts with industry personnel. The survey conducted by the Naval Coastal Systems Laboratory (Appendix D) also included

specific inquiries about fatalities.<sup>4</sup> No one questioned could recall any industrial electrical underwater fatalities. The conclusion is that the history of commercial diving in underwater electrical work is similar to the Navy's accident record.

The NCSL survey also disclosed one apparent long-term problem associated with underwater electrical shocks and two non-electrical hazards directly associated with underwater welding and cutting. The long-term problem was a continuing deterioration or loosening of metal dental fillings and crowns or bridges among divers who conducted underwater cutting and welding on a regular basis.<sup>5</sup>

The two non-electrical hazards were gas explosions and skin burns. In some cases, when divers cut into or weld on closed compartments, they encounter collections of combustible gases which may explode or burn when the arc penetrates the compartment wall. In other cases, cutting or welding operations produce bubbles of oxygen-enriched gas that enter the diver's gloves, either through the cuff openings or through holes, and then explode or burn when ignition occurs, resulting in injury to the diver's skin.

Commercial experience with the effects of variations in diver dress and equipment on shock incidence in industry are very similar to those of the Navy.

#### Present Navy Requirements

The panel's survey of the present safety requirements for underwater cutting and welding disclosed few marked differences between the Navy and industry.

#### Navy Fleet Divers

Two underwater electric cutting processes are currently authorized for use in the Navy: Oxygen-arc and shielded metal arc cutting.

Of these, the oxygen-arc method is the most widely used for cutting plain carbon and low alloy steels. In the oxygen-arc process, the metal to be cut is preheated to incandescence by a high amperage arc and then subjected to a jet of pure oxygen that rapidly burns the metal. The procedure can be learned quickly with minimal training.

Shielded metal arc cutting requires greater skill and experience on the diver's part, but can be used to cut

oxidation-resistant steels and non-ferrous materials that are difficult or impossible to cut using the oxygen-arc method. The metal arc process employs a "stick" type electrode. The cutting action depends on the heat of the arc, combined with the mechanical pushing of the molten metal out of the kerf with the tip of the electrode. The operation is one of melting rather than burning or oxidation.

Which of the two methods of underwater cutting is used on a given operation often depends upon the availability of equipment. However, as a general rule, oxygen-arc is preferred for cutting ferrous metals and shielded metal arc for cutting non-ferrous metals.

For welding under water, the Navy approves only the shielded metal arc process. The weld is produced with the electric arc by heating a flux-covered metal electrode and the parent metal until both are molten. The arc heats the flux covering so that some of the constituents of the flux decompose into gases which shield the molten metal from contamination. Underwater welds using the shielded metal arc technique made in mild steel plate under test conditions have consistently developed over 80 percent of the tensile strength and 50 percent of the ductility of companion welds made in the air.<sup>6</sup>

The frequency with which underwater electric welding and cutting are used varies widely in fleet activities. Some units, such as salvage ships, routinely conduct underwater electric cutting operations and occasionally do some underwater welding. Other ships, such as submarine rescue ships, seldom employ either. Still others, such as tenders, routinely weld zinc anodes under water and occasionally do some cutting. Some ships whose activities infrequently engage cutting and welding operations do not even possess the equipment. Thus, great differences exist among Navy divers in levels of experience.

A great disparity also exists between actual diving procedures and those contained in the Navy Manual on Underwater Cutting and Welding. Most Naval personnel responsible for diving activities contend that they follow the Manual quite closely. However, some activities, especially those in warmer climates, routinely violate safety precautions, including the restrictions concerning the diver's dress. For example, cutting and welding are routinely carried out in other than approved diving dress, and with no voice communications between the diver and the tender for opening and closing the topside safety switch.



Although no injuries involving shock have been reported, any violation of safety standards can lead to further violations. This laxity may eventually lead to a dangerous situation.

Fleet divers commonly complain about the lack of realistic training in underwater cutting and welding. The Navy often subcontracts to a commercial firm for large salvage operations requiring qualified underwater cutters and welders, citing that Navy divers lack the necessary experience. Thus, Navy divers cannot easily gain extensive experience because most of the large jobs that would afford them "on-the-job training" are done by commercial contractors.

On the other hand, Naval shipyard divers said that they follow the Navy Manual when carrying out underwater cutting and welding. Unlike most fleet activities, the shipyards have ongoing training programs for both underwater cutting and welding. Slack periods are used for training to increase diver proficiency. Naval shipyard divers are generally not allowed to perform actual work dives requiring underwater cutting or welding until their proficiency has been proven under controlled training conditions.

#### Present Offshore Oil Industry Requirements

The installation and maintenance of offshore platforms and pipelines by the oil industry often requires diving operations. Industry has evolved safe, standard operating practices for underwater welding and cutting over the past 20 years.

Most underwater cutting and welding by the oil industry is for maintenance and repair work performed in the open sea. However, some underwater production welding is undertaken in an inert gas environment when high quality welds are required, such as on pipelines.

#### Ship Salvage /Ship Husbandry Industry

While no detailed breakdowns exist, the panel estimates that more than 90 percent of all the underwater electrical work performed by divers for commercial ship salvage and repair involves oxygen-arc cutting of steel. The method achieves excellent results, is relatively safe and easy to use. Welding is generally attempted only by very skilled personnel, when no other course seems feasible.

Oxygen-arc cutting is far easier to perform than underwater welding. Much of the cutting takes place in ship salvage operations to remove an entire ship or to perform more limited tasks in order to sever structural sections.

Welding is less commonly done under water than cutting. But, as the only practical method of making underwater attachments or emergency repairs to ships, underwater welds have proved reliable for a year or more on vessels operated by commercial transport companies. While attempting to keep underwater welding to a minimum because of its high cost, many commercial companies are beginning to regard it as a practical way to accomplish selected construction and maintenance objectives.

#### Systems Approach

Figure 1 outlines the study approach used by the panel in the systems analysis of underwater cutting and welding, and indicates those elements considered by the panel during its study. The "systems approach" analyzes all of the various elements in underwater cutting and welding together, including the interrelationships and interactions, rather than individually. The panel found four specific instances of Navy equipment where systems analyses should have been made.

1. The Naval Undersea Center-Naval Facilities (NUC-NAVFAC) SNOOPY undersea inspection and observation vehicle;
2. The Wigdahl (patented) underwater torch, which includes an on-off safety device to control the welding and cutting power;
3. The standard Navy 100-watt and 1,000-watt, 110-volt, 60-Hz, underwater diver's work lights; and,
4. The standard Navy 120-volt underwater torch igniter.

In the case of the SNOOPY vehicle, the panel's concern led the Navy to conduct an underwater electrical systems or hazards analysis (see Appendix E).<sup>7</sup> The analysis is outlined in Table I to briefly illustrate its major elements.

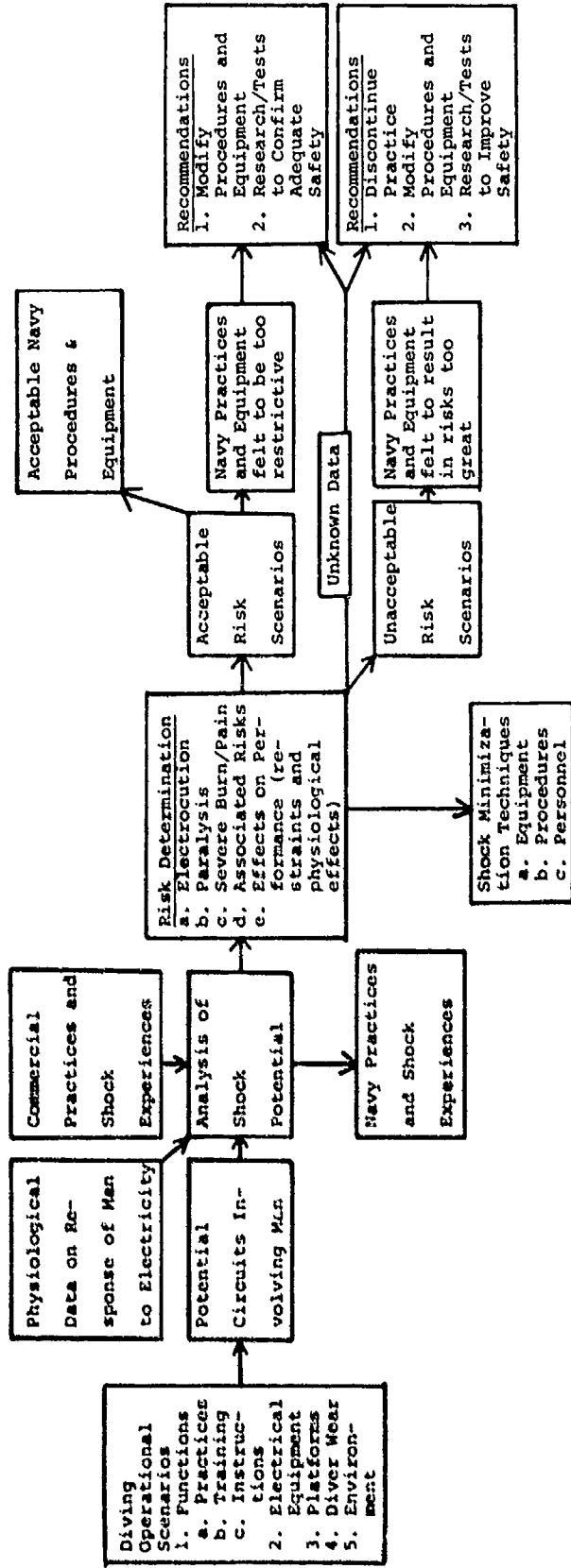
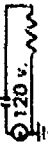



Figure 1: Study Outline for Under-water Cutting and Welding System

TABLE I

OUTLINE OF ELECTRICAL SHOCK HAZARDS ANALYSIS FOR U. S. NAVY "SMOOPY"  
 (based on analysis by R. A. Marrone, Naval Undersea Center, San Diego, 23 October 1974)

Part	ITEMS ANALYZED		Electric Field Model	Diver Current Limit	Shape & Size of Area Exceeding Diver Limit	Remarks
	Operation	Possible Fault				
Cable	On-Deck Handling	<p>Crewman's hand around coax power cable (no damage)</p> <p>Crewman's hand around coax power cable with nick in cover exposing shield.</p>	<p>Capacitive Coupling</p> <p>Direct contact</p>	<p>10 ma (see Remarks*)</p> <p>10 ma (see Remarks*)</p>	<p>None, unless transformer insulation and isolation transformer fail.</p> <p>None, unless transformer insulation and isolation transformer also fail.</p>	<p>(* 10 ma AC is "Let-go" value for 99.5% of population) Max. current is <math>12 \mu a</math> and is below level of sensation unless noted double failure occurs.</p> <p>Max. current is 0.36 ma and is below level of sensation unless noted triple failure occurs.</p>
Cable Connector	Diver in Water	Leaky connector (one pin)	 <p>120 v</p>	10 ma (see Remarks*)	None	Max. current in sea water is $12 \mu a$ . Fault requires leakage of oil-filled pressure-balanced connector.
Cable	Diver in Water	<p>Nick in cover exposing shield.</p> <p>Current to sea water thru two conductors:</p> <p>a. Cable severed</p> <p>b. Cable nicked to expose center conductor in one place and again to expose shield in another place far away</p>	 <p>300 v</p> <p>Current: dipole, <math>E_i = f(r)^3</math></p> <p>Current monopoles, <math>E_i = f(r)^2</math></p>	<p>10 ma (see Remarks*)</p> <p>10 ma (see Remarks*)</p>	<p>None</p> <p>None</p>	<p>Max. current in sea water is 0.36 ma.</p> <p>Based on diver conductivity of 0.2 mhos/meter, a field of 0.2 volts/meter will induce the 10 ma limit current.</p> <p>a. Field strength falls below 0.2 volts/meter everywhere outside a sphere of 0.17-meter radius centered on end of severed cable</p> <p>b. Field strength falls below 0.2 volts/meter everywhere outside of spheres of 0.55-meter radius centered at each fault</p> <p>The situations require double failures: one, for a fused circuit to carry twice its rated 3-amp current load for more than a few seconds; and two, for the noted cable failures to occur.</p>

All other potential diver-electric field contacts are prevented by insulation, plus the isolation transformer, plus oil-filled pressure-balanced connectors and harnesses.

The Wigdahl unit was developed to reduce or eliminate the electric shock which occurs when a diver initiates the arc as the first step in underwater cutting and welding. Unfortunately, the DC circuit or a 110-volt AC circuit, which the original Wigdahl unit used, was potentially more lethal than the DC shock that it sought to eliminate. The panel's concern led to the Navy postponing the use of this potentially dangerous item of underwater electrical equipment. An adequate systems safety analysis, possibly an abbreviated version of Military Standard 882 (Safety Program for Systems and Associated Sub-systems and Equipment: Requirements for), could eliminate such an existing hazard in underwater operations rather than simply replacing it with a possibly greater hazard.<sup>8</sup>

The underwater work light and the oxygen torch igniter are ancillary underwater equipment which have been in authorized use for many years. However, the Navy now recognizes them as hazardous. Proper analyses would probably eliminate the hazards.

The ability to undertake systems analyses to improve the safety of underwater equipment and operations exists in most engineering sections of the Navy and its technical contractor firms. Systems analysis should be routinely conducted on all underwater electrical applications--tools and support systems alike.

## CHAPTER II

### HUMAN PHYSIOLOGY

Data on the physiology and pathology of electric shock in a dry environment is plentiful, but inadequate information has been provided and little research done on the specific problem of underwater electrical shock hazards. Electric shock effects which have been studied in a dry environment are probably at least partially applicable to the underwater environment. Indeed, the effects of electric currents on body tissues are not dependent on the source of the electric current. Thus, the underwater environment will only cause variations in the body's response to electric shock, primarily because of the mode of entry of current to the body and the distribution of the current density.

Most work done on electric shock hazards has been oriented toward understanding the effects of 60-Hertz electric current on body function. Almost all of the power used in the United States is generated at 60-Hertz AC; while power in Europe is generated at 50-Hertz AC. The effects of DC on the human body must also be evaluated to understand the underwater welding problem. To date, the effects of DC have been less adequately studied than equivalent AC effects. Some data is available on DC effects, however, and where possible it has been evaluated. An attempt has been made to extrapolate dry-land data to the underwater environment.

#### Physiology of Electric Shock

The effects of electric currents on muscles have been known for centuries. For example, experiments conducted in the 15th and 16th centuries, long before man understood electricity or the biologic function of cell membranes, showed that galvanic stimulation of a frog's muscles produced a muscular twitch. Recent studies by several investigators have shown that the effects of electric shock can be graded, based on the amount of current that enters the body through the skin.

At levels of 1 to 3 milliamps AC at 50 to 60 Hertz, a warm or tingling sensation is felt at the point of entry of the current. As the level of current increases, the tingling and warmth sensation merges into pain. The pain increases in severity as the current increases. At a level between 9 and 16 milliamps AC, muscular contraction occurs, preventing the individual from releasing a grip

on the conductor--labeled the "let-go current" by Charles Dalziel because it is the point where the electrical effects on skeletal muscle prevent voluntary relaxation of the muscles controlling the hand.<sup>9</sup>

The Dalziel sample used lightly built, non-muscular women of 18-22 years of age. They were probably not the type of women, in either weight or strength, likely to be employed in the construction industry. Further, the men used in the Dalziel sample were not selected on a muscular basis. But, in general, the commercial diving industry tends to employ stronger individuals than are found in the population as a whole.

The female diver of the future will probably fall within the 99.5 percent let-go current profile described by Dalziel. Also, probably more than 99.5 percent of the present male commercial diver population would have let-go tolerances higher than found in the Dalziel sample.

As current increases above the let-go level to approximately 22 milliamps AC, paralysis of the chest muscles occurs and respiration ceases. An individual sustaining electric currents at this level will have a respiratory arrest and will die from asphyxia in 5 to 10 minutes unless given artificial respiration. Individuals can survive electric current of this intensity without residual damage if the period of respiratory asphyxia is not excessive.

At current levels above 22 milliamps AC, the major effects are on the heart. As current increases from 20 to 40 milliamps AC, cardiac function is reduced, producing a shock-like state. As current increases from 50 to 75 milliamps AC, ventricular fibrillation--disorganized, non-functioning contraction of the heart muscle--will occur, producing circulation failure, lack of perfusion of vital organs and tissues, and almost immediate death.

The effects of the frequency of alternation of electric current have also been studied. Unfortunately the current which produces the greatest number of biological effects is at the power line frequencies in both the United States and Europe, ranging between 50 and 60 Hertz. As frequency increases above the range of 100 to 300 Hertz, the effect of electric current on biologic function diminishes. Thus, for frequencies above 300 Hertz, in comparison to 60 Hertz, larger currents are required to produce similar effects.

In the other direction, where frequency approaches the DC level, the required current also increases to produce effects similar to 60 Hertz. With DC, a five to seven fold increase in current is needed for similar biologic effects. Thus, the DC and high frequency ends of the spectrum are safer than the power frequencies of 50 to 60 Hertz.

The frequencies ranging from zero (DC) to 400 Hertz produce all of the effects described above, although the currents required are greater than those required for 50 to 60 Hertz. Higher frequency currents of 1 kilohertz and above do not produce biological effects from stimulation of muscles, but, instead, produce heating effects which can cause thermal overload of tissues.

Although some data suggest that the polarity of DC may cause variation in shock effects, the variation is small. Thus, welding polarity should be decided by the engineering requirements of the job, not by physiologic considerations.<sup>10</sup>

Electric currents cause physiological effects other than those on muscle and nerve cells. Severe electric shock has been found to cause death by deep thermal burns which originate at the site of entry of the electric current and follow irregular pathways through the body tissues where the current has flowed. These thermal burns are the result of resistive heating by the current as it passes through the tissues. The excess heat (essentially tissue cooking) results in the loss of function and death of the tissue.

Electrical injury of this type usually results from high-intensity electric current produced by contact with high-voltage power lines. These injuries occur often, but are not necessarily fatal. Recovery, however, is frequently complicated by infection and often requires multiple skin grafts and extensive surgery for removal of dead tissue.

Electrical accidents of this type occurring under water appear unlikely at present. The chance of an isolated contact with a very high-voltage power transmission line is remote. In addition, because of the nature of the water surrounding the diver, a single contact with a high-voltage source is not likely. In the future, however, when more electric power is transmitted to the undersea environment, accidents of this type might be more likely.



The entry of a diver or swimmer into a strong AC electrical field is a more likely future hazard. In this case, the major lethal effect would be cardiac fibrillation.

Not as much is known about the chemical effects of electric current as is known about the direct thermal effects. Several reports from hospitals have described alkali burns produced by electric current associated with the use of solutions of sodium chloride and water. Sodium chloride solution is commonly used biologically because it is similar to body fluid. Electric currents passing through a sodium chloride solution will electrolyze the sodium and chloride and produce sodium hydroxide. This can cause alkali burns in the area of the cathode, usually when direct current is used.

In terms of skin contact, the electrodes themselves can be a significant problem. In sea water, which is primarily a sodium chloride solution, alkali burns would seem likely. However, the sea water milieu is dilute enough so that no significant levels of alkali should form around the welding torch.

#### Dental Involvement

Underwater electric current also effects teeth. The NCSL survey showed that about one-third of commercial divers who spend a significant amount of their time in underwater cutting and welding need to have their dental fillings replaced every six months to one year.<sup>11</sup> Divers also complain frequently of a metallic taste in their mouth when they are employing an electric arc.

The nature of the damage to dental fillings is obscure, but there are several possibilities. One is the effect of electrolytic processes on dental fillings. When DC flows from the water through the diver, electrical fields are generated in the mouth. Electrodiolysis can occur between dental fillings and saliva, producing filling erosion by electrochemical removal of metallic ions from the filling.

Tooth or filling problems due to electric currents should be less frequent among Navy divers because they usually do not spend more than two or three days per month at electric arc welding. It is unlikely that they would note dental abnormalities. Nevertheless, this problem is of interest to both the Navy and to the diving community in general since it involves a long-term effect of underwater

welding and cutting.

Since data is unavailable concerning the mechanism of tooth filling damage, the frequency of tooth damage in the diving population, and the degree of electrolysis of tooth fillings in situ, controlled experiments should be undertaken. These studies might determine the prevalence of the dental problem, and the level of heavy metal ions in saliva and blood following diving operations.

#### Physiologic Basis for Electric Shock Effects

Recent advances in the understanding of cell membranes, which are vital to the normal functioning of both muscle and nerve cells, have made interpretation of electric-shock data possible. Several studies have shown that electrical activity in the cell membrane is important for normal cell function in muscles and nerves, which require a depolarization of an electrically-charged cell membrane.

As depolarization occurs, transfer of several ions--notably sodium, potassium, and calcium--takes place across the cell membrane. The depolarization of the membrane travels along the cell as a wave front, so that the total cell membrane is depolarized over a short period of time (milliseconds). As it moves along the muscle cell membrane, calcium enters the cell and causes a contraction of the muscle.

This effect can be induced by externally-applied electric current of sufficient intensity to cause depolarization of the cell membrane. Muscles are sufficiently sensitive so that cell stimulation occurs when nine milliamps AC or more flows into a body extremity. The repetitive stimulation of 60 Hertz will produce a sustained contraction of an entire muscle. DC can also produce these effects, but currents five to seven times greater are needed. (See Appendix B.)

Electric current in tissues may cause damage to sub-cellular components necessary for normal cell function. Thus, electric shocks, of any intensity, should not be tolerated in underwater cutting and welding even though no apparent injury results. In addition, minor shocks may cause loss of control, panic, or injury due to involuntary muscle contraction. New equipment and techniques should be designed to eliminate shocks.

## Underwater Electrical Hazards

Several studies have attempted to identify current values and electric-field configurations which could produce lethal underwater electric shocks (see Appendix A and references 12-16). The diver dress, which is usually determined by the local environment, must also be evaluated, since different types of dress offer significantly different electrical resistance.

For example, a diver welding or cutting under water clad in only bathing trunks is more prone to the effects of electric current than a diver clothed in a full dress where no areas of the body are in direct contact with the surrounding water. According to many commercial divers, when full dress is used, the incidence and intensity of electric shocks is diminished in comparison to when either wet suit or bathing trunks are used.

Evaluation of the use of wet suits in underwater electrical welding and cutting done to date is inadequate to thoroughly understand the problem. Further studies should be undertaken to provide reasonable guidelines concerning the use of underwater electric equipment with wet suits. These studies should also consider environmental conditions where wet suits can be used for underwater welding and cutting, such as in shallow, relatively warm water or for ship repairs.

In addition, studies of electric-field effects in water with both hat and full (helmeted) wet suits should be conducted to determine the electrical insulation value of the type dress, the effects of leakage in the dress, and the problems with gloves and metallic helmets or helmet hardware. Attempts should be made to identify levels of current which produce known physiologic effects, such as warmth, tingling, pain, and the let-go phenomenon.

## Possible Effects of Future Diver Environments

The anticipated progression of diving activity to greater depths and longer staytimes under water will undoubtedly include cutting and welding. This, in turn, will expose divers to electric shocks in environments of greater pressure, various mixed breathing gases, and tissue saturation with gases other than air for relatively long periods of time. Current knowledge of cellular aspects of electric-shock effects, combined with the now-known cellular or tissue-related effects of the new diving environments, provide

hints of some possible future effects. For example, helium-oxygen breathing at depths of 1,000 feet or greater causes hyperactivity of the nervous system, which could make a diver more susceptible to electric shocks.

In view of the apparently similar cellular bases for these phenomena, there may be some synergistic interactions which could cause the combination of electric shocks and new pressure or breathing-gas environments to modify their presently-known individual effects. Thus, the panel believes an investigation of such synergistic effects should be conducted. Divers should at least be aware of their possible occurrence.

CHAPTER III

EQUIPMENT

The growing interest in the exploration and development of marine resources has occasioned a rapid increase in Navy and commercial underwater activities within the past few years. High quality welds or cuts may be required in developing marine resources. Attempts to attain that quality may change the accustomed electrical fields around the diver. To ensure divers' safety, the electrical nature of present and future underwater welding and cutting equipment and processes should be fully understood. Based on this information, and comparable information on human physiology, a model for underwater circuit analysis may be postulated for use in safety analyses.

Electrical Characteristics of Equipment

In a welding arc, a sustained electrical discharge through a high-temperature conducting plasma produces sufficient thermal energy for the joining of metals by fusion and for cutting metals by either fusion or oxidation. Welding arcs can be produced in both air and water environments with either DC or AC. The current is relatively high and the voltage relatively low compared to other gas discharges.

Volt-Ampere Characteristics

The static volt-ampere characteristics of electric arcs do not follow Ohm's law. The volt-ampere relationship is constant in shielded-metal arcs and displays a rising characteristic in high-current-density welding processes like gas metal-arc, submerged-arc, and gas tungsten-arc welding.

A definite relationship exists between voltage drop across the arc gap and current strength immediately after the arc is established. Since voltage drop depends on the electrical resistance of the arc gap and on the arc length and chemical composition of the gas surrounding the arc, the electrical field strength in the welding and cutting arc increases with increasing current and arc length.

Underwater welding and cutting in deep water is usually associated with higher voltage due to:

- (1) Hydrostatic pressure effect. With increasing

water depth, the column diameter of the current-flow path decreases and the arc voltage increases.

- (2) Hydrogen effect. The high hydrogen content in the arc zone increases the electric resistance of arc gap which causes higher voltage.
- (3) Cooling effect. Due to fast cooling rates, more heat dissipates into the surrounding water and more heat input is necessary. Thus, higher voltage is required.
- (4) Cable effect. The voltage drop in the cable increases with an increase in the cable length. This effect is predominant in direct current applications.

Figure 2 shows the underwater DC arc characteristics obtained by Avilov.<sup>17</sup> The voltage range used in shallow water (less than 100 ft.) with conventional welding and cutting processes is between 20 and 60 volts. The current range is between 150 and 500 amps, depending upon the electrode size and the process used.

In general, DC welding machines have a specific relationship between current and voltage, but the current is treated as the only independent variable. The recommended current for shallow-water cutting is approximately 400 amps with straight polarity, DC.<sup>18</sup> Table II shows the recommended welding speed and current for wet, shielded, metal-arc welding. The current ranges from 50 to 210 amps.

The overall characteristics of AC arcs are essentially the same as those of DC arcs. There are, however, some differences. In a 60-Hertz AC arc, the current is reversed 120 times a second. This, in turn, causes changes with time in the electron flow, density of ions, cross section of the arc plasma, and temperature of the arc.

Figure 3 is an oscillogram of a common AC welding arc. When the open-circuit voltage of the power supply is considerably higher than the arc voltage, the current varies approximately sinusoidally with time, as shown in Figure 3a. The pattern of the voltage variation, on the other hand, shows a rectangular shape, which is characterized by an almost instantaneous rise in voltage to a peak value at the beginning of each half cycle, followed by a slow drop and then an almost instantaneous drop and reversal at the end of the half cycle, as shown in Figure 3b. Figure 3c

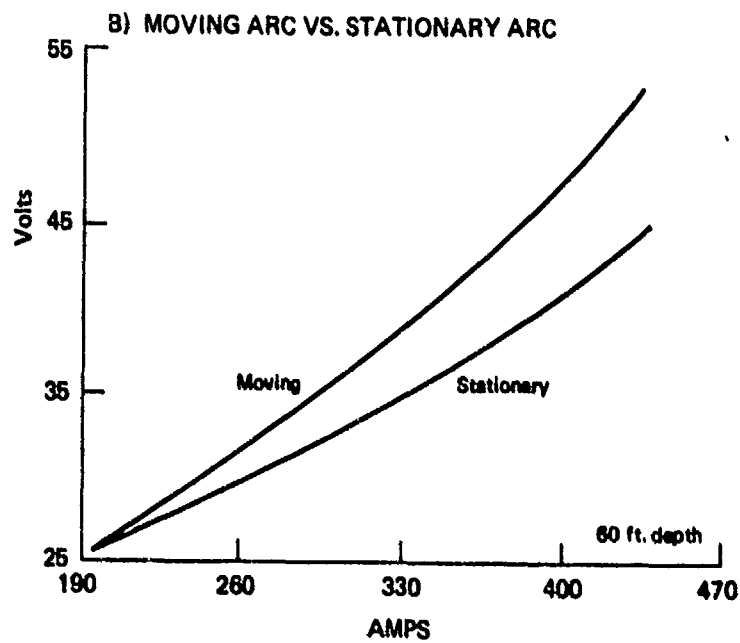
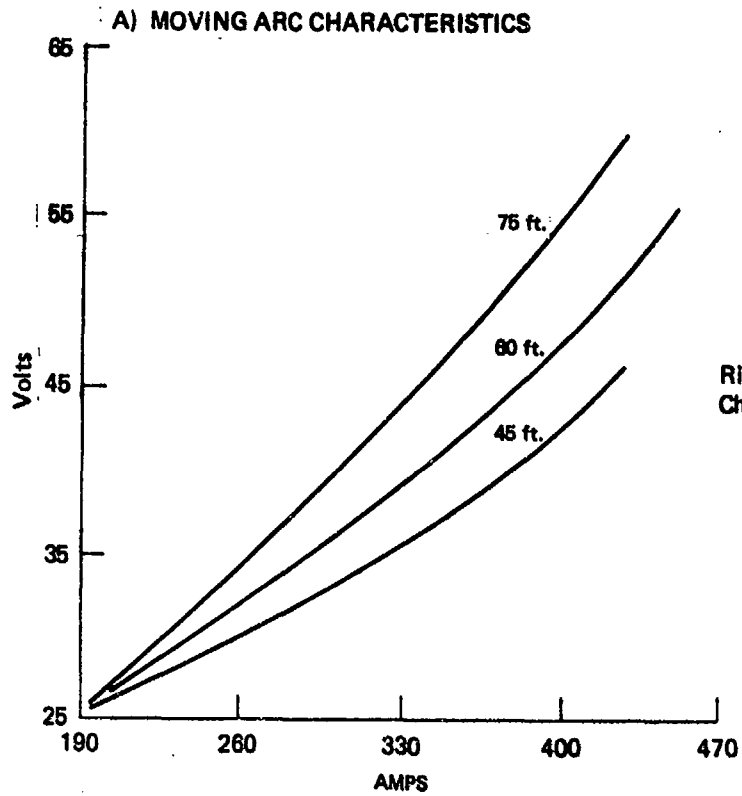
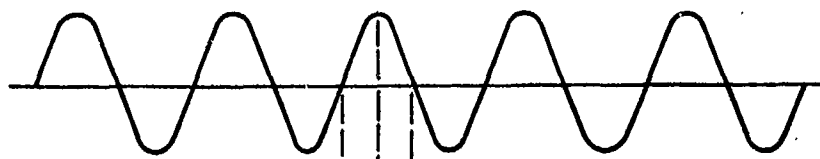


Figure 2: Voltages by Underwater DC Arcs

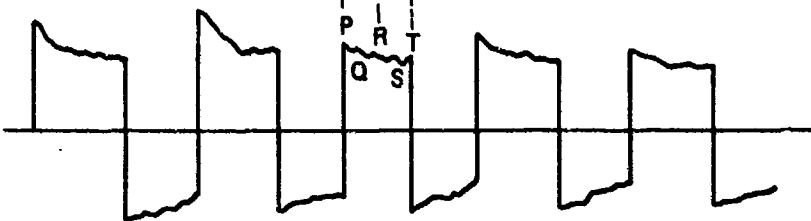
TABLE II  
Welding Speed, Current and Power Input

ELECTRODE	CURRENT (amp)	VOLTAGE (volt)	POWER (kilo- watts)	SPEED (ipm)	HEAT INPUT (kj/in)
6013 AIR 1/8" SP RP	90-110 130-150 130-140	20-23 25-27 26-27	2-2.5 3.4-4 3.4	12-16 24-25 17-22	9-10 9-10 9
6013 AIR 5/32" SP RP	130-170 160-190 150-180	23-27 25-29 21-24	3.5-4.2 4-5 3.6-4	17-19 20-25 19-23	11-13 11-12 10-11
6013 AIR 3/16" SP RP	160-180 180-210 160-180	20-23 23-30 27-28	3.4-3.8 4.6-5.4 4.6-4.8	15-17 16-18 22-23	14-17 13-18 15-24
7014 AIR 1/8" SP RP	130-150 150-160 140-150	24-26 27-28 27-28	3.5 4-4.5 4.3-4.7	13-15 19-21 22-25	14-15 11-12 13-15
7014 AIR 5/32" SP RP	160-180 170-190 130-170	23-26 27 27-30	4-4.3 4.6-5 4-4.8	12-13 12-17 11-13	17-19 18-23 20-23
7014 AIR 3/16" SP RP	200-240 160-190 120-180	23-26 28-35 30-45	4.8-5.8 5.8 4.5-5.5	11-13 12 7-8	23-26 34-36 38-48
6027 AIR 3/16" SP RP	120-180 --- 80-130	32-42 --- 38-42	4.3-5.4 4.5-5.5 5-5.5	10-11 --- 7	28-32 --- 28-42
6027 AIR 3/16" SP RP	140-170 150-190 100-160	34-39 35-45 34-40	5-5.5 4-5.5 4-5.5	10 9 8	29-36 36-44 36-52
7024 AIR 1/8" SP RP	120-150 150-160 50-100	26-31 30-35 37-43	3.5-4.3 3.5-5.5 3.7	12-14 15-16 7-9	18-30 21-22 23-32
7024 AIR 5/32" SP RP	140-160 130-180 80-200	30-35 35-45 35-45	5-5.2 3.6-6.3 4-5.3	13-15 13 7	24-27 33-36 35-44

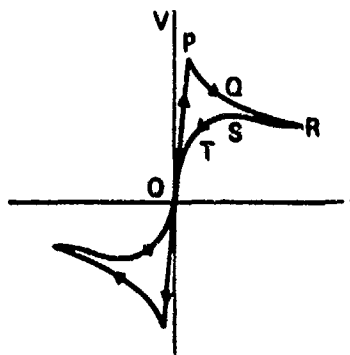




a. CURRENT,  $i$



b. VOLTAGE,  $v$



c. RELATIONSHIP BETWEEN CURRENT,  $i$ , AND VOLTAGE,  $v$

Figure 3: Dynamic Characteristics of an AC Welding Arc

shows a hysteresis phenomenon in the voltage-current relationship of the dynamic AC welding arc. Because the current and voltage periodically become zero, an AC arc extinguishes itself at the end of each half cycle and reignites at the beginning of the next half cycle. Therefore, an AC arc is less stable than a DC arc.

### Polarity Effects

The effect of DC polarity has not yet been studied. Although a minor factor in underwater electrical safety, polarity is a major factor affecting the quality of welds and cuts because of the heat distribution in the arc. On an average, the heating is 80 percent to the anode, 5 percent to the cathode, and 15 percent carried away by the surrounding medium. Thus, in arc cutting, straight polarity is preferred in order to concentrate the heat in the metal to be fused.<sup>19</sup>

In arc welding, on the other hand, the polarity effects on quality are different. The effects appear to be completely opposite between gas tungsten-arc (GTA) welding and gas metal-arc (GMA) welding. In general, straight polarity is used in GTA welding and reverse polarity in GMA welding. In shielded metal-arc (SMA) welding, either straight polarity or reverse polarity can be used, depending upon the type of electrode coating (see Table III).<sup>20</sup>

### Direct vs. Alternating Current

The use of AC for underwater welding and cutting should be either prohibited or severely restricted. The major reasons are:

- (1) AC has more dangerous physiological effects than DC.
- (2) The AC welding arc is less stable than the DC welding arc due to the alternating nature of AC, and, consequently, a relatively higher open-circuit voltage is required to obtain a stable AC welding arc.

Theoretically, AC is a combination of half DC straight polarity and half DC reverse polarity. In underwater welding, moisture and the surface of the plate prevent (partially or completely) the flow of current in the reverse polarity direction. This is called rectification, and may become a problem in welding at greater water

TABLE III

## Electrodes Commonly Used for Welding Low-Carbon Steel

AWS-ASTM Electrode Class	Coating	Current, Polarity*	Welding Position†
E6010	High cellulose, sodium	dcrp	F, V, OH, H
E6011	High cellulose, potassium	dcrp, ac	F, V, OH, H
E6012	High titania, sodium	dcsp, ac	F, V, OH, H
E6013	High titania, potassium	dcsp, ac	F, V, OH, H
E6014	Iron powder, titania	dcsp, ac	F, V, OH, H
E7016	Low-hydrogen, potassium	dcrp, ac	F, V, OH, H
E7018	Low-hydrogen, iron powder	dcrp, ac	F, H
E6020	High iron oxide	dcrp, dcsp, ac	F, H
E7024	Iron powder, titania	dcrp, dcsp, ac	F, H
E6027	Iron powder, iron oxide	dcrp, dcsp, ac	F, H

\*dcrp--direct current reverse polarity, electrode positive; dcsp--direct current straight polarity, electrode negative; ac--alternating current

†F--flat; V--vertical; OH--overhead; H--horizontal

depths than are encountered at present.

In case of emergency, or when very long cables are required in deep sea applications, AC power may have to be used. In these cases, high frequency and high voltage are preferable. In the frequency range beyond 300 Hertz, the ill effects of electric current on the divers diminish.<sup>21</sup> The combination of high voltage and high frequency in the AC welding circuit improves the arc stability and the ability to strike the arc without touching the electrode to the workpiece. Voltage drop due to cable length is also diminished.

### Power Sources for Arc Welding

#### Electrical Requirements for Arc Welding

The electrical power required for machinery, heating, or lighting usually remains fairly constant, whereas the electric arc varies considerably in its demand for both current and voltage. Whenever an arc is struck by causing the electrode to contact the work, a short circuit occurs. The lowered electrical resistance causes a sudden surge of current unless the power supply is designed to prevent excessive variations of current at such times. In some welding processes, the molten globules of weld metal crossing the arc several times each second also cause short circuits. A constant-current power supply is designed to limit the sudden surges of short-circuit, thus eliminating the major cause of excessive spatter during welding.

When the arc gap is short circuited by the deposition of a globule of weld metal, the voltage falls practically to zero. A fraction of a second later, a gap again exists between the electrode and the work. To bridge this gap, a considerable voltage is required instantly or the arc will not be reignited. Whenever the arc is lengthened, additional voltage is required.

#### Classification by Current Type

Welding power supplies are classified as DC or AC depending upon the type of welding current delivered to the arc.

The power necessary for DC arc welding is best provided by a rotating machine DC generator driven from a suitable source of energy. In the case of the AC-DC

generator, the driving force for the DC generator is provided by an electrically decoupled AC driven motor. The DC generator may also be driven by an internal combustion engine or turbine. Rectification of AC power from either commercial power lines or a local AC generator is also used to obtain DC current for non-underwater welding and cutting, but is not recommended for underwater work.

#### Classification by Volt-Ampere Characteristics

Depending on their volt-ampere characteristics, welding power supplies also can be classified as:

1. Machines with drooping or constant-current characteristics; and
2. Machines with constant-voltage or increasing-voltage characteristics.

Welding machines with drooping or constant-current characteristics are best suited for manual welding in which variations in arc length are apt to occur due to the individual characteristics of the welder.

Machines with constant-voltage or increasing-voltage characteristics are used for gas metal-arc processes in which the consumable electrode is fed by a machine into an arc with high current density. A welding arc is essentially a self-regulating load. Arc length, weld current, and arc voltage are all interrelated.

If the power supply is capable of providing large current variations and maintaining nearly constant-voltage, a constant-speed system for wire feed is advantageous. For example, if speed decreases for a moment, the arc length increases, causing an instant decrease in current. This causes a decrease in electrode burn-off rate and, thus, a constant arc length can be maintained.

#### Open-Circuit Voltage

The open-circuit voltage of a welding machine must be

high enough to initiate the arc easily. When the open-circuit voltage increases, however, the possibility of electric shock increases. According to the standards set by the National Electrical Manufacturers Association (NEMA), the maximum allowable open-circuit voltage are 80 volts for a power source for manual welding and 100 volts for automatic machine welding.

#### Power Sources for Underwater Cutting

A DC welding power source capable of furnishing at least 300 amperes is necessary for underwater cutting, but it must have a safety switch in the secondary circuit so that the power can be shut off except while cutting.

#### Underwater Shielded Metal-Arc Welding

In SMA welding, the arc burns in a cavity formed inside the flux covering. The flux is designed to burn slower than the metal barrel of the electrode. A constant arc is thus maintained, even in very poor visibility conditions.

In shielded metal-arc welding with covered electrodes, both DC straight polarity and DC reverse polarity are employed (See Appendix B), depending on the type of electrode. Table III lists electrodes commonly used for welding low carbon steel. The American Welding Society specifies current and polarity to be used for each electrode class. Table II shows the recommended current and voltage range for underwater welding with different types of electrodes.

AC could be used if potassium silicate was used as a binder in the coated flux. The potassium forms a lower ionization path between the electrode and the work, and increases the cathode emissivity to permit easy reignition. Electrodes containing large quantities of rutile or lime are also thermionic and do not require potassium-containing binders when stability with alternating current is necessary.

Welding under water requires about 25 percent more power than welding in air. A 300-ampere DC generator is recommended for depths to 200 feet and 350-400 ampere DC generators for greater depths.<sup>22</sup> The British Royal Navy Diving Manual specifies a DC generator with a 70-75 volt, open-circuit voltage, and a maximum intermittent output of 300-400 amperes.<sup>23</sup> Emerson reports the use of a 600-ampere DC generator for welding at depths of 600 feet in the Gulf of Mexico.<sup>24</sup>

## Underwater Gas Metal-Arc Welding

GMA welding is a gas-shielded arc process in which the welding heat is obtained from an arc between a consumable electrode and the workpiece. The filler wire (electrode), in coil form, is mechanically driven into the weld zone. The electrode is melted in a gas atmosphere and transferred to the joint. Various shielding gases, including argon, carbon dioxide, and helium, are used, depending on the metal to be welded.

The mode of metal transfer is the primary factor in selecting the polarity. The three modes of metal transfer in welding arcs are:

1. Globular or drop transfer, in which the metal is transferred in large drops that travel slowly;
2. Spray transfer, in which the metal is transferred in many fine particles that travel at high rates; and
3. Short-circuit or dip transfer, in which the metal is transferred by direct metal-to-metal contact between the electrode and the weld pool.

The metal transfer is in the globular mode when the current is low, but changes to the spray mode when the current exceeds a certain level (called the transition current). The transition current for steel wire welding in air with argon shielding (containing 5 percent oxygen) are:

<u>Wire Diameter, Inch</u>	<u>Transition Current, Amperes</u>
0.030	160
0.045	200
1/16	275

When welding under water, the transition current may be higher.

In the spray transfer, the metal is transferred in many fine particles in the direction of the electrode axis. This is well suited for all-position welding. In GMA welding, more than 90 percent of the DC welding for all metals uses reverse polarity. In GTA welding, more than 90 percent of the DC welding (except aluminum) uses straight polarity.

The spray mode is difficult to obtain when helium and

carbon dioxide are used as the shielding gas. Thus, argon (sometimes with oxygen) is most commonly used as the shielding gas. When carbon dioxide is used, a technique utilizing the short-circuit transfer is employed.

Although most current underwater welding employs the SMA process using covered electrodes, GMA will likely be used more extensively in the future. For example, Hydro-Tech of Houston, Texas, and the British Oxygen Company use the GMA process with a movable dry chamber for underwater welding operations.

However, GMA poses an electrical safety problem. Welding power sources for the GMA process have constant voltage or even rising characteristics, while power sources with drooping or constant-current characteristics are commonly used for manual SMA welding. When power sources with constant potential (voltage) or rising characteristics are used, accidental short circuiting (for example, a contact between the welding gun and the workpiece) may result in a sudden surge of electric current. Compared to ordinary air welding, the chance of such a short is great. Furthermore, the consequences are considerably greater under water. Additional precautionary measures, such as installment of a special circuit breaker, appear necessary when the GMA process is used under water.

#### Underwater Gas Tungsten-Arc Welding

In GTA welding, the arc is maintained between the tungsten electrode and the workpiece. The electrode is neither melted nor used as a filler metal. The weld zone is shielded from the atmosphere by a stream of inert gas (argon, helium, or a mixture of the two). On joints where filler metal is required, a welding rod is fed into the weld zone.

In DC welding, straight polarity is required for the GTA process. The electrons traveling toward the workpiece hit the plate surface with a high velocity producing considerable heat upon penetration. In reverse polarity, the additional kinetic energy induced by the electrons melts the end of the non-consumable tungsten electrode.

Constant-current or drooping type power machines are, in general, used for GTA welding. The standard DC power supply, normally used for welding with covered electrodes, may be used as power units for this process. Special DC and AC units, however, designed for use in GTA welding, are



available with automatic means for controlling the gas, arc voltage, and wire feed. In general, GTA welding is used in a dry, underwater, hyperbaric chamber when a high quality weld is required.

AC may be used for GTA welding, but special safety precautions, such as clamping the ground lead near the weld and assuring that the electrical current is restricted to the zone of the workpiece and isolated from the welder, must be taken because of the increased hazards.

#### Underwater Shielded Metal-Arc Cutting

SMA cutting consists of melting a localized zone of the metal and allowing the molten metal to flow or be pushed away from the resultant kerf.

Any standard DC welding power source of at least 300 amperes capacity can be used for SMA cutting. For cutting steel plates, the suggested currents for various plate thicknesses are as follows (cutting with 5/16 inch electrode):

<u>Plate Thickness</u>	<u>Suggested Current</u>
0.5 inches	500 amperes
3/8 inches	400 amperes
1/4 inches	300 amperes

Larger electrodes and heavier currents are required for cutting thicker plates.

#### Underwater Oxygen-Arc and Water-Arc Cutting

In oxygen-arc cutting, the oxygen melts the steel and blows the molten metal out of the cut. The rate of oxygen consumption is not critical. However, applying less than the optimum rate may slow down the operation and require more careful attention by the diver. Too much oxygen for a given plate thickness wastes oxygen and may also increase diver fatigue by creating excessive back pressure at the nozzle. The oxygen pressure varies from 20 psi to 75 psi (over bottom pressure) or more depending upon the plate thickness.

Water-arc cutting is essentially a melting process. Water is merely used to blow the molten metal out of the cut. Since the cutting is dependent on the melting action of the arc, all the current available, up to a maximum of 500 amperes, should be used.

## Engineering and Safety Concerns

Most of the panel's efforts have dealt with the hazards of electric power used in underwater welding and cutting. Strict observance of all safety precautions for topside equipment is equally important, since equipment failure, explosion, or fire could endanger the lives of the operators below as well as above the surface.

Both the engineering and safety concerns are important and must be satisfied. Because time is vital in underwater work of any nature, saving even a few manhours is important. Continued improvements in underwater welding techniques will be made which will be applicable to both naval and commercial operations. However, systematic safety analysis should be undertaken as part of the development or acceptance of new underwater welding equipment.

## CHAPTER IV

### UNDERWATER ELECTRICAL CIRCUITRY

#### The Electrical System

Any circuit model of a diver working under water with electrical power is complicated by the fact that the circuit elements are not clearly defined, nor are the electrical properties of the human body precisely known. To determine the current flow through a diver's body and to predict an electrical shock hazard, the total electrical system must be considered, including the power source, conductors, tools, the medium surrounding the diver, the diver's body and protective clothing, and the relative geometry of all these factors.

#### Field Approach to Circuit Solution

The general problem is actually a three-dimensional field involving: the medium (fresh or saltwater), with a certain electrical resistivity; the diver, representing a rather complicated, non-uniform conductive medium; and all other components of the system, such as tools, cables, and clothing. In most instances, a fault, or sometimes a double fault, must occur in the electrical system to establish a field of sufficient strength to be dangerous, such as would result from poor insulation, a leaky multi-conductor cable connector, or a severed power cable. The field around a fault is distorted by all the bodies of varying conductivity which are in the surrounding space. Consequently, determining the exact current flow in any element of the system is difficult. The human body forms a multi-element distributed parameter circuit, the values of which are not precisely known, and moreover, depend on the position of the body relative to the source of electricity.

One simplification of the problem has been to represent the diver by a two-dimensional model, such as a "man-sized ellipsoid" or a "spherical man" with uniform electrical conductivity, and to calculate the field gradient (volts per meter) required across the plane surface of the model to safely limit current.<sup>25 26</sup> Suggested values for the 60-Hertz AC gradient which would paralyze the diver range from 0.06 volt per foot (2 volt per meter) to 10 volts per foot (30 volts per meter). Corresponding values for DC fields are difficult to establish since the shock

mechanism is quite different from AC. It is known, however, that a 9 milliamp (ma), 60-Hertz AC current, or a 60 milliamp DC current, through the human extremities have produced muscle contraction in experiments.<sup>27</sup> Thus, electric fields capable of producing these currents should be avoided.

### Systems Components and Nomenclature

A topside DC generator (diesel or gasoline-engine driven, or AC motor driven) is used for most underwater cutting and welding to supply power via large conductors. DC rectifier-type and AC cut/weld power supplies commonly used on land are not recommended for use under water (see p. 43).

Typically, the negative side of the DC supply is connected to an electrode held in a torch or holder commonly referred to as a "stinger." When oxygen-arc cutting is employed, a hollow steel or ceramic electrode serves as an electrical conductor, and also provides a flow of oxygen under the control of a hand lever on the torch.

The shielded-metal arc cutting or welding electrode is a somewhat smaller diameter, solid electrode. Both the oxygen-arc and shielded-metal arc electrodes are consumable and, when inserted into the electrode holder, are insulated by a coating, except at the working tip. The electrode insulation concentrates the electrical connection in the tips, which also limits the area of exposed conductor surface which the diver might contact. Removal of any of the coating by mechanical damage reduces the insulation of the electrode.

The positive side of the DC generator is connected electrically to the workpiece. If the workpiece is relatively small, the connection is direct (called a "workpiece ground"). In the case of a structure extending out of the water, such as a bridge pier or piling, the connection may be made at any convenient place on the structure, often above water (called "structure ground"). A third method, sometimes used when working on large submerged structures over a considerable area, makes the connection to the hull of the steel diving support barge. The conductive seawater path between the barge and the workpiece is used to complete the welding circuit (called a "barge ground").

The above system is referred to as DC straight polarity (DCSP), while a reversal of the connections to the elec-

trode holder and the workpiece is referred to as DC polarity (DCRP).

Very little current is taken from the generator before an arc is initiated. Most of the open-circuit voltage (80 volts maximum) appears between the electrode and the workpiece. After the arc has been established, the arc has 14-40 volts. Arc currents of 200-400 amperes may flow in the generator-cable-torch-arc workpiece electrical circuit. A topside safety switch in the cable leg is connected in series with the lead of the stinger, and is operated by the diving tender, who should be in communication with the diver at all times. Normal operating procedure is for the diver to call for "switch-on" when contact between the electrode and the workpiece has been made, and for "switch off" when the electrode is ready to be replaced or when the work is completed.

Given the specific circuit in the cut/weld operation and the general problem of analyzing underwater electrical circuits, and assuming that under normal circumstances the diver avoids direct contact with the uninsulated portion of the electrode, (many commercial divers report they change electrodes with power on without significant shock) the problem is to determine the maximum DC field gradient which the diver might encounter for both the arc and no-arc conditions and for various relative positions of the diver, stinger, and workpiece.

#### Welding Circuit Characteristics

The cut/weld diver circuit problem is characterized by an 80-volt DC maximum open-circuit generator voltage capable of supplying several hundred amperes of arc current with an arc voltage of 14-40 volts, depending on the type of electrode and the length of the arc. The power cable between the generator and the work has sufficient cross section to limit line voltage drop to approximately 10 percent of open-circuit voltage. The welding generator usually has a "drooping" load voltage characteristic so that the total voltage loss from generator to load is due to line drop plus the characteristic curve of the generator. This is referred to as a constant-current or variable-voltage generator since the arc current remains fairly constant as the arc voltage varies.

By adjustment of the compound field windings of the generator, the voltage-current characteristic can be modi-

fied. In general, the shunt field control is used to change the open-circuit voltage and the series field control changes the slope of the voltage-current (V-I) curve. Constant-voltage machines are limited in application to automatic processes, such as metal inert gas welding, where the arc length is more or less constant, since the electrode consists of a metal filler wire which is machine-fed from a supply reel. Such machines are excluded from this discussion.

The typical DC cut/weld generator-supplied system has two important characteristics: (1) under large loads (hundreds of amperes), the generator exhibits a constant current (variable voltage load curve), although any small additional current load flowing through seawater, which may or may not include a diver, will not cause the arc voltage to change appreciably, and the diver circuit is supplied by the nearly constant voltage of the arc; and (2) with no arc, the diver circuit is supplied by a nearly constant open-circuit voltage.

The small resistance of the welding cable, typically 0.02 ohms for 200 feet of cable, and relatively flat portion of the generator's V-I curve at no load, combine to provide a constant voltage for any small load (less than 1 to 2 amperes) drawn by the diver circuit. The resistance of any shunting seawater path would have to be small, compared to the cable resistance, or at least less than 1 ohm, for diver circuit current to be affected appreciably.

The NCSL survey indicated that commercial divers experienced shocks more often when using old cables. The fine copper wires in old cables may be highly oxidized and have higher resistance. If a barge ground is used on the surface generator coupled to the cutting grounding lead, the diver may place himself between the barge and the electrode and experience more shocks. Even under these circumstances however, no shock injuries have been documented.

From the characteristics of both the welding generator source and the arc, and from the generalized circuit model, any current passing through the diver calculated on the basis of the one-dimensional field model depends almost entirely on the arc voltage, or on the open-circuit generator voltage, and the total resistance of the conductive path through the diver's body.

If, for example, the diver's hand should come in con-

tact with an uninsulated portion of the electrode while his feet make electrical contact with the workpiece, either directly or through some protective footwear, a current path is established. Little regulation or decrease in source voltage results from the small currents (compared to arc current) through the diver or via shunting seawater paths. Consequently, the diver circuit resistance is most important in limiting current through the body.

#### Intrinsically-Safe Power Supply Design

The design philosophy of intrinsically-safe power supplies minimizes the exposure of the diver to electrical shock.<sup>28 29 30</sup> If the minimum internal resistance of a human body between extremities (hand-hand or hand-foot) is taken to be 500 ohms, and the maximum "safe current" for DC is taken as 60 ma, then a maximum source voltage of  $500 \times 0.06 = 30$  volts DC should be "intrinsically-safe." This design approach is inapplicable to the cut/weld problem because arc voltages may be as great as 40 volts and open-circuit voltages of 80 volts may be realized. However, this concept may have merit for other applications of underwater electrical power.

#### Welding Demonstration - DC Field Measurements

A study done by the Battelle Memorial Institute included a welding demonstration in which a wetsuit-clad diver operated a standard underwater DCSP system in a 50-inch deep pool of 14 ohm/cm resistivity seawater.<sup>31</sup> Field gradient measurements were made under a variety of conditions and are summarized in Table IV.

With the exception that the diver's head, chest, and upper arms were above water because of the 50-inch pool depth, these demonstration tests represented a typical cut/weld situation. They showed that if the diver maintains a distance of 4 inches or greater from the electrode during cut/weld operations, or from the hot electrode when the diver is between the electrode and the workpiece, a DC field of no greater than 0.5 volt per foot would be encountered.

Most studies have been confined to AC rather than DC fields since these pose a considerably greater threat to the diver. One study of the NAVFAC SNOOPY system (see Appendix E) indicates that a calculated value for the critical 60 Hertz AC field in seawater using the "spherical man" in a two-dimensional field is 0.48 volts per meter (0.146 volts per foot). Based on the ratio of 60 milliamps

TABLE IV

Battelle Memorial Institute Welding Demonstration

Test	Welding Supply	Conditions	Probe	Maximum DC Field
A	80 volt open circuit	No diver. Electrode suspended over workpiece and arc struck	Vicinity of electrode	0.5 volt/foot approx. 4 inches from electrode holder
B	59 volt open circuit	Diver in 3/16 in. wet suit, gloves and boots; electrode suspended about 2 feet from workpiece	Ahead of diver as he walked slowly toward workpiece	No measurable field
C	59 volt open circuit	Diver picks up holder, strikes arc and proceeds to weld	Around diver, holder, and workpiece	Small gradient only within 6 inches of arc
D	59 volt open circuit	No arc. Diver between holder and work which are approx. 3 feet apart	Between holder and workpiece	- 0.5 volt/foot within 4 inches of electrode tip



DC to 10 milliamps AC (both capable of causing muscle contraction), the critical DC gradient should be 6 times the AC gradient or approximately 1 volt per foot. Using this estimate with the measured data from the Battelle study, the diver could encounter a hazardous DC field when within 2 to 3 inches of the electrode.

#### One Dimensional Field Model

If the electric field can be assumed to vary linearly in one direction throughout the medium encountered by the diver, a one dimensional field model can be used. Current flow through the diver would be determined from the electrical potential across the diver circuit and the resistance of all the elements between the two points of contact with the power source. The Battelle and diver tool studies used this approach. Although only approximate values of current flow through the diver's body can be found using this technique, it provides a simplified analytical approach to the problem of evaluating current flow through the diver. For a further treatment of this approach to the problem, the reader is referred to Appendix A.

CHAPTER V

USE AND PROTECTION OF UNDERWATER  
ELECTRICAL DEVICES FOR DIVER SAFETY

General Requirements

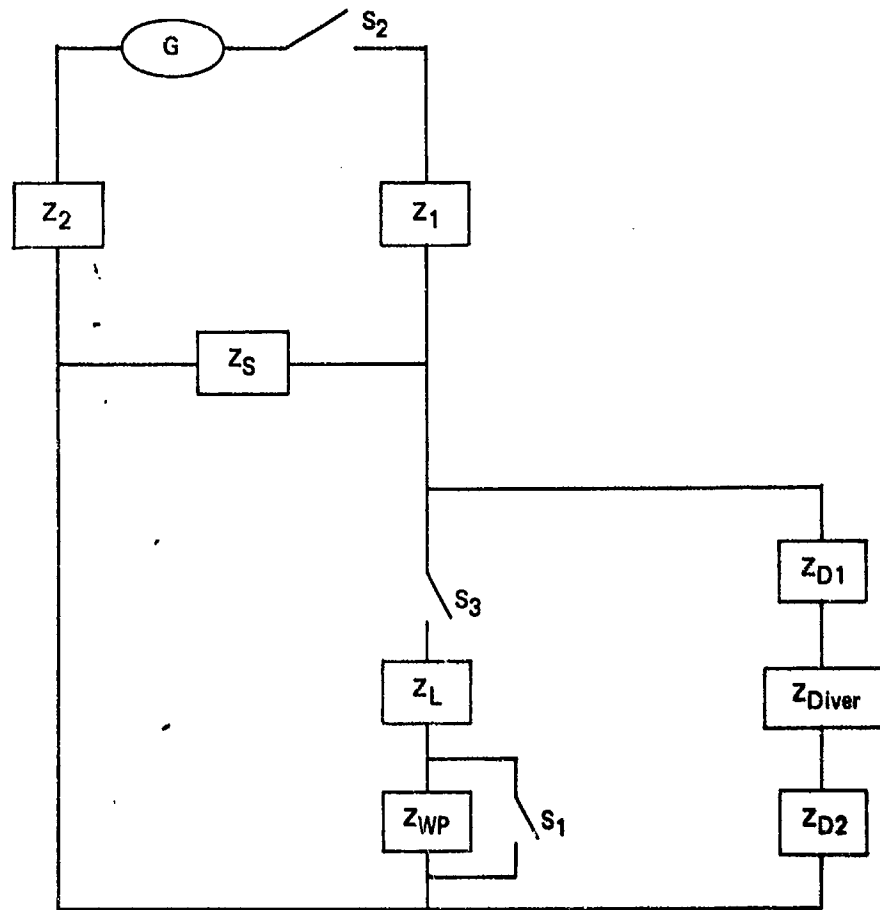
The let-go current appears to be a reasonable criterion for deciding on a level of protection to prevent serious injury or death of a diver exposed to underwater electric fields. An electrical current of 9 ma AC or 60 ma DC entering the body will produce muscle contracture. Such a current is likely to produce an underwater accident if that level were maintained continuously for a length of time. It could also cause respiratory and cardiac arrest.

The level of protection required to protect divers against potentially dangerous electrical currents depends on adequate diver dress, including wet or dry suits, boots, gloves, and full head cover (see Figure 4 and Appendix A).

Attention should also be given to AC problems and long-term effects of low-level currents which do not cause immediate problems. The panel believes that repeated electric shocks of even a low level, often considered "routine" in present underwater welding and cutting operations, should be eliminated whenever possible. Shocks of this level might startle divers causing them to drop tools or fall against an obstruction. Divers may become so accustomed to the shocks that careless safety practices may result (see Appendix B). In addition, long term tissue injury may occur. Alterations in equipment design are necessary to effectively reduce low level shocks since total insulation of the diver seems impractical at the present time.

Protection of AC Circuits

Although the panel was concerned mainly with electric circuits for underwater cutting and welding, other underwater electric usages were considered. New ground-fault detectors (GFD) are being used where low-level (5-10 ma) AC leakage through a human contact to ground must be prevented. These detectors, or ground-fault interrupters (GFI), are presently available for protection of AC circuits carrying loads of from a few to hundreds of amperes. They detect leakage currents of 10 ma and either interrupt the circuit (GFI) or indicate that a ground fault exists.



- G Power Source
- $Z_1$  Transmission Line Impedance (Series) Hot Side
- $Z_2$  Transmission Line Impedance (Series) Common Side
- $Z_s$  Leakage Impedance (Shunt)
- $Z_L$  Load (Tool) Impedance
- $Z_{DIVER}$  Diver Impedance
- $Z_{D1}$  Diver to Source High Side Impedance
- $Z_{D2}$  Diver to Source Common (Workpiece) Impedance
- $Z_{WP}$  Workpiece (Arc) Impedance with  $S_1$  Open
- $S_1$  Open for U/W Arc Cut/Weld Only
- $S_2$  Topside Disconnect
- $S_3$  Diver Operated Disconnect

Figure 4: Underwater Working Diver -- Generalized Circuit Model

In the underwater employment of AC power for tools, lights, and electric motors used as mechanical power sources, ground-fault detection or interruption devices should clearly be used for diver protection. These practices, though now fairly general within the commercial diving industry, are not as yet routinely followed in the Navy.

In large power applications, such as supplies to underwater habitats or vehicles, ground-fault interruption may become impractical if life support, propulsion, or other vital systems are supplied by AC power. In these cases, other design precautions, such as special insulation or connectors, should be implemented. In addition, when heavy power transmission occurs under water, special shielding of conductors and special training of divers should be undertaken.

When non-critical power-transmission lines are used under water, ground-fault interrupters are still recommended in one-two-or three-phase supply lines.

#### Static Welding Power Supplies

Although static AC welding equipment transformers are available, they are not recommended for underwater use because of the danger of serious or lethal electric shock.

Static DC welding power supplies, consisting of an AC transformer and rectifier system, should also be prohibited for underwater use. These devices are dangerous or lethal should the rectifier fail. In this case, AC will appear on the welding lines and can produce a serious electric shock.

#### Protection of DC Welding Power Supplies

DC welding supplies driven by internal combustion engines are the safest available because no AC is present in the welding supply generator.

DC welding power supplies, consisting of an AC motor coupled to a DC welding generator, are considered safe for underwater use only so long as the AC motor has an appropriate ground-fault interrupter to prevent leakage of AC from the drive motor into the DC welding supply.

Several changes in the DC welding circuit should be considered. An inherent problem is the presence of an open-circuit voltage of approximately 80 volts prior to arc

initiation. Circuitry should be designed to inhibit open-circuit voltage until the electrode is placed on the work. This circuit could be manually operated by the diver using a switch on the electrode holder, or it could be automatic, controlled by changes which occur in the welding-circuit resistance when the welding rod contacts the workpiece.

The characteristic voltage change of the welding supply might be altered to prevent large voltage transients which can produce electric shock. If a voltage-current characteristic could be found which allows proper arc initiation and suppresses large voltage transients, the incidence of shock to the diver associated with initiation and cessation of the arc will be reduced.

#### Protection of DC Supplies for Small Equipment

The possibility of DC power transmission under water for non-welding uses includes DC-operated lights or specialized hand tools or instruments. Although DC is safer than AC under water, the potential for serious or fatal electric shock still exists. GFI-type devices should be designed for DC circuits. Another solution to the DC problem is to keep the supply voltage low to provide intrinsic safety.

## CHAPTER VI

### PROCEDURES

#### Navy Manual

Underwater cutting and welding was first undertaken by the Navy in technical studies conducted during the 1930's. Information from these studies was collected and published in the U.S. Navy Safety Notes, published in the mid-1940's. The first Navy Underwater Cutting and Welding Manual (Nav-Ships 250-692-9) was issued in 1953 and updated in 1969 as the Technical Manual on Underwater Cutting and Welding (Nav-Ships 0929-000-8010).

The 1969 manual is little more than a rewrite of the 1953 version. The most severe problem with the present manual is its ambiguity, particularly about the use of AC as a power source and the various uses of a wet suit in underwater cutting and welding (see Appendix C). The more important of the manual's safety regulations are discussed below.

#### Trapped Explosive Gases

The Battelle study noted the presence of explosive gases in compartments undergoing cutting operations.<sup>32</sup> Gas pockets may be vented by drilling holes in suitable locations. Though not spelled out specifically in the manual, the rule is "when in doubt--vent."

#### Falling or Rolling of "Cut-Away" Pieces

Careful examination should be made before starting work to determine how the cut-away pieces will fall and whether there are any pipes, wires, or projections which may foul lines or cause the workpiece to swing around in an unexpected manner.

#### Electric Shock

The use of electric power in underwater cutting or welding presents a potential shock danger both to the diver and the tender. Thus, proper electrical insulation is of considerable importance. All personnel engaged in underwater electric cutting and welding should be thoroughly trained in first aid measures so they can render immediate assistance in the event of a serious accident.

### Additional Navy Sources of Advice

The diving and salvage section of the Naval Safety Center, Norfolk, Virginia, has maintained a data collection system since 1970. It receives reports on about 90 percent of all Navy and Navy-related dives, regardless of whether an accident occurred. The reporting of accident-related dives appears to be considerably higher than the 90 percent figure for all dives.

The reporting system is currently being updated to increase the amount of information available to indicate, for instance, whether or not electrical tools were used during a particular dive. The Safety Center issues an annual report and, with the concurrence of the Navy Supervisor of Diving, periodically issues safety notes concerning specific diving problems. The notes effectively disseminate information throughout the fleet. Additional diving information is disseminated by the Naval Safety Center magazine Fathom, and also by the Naval Sea Systems Command's diving magazine Faceplate.

### Navy Practices

Theoretically, all Navy underwater cutting and welding is done in accordance with the current manual, which despite errors and ambiguities, does contain useful information about equipment and techniques. However, fleet divers appear to routinely flout the standards set by the Navy manual in their dress. Although any deviation from established standards could be dangerous, the most serious aspect of disregarding rules may not be the initial deviation, but the tendency to treat other rules just as casually. Relaxation of standards may eventually lead to a dangerous situation. Deviation from established Navy policy often occurs because the diver, on the low end of the information chain, is simply "not getting the word." Though this problem will probably never be completely eliminated, information should be completely disseminated.

### Industry Manuals

No single, universally-accepted manual on underwater cutting and welding exists in the commercial industry. Each of the major diving contractors has some form of internal manual or guidelines. The Association of Diving Contractors published a Manual of Safe Diving Practices in 1975.<sup>33</sup> The safety precautions of the Chicago Bridge and Iron Company for underwater cutting and welding are listed in Table V.



**SAFETY OF OPERATIONS  
REQUIRING UNDERWATER WORK**

**6.0 UNDERWATER CUTTING AND WELDING  
SAFETY PRECAUTIONS**

Personnel assigned to operate welding equipment must be properly instructed and familiar with all precautions necessary for safe underwater cutting and welding.

**6.1 Precautions against electrical hazards are:**

- 1 A positive operating disconnect switch must be used in the electrical circuit and be located in such a position that the diver tender on the intercommunication system can operate or oversee its operation at all times that the diver is below the surface. Keep the disconnect switch in the off position except when the diver is actually cutting or welding.
- 2 Securely attach the welding ground cable connection, by weld or clamp, to the structure being welded and within 2' of where the weld is being made.
- 3 Ground all welding machine frames before starting operations.
- 4 Take precautions to insure that power supply cables other than the welding leads do not contact the welding cables in such a way as to create a potential short.
- 5 Use rubber gloves or other insulated gloves during underwater electric cutting or welding operations.
- 6 From the surface, turn off all hand held electrical equipment when lowering it into the water or retrieving it from the water.

**6.2 To protect against gas explosions:**

- 1 Treat compressed gas cylinders with care to prevent damage to the cylinders and valves. Particular precautions must be taken to prevent the cylinders from being knocked over and to protect the valves from physical damage.
- 2 In underwater cutting or welding operations, the diver should take all possible precautions to insure against entrapped gas explosions.
  - a Any compartments containing unknown or explosive gases must be purged or filled with water prior to cutting or welding operations.

- b Gases produced by underwater cutting are rich in oxygen and hydrogen and will explode if trapped and ignited. Sparks from cutting or welding will ride bubbles up several feet and cause trapped gases to explode. Gases from underwater cutting will collect in pipelines, manifolds, compartments, tubular members of structures and under structural members such as "H" beams. Before cutting, always vent members, pipes and compartments so gasses cannot be trapped.

**Source: Chicago Bridge and Iron  
Company Standard 155-5-20,  
June 1974, Page 5.**



These precautions are less restrictive than those in the Navy manual. A committee of the American National Standards Institute (ANSI) is now developing a set of standard practices for commercial underwater diving and welding.

### Industry Practices

The NCSL survey indicated:<sup>34</sup>

#### Equipment

- A safe, reliable, diver-operated switch with topside backup would be useful.
- The telephone should be used for diver communications.
- Playtex-type gloves, with another set of heavy rubber gloves worn over them are useful in salt water. Rubber gloves with cotton over them are useful in fresh water. Precautions should be taken to protect the gloves from holes.
- Hot-water suits are used unless the diver prefers a dry suit.
- A one-piece suit seems to give the greatest protection against shock.
- Straight polarity is generally used for cutting, while reverse polarity is used for welding.

#### Shocks

- Divers are always able to feel the presence of electric current.
- Fewer shocks occur in a dry suit.
- Shocks are commonly caused by faulty connections.
- At arc initiation, divers feel a twinge 50 percent of the time; 10 percent of the time divers experience an unpleasant shock.

- Severe shock from underwater television has been reported by divers.
- A diver wearing coveralls must be careful not to get between the ground and the stinger. When this occurs, a tingle is felt in the least-covered portion of the body.
- Most underwater electrical shocks are not as painful as shocks received from a spark plug.
- Many shocks occur in hyperbaric (dry habitat) welding. In this type of welding, the humidity is high, the divers have their feet in the water, and they are wearing wet suits. The divers must brace themselves when starting to weld so that muscle spasms will not cause erratic movement of the electrode.
- Divers do receive shocks, but they become used to them.

#### Manuals

- The Navy Diving Manual is not used in practice by commercial divers.
- Portions of the Navy Cutting and Welding Manual and the Craftsweld (TM) Manual are used.

#### General

- Operational safety is considered the responsibility of the supervisor.
- Divers are cautioned to perform welding with their mouths open to avoid welding their fillings together.
- Considerable care must be taken to ensure that leads are not switched during repair.

The NCSL survey indicates that some procedures used by commercial diving companies are not "permitted" in the Navy. However, since no fatal accidents have occurred during thousands of welding and cutting hours annually, the panel cannot contend that commercial diving procedures are unsafe.

The absence of a direct correlation between relative

shock frequency and safety practices probably indicates that no one element of the system holds the magic key to shock avoidance. Rather, the whole system and the inter-relationships among the various elements has to be considered.

Commercial diving companies recognize that underwater electrical cutting and welding is dangerous. Yet, current practices indicate that they consider the hazards of cutting and welding to be no more dangerous than any other hazards related to diving.

An overall comparison of Navy and industry practices, written and actual, is presented in Table VI. The major safety-related differences noted are:

- Navy fleet divers do not receive adequate training and retraining to provide and maintain real proficiency in underwater cutting and welding.
- Reverse polarity is not recommended by the Navy manual, and is not used by Navy divers, but is used by commercial divers.
- Diver-to-tender voice communications and fully-insulated diver dress are considered mandatory by the Navy manual, but are not always used by Navy fleet divers and commercial divers.
- The Navy manual prohibits cutting and welding in wet suits that have been compressed wet to depths greater than 50 feet, but Navy fleet divers appear to ignore the rule and follow commercial practices.

Table VI : Comparison of Navy and Industry Practices

Subject	Navy Manual	Navy Fleet Divers	Navy Shipyard Divers	Commercial Divers
<u>Training</u>				
Are divers given formal training in underwater cutting and welding?	Yes	Doubtful (Indoctrination Only)	Yes	Yes
Do the divers feel that the training they receive makes them proficient in underwater cutting and welding?	--	No	Yes	Yes
Do the divers routinely receive retraining in underwater cutting and welding?	--	No	Yes	Yes
Are competent topside welders specifically selected and trained as divers so as to perform as underwater welding specialists?	No	No	No	By some
Is welding performed by the self-consuming technique?	Yes	Yes	Yes	Yes
Is welding performed by other than the self-consuming technique?	No	No	No	Yes
Are special waterproof containers used to keep the electrodes dry underwater prior to their use?	No	No	No	By some
<u>Power Leads</u>				
Are ground leads connected as close to the work site as possible?	Recomm.	Sometimes	Yes	Sometimes
Are cable connections waterproofed?	Recomm.	Sometimes	Yes	Yes
Are periodic insulation checks required/undertaken?	Yes	Yes	Yes	Yes
<u>Shock Sensation</u>				
Do the divers experience powerful shocks (other than tingling sensation)?	--	No	No	Rarely
Is the tingling sensation shocks commonly experienced while cutting and welding?	--	Yes	Yes	Yes
(continued)				

<u>Shock Sensation (cont'd)</u>	Navy Manual	Navy Fleet Divers	Navy Shipyard Divers	Commerc Divers
Do divers consider shocks received while welding and cutting hazardous?	--	No	No	No
Do divers consider welding or cutting work more dangerous than most other work?	--	No	No	No
Do divers experience dental filling problems due to underwater cutting and welding?	--	Rarely	No	Yes
<u>Power Supply</u>				
Is DC power used?	Recomm.	Yes	Yes	Yes
Is AC power used?	In Emerg- ency	No	No	No
Is reverse polarity used?	Not Recomm.	No	No	Yes
Is the generator always a rotating one?	Recomm.	Yes	Yes	Gener
Is a static rectifier allowed/used?	In Emerg- ency	No	No	Seldo
If a static rectifier is used, is the AC circuit protected?	No	No	No	No
<u>Knife Switch</u>				
Is a knife switch always installed in the welding/cutting circuit?	Yes	Yes	Yes	Yes
Is the knife switch always placed in the open position when changing electrodes?	Yes	Yes	Yes	Yes
Is the ampere rating of the knife switch greater than the actual amperage used for all cutting?	No	No	No	Yes
Is the ampere rating of the knife switch greater than the actual amperage used for all welding?	Yes	Yes	Yes	Yes
Is knife switch single throw off/on?	Yes	Yes	Yes	Yes
Is a specific model or federal stock number knife switch required?	No	No	No	No

<u>Communications</u>	Navy Manual	Navy Fleet Divers	Navy Shipyard Divers	Commercial Divers
Are diver-to-tender voice communications mandatory?	Yes	No	Yes	No
Do divers feel that hand signals are an adequate means of communications if voice communications are not available?	No	Yes	No	Yes
<u>Diving Dress *</u>				
When underwater cutting or welding, are the divers always fully clothed in a diving dress that fully electrically insulates them?	Yes	No	Yes	No
Once a wet suit is used to a depth greater than fifty feet, is it marked in any manner to designate that it is no longer suitable for use in underwater cutting and welding?		No	No	No
Is cutting and welding performed in wet suits that have been compressed at to depths greater than fifty feet?	No	Yes	No	Yes

- \* The primary reason that most underwater cutting and welding is performed by fully-suited divers is to insulate the diver from cold-water temperatures.

In areas of warm water, little thought is given to electrically insulating the diver, with the exception of the hands, which are insulated by some type of rubber/neoprene gloves.

CHAPTER VII

TRAINING AND QUALIFICATIONS

U.S. Navy Training for Fleet Divers

In reviewing Navy training procedures for underwater welding and cutting, the panel consulted with instructors from both the Salvage and Diving School, Washington, D.C., and the Second Class Diving School San Diego, California. Course material, including movies and lesson plans covering both oxygen-arc cutting and welding, were reviewed. The lesson plans seek to acquaint the students with the maintenance and operational techniques of both oxygen-arc cutting and welding, to develop skills in these procedures, and to provide practical experience.

The officials at the two schools contend that the training given Navy personnel in these courses is inadequate, and that the graduates are not proficient in underwater cutting or welding. The schools view the training as nothing more than orientation since little time is allotted for hands-on training, with actual equipment, in either cutting or welding. This pragmatic evaluation is shared by the panel and, as indicated in Table VI, by the Navy graduates.

The officials said that the training given is in strict accordance with the Navy manual. The panel notes, however, that this is not the case. A close review of the lesson plans reveals that the references and reading assignments cited are all based on the 1953 edition of the manual, rather than the 1969 edition. The training films are likewise badly out of date, as is much of the general information in the lesson plans.

The panel further noted that the training courses do not deal with underwater electric shock hazards, safety, or first aid. This is a serious shortcoming since it should be assumed that all Navy divers will, at one time or another, work with some sort of underwater electric apparatus, such as lights or television, whether or not they do any oxygen-arc cutting and welding.

The panel also attempted to determine whether or not the graduates had any special training to prepare them for the "real world" of underwater cutting and welding. The panel concluded that no preparation is given the student as to common practices which deviate from the

written word of the manual.

Once the diver completes the training course and returns to the fleet, any one of the following three situations may occur:

- a. The activity does only occasional cutting and welding, in strict accordance with the manual.
- b. The activity does no underwater cutting or welding.
- c. The activity does occasional cutting and welding, without following safety rules established in the manual.

The instructions received at the Navy diving schools cover the first two activities adequately, but not the third. Few, if any, fleet activities permit time to train divers specifically in underwater cutting and welding in order to raise proficiency levels. Fleet divers almost unanimously complain, as noted in Table VI, that they lack the opportunity to maintain skills in underwater cutting and welding.

In several instances, the panel discerned that training at the diving schools was somewhat at variance with the Supervisor of Diving. For instance, the Salvage and Diving School apparently considers the Navy Safety Center's Safety Notes to be legally binding. When listing safety precautions concerning the use of the wetsuit, the School states, "Safety Center Note--March 15, 1972, supersedes the Cutting and Welding Manual." This is in direct variance with information provided the panel by the Supervisor of Diving.

Another example involved the so-called Wigdahl torch. The panel was informed that instruction in this "non-regulation" equipment was being given at the school in San Diego. As previously noted, the panel has pointed out an AC electric hazard with this device. The panel understands that the Wigdahl torch has since been discontinued from training.

In view of the foregoing, the panel views the state of Navy training in underwater cutting and welding to be less than optimum. Certainly, the training should be based on current publications and approved equipment.



Close coordination between the training schools and the Supervisor of Diving, not outwardly evident, should be mandated.

The panel recommends that a study be undertaken to determine the Navy's requirements for underwater welding and cutting skills, and whether or not it is necessary to train all divers in this field. If skills in this area are thought necessary, several options are possible.

- a. A two-to-four week add-on training period at the existing diving schools, whereby specified rates are given extensive training in underwater electric arc cutting and welding.
- b. Establish "B-courses" at existing diving schools for specific training in underwater welding and cutting. These courses might be open for both basic training and refresher training. Graduates of these courses would carry a specific enlisted classification number to indicate the specialized training, and thus maintain their qualifications.
- c. Arrange for ad hoc special training in underwater cutting and welding for fleet divers at various naval shipyards where a considerable skill level already exists.
- d. Contract with one or more of the commercial firms that already have comprehensive courses for their employees to undertake training small groups of selected Navy divers on an "as needed" basis. The panel realizes that this option has the inherent hazard of allowing the commercial firm to recruit the more skilled Navy divers.

#### U.S. Navy Qualification Designation

The Navy does not appear to have a system for determining whether a diver is qualified to perform underwater cutting or welding. As noted, all diving trainees are given some instruction in the subject but, at best, the training is perfunctory and little more than orientation. Yet, divers assigned to tenders or salvage ships will likely have to perform underwater cutting and welding. There is no apparent effort to provide, for instance, shipfitters with special or advanced training in underwater cutting and welding, rather than boatswain's mates. In fact, one

consultant to the panel indicated that some of the best underwater cutters were hospital corpsmen.

The panel recommends that divers on salvage ships and tenders, and particularly those in the shipfitting and related ratings, should be trained as specialists in underwater arc welding and cutting.

The situation regarding qualification for underwater welding and cutting is somewhat better in the naval shipyards, where the relatively long tenure of divers allows some to specialize in underwater cutting and welding. These civilian diver welder/cutters are a real asset in the Navy--both in performance of work and as a potential for training fleet divers.

#### Cutting and Welding Training in Commercial Diving Firms

The training of underwater cutters/welders in the commercial diving firms is dramatically different from that of the Navy. Most of the major firms conduct extensive and respectable training programs, placing considerable emphasis on proficiency.

A typical example of a commercial firm's diver cutting program follows:

- The class is composed of 10 student divers who are instructed by a diver experienced in underwater cutting. The instructor is also the diving supervisor in the field.
- The training course consists of a full two-week, hands-on course--five days a week, eight hours a day.
- The first two days are spent in equipment familiarization and topside cutting, followed by five full days in the water, with the student actually cutting with the equipment used in the field.
- The last three days of the course are spent cutting under water; however, during these last days, various casualty exercises are undertaken. For instance, the oxygen pressure is lowered to below normal and then raised above normal pressure. Similarly, the amperage is lowered somewhat below normal and then raised to a point somewhat higher than needed. The students are

trained to cope with these variations. This training in "real world problems" is particularly valuable and, it should be noted, is found nowhere in the current Navy training program.

Some, but not all, commercial diving firms have similar training programs for underwater welders. In some cases, the trainees are "regular divers." In other cases, the company hires experienced surface welders and trains them to be deepsea divers, as well as underwater welders.

All commercial diving firms are careful to identify those divers particularly proficient and qualified in underwater cutting and welding and, further, in special types of underwater cutting and welding.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The panel, in completing its review of the equipment, procedures, and personnel of the Navy and commercial underwater cutting and welding operations, makes the following conclusions and recommendations.

Overall System

Conclusion: Although there is no evidence of fatal accidents in underwater cutting and welding, continued increases in working depth and in the general tempo of such activity may lead to future hazards.

Recommendation: Attention should be focused on the hazards of underwater cutting and welding, particularly as new developments occur in the field of diving in general.

Conclusion: There are few significant differences between the procedures specified in the Navy Technical Manual on Underwater Cutting and Welding and present commercial practices. Those differences that do exist are principally in the areas of diver dress, communication procedures, and training. Navy field practices diverge from prescribed procedures, principally in the areas of diver dress and diver-to-tender communication.

Conclusion: The panel has found no evidence that either a systems design approach or a complete systems analysis of Navy or commercial underwater welding or cutting has been undertaken. The rudiments of such a method of analysis have been developed. The panel believes the study confirms the efficacy of such an approach.

Recommendation: The systems approach, in which all elements of the problem and their mutual interactions are considered, should be adapted to all future efforts on underwater cutting and welding changes that may affect safety, such as remote controlled knife switches. Present practices should be evaluated as a total package rather than as individual elements. New programs should apply systems safety analysis, such as MIL-STD-882.

Equipment

Conclusion: AC power, when used in water or other

conductive environments, is lethally hazardous to a submerged diver.

Recommendation: Because of the lethal electrical hazards, AC cutting and welding equipment should not be used in underwater operations. Further, when an AC motor is used to drive the DC welding generator on deck, the AC motor should be equipped with ground-fault detection and interruption devices. Welding systems using AC-to-DC static rectifiers should not be used at all for underwater work.

Conclusion: AC ancillary equipment requires careful grounding and other devices for shock protection.

Recommendation: All AC powered ancillary equipment and systems for use under water should be safety checked through the use of systems analysis techniques and should include GFD or GFI circuitry, as appropriate.

Conclusion: DC underwater cutting and welding equipment can now be built and operated in a relatively safe manner. Further, no evidence was found of any safety-related effects of polarity of DC underwater equipment.

Recommendation: Navy equipment specifications should be updated to include the three previous recommendations and the following recommendation.

Conclusion: The primary item of diver-support equipment that can provide absolute protection is the completely insulated suit or garment, including non-conductive coverage of the head, hands, and feet. With a maximum open circuit voltage of 80 volts DC, an overall diver-dress resistance in the current path of about 2,000 ohms should be sufficient to prevent all fatalities and to protect approximately 99.5 percent of the diver population from exceeding the "let-go" current limitations of 60 milliamps DC. Six times as much insulation is required for protection against 60 cycle AC electric shock.

Recommendation: The requirements for diver dress and headgear should specify the complete coverage, preliminary resistance values, and physical conditions noted in the previous, and following, conclusion. The panel further recommends that these values be substantiated by additional work. If the Navy foresees cutting and welding at deep depths using wet suits, values of wet suit electrical resistance should be determined as a function of depth to ascertain the degree of protection the suits provide.

Conclusion: The proper measures of physical condition of diver clothing for adequate protection from severe electrical shocks or burns are the maintenance of the 2,000-ohm resistance value and the absence of worn spots, holes, and small area electrical contact points, rather than an arbitrary limitation on prior usage at any particular depth.

#### Procedures

Conclusion: The Navy's infrequent need for underwater welding and cutting, and the consequent lack of proficiency maintenance on the part of Navy personnel, makes good written procedures and reference material imperative.

Conclusion: The Navy Technical Manual on Underwater Cutting and Welding represents a more formalized approach than the commercial diving industry has for its procedures. However, the present manual suffers from ambiguities, inaccuracies, and omissions.

Recommendation: The manual should be updated and revised to clarify ambiguities and to include applicable information developed in the present review, as well as appropriate information from other sources. Such revision should include provision for periodic updating, as required.

#### Training

Conclusion: Currently, Navy diving schools do not train student divers to be proficient at either underwater electric arc cutting or welding. The present course provides no more than an orientation with the equipment and the manual. The course allows the student to perform only a limited amount of actual underwater cutting and welding. Commercial diving companies maintain training courses that are much more comprehensive than those run by the Navy. Compared to Navy divers, graduates of commercial schools are indeed proficient. The lesson plan for underwater cutting and welding currently in use at the Navy Salvage and Diving School is badly out of date and does not even cite the current edition of the manual.

Recommendation: The Navy should re-examine its overall requirements concerning underwater electric arc cutting and welding. If the re-examination determines a real need in the fleet for proficiently trained underwater cutters

and welders, the Navy could exercise one of the following options:

- a. Establish training courses for both underwater electric arc cutting and welding of about two weeks in duration for each. They would be scheduled and administered on an "as needed" basis by selected diving schools or shipyards.
- b. A possibly more cost-effective solution might be to contract with one of the commercial diving companies that presently conduct high quality cutting and welding training to train small groups of selected Navy divers on an "as needed" basis.

If the re-examination does not reveal a pressing need for specially trained cutters and welders in the fleet, the Navy should update and continue its present one week orientation course. That portion of the training for officer and master diver training that deals with electrical safety should be strengthened.

#### Human Physiology

Conclusion: Present knowledge of the physiological effects of electric fields on humans is adequate for developing safe procedures and equipment, using present technology, to protect personnel from nearly all lethal hazards under present operational conditions. From the standpoint of direct electrical hazards, simplistic models can be used to analyze the effects of the human in the electrical circuit.

Recommendation: In order to improve the overall confidence in present diver dress, protective equipment, and procedures, continued study of the effects of electric shock and electric field phenomena on divers is recommended. Specifically, work is needed to obtain a more complete understanding of the effects of underwater electrical fields on humans and to verify and extend the available first-order simplistic models.

Conclusion: Deterioration of dental fillings in underwater cutters and welders as a result of continued exposure to non-lethal electrical shocks requires increased attention. This is more applicable to the commercial diving industry due to the large amount of cutting and welding operations it performs.

Recommendation: The possibility of dental and other long-term effects of continued exposure to relatively small, non-lethal, electrical shocks should be explored, possibly in cooperation with the commercial diving industry.

Conclusion: As expected, gaps exist in the panel's knowledge of how to handle human safety in future, yet undefined, diving environments, where one may anticipate increased operational depths, "new" mixed breathing gases, and other possible future operational requirements.

Increased attention should be devoted to all aspects of underwater electrical safety. Although not directly related to underwater cutting and welding equipment, other AC-powered devices such as lights and hand tools are also potentially lethal to divers when faults occur and should, therefore, be equipped with ground fault detection and interruption devices.

Recommendation: In looking to the future, studies of human electric properties and limitations should be extended to higher pressures (greater depths) and to the influence of breathing gases other than air.



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APPENDIX A

Current Flow Through a Diver for Typical Work Situations

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Determination of Practical Diver Shock Modes

The objective of this exercise is to review the various factors which contribute to the existence of a potentially dangerous underwater electrical shock hazard, to reduce these to a manageable and meaningful number and to use combinations of these factors to define a set of diver shock modes. Given a particular diver scenario, it can then be defined in terms of these combinations, along with other specific information as required, to develop a model electrical circuit.

Contributing Factor - Underwater Electrical Shock

MEDIUM

- Salt water
- Fresh water
- Air/Water, Splash Zone

DIVER

- Clothing
- Anatomic

DIVER EQUIPMENT

- Tools
- Life Support, Including Communications
- Task-Related Hardware

TOPSIDE EQUIPMENT

- Power Source
- Control
- Transmission
- Safety, Including Overload and Fault Protection

ELECTRICAL POWER

- Frequency - DC, AC, HF
- Level

U/W WORK PLATFORM

WORKPIECE

## Diver Shock Mode Components

The six major diver shock mode components, derived from the contributing factors, are judged to be sufficient to categorize most diver scenarios, in particular, all cut/weld operations. The column identified as "other factors" in Figure 5, contains suggestions for more specific factors which may be peculiar to the situation but which must be known in order to model the electrical circuit.

DIVER DRESS/HELMET CONFIGURATION (5)	MEDIUM (4)	TASK/TOOL (2)	POWER SOURCE (2)	GROUNDING PRACTICE (3)	BODY CURRENT PATH	OTHER FACTORS
DRY/METALLIC	SALT	CUT/WELD	DC	WORKPIECE	HAND/HAND	CABLE LENGTH
DRY/NON MET	FRESH	OTHER (TOOL)	AC	BARGE GROUND	HAND/FOOT	FAULTS
WET/METALLIC	SPLASH/SALT			STRUCTURE GROUND	HEAD/HAND	SKIN CONDITION
WET/NON-MET	SPLASH/FRESH				HEAD/FOOT	ETC.
BARE/ANY						

Figure 5 - Diver Shock Mode Components

For each component, a number of conditions are described. These are more or less apparent with the exception of the five diver dress/helmet configurations. Dry, wet, and bare refer to a drysuit, wetsuit, or swimsuit clad diver. Metallic helmet refers to any head covering which can provide a conductive path from outside to inside; for example, the Navy Standard Mark 5 Deep Sea Helmet or the Mark 12 plastic helmet with metal feed-throughs which can make electrical contact with the diver's face.

The total number of diver shock modes found from combination of these components is  $(5) (4) (2) (2) (3) (4) = 960$ , but all cut/weld with AC are excluded (480); since other tool tasks are independent of grounding practice, exclude (32); and since non-met helmet are not compatible with head-hand or head-foot current paths, exclude (192). This leaves some 208 modes, some of which may still be trivial or nearly duplicative.

No attempt is made here to identify all probable shock modes, but rather to draw attention to the important variables which must be considered in developing a circuit model for electrical shock analysis.

Diver scenarios might be described by a word picture of the conditions leading to a shock situation or in an abbreviated form as shown in the diver scenario work sheet of Figure 6 where three representative scenarios are presented. Figure 7, diver scenario circuit models and safety analysis, has been prepared from the diver scenario worksheet. Each of the scenarios is identified in terms of the six major diver shock mode components. The remaining entries in this table summarize the results of the circuit analysis described in detail below.

## Diver Model Circuit

### 2.1 Generalized Circuit Model

Recognizing that the one-dimensional field model for the underwater diver electrical circuit is imperfect, an exercise was conducted to determine the effect of the major circuit components of a typical underwater electrical work system on the the current flow between the extremities of a diver. The generalized circuit model and circuit parameter definitions are given in Figure 8 which represents both the cut/weld task as well as the general underwater tool task. Power is supplied from source G through a topside disconnect  $S_2$ .  $Z_1$ ,  $Z_2$ , account for series line impedance and  $Z_g$  represents leakage between supply lines. For cut/weld,  $S_3$  is closed,  $S_1$  open and  $Z_L = 0$ .  $Z_{WP}$  then represents the workpiece impedance which depends on arc drop and arc current during weld and depends on seawater path resistance between electrode and workpiece before the arc is struck. For diver tool analysis,  $S_1$  is closed,  $S_3$  is a diver disconnect, and  $Z_L$  represents the tool impedance based on the power rating of the tool. The two series elements  $Z_{p1}$  and  $Z_{p2}$  correspond to the impedance from the skin surface to the appropriate source terminal and  $Z_{DIVER}$  represents the body resistance between extremities, including the skin surface and internal body paths.

### Model Circuit Parameters

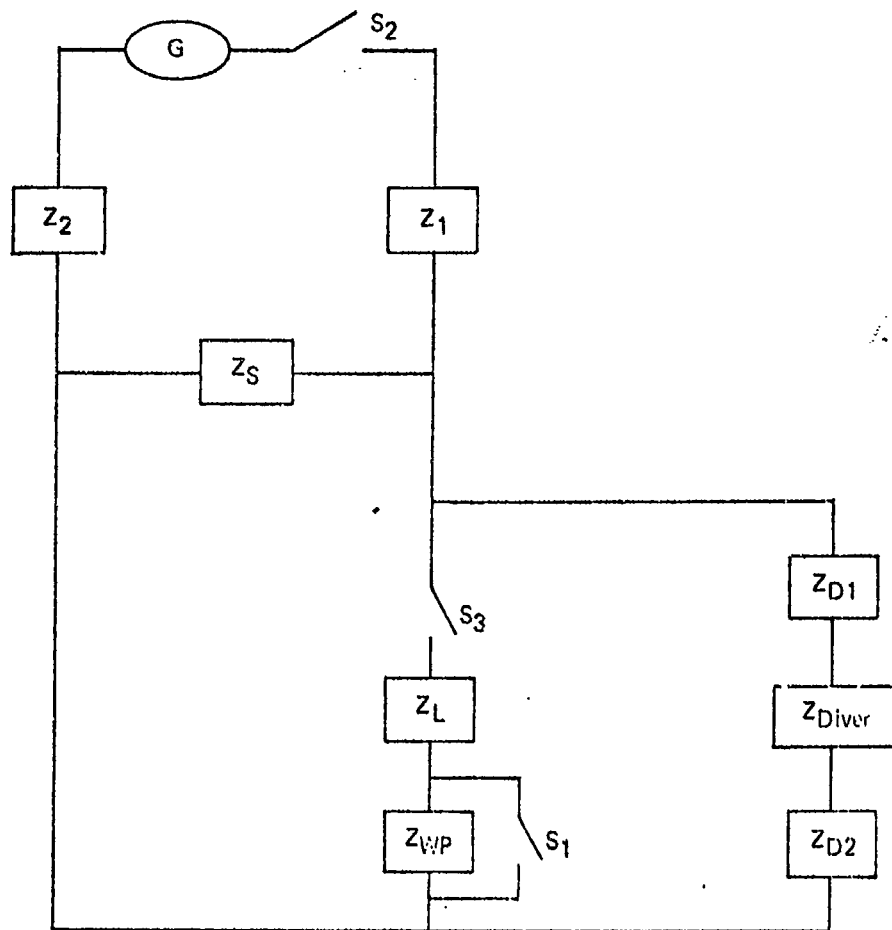
In order to determine representative values for the model circuit parameters, a review of the literature was conducted and values for each parameter are summarized in the following section. The expected ranges of component values for the model circuit are also summarized below. These tabulations include source voltages over a typical operating range of 20-120 volt; power cable resistance ranging from high-current

SCENARIO CONDITIONS	BASIC WORK FUNCTION	MISC. FACTORS	WORK SUPPORT PLATFORM	ENVIRONMENTAL CONDITIONS	ELECTRICAL EQUIPMENT	DIVER FACTORS	DIVER WEAR	ASSOCIATED EQUIPMENT	OVERALL SITUATION	COMMENTS
	a. work type b. material c. purpose d. add'l info.	a. urgency b. location c. unusual conds. d. other	a. type b. mooring c. position w/respect to work d. add'l info.	a. sea cond. b. depth c. salinity d. temp. e. visibility f. lighting g. other	a. generator-isolation b. cables c. grounding d. switching e. U/W equip. f. diver control g. prot. circt.	a. basic training b. equip. train'g. c. job train'g d. phys. conds. e. dent'l conds. f. psych. conds. g. other	a. helmet b. suit c. gloves d. boots e. eye shield f. other	a. communi-cations equipment b. add'l tools c. other	a. shock experienced (hi, lo, none) b. dental c. work efficiency d. other	
SCENARIO I CONDITIONS	cutting steelwork piling/structure	non-urgent splash zone seawater	standing on bottom or platform to shoulders in water	wave action 2-3 foot 3% salinity any temp. poor visibility in water good in air	DC generator straight pol. workpiece gnd. std. knife switch closed during rod change no diver prot. circuits	adequate training, excellent condition	helmet full wet suit	comm. adequate	high level shock experienced work eff. drops	
SCENARIO II CONDITIONS	underwater grinding 110v AC power tool	unusual conds. broken gnd. wire no gnd. fault detector	ship bottom work on frogging line	40-50 feet seawater poor visibility	110v AC from ship's supply inadequate gnd. to tool and plug reversed in socket diver contacts "hot" tool w/hand	adequate training no train'g in elect'l equipment safety excellent conds.	wetsuit full face mask, Jack Brown etc. no gloves	none	possible serious or lethal shock on contact w/tool	
SCENARIO III CONDITIONS	underwater welding on steel structure	non-urgent	diver stage	saltwater any depth any temp. any visibility	rectifier welding supply fault in rectifier AC volts to diver stand-ard welding rig	adequate training excellent condition	full dry suit and helmet surface supplied cotton gloves/rubber outer	std. comm. for full dress	diver experiences serious or fatal shock when contact AC line volts	

Figure 6: Diver Scenario Work Sheet







- G Power Source
- Z<sub>1</sub> Transmission Line Impedance (Series) Hot Side
- Z<sub>2</sub> Transmission Line Impedance (Series) Common Side
- Z<sub>S</sub> Leakage Impedance (Shunt)
- Z<sub>L</sub> Load (Tool) Impedance
- Z<sub>DIVER</sub> Diver Impedance
- Z<sub>D1</sub> Diver to Source High Side Impedance
- Z<sub>D2</sub> Diver to Source Common (Workpiece) Impedance
- Z<sub>WP</sub> Workpiece (Arc) Impedance with S<sub>1</sub> Open
- S<sub>1</sub> Open for U/W Arc Cut/Weld Only
- S<sub>2</sub> Topside Disconnect
- S<sub>3</sub> Diver Operated Disconnect

Figure 8 : Underwater Working Diver -- Generalized Circuit Model

cut/weld application to medium-duty power-tool utilization; cable leakage resistance corresponding to high-quality, medium-quality, and poor-quality insulation; total diver circuit resistance values to account for diver internal body resistance plus one or two layers of protective wetsuit insulation; finally, a range of shunt path resistance values ( $R_{\text{workpiece}}$  for cut/weld or  $R_{\text{load}}$  for tool use) to account for various arc drop voltages at the low resistance end through typical power tool load resistances to a relatively high waterpath resistance.

#### Determination of Typical Parameter Values for Generalized Circuit Model

NOTE: Although impedance (Z) values are designated for the general circuit model, DC resistance values are assumed for the static DC-powered case.

#### Z<sub>DIVER</sub>

Represents the total body resistance = sum of internal resistance plus resistance of the appropriate extremities to the surface of the skin and not including protective clothing. If skin is punctured at points of contact  $Z_{\text{DIVER}}$  is greatly reduced.

Ref. (1) \*Battelle, 1969

PATH	BARE $\Omega$ SKIN	WET $\Omega$ SUIT	DRY $\Omega$ SUIT
Thorax	65	210	310
Hand-Hand	1500	6000	$10^6$
Hand-Foot	1500	5000	$10^6$

Ref. (2) Hackman & Glasgow, 1968

Wet Skin	500 $\Omega$
Dry Skin	3600 $\Omega$
Hand-Foot	3600 $\Omega$
Diver in Seawater	1000 $\Omega$ (500+500)

\* References are listed at the end of Appendix A

Ref. (3) Lee, 1964

Hand Immersed 200Ω

Foot Immersed 100Ω

Body (Internal) 300Ω

Ref. (4) Lee, 1966

Damp Soft Skin 1000Ω

Body (under skin)  
between any two  
limbs 500Ω

Ref. (5) Kouwenhoven, 1937

Body (minimum for  
hand to foot path-  
way) 500Ω

Example:  $Z_{DIVER}$  for bare intact skin, hand-to-foot =

	1500Ω	Using Ref. (1)
	1000Ω	Using Ref. (2)
300 + 200 + 100 =	600Ω	Using Ref. (3)
500 + 200 + 100 =	800Ω	Using Ref. (3) & (4) or (3) & (5)

$$\underline{600 \leq Z_{DIVER} \leq 1500}$$

$Z_{D1} Z_{D2}$

Refer to the resistance of pathway from skin surface to immersion medium, including protective clothing, plus pathway through immersion medium to source terminals.

Ref. (1) Battelle, 1969

Typical Wetsuit Material (Immersed 96 hrs.  
plus 1 cycle to 250 psig N<sub>2</sub>)

NOTE: Resistance values determined  
using 2" diam. (20.3 cm.<sup>2</sup>)  
electrodes.

MATERIAL	SURFACE	100 Ft. SEAWATER		
		Dive 2	Dive 4	Dive 6
1/4 DESCO	125KΩ			
1/4 PARKWAY	8KΩ	28KΩ		2KΩ
		8KΩ	4KΩ	

Example 1.  $Z_{D1} = Z_{D2}$  for hand (foot) direct contact to source terminal through multi-pre-pressurized, 1/4" nylon lined, closed cell, neoprene foam =

$$2K\Omega \leq Z_{D1,2} \leq 4K\Omega$$

Example 2. 2-10 ohms for relatively large area of electrode (exposed conductor at fault) in contact with seawater. 100-1000 ohms for small contact area.

### $Z_{WP}$

Refers to the resistance of an electric arc, based on typical arc drops and an assumed 300A arc current.

Ref. (6) Haigh, 1975

$$V_{ARC} = 40 - 60 \text{ v.}$$

Ref. (7) Am. Weld. Soc., 1958

For shielded-metal arc

$$V_{ARC} = 14 - 24\text{V. light coated electrode}$$

$$V_{ARC} = 20 - 40\text{v covered electrode}$$

Example 1.  $Z_{WP} = \frac{V_{ARC}}{I} = \frac{V_{ARC}}{300}$

$$\text{using } 14\text{v} \leq V_{ARC} \leq 40\text{v.}$$

$$0.05\Omega \leq Z_{WP} \leq 0.15\Omega$$

### $Z_L$

Refers to resistance of diver tool (electrical device) and is zero for the arc cut/weld case.

Example 1. Assume 1 , 120 v. 60 HZ sources and power range from small hand tool (1/4 HP) to medium level (p.e. heated suit)

Approx. range  $250\text{w.} \leq P \leq 2.5 \text{ Kw.}$

$$\underline{5\Omega \leq Z_L \leq 50\Omega}$$

Example 2. Assume 30v. DC source and same power range as above.

Approx. range  $\underline{0.4\Omega \leq Z_L \leq 4\Omega}$

### Z<sub>1</sub>Z<sub>2</sub>

Refer to the series transmission line resistance between source and load and usually is balanced between the two sides of the line. Values depend on wire size selected for allowable line voltage drop.

Ref. (8) USN, 1969

CIRCUIT LENGTH (FT.)	REQ'D AWG	Ω/100 FT.
<300	1/0	0.010
300-400	2/0	0.0083
>400	2-1/0's	0.005
	or	
	2-2/0's	0.0042

Example 1. 2-conductor cable for electric arc cut/weld with workpiece to source positive (DCSP) and 300 A. load. Source to workpiece distance is 100 Ft.

200 Ft. of 1/0 Conductor

$$Z_1 = Z_2 = \frac{2 \times 0.010}{2} = 0.010\Omega$$

Example 2. Electric arc cut/weld with seawater barge ground

$$Z_1 = 0.010 \Omega/100 \text{ Ft. barge workpiece distance}$$

$$Z_2 \text{ for large barge and workpiece (50' X 100')} \text{ in 100 Ft. SW} = 0.01\Omega$$

$$Z_2 \text{ for large barge and small workpiece (2' x 5')} \text{ in 10 Ft. SW} = 0.5\Omega$$

### Z<sub>S</sub>

Refers to leakage impedance between conductors - taken to be at load side of line but could act at source side or both sides. Normally equal to insulation resistance of cable but includes effects of connectors and damage to insulation.

Example 1. Two insulation failures, 1-2 sq. cm exposed

$$100\Omega \geq Z_S \geq 50\Omega$$

Example 2. Good condition cable, high-quality insulation.

$$Z_S \geq 10,000$$

Range of  $Z_S$  not including direct short  
between conductors.

$$100\Omega \leq Z_S \leq 10,000$$

Expected Range of Component Values - Summary

Power Source 20, 40, 60, 80, 100, 120 volts

Total Cable Resistance $R_1 + R_2 = R_C$	Distance Source Load	Wire Size
0.005	25 Ft.	1/0
0.01	50 "	1/0
0.03	200 "	2/0
0.05	500 "	2-1/0's
0.10	50 "	#10

Cable Leakage Resistance

Condition

$R_S$   
10,000 ohms  
1,000  
100

Adequate cable insulation  
Leaky cable  
Severe electrical leakage

Total Diver Circuit Resistance

Condition

$$R_{D1} + R_{D2} + R_{DIVER} = R_D$$

500ohms  
1000  
1500  
2500  
4500

Diver - no protective clothing  
Diver - one layer of poor  
(500 ohm insulation)  
Diver - two layers poor in-  
sulation  
Diver - one layer good (2000  
ohm) insulation.  
Diver - two layers good in-  
sulation

Shunt Path Resistance =  $R_W$

Condition

$R_{WP}$  for cut/weld,  $R_L$  for TOOL

0.05 ohm  
0.10  
0.15  
0.50  
5.0

15v. arc drop @ 300 A.  
30v. arc drop @ 300 A.  
45v. arc drop @ 300 A.  
high-power, low-voltage tool  
low-power, low-voltage or  
high-power, high-voltage tool  
low-power, high-voltage tool  
or low-res. water path  
high-resistance water path

50  
1000

## Analysis of Typical Diver Electrical Tasks

### System Safety Design

To design a diver work system that is safe from all possible electrical shock injury would require a degree of "over design" that would no doubt seriously impair the diver's effectiveness. Thus, as in any system safety design, certain compromises between work efficiency and ultimate shock protection must be effected. The objective then is to develop a system that under strict requirements for equipment inspection, maintenance, and repair and with rigorous training and procedural methods established for the diver, permit the task to be completed efficiently with little chance of a serious electrical shock occurring.

### Model Circuit Solution Based on Typical Diver Scenarios

As a guide to the design of diver work systems involving electrical equipment or for analyzing an existing system, the procedures outlined here might be applied.

Figure 7, Diver Scenario Work Sheet, summarizes the important conditions which might exist in three possible diver scenarios and which might lead to an electrical shock situation. Figure 7, Diver Scenario Circuit Models and Safety Analysis, has been prepared from the diver scenario work sheet. This consists of a tabulation of the six major scenario conditions previously described, the status of the three switches,  $S_1$ ,  $S_2$ , and  $S_3$  in the generalized circuit model of Figure 8 ( $O$  = open,  $C$  = closed), the nature of the power source  $G$ , and the numerical values for all parameters in the model circuit. Finally, the current or range of current flow through the diver is calculated.

In order to interpret levels of diver current in terms of safety from electrical shock, two critical levels of current flow through the human extremities are adopted. These are a 10 ma. 60 HZ current and a 60 ma. DC current, both of which have been determined experimentally to produce muscle contracture and hence pose a serious threat to the immersed diver.

The  $I_{DIVER}$  values of Figure 7 suggest that the diver of Scenario 1, with a minimum of diver circuit resistance, could have a current flow between hand and foot of 70 ma. DC and would probably experience severe muscle contracture. In Scenario 2, the diver would be subjected to an AC current of 73.3 ma.

which might very well prove fatal. Current flow through the diver of Scenario 3 appears to be somewhat below the threshold for AC, but since critical current levels suggested above are only guidelines, and a minimum diver circuit resistance of 5 K ohms is assumed, there is a serious threat of electrical shock.

It should be emphasized that this analysis depends not only on the assumed validity of the one-dimensional model, but also on the ability to identify all the elements of the work system accurately and to select all circuit values with a high degree of confidence. In light of these uncertainties, the calculated  $I_{DIVER}$  should be taken as only a guide to the true current through the diver.

### Computer Analysis of Estimated Current Flow Through Diver

#### Summary

A second approach to the diver circuit analysis was to obtain a series of plots showing the dependence of diver current on the various components of the model circuit. Using the expected range of component values presented previously, a computer-generated set of data was obtained by holding all component values except one constant and iterating the solution through the range of the variable component. From this data, selected plots were made to illustrate the relation between  $I_{DIVER}$  and the principal circuit parameters.

#### Circuit Solutions

To calculate  $I_{DIVER}$  for the generalized circuit model of Figure 9, the following notation is used:

$R_C = R_1 + R_2 =$  Total series line resistance

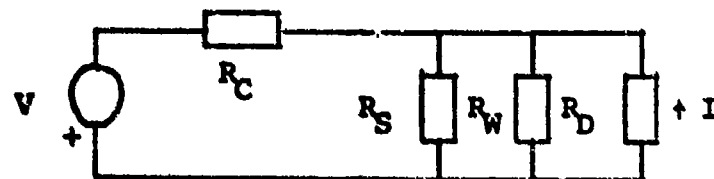
$R_S =$  Line leakage resistance

$R_W =$  Workpiece resistance

$R_D = R_{D1} + R_{D2} + R_{DIVER} =$  Total diver circuit resistance

$V =$  Source voltage

$I = I_{DIVER} =$  Current through diver circuit





The solution of this simple circuit for  $I = I_{DIVER}$  is:

$$(1) \quad I = \frac{V}{R_C + \frac{1}{\frac{1}{R_W} + \frac{1}{R_S} + \frac{1}{R_D}}} \times \frac{1}{\frac{1}{R_W} + \frac{1}{R_S} + \frac{1}{R_D}} \times \frac{1}{R_D}$$

Rearranging and putting this expression in a more useful form:

$$(2) \quad I = \frac{V}{R_D (1 + R_C/R_W + R_C/R_S) + R_C} = \frac{V}{R_D (1 + A + B) + R_C}$$

$$\text{where } A = R_C/R_W, \quad B = R_C/R_S$$

The above expression for diver current shows clearly that when  $A = R_C/R_W$  and  $B = R_C/R_S$  are small compared to 1.0, current depends on the total series resistance  $R_D + R_C$ . Only when the workpiece resistance or the leakage resistance is of a magnitude comparable to the line of resistance or smaller, are the terms A and B effective in reducing current to the diver.

#### Data Plots of Calculated $I_{DIVER}$

A series of calculations for I in Equation (2) was made over the ranges of values of V,  $R_C$ ,  $R_S$ ,  $R_W$ , and  $R_D$ . In order to display the results of these calculations and to illustrate the dependence of I on certain circuit parameters, three sets of curves were plotted. Figure 9 labeled weld-arc, corresponds to a typical cut/weld operation with arc established. The variation of I vs.  $R_D$  for  $R_C = .03$ ,  $R_W = .05$  and  $R_S$  between 100 and 10,000. The numerical values for  $A = R_C/R_W$  and  $B = R_C/R_S$  indicate that since  $R_W$  is comparable to  $R_C$ ,  $A = 0.6$ , and does affect the current while the B term is negligibly small for practical values of leakage resistance.

Figure 10, labeled weld-no arc, corresponds to a typical cut/weld operation before the arc has been established. Using values of  $R_C = .03$ ,  $R_S = 100$  (large shunt leakage), and  $R_W = 5$  (low resistance water path from electrode to workpiece) gives  $A = 0.006$  and  $B = 3 \times 10^{-4}$ . Current I is affected slightly by the A and B ratios but--

$$I = \frac{V}{1.0063R_D + R_C} \approx \frac{V}{R_D}$$

and depends almost entirely on the source voltage and the diver circuit resistance.

Figure 11, labeled Tool, illustrates the range of diver currents that might be encountered for various diver circuit resistances and two typical power capacities. With cable series resistance  $R_C = .1$  and  $R_W = 5$ , the  $V=120$  curve represents a high voltage, high-power tool (3KW) and  $V = 40$  represents a low-voltage, low-power tool (300W).

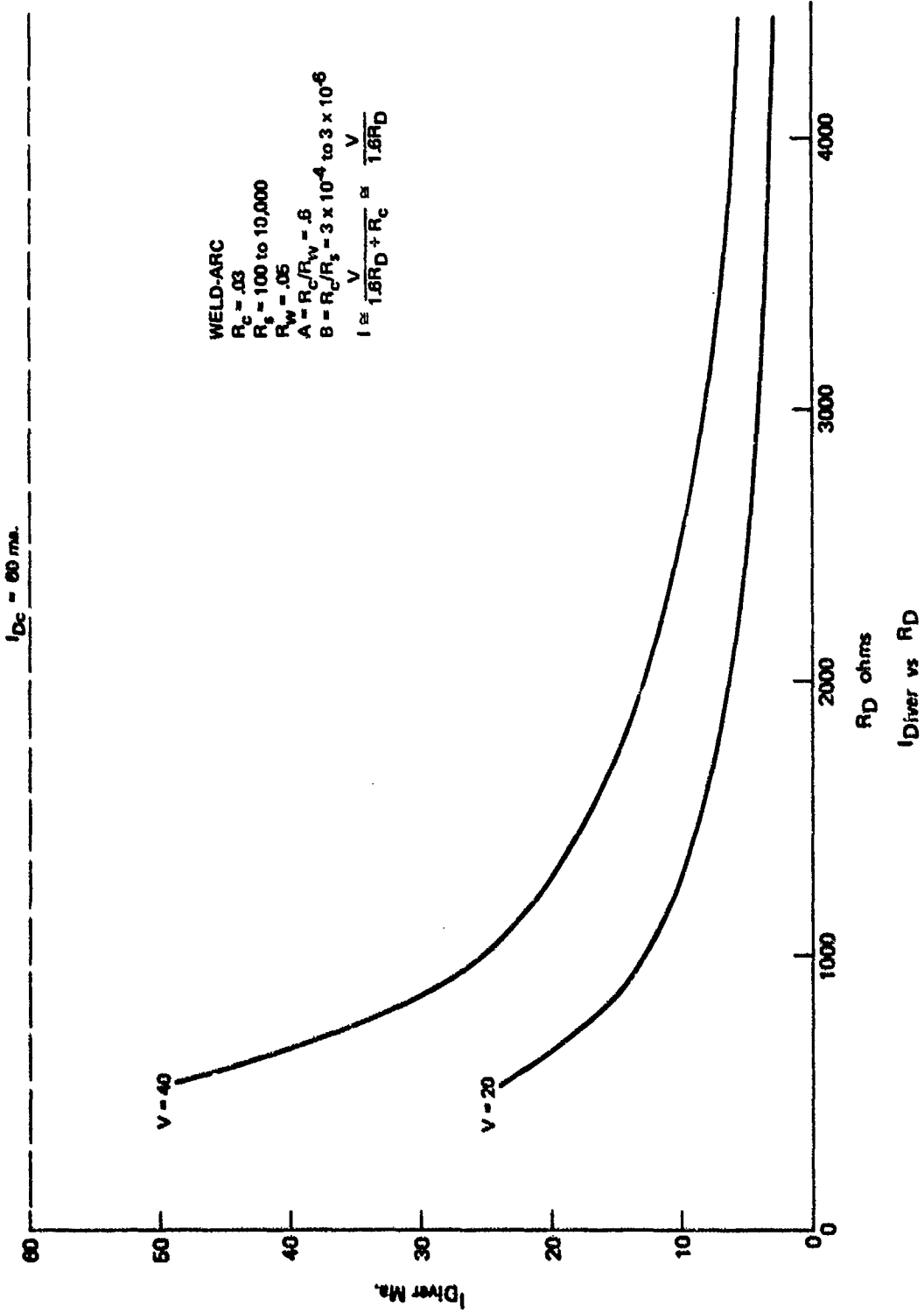
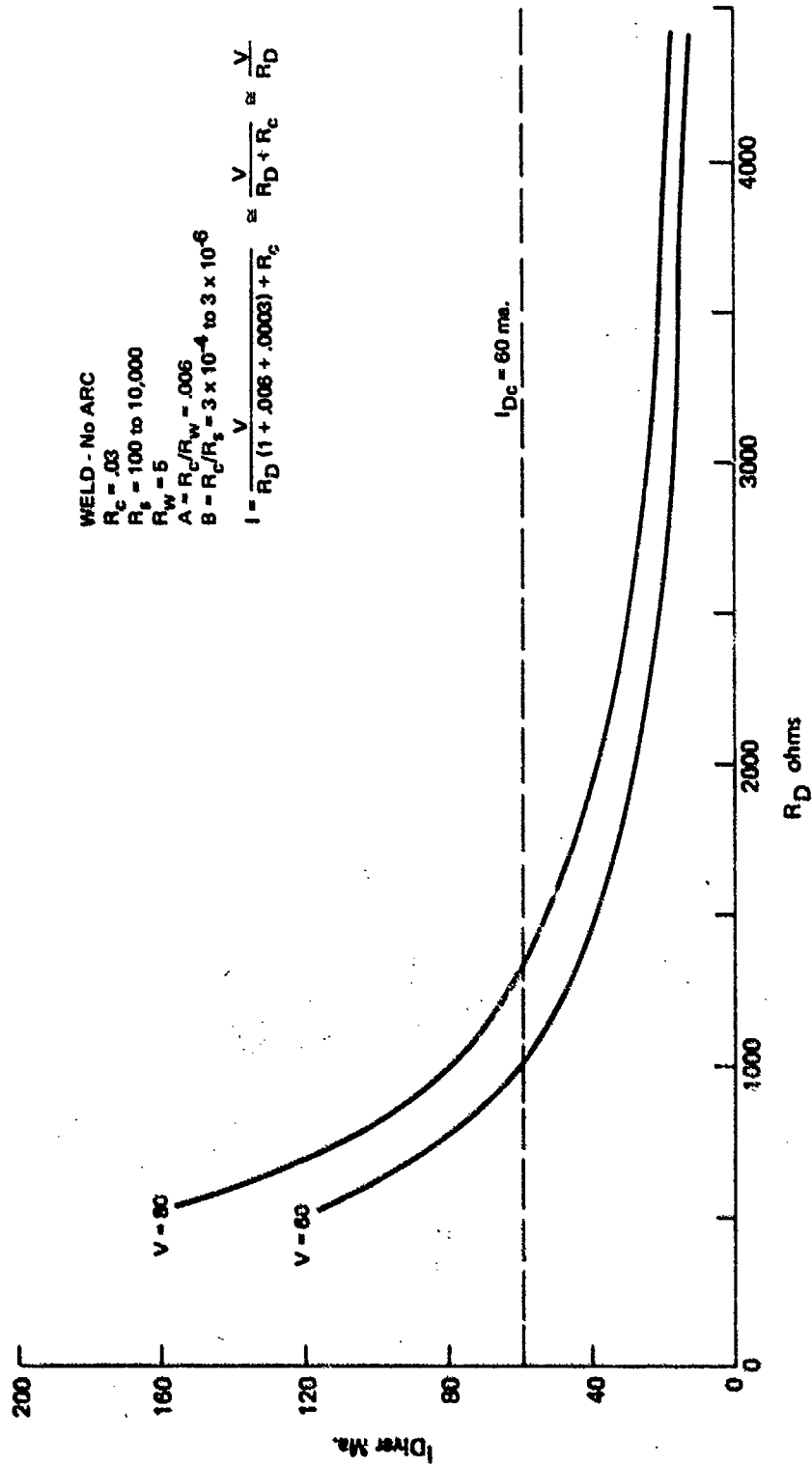


Figure 9  
Weld-Arc



$I_{Diver}$  vs.  $R_D$

Figure 10  
Weld-No Arc

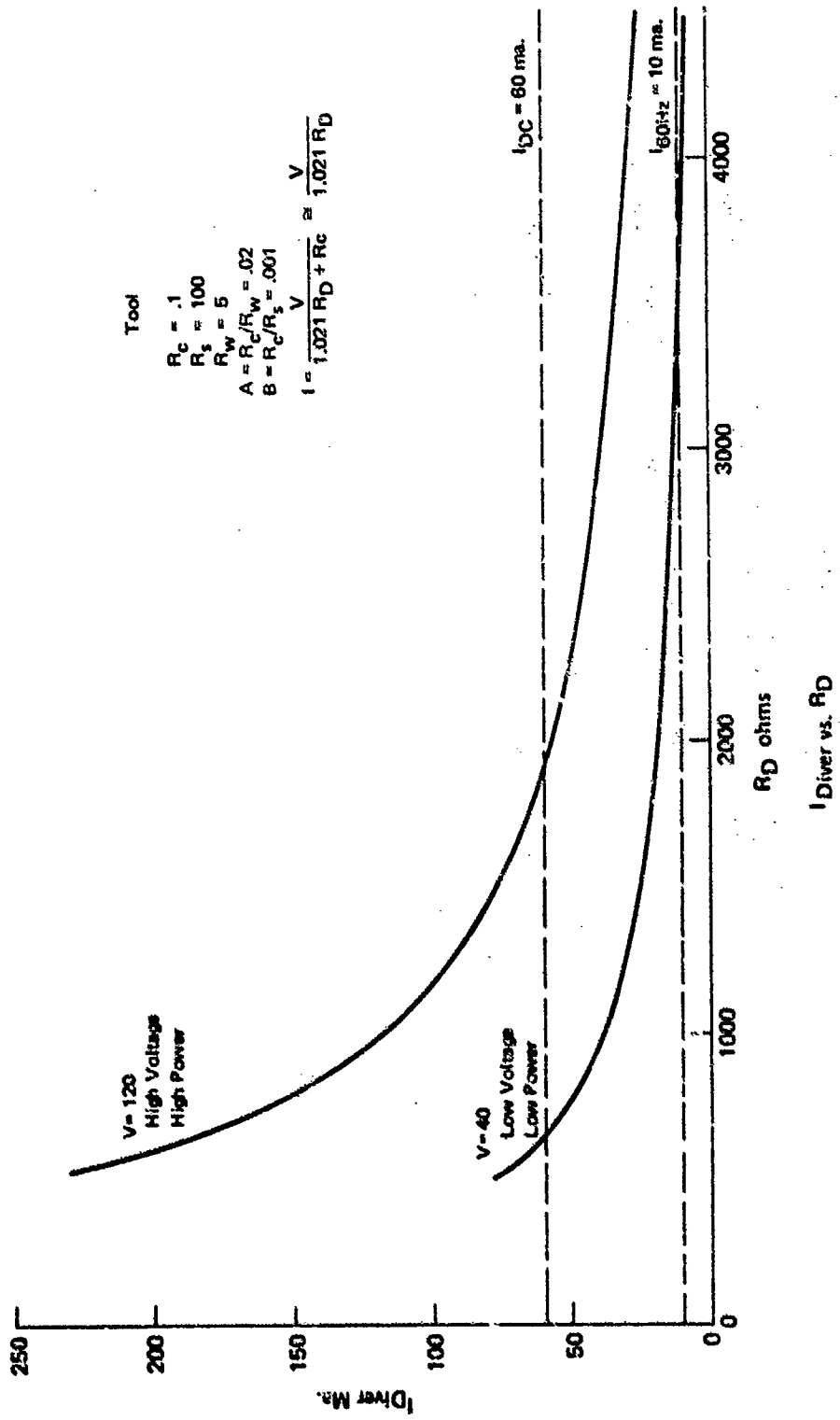


Figure 11  
TOOL

Other choices of data could be made to show the effect of a particular circuit parameter on current flow through the diver, but, as indicated previously, the nature of this simple electrical circuit is such that diver resistance  $R_D$  is the principal current-limiting component. Only when the shunting resistance  $R_W$  and  $R_S$  are comparable to the total series cable resistance is there an appreciable reduction in the current below the value given by  $I = \frac{V}{R_D}$ .

DATA SUMMARY FOR CURVES - Figures 9, 10, and 11

Figure 9 Weld-Arc

$$R_C = .03$$

$$R_S = 100 \text{ to } 10,000$$

$$R_W = .05$$

$$A = R_C/R_W = .6$$

$$B = R_C/R_S = 3 \times 10^{-4} \text{ to } 3 \times 10^{-6}$$

$$I \cong \frac{V}{1.6R_D + R_C} \cong \frac{V}{1.6R_D}$$

$R_D$	I	
	V=20	V=40
500	24.9	50
1000	12.5	25
1500	8.3	16.7
2000	6.3	12.5
2500	5.0	10.0
3500	3.6	7.1
4500	2.8	5.6

Figure 10 Weld-No Arc

$$R_C = .03$$

$$R_S = 100 \text{ to } 10,000$$

$$R_W = 5$$

$$A = R_C/R_W = .006$$

$$B = R_C/R_S = 3 \times 10^{-4} \text{ to } 3 \times 10^{-6}$$

$$I = \frac{V}{R_D(1 + .0006 + .0003) + R_C} \cong \frac{V}{R_D + R_C} \cong \frac{V}{R_D}$$

$R_D$	I	
	V=60	V=80
500	119.2	159
1000	59.2	79.5
1500	39.7	53.0
2000	29.8	39.7
2500	23.8	31.8
3500	17.0	22.7
4500	13.2	17.7

Figure 11 Tool

$$R_C = .1$$

$$R_S = 100$$

$$R_W = 5$$

$$A = R_C/R_W = .02$$

$$B = R_C/R_S = .001$$

$$I = \frac{V}{1.021R_D + R_C} \approx \frac{V}{1.021R_D}$$

$R_D$	I	
	V=40	V=120
500	78.3	235
1000	39.3	117.5
1500	26.1	78.5
2000	19.6	58.8
2500	15.7	47.0
3500	11.2	33.6
4500	8.7	26.1

## Interpretation

In order to interpret the data plotted in Figures 9, 10, and 11 in terms of a potential dangerous electrical shock condition, the critical current levels of 10 ma. 60 Hz and 60 ma. DC discussed previously, are used as a reference.

Figures 9 and 10 represent a DC cut/weld task and the 60 ma. DC level superimposed on the curves can be used as a guide to establishing safe operating requirements. The weld-arc data of Figure 9 indicates that for  $R_{DIVER}$  in excess of 300 - 500 ohms, diver current will be maintained below the 60 ma. level. However, it should be realized that once the skin surface has been punctured internal conductive path resistance is greatly reduced. Values cited from the literature, suggest 300 - 500 ohms for the internal body resistance alone. It would appear then that a diver with no protective covering on hand or foot could be subjected to dangerous current flow if he grasped the welding electrode while his feet were in contact with the workpiece and the arc voltage was 40 volts or greater.

Interpreting the information contained in Figure 10 in a similar manner, the DC cut/weld task with the arc not yet established (denoted as weld-no arc) could be a definite threat to diver safety. In order to limit diver current to 60 ma., the total diver circuit resistance must exceed 1,000-1,500 ohms. Some diver protective covering of the extremities would be necessary if for example, the diver should choose to change electrodes with power on while standing on or otherwise maintaining body contact with the workpiece.

The data of Figure 11 for the tool task can be applied to both AC and DC power systems if values for the diver circuit parameters are taken as impedances for the AC case. The 10 ma. 60 Hz level and the 60 ma. DC level are both indicated on the curve sheet. Some general observations can be made relative to safe operating conditions. It would appear that the low voltage-low power system is safe for 60 Hz operation only with an  $R_{DIVER}$  of 4000 ohms or greater. Operation at high voltages is extremely hazardous. To maintain diver current below 60 ma. DC level requires a minimum of approximately 700 ohms for the low voltage-high power system. For DC operation, protection against dangerous current levels can be provided by high quality protective covering of the diver's extremities.

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APPENDIX B

Underwater Electrical Hazards and the Physiology of  
Electric Shock

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Introduction

Direct Electric Shock Effects  
The Physiology of Electric Shock  
The Physiologic Basis for Electric Shock Response  
in Man  
Direct Current Effects  
Electrically-Induced Tissue Burns  
Oxygen Burns

Dental Problems in Underwater Welding and Cutting

Electric Shock and the Underwater Environment

Diver Dress and Electrical Safety

Equipment Considerations for the Underwater  
Environment

Underwater Welding and Cutting  
Alternating Current Equipment

Figures

References

# Underwater Electrical Hazards and Physiology of Electric Shock

## Introduction

This report summarizes the known effects of electric currents on man and animals in relation to alteration of physiologic function of nerve, skeletal muscle, and heart. Aside from these effects, electric currents can produce thermal burns of both surface and deep tissues and opacities in the lens of the eye (cataracts).

A large body of information is available on the effects of electric currents in dry environments. These data provide a base from which electric-current effects in the underwater environment can be understood. However, because little data are available specifically on electric-current effects underwater, the dry environment data must be interpreted with some reservations. It is reasonable to assume that currents of equal intensity passing through an organ or tissue will produce similar effects regardless of the environment. The greatest problem in the underwater environment is understanding the effects of the surrounding water and the diver's dress on current flow into the diver. It is this poorly understood relationship which adds some uncertainty to the interpretation of dry electric shock data in a wet environment. Since this area is not well understood, a need for further research on underwater electric fields is evident. Some efforts in this direction have been established but the resultant data are presently unavailable for security reasons (see Appendix A for further discussion of this topic).

An attempt has been made in this report to explain documented underwater electric shock problems based on the described biologic effects of electric shock. In addition, from the same data several considerations for improved electrical safety underwater are discussed.

## Direct Electric Shock Effects

### The Physiology of Electric Shock

Effects of electrical currents can be divided into several categories. Direct responses include the effects of electrical currents on the membranes of muscle and nerve cells. These effects can be related to the amount of current which passes through a specific muscle or group of muscles, through the heart, or through the central nervous system. The electric shock response varies depending on body size, current pathways, skin resistance, the individual psychological reaction, the frequency of alternating current, and the mode of entry of the electrical current into the body (10, 5, 6, 15, 28). Since muscle and nerve cell membranes are normally activated by electrical currents, it is reasonable to expect that stray electric currents which pass through muscle or nerve tissue will produce cell membrane activation, with subsequent contraction of muscle cells or discharge of nerve cells (neurons).

The clinical responses to electric shock can be explained by considering the action of electrical currents whether on cell membranes or on central nervous system tissue i.e. brain, spinal cord. The cellular response will be discussed in detail below. When a normal man is connected through each hand to an electrical circuit supplying 60 Hz AC, 2 to 3 milliamperes of current produce a tingling sensation and warmth in the area of contact (6,7). No other response is noted at this level of current and there is no evidence of muscular contractions. As current flow increases through skeletal muscle, there is muscular contraction. At approximately 16 ma. 60 Hz there is uncontrolled contraction of the muscle. In a population of normal men Dalziel (5,6) found the average AC current necessary to produce uncontrolled muscular contraction was 16 ma. He considered a level that would not affect 99-1/2% of the population to be a maximum safe level. Using this criteria, he found the average AC current to be 9 ma in men. This current was labelled the "Let Go" current. Equivalent "Let Go" currents for women are lower (average; 10.5 ma; 99 1/2 percent safe level: 6 ma, AC). Dalziel (5) labelled this current the let-go current because it produced muscular contraction severe enough to prevent voluntary release from the electrical conductor providing current. As current level increases above the let-go current, inhibition of normal respiration is observed. This effect is due to stimulation of the muscles of the chest producing a paralysis of chest wall motion. If this current level ( usually between 18-22 ma AC) is maintained, the individual sustaining this level of electric shock will die from asphyxia. At this current level of cardiac abnormalities do not occur and if the current is shut off and artificial respiration provided, the individual will recover.

The most serious complication of electric shock is ventricular fibrillation, a disorganized useless contraction of the heart. As current is increased above the level which produces respiratory arrest, ventricular fibrillation is observed. The probability of fibrillation occurring increases as current flow through the chest increases. Fibrillation current has been studied in some detail. It was found by Dalziel (5-7) that the fibrillating current in dogs is approximately 150 ma for a one-second exposure. Using the 99-1/2% safe level as a safe limit, in dogs where the average of fibrillating current was 150 ma, maximum safe level was 50 ma. These currents were applied between one upper and one lower extremity in the dog. The current pathways used in these studies were analogous to current pathways in the human. Others (20,2,23,25) have found similar data. Dalziel derived an inverse relationship between minimum fibrillating current and shock duration (5,6). Thus, as the period of exposure to electric current increased, less current was needed to produce ventricular fibrillation. His data in animals show that for 10 seconds, a current of approximately 120 ma will produce fibrillation, while at 0.1 seconds, a current of 600 to 700 ma is required to produce ventricular fibrillation. Figure 13 summarizes the above discussion and describes current levels for several biologic effects in man.

Another variable found to be significant in determining fibrillating current was body weight (6,9,15). In dogs weighing 20-35 kilograms, fibrillating currents in the range 50 to 100 ma were found; while in larger animals, such as sheep and calves where body weights range between 60 to 80 kilograms, fibrillating currents were 200 to 300 ma. In Dalziel's studies, 60 Hz AC current was applied to the extremities and represents current through the total chest conductance. Studies by Roy (23) and others (20,21) show, however, that currents delivered directly to the heart by a directly-placed wire can be as small as 50 microamps to produce ventricular fibrillation. Roy's studies have also indicated that current density in the myocardium is the most important parameter. He has shown that catheters with small cross-sectional areas can produce fibrillation with small currents because they produce high current density. A study by Starmer and Whalen (25) in 1973 verifies these results. They found, both in humans and animals given a shock which produced ventricular fibrillation, that the fibrillation threshold was a function of current density rather than absolute current value. In the study by Starmer and Whalen, the investigation of human responses was done during cardiac surgery where ventricular fibrillation is produced to provide optimal surgical technique during open-heart surgery. The patients suffered no adverse effects and responded normally to the surgery.

The effects of electrical current on the central nervous system have not been studied as extensively as the cardiac effects. Electrical stimulation of the brain is used as a clinical tool in the treatment of depression. It is known that a 150-volt potential applied across the head will produce seizures.

#### The Physiologic Basis for Electric Shock Responses in Man

Present knowledge of the function of nerve and muscle cells is adequate to provide an understanding of the effects of electric shock in terms of basic cell membrane physiology (4,27,30). Nerve, skeletal muscle, and cardiac muscle, cells all require electrical activity of the cell membrane to produce normal function of the cell. In the case of nerve tissue, normal activity causes the propagation of an electrical impulse along the nerve fiber. In the case of both cardiac and skeletal muscle the response to electrical activity in the cell membrane is a mechanical contraction. Contraction of skeletal muscle produces useful work. Contraction of cardiac muscle provides the normal function of the heart.

From an electrical point of view, the cell membrane can be considered as a transmission line. There is capacitance and resistance distributed along the membrane, and current flow across the membrane is produced by the transfer of sodium, potassium, and calcium ions. In the resting state, most membranes are charged to a level of 90 millivolts with the inside of the membrane being negative (31,32). This charge is maintained by active metabolic processes in the membrane which sustain a concentration gradient of charged particles (ions) across the membrane. The difference

in concentration of charged particles across the membrane produces a potential difference which provides normal membrane function. For a membrane to be activated, an electrical impulse must occur that raises the resting potential from minus 90 millivolts to a threshold potential of smaller value usually on the order of minus 60 millivolts.

Upon depolarization of the membrane to this level, a regenerative or self-sustaining process occurs which allows rapid depolarization of the membrane to zero potential or above (31). This regenerative process involves the flow of sodium ions across the membrane into the cell, and, once underway, is opposed by the flow of potassium ions across the membrane in the opposite direction (27). Thus, upon initial depolarization to threshold level, the membrane will rapidly and spontaneously depolarize a slightly positive potential, and generate an electrical impulse called an action potential which will propagate along the membrane as though the membrane were an electrical transmission line. Currents flowing through tissues as a result of contact with an outside electrical source, such as in an electric shock incident, will depolarize cell membranes to an above-threshold level and allow an action potential to be propagated, producing an abnormal activation of cell function. In the case of neurologic tissue, the cell propagates an action potential, and produces the sensation of pain or some other sensory perception.

Low levels of electric current flowing through skin and muscle are known to produce sensations of warmth and tingling (5,6,15). These sensations represent stimulation, by extraneous stray currents, of nerve fibers in the region of entrance of the current pathway into the body. The response of these nerve cells is interpreted by the brain as some familiar sensation. In the case of skeletal muscle, stray current entering the muscle tissue produces depolarization of the muscle cell membrane and activates the skeletal muscle to contract. When this occurs the response is an uncontrolled contraction of the muscle. In the heart, electrical stimulation will also produce uncontrolled contraction which compromises cardiac function, and ultimately disorganized contraction of the heart muscle (ventricular fibrillation) will occur. Figure 13 outlines the potentials present in the cell membrane and indicates the level of threshold at which depolarization will produce an action potential which subsequently activates the entire cell.

The frequency of stimulation is of interest in the context of electric shock problems. It is known that skeletal muscle and nerve cell membranes will respond to different frequencies of stimulation with different responses. Figure 14 shows the relationship of frequency and pulse intensity needed for production of an action potential by the cell membrane. This figure indicates that pulses of short duration require very high intensities to activate the cell, whereas pulses of longer duration require lower intensity. This relationship indicates that high-frequency pulses will not depolarize the cell membrane. Since they are of sufficiently

short duration, they will not persist for a long enough time to produce a shift of cell membrane potential to threshold.

Figure 15 indicates the responses of skeletal muscle to repetitive stimuli in the low-frequency range. One may note that as the frequency of stimulation increases, relaxation between stimuli disappears and ultimately the muscle attains a state of continuous contraction which produces a more forceful sustained contraction than any single stimulus can produce. This phenomenon in skeletal muscle is called tetanus, and for a normal skeletal muscle, the frequency range for production of tetanus lies between 30 and 60 Hertz. The curve presented by Dalziel (5,6) of the effect of stimulus frequency on electric shock response (Figure 16) can be explained on the basis of the tetanus phenomenon (Figure 14). Note from Dalziel's data that the frequency which produces maximum effect lies between 30 and 100 Hertz. Above 100 Hertz, larger potentials are needed to produce electric shock effects, and below 30 Hertz a similar increase in the intensity of the current is required to produce equivalent shock effects.

The preceding discussion concerning cellular response to various frequencies of stimulation provides a basis for understanding of the alterations in skeletal muscle response to frequency of the shocking current.

#### Direct Current Effects

Explanation of direct current effects on skeletal muscle, heart, and neurologic function is more difficult. Continuous depolarization of cell membrane, such as would occur with a DC electric shock, produces alterations in ionic flow across the membrane. Continuous depolarization of the membrane activates calcium in the cell, and in the case of cardiac muscle produces a flow of calcium ions, across the cell membrane to the intracellular media (13,27). Present evidence indicates that the calcium ion is necessary for skeletal and cardiac muscle contraction (4,27,30). Thus, continuous discharge of the cell membrane of skeletal and cardiac muscle produces a continuous activation of the contractile apparatus of the cell. With continuous depolarization, the excess free calcium produces a sustained contracture of skeletal muscle.

In the case of cardiac muscle, excess free calcium available to the contractile mechanism due to DC current, will produce sustained contractures. Because muscle cell contracture requires total depolarization of the cell membrane (to a positive value), the DC current to skeletal muscle from an electric shock would need to be of greater magnitude than in the AC case, since alternating current only requires the shift of the membrane to a threshold level (-60 MV) rather than a depolarization to above 0. The voltage shift from resting to threshold potential for AC would be 1/3 to 1/5 of the voltage shift needed to produce the complete depolarization necessary in the DC case. Thus, alternating currents should be three to five times more effective in producing electric shock response than direct currents.

This consideration agrees well with the data of Dalziel, who found a seven to one effectiveness ratio between alternating and direct current (7).

A report presented recently (14) suggested that electric shock produces cellular damage which may be of long duration. Jones *et al.* (14) reported that DC shocks sufficient to produce muscle contracture altered intracellular structure producing disorganization of contractile apparatus and disappearance of mitochondria (small cellular particles which provide energy to the cell). They postulated that the changes could be due to massive infusion of calcium into the cell as a consequence of the depolarizing current flow across the cell membrane.

#### Electrically-Induced Tissue Burns

Electrical current flowing through a resistive medium will dissipate power as heat. The amount of heat is a function of both resistance and current. Heating effects can occur with any frequency, and alterations of tissue function which occur are due to actual burning or coagulation of tissue by excess heat. In serious, severe, high-voltage electric shock, burns are common (8,10,28). These are often fatal, and are associated with severe deep tissue damage noted in the region of entrance and exit of the electrical current from the body. In individuals who sustain electrical burns without death from electrocution, the electrical burns are usually deep and slow healing. These burns can follow complex pathways through extremities or other tissue masses and may produce infections deep in tissues in irregular patterns which follow the current path through the body. The heating effects of electrical current have been reported to produce cataracts in the eyes in several cases (10).

A second mechanism producing electrical burns involves electro-chemical changes induced by the current flow through an electrolyte solution. This effect requires direct current or rectification of alternating current, and has been reported in hospital operating rooms where sodium chloride solutions are used to provide conduction between electrodes and patient's skin for electrocautery during surgery (2,16). A chemical reaction occurs at the cathode where sodium chloride reacts with water to produce sodium hydroxide, a strong alkali, produces chemical tissue burns. This effect has been reported with voltages as low as 10 to 14 volts DC (15). Although this electro-chemical phenomenon might be considered in underwater DC welding in sea water, the large volume of dilution available for any sodium hydroxide that is produced would produce negligible concentrations. Because of this large dilution factor, any sodium hydroxide formed at the cathode would be unlikely to produce burns during underwater welding.

In the report concerning alkali burns in a hospital operating room, an important secondary effect was a reduction in skin resistance which allowed current to enter the body more readily due to the more conductive current pathways through the

skin. The resultant higher current flow will produce more severe electric shock effects.

#### Oxygen Burns

Divers interviewed by the Navy Coastal Systems Laboratory (NCSL) survey team (18) have reported burns around the hands when using oxyarc cutting techniques. These burns are due to small oxygen-induced flashes which propagate from around the arc through defects in diving gloves. These thermal burns can produce significant skin injury around the hands, and can be avoided by use of gloves without holes or leaks when welding or cutting with oxyarc.

#### Dental Problems in Underwater Welding

Divers involved in underwater electric arc use report loose tooth fillings which require replacement after prolonged exposure to underwater welding and cutting. The NCSL survey (18) indicated that one-third of the divers involved in underwater cutting and welding experience tooth problems which required replacement of fillings. Most divers engaged in underwater welding and cutting report a metallic taste in their mouth during the time current is on, especially with use of the wet suit and face mask. The nature of this sensation is obscure. Several mechanisms are possible. (A) An electrolytic process may occur between filling and the surrounding saline solution in the mouth (saliva). The electrolytic process, induced by stray currents flowing through the diver's mouth, if of sufficient intensity, will cause migration of metal from filling into the aqueous medium of the mouth, ultimately reducing filling size and producing loose or lost fillings. In addition, a metallic taste will occur because of metal ions in solution in the saliva. Electrolytic erosion of metals is observed in many metallic structures which carry stray current. Corrosion is a significant problem where stray currents leave the metallic structure to enter the surrounding medium (earth or water). At this location significant amounts of metal are removed. There is no clear evidence that an electrolytic process is occurring in the mouth, however, and studies directed toward obtaining further insight into this phenomenon would be of value. (B) It is possible that arc-generated radio frequency fields, which are common in welding, are rectified at the filling tooth junction and produce DC currents which result in electrolysis of the tooth filling. Tooth fillings can act as radio-frequency rectifiers (radio receivers) and produce audio signals, probably from piezoelectric effect. Although a mechanism of this type can be postulated, the magnitude of radio frequency fields generated by the electric arc is small and their effects on tooth structure are questionable.

Although other mechanisms are possible, it is more likely that an electrolytic process occurs in the mouth during underwater welding and cutting. Documentation of this process might be possible by measuring the concentration of metallic ions found in the saliva during exposure to underwater electric fields, or



by repeated dental examinations during actual work exposure. No clear solution to this problem is evident. Many divers report that it is necessary to consult a dentist for correction of loose fillings at regular intervals when employed extensively in underwater welding or cutting operations.

Personal conversation with several underwater welders concerning dental problems revealed the following:

(A) A metallic taste in the mouth frequently occurs when using electric arc equipment underwater, especially when mask and wet-suit dress are used.

(B) After long exposures (hours) to continuous underwater electric areas, a dark film may form over the teeth and gums (one diver).

(C) Frequent replacement of tooth fillings is necessary when exposure to underwater electric arc is high.

One diver with extensive dental problems gave permission for his dentist to provide his clinical record. The dentist's summary made the following points:

1 - No filling erosion was seen.

2 - There were many large fillings which had fractured and needed replacement.

3 - Enamel erosion was present, but was considered to be due to poor brushing techniques (a common problem), and normal wear with age.

4 - Dental hygiene was not adequate.

Personal examination of several other divers extensively exposed to underwater electric arcs, failed to reveal serious dental problems. These divers practiced good dental hygiene. These data suggest the following observations which require further documentation for proof:

(A) Dental hygiene may be important in reducing electric field effects.

(B) Large fillings which are ordinarily prone to fracturing due to poor structural support may be especially susceptible to welding damage because of the large mass of metal.

(C) Enamel erosion is due to many causes, and underwater electric arc exposure probably contributes little to the total erosion which occurs over a lifetime.

(D) Data on diver's habits of gritting or grinding their teeth while in a diving helmet may be useful since this habit tends to produce filling fracture and excess wear of filling contact surfaces.

#### Electric Shock and the Underwater Environment

The introduction made note of the fact that the preceding data on electric shock effects for the most part have been derived from dry-surface conditions. The extrapolation of these data to the underwater environment is difficult and limits the ability to interpret dry-surface data in relationship to problems of underwater electrical safety. A major consideration in extrapolating the dry data to diving is the fact that the

diver in sea water is immersed in a continuous medium which has significant electrical conductivity. Sea water is more conductive than the diver in a wet or dry dress (3,11,12). The conductivity relationship suggests that the diver in sea water may have less risk than his counterpart on dry land or in fresh water since electric fields produced in sea water would tend to flow around the diver and follow the path of least resistance through the water. The report from the Naval Coastal Systems Laboratory (18) indicates that electric shock hazards in divers totally immersed are less serious and less frequent than partially-immersed divers. These data strengthen the concept that total immersion in a conductive medium is protective to the diver exposed to electric fields.

Although fresh water is a reasonably poor conductor, it still is a better conductor than air, and a diver immersed in fresh water may gain some degree of protection by being immersed in a volume conductor. If the diver is totally clothed in diving dress which has a reasonable amount of resistance, the surrounding medium, even if fresh water, will be more conductive than the diver and his dress combined, and will provide protection from currents flowing through the diver. The study by Hackman, *et al.* (11), demonstrated the value of diving dress in providing additional electrical insulation. Both wet and dry dress afford protection from electric shock, but dry dress is most efficient. Experienced commercial divers also state that shocks are less frequent in dry dress.

A report from the Los Angeles, California, coroner's office described a fatal electrocution from an electric field present in water. A teenage boy was swimming in a marina when he suddenly gasped and sank underwater. He was found drowned in the area where he sank. Upon investigation it was found that significant 60 Hz AC voltage was present in the water where the individual drowned. The electric field in the water was of sufficient magnitude to produce respiratory paralysis from electric shock. The coroner's report postulated that the victim drowned because the electric current passing through his chest produced respiratory arrest with subsequent drowning. The experience of commercial underwater welders suggests that even minimum diving dress provides reasonable protection from electric shock. There are reports of divers in warm-water environments working only in bathing trunks (18). No serious or fatal shocks occurred although divers usually report more frequent shocks. The study by Hackman and others (11) showed that sea water does indeed provide a lower resistance pathway for electrical current. Their study also indicated that electrical fields generated during welding or cutting in sea water would not be high enough to produce detectable electric shock sensations. This concept is valid because the electric field generated during arc operation is concentrated in a small volume where the electrode is in proximity to the metal to be welded or cut.

In further studies by Hackman, *et al.* (11), it was found that an electric field in water may be of significant magnitude to produce electric shock in humans. They found that a field of

2 volts per foot in salt water could produce paralysis of a diver's leg when immersed in the field, and a field strength of 0.2 volts per foot would produce a chest current flow of 5 ma. It was suggested that higher field strengths would produce proportionally increased current flow across the chest. When a significant field is present in either sea or fresh water, it must be assumed that lethal currents can pass through the human body. The most dangerous situation for producing electric shock in or near water is when the individual is only partly submerged. In swimming pools, for example, it is possible to have the water in the pool above ground potential because of a faulty electrical fixture. This situation is known to occur and has been considered in the design of swimming pool electrical equipment (24). When an electric field is present in a pool, an individual in the water who makes contact with a metallic object which is well grounded will complete a circuit between the higher-potential water and earth ground, and will be subject to electrocution. In these situations an individual leaving the water by contacting a ladder or other metallic poolside hardware risks electrocution at the time he contacts the metallic objects.

Similar situations will occur when divers or welders are working in tidal zones where they are partly or intermittently submerged because of tidal wash or wave action. In these situations the same type of circuit as in the swimming pool example may occur. In this situation the water is the earth ground and the diver or welder carrying an electrode above earth ground becomes part of the circuit. When the diver becomes part of the electrical circuit, he will be subjected to serious electric shock or electrocution. The study by Smoot and Bentel (24) on swimming pool safety design indicated that an individual standing knee high in water with an electric field of 2-2.5 volts per foot experiences paralysis of both legs.

These data are in agreement with the data of Hackman, et al., that approximately 2 volts per foot electric field strength will produce paralysis of muscles immersed in water containing that field (11).

The paralyzing effects of electric shock are a significant problem in the underwater environment. It is of considerable hazard to experience electric field strengths of sufficient magnitude to produce paralysis, since loss of muscle function in an extremity would prevent the diver from functioning normally underwater and respiratory paralysis and asphyxiation is possible with high currents. One documented case of underwater electrocution is available from Navy records. This case occurred at the U.S. Navy Deep Sea Diving School in 1943 (22). A diver was training in the open-water tanks at the diving school. His dress was a Navy Mark 5 hard hat helmet and breast plate without associated diving dress. The diver was welding with 35 volt DC open-circuit equipment and had stopped, with the current turned off, to change the welding electrode. After a brief interval, the diver signaled for current to be turned on. At the time the switch was closed, no arc was seen. The diver fell forward and there was no response to the topside tenders' signal. The diver was pulled out of the water unconscious, not breathing, and resuscitation was unsuccess-

ful. After a detailed inquiry, it was felt that this was a case of electrocution, where the diver became part of the current path between the electrode and the metal frame of the work, which was grounded.

#### Diver Dress and Electrical Safety

Although Navy regulations limit diving dress for cutting and welding, there is a wide range of diver dress actually used in underwater cutting and welding in fleet operations, and in commercial activities, no dress regulations are provided. Diving dress can range from full Mark V hard hat standard Navy dress to a makeshift dress consisting of bathing trunks, galoshes, and cotton gloves worn over rubber household gloves. The survey of commercial diving practices by NCSL (18) suggests that this wide spectrum of dress is indeed in use and the exact dress depends on climate and underwater environment. The U.S. Navy Underwater Cutting and Welding Manual (26) contains detailed instructions concerning the diving dress which is to be used with welding and cutting in the fleet. It states that the diver must be fully clothed in diving dress, that the Navy Deep Sea diving dress is suitable for welding, provided it does not leak, and the diver's head should be insulated from the copper helmet by wearing a wool-en cap. It also suggests that the exhaust chin button be insulated with rubber tape to protect the diver from electric shock at that point.

Detailed and complex instructions are given for use of wet-suit diving dress in underwater welding and cutting. These instructions are so complex as to be impractical in actual use. In the study by Bridge and co-workers (3), it was found that a single compression of a wet suit to 250 psi gage pressure did not alter electrical resistance in neoprene. However, when subsequent compression cycles were executed, the neoprene showed a significant irreversible reduction in electrical resistance. These investigators felt that repeated cycling of the wet suit irreversibly destroyed the electrical resistance of the material. When compressed in a dry environment, this did not occur. Their study also showed that a diver using 3/16-inch wet suit gloves and 3/16-wet suit boots would develop sensations of electrical current passing through his hands when contacting a 20 to 30-volt potential by the gloved hand. This did not occur with the Navy standard Mark V dress. These investigators stressed the importance of the integrity of the diving dress. There should be no leaks where electric current can find a path to the diver.

From these studies, the following conclusions were made:

- (A) Resistance of a wet-suit dress was variable, depending on the amount of air trapped between the wet suit and the diver's skin.
- (B) The dry suit, or the standard Mark V Navy dress, had a variable resistance depending on the amount of inflation of the total suit. When the suit was highly inflated there was a higher resistance than when the suit was minimally inflated or deflated to the point where it was in contact with the diver's skin.
- (C) Touching the exhaust button on the hard hat helmet had little effect on the total overall resistance. Thus contact with the exhaust button

is not a major determinant of conductivity between the diving dress, the outside environment, and the diver. (D) All the wet suit material studied was found to have a significant degradation in electrical resistance when the material was compressed to 250 psi in sea water. This did not return to pre-compression values, but instead returned to values lower than the initial resistance.

The aforementioned conclusions from the study by Bridge and co-workers (3) were used to develop guidelines for welding and cutting using wet suits in the U.S. Navy. Extrapolation of the data derived from 250 psi divers (560 feet of sea water) to the shallow-working diver are probably not justified. In addition, degradation of electrical resistance in wet suits after compression does not constitute a major electric shock hazard. The lower values of suit resistance (2,000 ohms) that they found after cycling the suit material under pressure is still adequate for electrical protection in most cases. The major hazard in wet suit use is inadequate electrical insulation around the hands due to inadequate or leaky gloves. To determine the conditions when a wet suit can be used for welding or cutting underwater, studies are needed which simulate operations which most frequently are done in wet suits. Thus studies at shallow depths with full and partial face mask, and with and without neoprene gloves, should be done to determine the limits of wet suit dress in underwater cutting and welding.

The NCSL survey (18) confirmed that a variety of diving dress is used during welding and cutting operations underwater by commercial divers. Wet suits are used frequently, and without regard to the history of their previous use. In discussing diving dress for welding and cutting with most commercial divers and diving companies, it was evident that the absence of leaks, especially in and around the hands, was of significance in shock protection. When using surface-supplied, helmet-equipped diving dress, no attempt is made to insulate internal metal fittings or to prevent contact of the head or face with the inside of the diving helmet. Holes in gloves were said to produce oxygen burns during oxygen-arc cutting. In this case, gases released from the arc underwater find their way into the holes in the gloves and produce small thermal burns. Use of gloves with holes or leaks also increases the incidence of electric shock when welding or cutting under water.

In summary, when care is taken to prevent leaks, the diving dress appears to be of secondary importance in the safety of the diver during welding. Wet suits have been used many times with a small increase in the incidence of electric shock, but no record of serious shock problems. Well insulated gloves and a non-leaky suit are of importance. Small leaks in and around the glove increase the incidence of electric shock and oxygen-induced thermal burns. With present commercial diving-dress practices, however, there are a significant number of electric shocks of minor degree. Many of the shocks mentioned by the commercial divers are of low magnitude, usually representing a mild sensation which is expected at the initiation and disruption of the welding arc. Few divers know of or have experienced serious shocks which caused them to

stop work or to be hospitalized, yet most say that they have experienced significant shocks at one time or another during their diving careers. A universal complaint was the increased incidence of shock when working in a splash zone. Most commercial divers have used dress ranging from dry, surface supplied, to bathing suit and scuba in a splash zone. This appears to be a valid complaint, since when working in splash zones where a diver may be totally submerged at one instant and partially submerged at another, there are times when the protection of the surrounding conductive medium of the water is lost and the diver constitutes a major pathway for return of electrical current from the electrode to the ground.

No evidence for excess precautionary procedures or changes in dress for the topside tenders was mentioned. The Navy Underwater Cutting and Welding Manual (26) suggests that topside tenders wear gloves and that generating machines for welding operations be mounted on a dry wooden mat or other insulating material and not rested directly on a metal deck.

### Equipment Considerations for the Underwater Environment

#### Underwater Welding and Cutting

In underwater welding and cutting operations, the major equipment considerations should be directed toward protecting the diver from electric shock from the arc current. For underwater use, DC equipment is highly recommended, since 60 Hz AC is 5 to 7 times more likely to produce shock effects than DC. Other protective measures should include adequately-insulated and properly-designed electrode holders. Ground cables should be directly attached to the work. Ship grounds, using water to complete the ground circuit to the work piece, should not be used. Present technology is available to develop a current controller for welding equipment which will hold open-circuit voltage at low levels and provide high currents when contact between electrode and work has been established. Circuits of this type would reduce the hazard to the underwater welder during the time the electrode is activated, but before it is placed on the work to establish the welding arc. At the welding generator, adequate care should be provided to properly insulate welding equipment from steel decks, to eliminate hazards of cable damage from motion of heavy equipment, and to prevent the welding tender from contacting significant voltages during his normal operations.

#### Alternating Current Equipment

Considerations in this category include power to underwater lights and power tools plus high energy transmission for operation of large underwater machinery. Power circuits which supply underwater lights with single-phase 60 Hz AC should have groundfault protection to prevent a short circuit through the diver. Similar protection should be used in single-phase portable power tools which are designed for use underwater. Insulation characteristics of underwater power tools should be such that they maintain the dry internal environment of the tool and provide adequate electrical insulation, including areas of switches and hand holds. For large power delivery underwater, several labora-

tories (12,17,19) have suggested that isolation transformers be used in any three-phase operation. Transformers ideally should have a Y-connected secondary with the center tap grounded through a ground-fault detector circuit. Since the center tap of the Y-connected transformer is usually a balanced neutral (17), current flowing through this point to ground will indicate imbalance in one of the phases thus indicating a short circuit to ground. In high-voltage power transmission to underwater habitats, care should be taken to prevent cable faults in the sea. Adequate circuit breakers and ground-fault detectors again play a role in protection of the diver from electric shocks from transmission lines.

Effect	A.C.	D.C.
Ventricular Fibrillation	100 ma	500-600 ma*
Respiratory Arrest	20	120-140
Muscle Contracture	9-16	70-80
Pain	6-9	40-50
Perception	1-3	5

\* Estimated From Ratio of Other Effects

Figure 12

Approximate Current Levels for Several Electric Shock Effects from AC and DC (5,6,7,21,28)



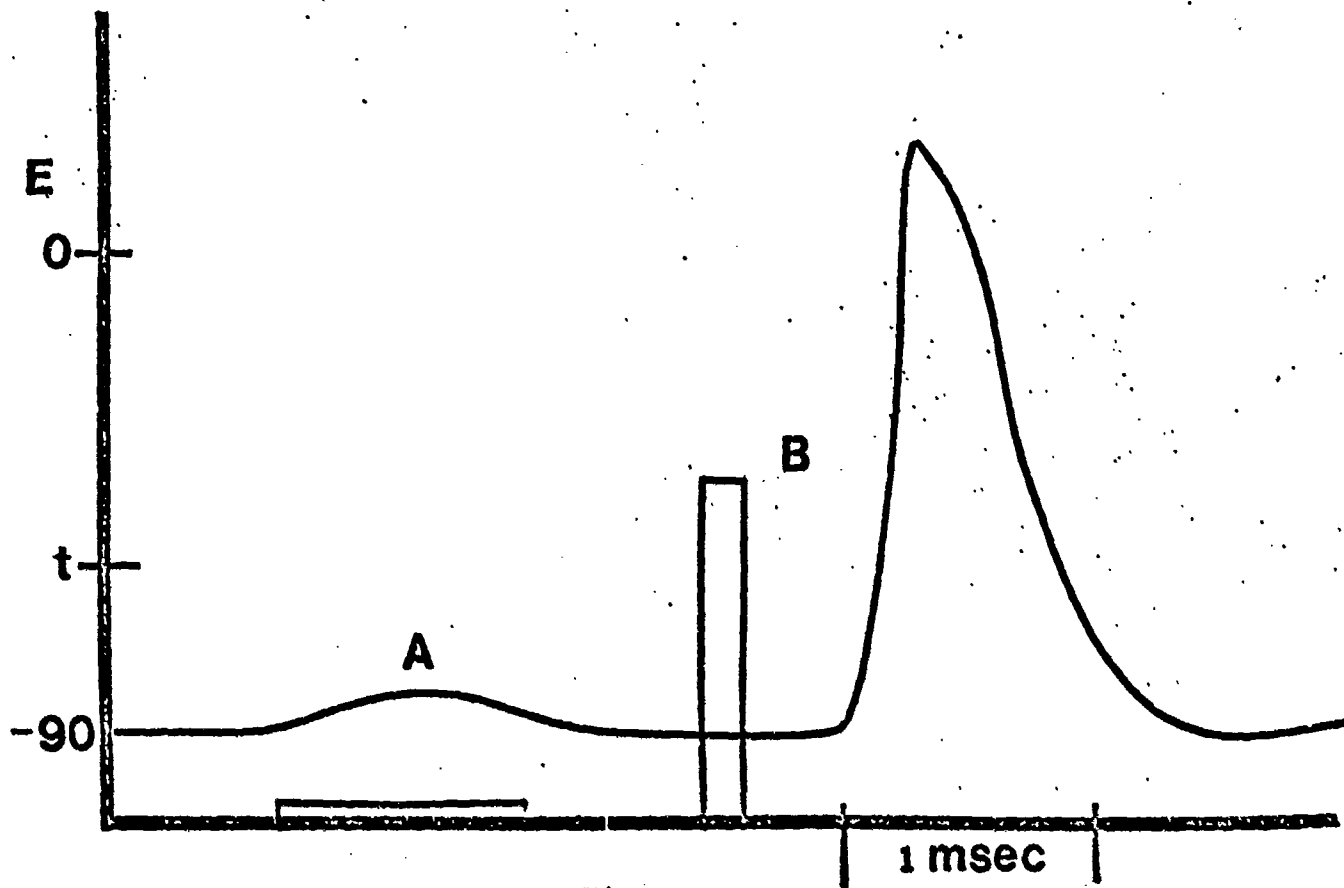


Figure 13

Electrical Activity of a Typical Nerve or Muscle Cell Membrane. E - Potential axis (MV), t - Threshold Potential. Resting Membrane Potential is -90 MV. A - Subthreshold Stimulus Produces Shift in Resting Potential But No Action Potential. B - Suprathreshold Stimulus and Action Potential Response.

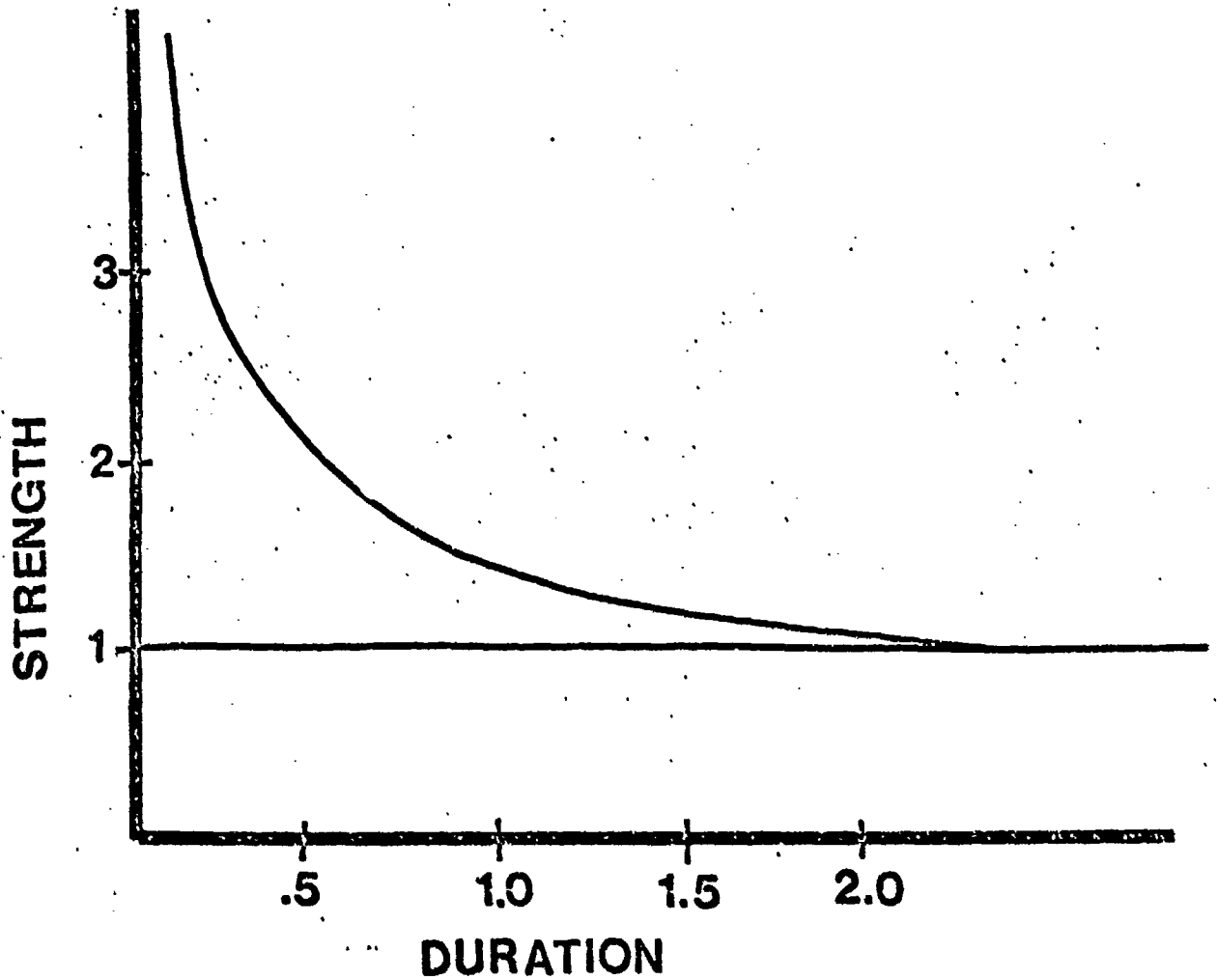



Figure 14

Strength-Duration Curve For Stimulus To Produce Membrane Activation. Strength Relative to Minimal Strength Required to Activate Membrane, Duration In Membrane Time Constants. Typical Muscle Time Constant is 35 MSEC (31)

Figure 15



Isometric tension of single muscle fiber (ordinate) as a function of time (abscissa) during continuously increasing and decreasing stimulation frequency (2 to 50 per sec.). Time intervals at top of record, 0.2 second. (From Buchthal, *Dan. Biol. Medd.*, 1942, 17(2):1-140.)  
Reproduced from Ref 32

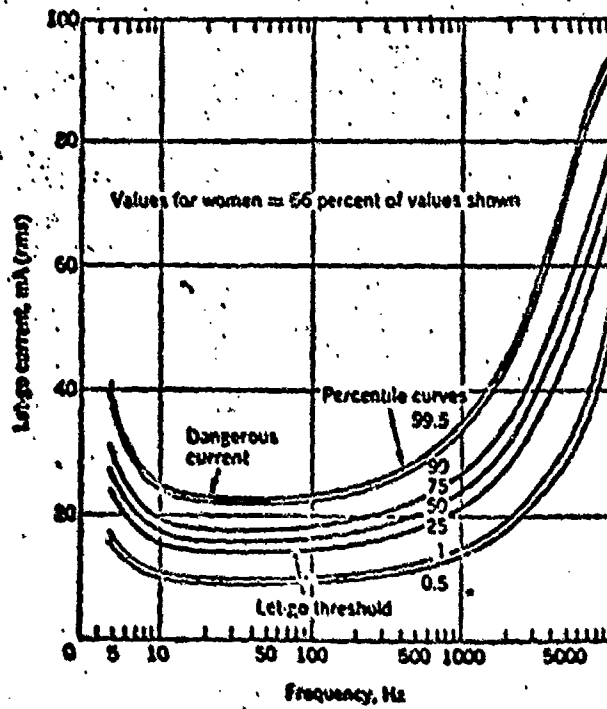


Figure 16

Let-go Current Plotted Against Frequency, From Data of Dalziel (5, 6)

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## APPENDIX C

### Review and Comments on Underwater Cutting and Welding

#### Technical Manual, NAVSHIPS 0929-000-8010

Prepared by the Panel on Underwater Electrical Safety Practices

The earliest use of oxygen-arc cutting in the United States is understood to have been associated with the salvaging of the steamship St. Paul in 1918. The torch, patented by J.W. Kirk and Ralph Chapman of the Merritt and Chapman Derrick and Wrecking Company, "utilized oxyacetylene in combination with an electric arc" and was employed at a depth of 60 feet. The Merritt firm became well known for its development of the oxygen-arc underwater cutting technique in the ensuing years, using it on numerous famous salvage jobs. The first Navy job which employed the Kirk-Chapman torch was the salvaging in 1921 of the submarine S-48 off Bridgeport, Conn.

Having kept abreast of the work of Merritt, in the late 1930's with the onset of World War II, the Navy undertook a project to further develop the technique. This project was assigned to the Navy Engineering Experimental Station at Annapolis, MD. -- now called NSRDC, Annapolis. Technical information and procedures concerning both underwater cutting and welding was developed and first disseminated to the fleet by means of Engineering Experimental Station Laboratory reports.

In 1966-67, the then Supervisor of Salvage/Diving instituted a program to update the Manual. This took the form of several projects at Battelle Memorial Institute (References 11, 13 and 24 of the basic report) and included a symposium on underwater welding, cutting and hand tools, held at Columbus, Ohio, in October 1967.

#### Manual Format:

The format of the current Manual is basically a good one and, with some minor modification, should serve well as a format for a revised manual.

#### Emergency Procedures:

In the current manual, emergency procedures are contained in the text that describe normal procedures for each cutting/welding method. It is recommended that emergency procedures be broken out from the basic text and restated in a separate section dealing only with unusual or emergency situations.

#### Obsolete Equipment:

When the Manual is rewritten, references to all obsolete equipment and procedure, such as carbon-arc (page 3-23) and Swafford-type electrodes (page 3-21), should be deleted.

Ambiguities:

Considerable confusion exists relative to the rules concerning the use of AC power because of the differences in the wording of the various paragraphs dealing with power supplied. For instance:

Page 3-2 Underwater Oxygen-Arc Cutting Equipment Power Supplies:

States - "Power supplies recommended for underwater oxygen-arc cutting are DC welding generators. AC welding power supplies are not recommended because they are not as safe as DC power supplies." The next paragraph goes on to say "AC power supplies are rarely, if ever, used for underwater oxy-arc cutting. In emergency situations, however, AC welding transformers may be used but it is mandatory that the safety measures recommended in section II be followed. Particular attention is directed to the greater hazards existing when AC power is used in underwater operations."

Page 4-3 Underwater Shielded Metal-Arc Cutting Power Supplies:

Power Supplies states - "While DC current is preferred for underwater shielded metal-arc cutting, AC may be used" -- "alternating current is also generally considered to be more hazardous from a safety point of view."

Page 6-2 Underwater Shielded Metal-Arc Welding Power Supplies

States - "In the event that a DC generator is not available, a 300 ampere AC transformer may be used, but special attention must be given to the safety rules when using AC."

Page 8-4 Parallel Connections for AC Transformer Type Power Supplies:

States - "Except in rare emergency situations, AC transformer type power supplies are not used for underwater cutting and welding operations. When AC power supplies are the only ones available and must be used, all safety regulations involved in their use must be strictly followed."

Procurement Information:

Procurement information for electric underwater cutting and welding equipment, as shown in the current Manual, is outdated and incomplete. It is shown on three separate tables: Table 3-1, page 3-3 for oxygen arc cutting; Table 4-1, page 4-2 for shielded metal arc cutting; and Table 6-1, page 6-3 for shielded metal arc welding. Prior to any rewrite of the Manual, this information should be corrected and updated.

The three procurement tables should then be cross-checked to ascertain that equipment common to all is shown identically on all tables.



Examples of present dissimilarity concerning common equipment are as follows:

Rubber gloves are shown on Tables 3-1 and 4-1, but not on Table 6-1.

A grounding clamp is listed on Table 6-3, but not listed on Tables 3-1 or 4-1.

The knife switch is listed as 300-ampere on Tables 3-1 and 4-1, but listed as only 200-ampere on Table 6-1.

It should be noted that the recommended knife switch for metallic arc cutting is listed in Table 4-1, page 4-2, as 300-ampere; however, the power supply is DC 400-ampere and the technique outlined on page 3-34 calls for 500-ampere.

Table 3-1, page 3-3, for oxygen-arc cutting calls for a 300-ampere knife switch and 300-ampere generator, but in the second paragraph, concerning cutting cast iron and nonferrous metals, on page 3-31, 500-ampere power is called for.

The list of preferred equipment and material requirements for underwater shielded metal-arc welding, Table 6-1, page 6-3, recommends a 300 ampere welding generator, but calls for a safety switch of only 200 ampere rating.

#### Page 2-6:

Next to last paragraph, 8th line down talks of a double-pole safety switch. The paragraph in the middle of page 3-6, entitled safety switches, also refers to a double-pole switch, yet the safety switches shown on the preferred equipment lists are shown as single-pole.

One approach might be that when the "preferred" equipment lists are redone, the equipment be referred to as "approved" rather than "preferred" and that each item of equipment be identified by either a Navy or a Federal Stock Number.

#### Technical Data:

Considerable error is believed to exist in the cutting rates shown in Figure 3-11, page 3-23.

Some of the information used in Figure 3-11 is dated December 11, 1940.

When the information is up-dated, the cutting rates should reflect operational, rather than laboratory conditions. These data could then also be used to verify or update the information presented in Table 3-3, page 3-25, concerning material consumption and procurement.

### Duplication:

Considerable duplication exists simply because much of the equipment is common to both types of underwater electric cutting and also to underwater welding. For sake of reference, the safety switch is covered on page 3-6, page 4-4, and again on page 6-2.

Similarly, power cables are described on pages 3-6 to 3-8 and again on pages 4-3 and 4-4, and once again on page 6-4.

In the interest of brevity, "common" equipment might be described fully in section III and the description be merely referred to in the other sections.

The procedure concerning the determination of the polarity of the DC generator as contained at the bottom of page 3-2 and the top of page 3-6, is duplicated almost verbatim under figure 3-2 on page 3-7.

It should be noted that the manner in which Table 3-1, page 3-3, and Figure 3-1, page 3-5, were inserted into the text somewhat confuses the polarity-determination instructions that start at the bottom of page 3-2, in that they jump to the top of page 3-6.

### Vague Wording:

The Navy Manual contains many loosely-worded statements that read correctly, but are somewhat meaningless to the average reader.

#### For Example:

- I. Page 2-3, paragraph 2. "Only approved electric welding machines and accessories that have been tested and found to conform to the applicable Navy Department specifications shall be used."

A casual reader might skip over the sentence; however, a curious reader might ask:

- A. Is there a list of approved machines?
- B. Where might I find this list so as to be sure my machine is on it?
- C. Is there a list of "approved" accessories?
- D. What accessories are included?
- E. Who is to do the testing and designation of the conformance?
- F. What are the applicable specifications?

Another example of loose-wording is on page 2-4, last sentence, paragraph 1. "only approved apparatus that has been examined and tested and proved safe in so far as is practicable shall be used."

When reading this sentence one must wonder the meaning of

"in so far as practicable." This phrase is repeated many times in the Manual.

During any rewrite of the Manual, a diligent effort should be made to try to tighten up any and all loose phrases and sentences.

#### Typographical Errors:

It is believed that the designation Mil-C-915, type TXRF, for welding cables shown on Table 3-1, page 3-3, should read TRXF.

Figure 3-3, page 3-10, the top line on the graph should read Size 1/0 (105,000 cir mils).

Under parallel connections for DC power supplies, page 8-1, fourth line, fifth paragraph states: "A single pole double-throw unfused safety switch is suitable." This should read "A double-pole, single-throw, unfused safety switch is suitable."

Figure 8-1, page 8-2--it should be noted that this schematic drawing of parallel generators does not show a knife switch in the cutting/welding circuit.

Page 8-5, fourth line, paragraph C--"In this event, make the primary cables, etc." - this should be changed to read - "in this event, mark the primary cables."

#### Wet Suit:

What is believed to be a typographical omission exists in one of the rules concerning the use of the wet suit. This has caused considerable confusion among fleet diving activities.

Rule 4.b, bottom of page 2-10, states: "Repetitive surface supported dives with the same wet suit must be limited to 50 feet, and more importantly, the wet suit must not have been previously compressed wet below 50 feet."

Rule 4.c, top of page 2-11, goes on to say:

"It is permissible to make one dive and perform arc cutting or welding operations in a wet suit only if the wet suit used has never been previously compressed wet to below 50 feet."

After reading rule 4.b concerning repetitive dives, rule 4.c concerning one dive makes little sense.

These rules were based on recommendations contained in the final report of "Comparative Insulation Study of Wet Suits and Standard Navy Deep Sea Diving Dress for Underwater Welding" by the Battelle Memorial Institute Columbus Laboratories dated March 12, 1969. (Reference 21 in basic report)

Recommendation (1) from page 5 of the Battelle report is quoted as follows:

" (1) Repetitive surface-supported welding dives with the same wet suit should be limited to 50 feet and, more importantly, the wet suit used must not have been previously compressed wet to below 50 feet. It is, however, permissible to make one dive to any depth and weld in a wet suit as long as the wet suit used had never been previously compressed wet to below 50 feet. Alternatively, repetitive welding dives can be made using the same wet suit if the wet suit was compressed dry prior to immersion and was virgin initially, e.g., operation from a PTC or equivalent. Apparently "to any depth" was inadvertently dropped when the recommendation was transposed into rule 4.c.

If the words "to any depth" were to be inserted between the words dive and and in the first line of rule 4.c, much of the confusion could be eliminated.

#### Sample Additions to the Manual:

##### Communications:

The paragraph starting at the bottom of page 2-6 concerning diver/tender voice communications might be strengthened to make voice communications absolutely mandatory.

##### First Aid:

A new part might be included in Section II that would describe in great detail the current, proper first aid to be administered to a victim of an electrical shock accident.

A new sentence as part of Section III, which fully describes how and where to properly attach the ground lead, is desirable.

##### New Equipment:

Any change or revision to the Manual should reflect new equipment, such as the relatively new "Sea Cutter" oxygen-arc cutting torch.

##### Splash Zone:

It is believed that the most hazardous location that the diver can be placed in concerning electrical shock is one where he is required to cut or weld in a "splash zone" where he is only partially immersed.

A sub-section warning of this hazard might well be contained in the safety section of the Manual.

APPENDIX D

Survey

of

Commercial Practices in Underwater Electric Arc

Cutting and Welding

Prepared by

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July 1974

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#### ADMINISTRATIVE INFORMATION

The information presented herein was acquired by a survey team convened by the Office of Naval Research. The team was composed of Denzil Pauli, Head, Code 485, who served as team leader; Charles Schilling, Captain, Medical Corps, U.S. Navy (Retired), Secretary, Undersea Medical Society; William Culpepper and the author, Naval Coastal Systems Laboratory (NCSL). The NCSL portion of the effort was funded under ONR Work Request 4-0253 and this included both the preparation of this summary of the team findings and participation in the team activities.

SURVEY  
OF  
COMMERCIAL PRACTICES IN UNDERWATER ELECTRIC ARC  
CUTTING AND WELDING

INTRODUCTION

Underwater electric arc techniques have been used successfully by commercial diving operators for many years. Until recently, these procedures were considered unsafe for Navy divers except in hard-hat diving dress. The latest Navy regulations permit the use of a wet suit in good condition which has never been compressed wet to below 50 feet. A new wet suit may also be used for repetitive dives if compressed dry prior to use. These dress restrictions severely limit the capability of Navy divers and should be modified if the hazard can be shown to be overestimated. This report summarizes the results of a survey of commercial practices, and an attempt is made to relate the electroshock incidents reported to the physiological effects of electric current on the human body described in the literature (see Bibliography).

RESULTS OF THE SURVEY

A survey team representing the Navy visited eight commercial diving organizations to elicit information on underwater electric arc cutting and welding. Discussion areas included: equipment used, grounding practice, welding and cutting techniques, diver qualifications and training, diver reactions, safety practices, and accidents resulting in injury or death from the electric current. A summary of the survey is presented in Table VII.

In an attempt to correlate the survey findings, a letter grade was assigned to each company in the areas believed relevant to protection of the diver from electroshock. The grades were averaged so that each company visited was assigned an overall grade intended to represent the degree to which their procedures were oriented toward electroshock safety. The grades obtained, together with numbers representing relative shock frequency and number of divers, are presented in Figure 17. A code number was assigned to each organization visited to conceal its identity. A substantial correlation was evident between the letter grade and relative number of divers; however, no apparent correlation was obtained with relative shock frequency.

It was found that all divers using underwater electric welding and cutting equipment experience shocks, but no incidents of injuries requiring treatment were reported and no organization contacted had even heard of such an incident. Several incidents of direct contact were reported. In one, the welding electrode was in contact with the diver's leg while he was grasping the side of a grounded barge when the tender misunderstood a shouted comment and activated the welding circuit. The diver experienced a strong shock, but, aside from a small wound where the electrode contacted the leg, the diver was unharmed and continued working after additional instructions to his tender.

Many of the divers interviewed stated that they could always tell when the current was on by a tingling sensation in the face. They also agreed that each time the current was switched on, a sensation was experienced. Minor shocks were experienced 30 to 60 percent of the time and severe shocks were experienced up to 10 percent of the time, at arc initiation.

Table VII: Summary of Commercial Underwater Cutting/Welding Practice

- Current Sources: Primarily Lincoln 300-600A, diesel-powered generators; dc only.
- Grounding Practice: Mainly bond to workpiece; some barge (salt water) grounding.
- Work Platforms: Drilling platforms, barges, PTCs.
- Current Control: Tender-operated knife switch actuated upon diver command.
- Fresh vs. Salt Water: Same procedures used.
- Diver Dress: Mostly ordinary wet suits, some coveralls; reports of work in bathing suits.
- Diver Gloves: Mostly Playtex (rubber) gloves with cotton or heavy rubber overgloves. Holes in gloves lead to increased shocks and O<sub>2</sub> burns.
- Diver Footgear: Mostly wet suit booties with rubber boots or swim fins.
- Diver Helmet: Most prefer helmets; some use face mask. Some scuba used but generally avoided. No attempt made to insulate internal metal fittings.
- Welding Lenses: Some use in clear water, others never use. Usually, arc cannot be seen.



- Diver Training: Most new divers come from commercial schools and tend for 1/2 to 2 years before fully qualified. Some formal training in arc work. Most have training tank for training and practice.
  - Diver Shock: All divers using underwater arc experience shocks. Considered part of job. No problems with diver apprehension. Divers like to cut. Bad grounds, bad connections, work in splash zone, and holes in gloves primary causes cited for excessive shocks.
  - Dental Effects: All report metallic taste during arc operations. One-third report loose fillings.
  - Safety Programs: Mostly informal. Safety responsibility of supervisor or diver. Do not consider work dangerous.
  - Accident Experience: None had ever experienced or heard of a serious accident due to arc current. Consider primary hazard detonation of gases evolved by arc.
  - Underwater Cutting: Total cutting time in U.S. estimated to be 8,000 to 15,000 hours per year (estimated from production of cutting electrodes). Very little welding is done.
- 

## DISCUSSION

A diver immersed in a conductive medium in the presence of an electric field can be most easily visualized by contemplating two rather different situations. In one case, the medium is substantially more conductive than the diver's body fluids, i.e., salt water; in the other, the medium is less conductive, which is the fresh water case. It should be recognized that some so-called fresh water may have an ionic content sufficiently high to fall into the "salt water" category although sodium chloride may not be a major constituent.

### Salt Water

In the case of a conductive medium, the medium itself acts to shunt the current around the diver's body, thus reducing the current flow through the tissue. Numerous investigators have shown that the physiological effects of electricity are due solely to the current flowing in the tissue and are not affected by the voltage, per se.

### Fresh Water

In fresh water with high resistivity, the situation is exactly the opposite that of salt water. The current will tend to flow through the diver's body instead of through the water. However,

Figure 17. Survey Summary

Area of Comparison	Company Code								
	1	2	3	4	5	6	7	8	9
Diver Suit	E	A	E	B	D	D	E	E	B
Diver Gloves	B	C	B	C	B	B	B	B	A
Diver Helmet	F	A	A	A	A	D	C	F	A
Diver Foot Gear	F	B	F	B	B	A	B	D	A
Grounding Practice	B	A	D	A	F	C	D	B	A
Use of Ground Fault Devices	F	B	A	C	F	F	F	F	C
Safety Program	E	A	E	D	C	B	E	E	E
Training Program	F	A	C	A	E	B	F	F	D
Average	E	B+	D+	C+	D	C	E+	E+	C+
Relative Number of Divers	2	6	4	5	3	3	1	2	6
Relative Shock Frequency	3	1	5	3	5	2	2	1	4

Rating System: A - Most electroshock safety oriented.

B - Least electroshock safety oriented.

unless the diver is quite close to, and between the electrode and the ground, the poorly conducting water will limit the magnitude of the current to a very low value, typically 1/500 of the salt water current. This may be the reason that none of the firms contacted used different procedures for the two situations. When asked whether more shocks were encountered in fresh or salt water, the reply was that they occurred in about equal numbers.

### Surf Zone

A rather interesting fact learned during the survey was that a welder working where he was occasionally immersed in salt water experienced a great deal more electroshock than in any other situation. Apparently, work on piers and breakwaters where he can be wet down by spray or waves from a passing boat, is much more conducive to severe shocks than when submerged.

A possible explanation for this can be found in the physiological response to electric current, particularly in air. As the AC current is increased from sensation threshold (approximately 0.2 ma), a point is reached where sufficient muscular spasm is produced so that the subject cannot let go of the electrode. This is defined as the "let-go current" and is approximately 15 ma. In the DC situation, which includes all of the welding and cutting of interest, the physiological effects are quite different. The sensation threshold is approximately five times greater than the AC case and no muscular spasms occur. The current the subject can withstand is limited only by his willingness to let go of the electrode, at which time he receives jolts of increasing severity. During the time a steady current is flowing, the sensation is not particularly painful. The DC equivalent to the AC let-go current is on the order of 75 ma. If this is the correct explanation, the increased incidence of electroshock episodes reported in the surf zone can be understood.

### COMMENTS

To many people, the lack of serious injuries or fatalities experienced while using underwater electric welding and cutting equipment is surprising, since the combination of wet skin and voltage sources on land is known to be extremely hazardous. The total immersion in water appears to be a protective factor rather than the hazard it would seem at first glance. Other factors which would act to reduce the adverse effect of the electrified water are: (1) while the total current through the body may be fairly large, the current density through any particular tissue volume is quite small due to the large area, i.e., the whole skin surface, through which it flows. It is the current density at a particular receptor site which is sensed as a physiological insult. (2) It is fortunately the nature of the welding/cutting process that the distance from the electrode to the grounded work

piece must be very small to achieve the desired effect. This confines the significant electric field to a volume extending only 2 to 4 inches beyond the electrode tip and makes it difficult for the diver to insert a substantial portion of his body into the field.

#### CONCLUSIONS

1. Underwater electric cutting and welding is not particularly hazardous. Other diving hazards, such as dysbarisms, entrapment, equipment failure, and blast, have resulted in injuries and death, while no account of such incidents has been found for underwater welding and cutting in commercial practices.
2. Ordinary wet suits, rubber gloves, rubber boots, and helmets provide adequate protection. Glove integrity appears the most important.
3. Good cables and connections, proper grounding techniques, and proper diver position tend to eliminate severe (jolting) shocks.
4. The use of AC current or rectified AC current should be prohibited. Rotary DC generators designed for cutting/welding should be used exclusively.
5. Fast, efficient, underwater cutting requires adequate diver training and periodic practice to maintain skills.

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APPENDIX E

Analysis of Potential Electrical  
Shock Hazards Related to  
The NAVFAC SNOOPY Vehicle System

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Ocean Technology Department

23 October 1974

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ANALYSIS OF POTENTIAL  
ELECTRICAL SHOCK HAZARDS RELATED TO  
THE NAVFAC SNOOPY VEHICLE SYSTEM

INTRODUCTION

The NAVFAC SNOOPY is an unmanned, tethered, undersea vehicle system designed to complement divers in inspection and observation of various objects and tasks. The vehicle receives its power from the surface through the tether cable which serves also to transmit command and sensor data signals. The power and signals are multiplexed on the RG-58 coaxial cable, as shown in Figure 20. In order to minimize both cable power loss and cable diameter, the "power" voltage is made as large as practicable to achieve a low line current. The design of this system calls for a transmission voltage of 880VAC, 60 Hz, single phase and a line current of approximately 3 amperes. Potential personnel electrical shock hazards under operating conditions fall into two categories: Cable handling by shipboard personnel, and submerged diver operations with the vehicle. These situations are developed to illustrate under what conditions a hazard may exist.

HAZARDOUS CURRENTS AND ELECTRIC FIELD INTENSITY

A commonly accepted fatal current threshold is 0.10 amperes. This nominally marks the onset of heart fibrillation. However, current levels of approximately 10 to 20 milliamps (ma) can be painful and result in muscular paralysis (let-go threshold). The level of 10 ma is therefore an appropriate figure to use considering the consequences of muscular paralysis for a diver.

The problem at hand, therefore, is to determine the electric field intensity into which the human body may be introduced which will force the threshold current of 10 ma through the body. Due to the great complexity of the body in terms of shape and conductivity, it must be modelled. One simple model is an ellipsoid of uniform conductivity,  $\sigma_i = 0.2$  mhos/meter. For a "man-sized" ellipsoid with semi-major and semi-minor axes of 3 feet and 0.75 feet respectively, the smallest external electric field intensity which is required to produce the 10 ma in the submerged body can be demonstrated to be approximately 0.2 volt/meter. Since this is simply a model, this figure must be used cautiously, and considered at best a rough approximation to a real, empirical solution.

## CABLE HANDLING

During vehicle launch and recovery, and also operations, the vehicle tether cable is tended manually by a crew member. Figure 21 illustrates two possible leakage path circuits which contain the crew member's body resistance by virtue of his hand capacitively coupled to the coax shield through the jacket, or his hand in direct contact with the shield due to a nicked jacket. In each case, leakage capacitances of the isolation step-up transformer limit the leakage currents to safe levels. The 0.36 ma level is below the threshold of sensation. Therefore, excepting transformer insulation failure, the system poses no threat of electrical shock to the cable handler.

## SUBMERGED DIVER

Figure 22 illustrates two possible leakage path circuits which include the seawater volume and the diver. These circuits each contain series leakage capacitances of the step-up transformer, as before, which limit the leakage currents to negligible levels, physiologically. In these two cases, note that only one side of the high voltage circuit is directly applied to the water volume, and it is so applied by virtue of a seawater leak to one pin of the connector. A similar circuit would apply for the case of a nicked jacket and exposed shield, but only for the 880VAC circuit.

Consider now the case in which both current carrying conductors of the high voltage circuit are exposed to seawater. One form of this situation is a completely severed tether cable. As shown in Figure 23, the exposed cable conductors may be modelled by a current dipole with the indicated electric field intensity which falls off with  $r^3$ . Assuming a homogeneous medium containing no other conductors, the electric field intensity will fall to below the safe level of 0.2 volt/meter everywhere outside a 0.17 meter radius sphere centered on the exposed cable conductors. This situation will exist for as long as the cable and power supply can provide twice the nominal load current of 3 amperes. Note also that the field intensity will decrease rapidly with distances comparable to the dimensions of the diver. Also, since the power supply is fused, this electric field is not expected to exist for more than a few seconds.

Another situation in which both conductors become immersed results from a connector leak exposing the cable center conductor and, a long distance away, the shield becoming exposed by virtue of a jacket leak (nick). In Figure 24, this case may be modelled by a current monopole. Note that here the field intensity falls off with  $r^2$ . In order that the diver not encounter a dangerous field intensity, he must now remain outside a sphere of radius 0.55 meter centered at either of the two faults (one is a current



source monopole, the other a current sink monopole). This situation will exist for as long as the power supply and cable are capable of supplying twice the rated load current of 3 amperes, load current into the load plus equal amount through seawater path.

#### DESIGN CONSIDERATIONS

In contrast to the convention of employing low voltage, high current design for underwater equipment, operational requirements on small vehicles typically tend to demand the use of high voltage for tether cable power transmission. Among these forcing requirements are minimum power loss in the cable and small, neutrally buoyant cable diameter which derive from the need to reduce  $I^2R$  heating of the cable when spooled on a handling reel, and to reduce cable drag in moderate to high ocean currents.

Although fusing the power circuit would perhaps prevent long term diver exposure to inadvertent electric fields, this may not alone be considered an adequate safety measure. Indeed the bulk of the protection is provided by the isolation step-up transformer and the oil-filled pressure balanced connectors and electrical harnesses used on the vehicle. These connectors and harnesses are designed for better reliability under pressure cycling than the conventional molded connectors and cable assemblies and, as such, offer more insurance against conductor shorts to the surrounding seawater.

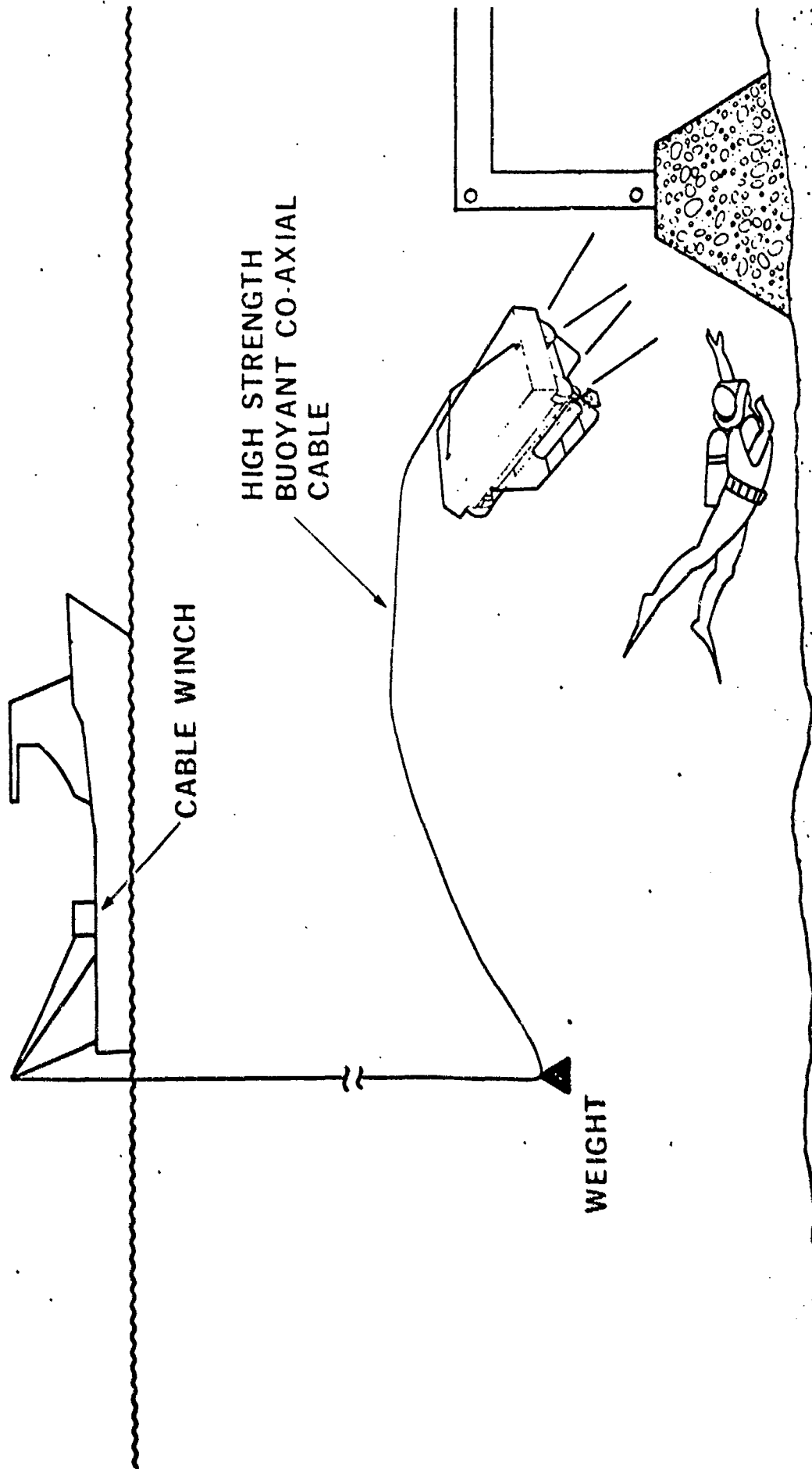
#### CONCLUSIONS

Under normal operating conditions, the NAVFAC SNOOPY Vehicle System poses no electrical shock hazard to shipboard personnel or divers. However, in the rare occurrence of the current monopole produced by widely separated immersion of both cable conductors a possible hazard will exist within 0.5 meter of such a fault. In the more probable case of a completely severed cable, the potentially hazardous region is limited to approximately 0.25 meter from the break. Some additional margin exists in these estimates in that the fields will continue to fall off with distances comparable to diver dimensions in a region free of other conductors. Such additional conductors would tend to distort the external fields resulting in larger and smaller field intensities at given distances from faults, but these are very difficult to model. Unfortunately, in problems of this complexity carefully instrumented testing is frequently prescribed to justify or replace the estimates obtained by modelling.

**NAVAC**

Figure 18:

# NAVFAC SNOOPY REMOTE UNDERWATER VEHICLE INSPECTION SYSTEM



**NSC**

Figure 19:

# NAVFAC SNOOPY VEHICLE

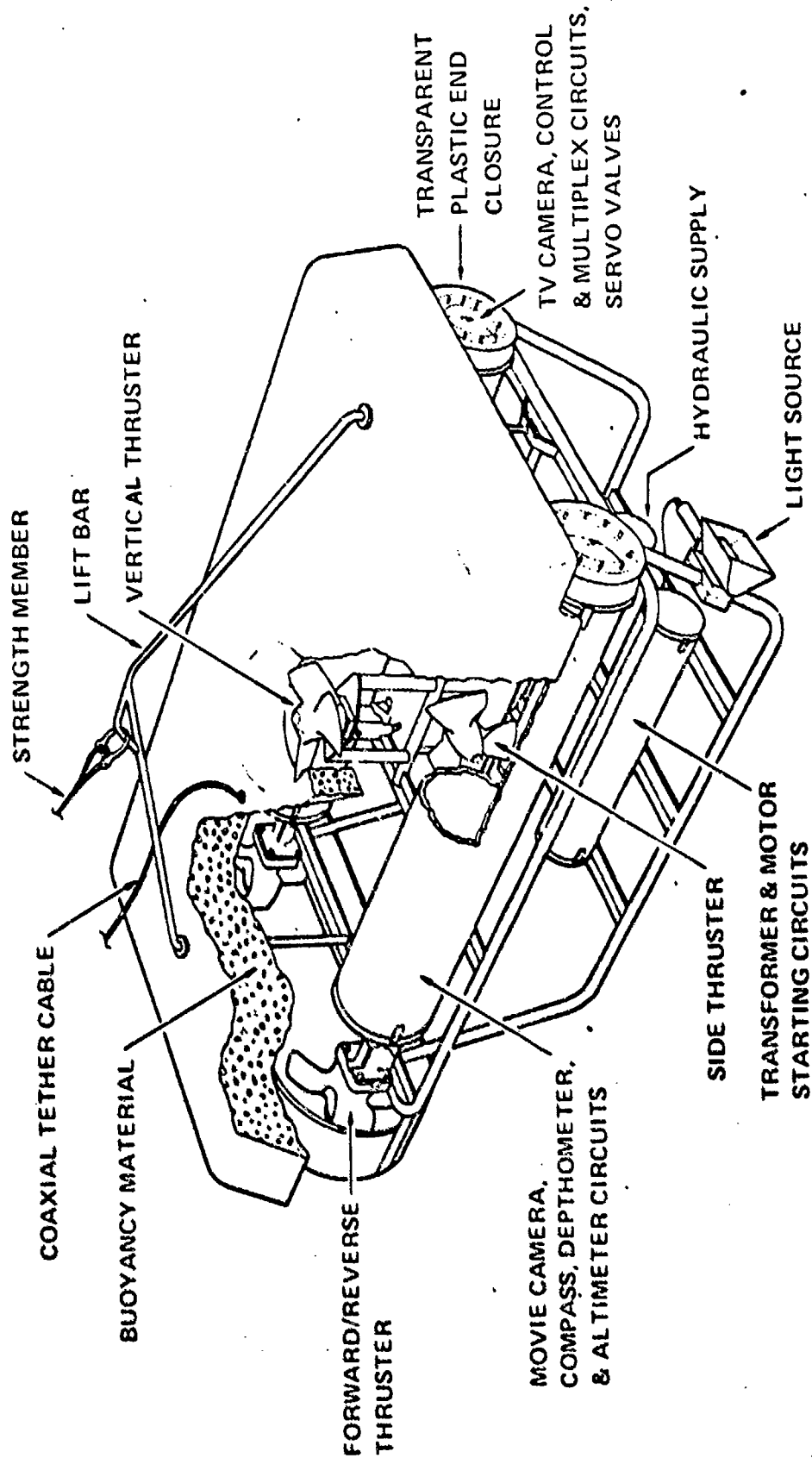


Figure 20:

# NAVAC SNOOPY POWER/SIGNAL TRANSMISSION SCHEME

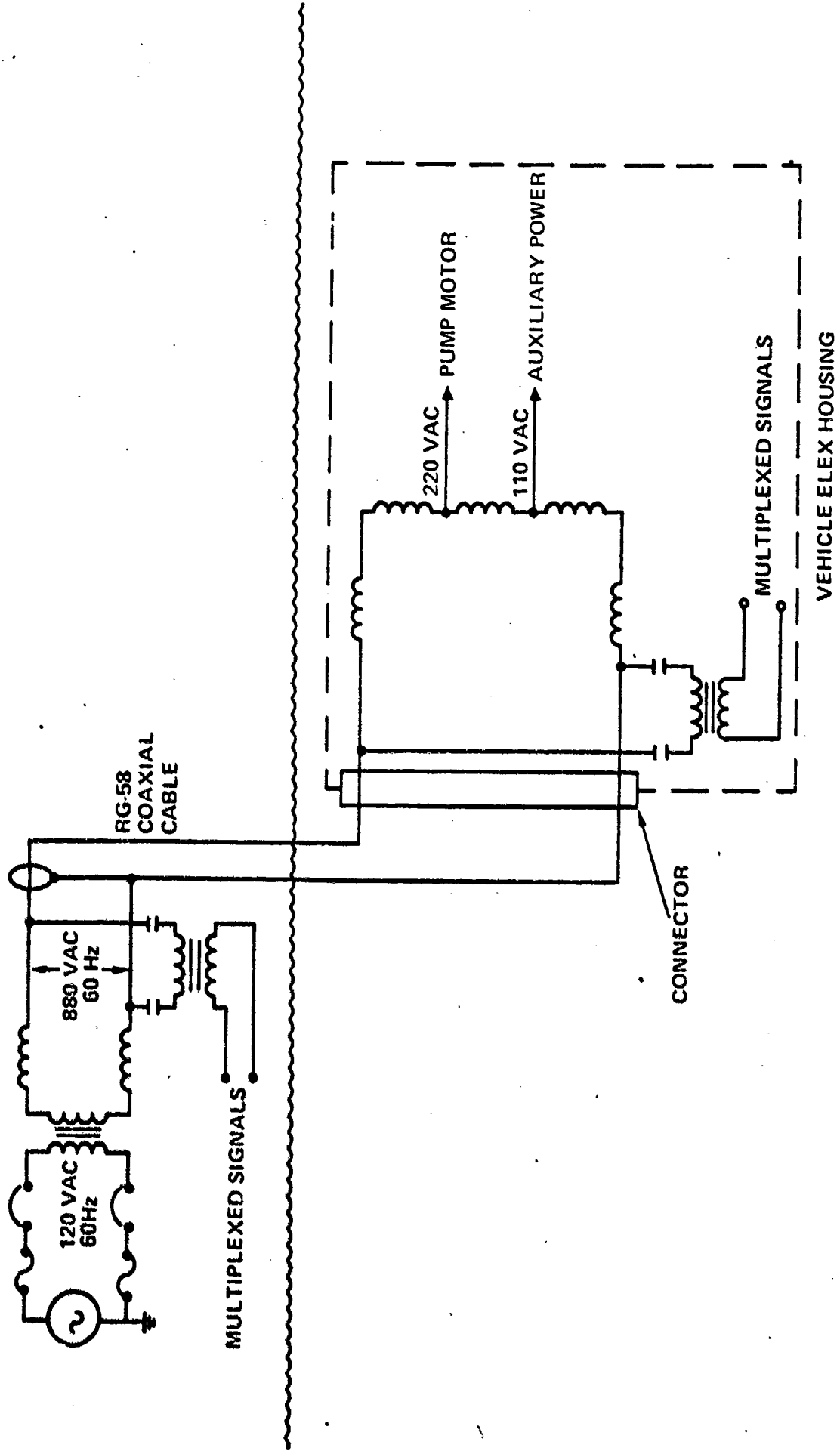
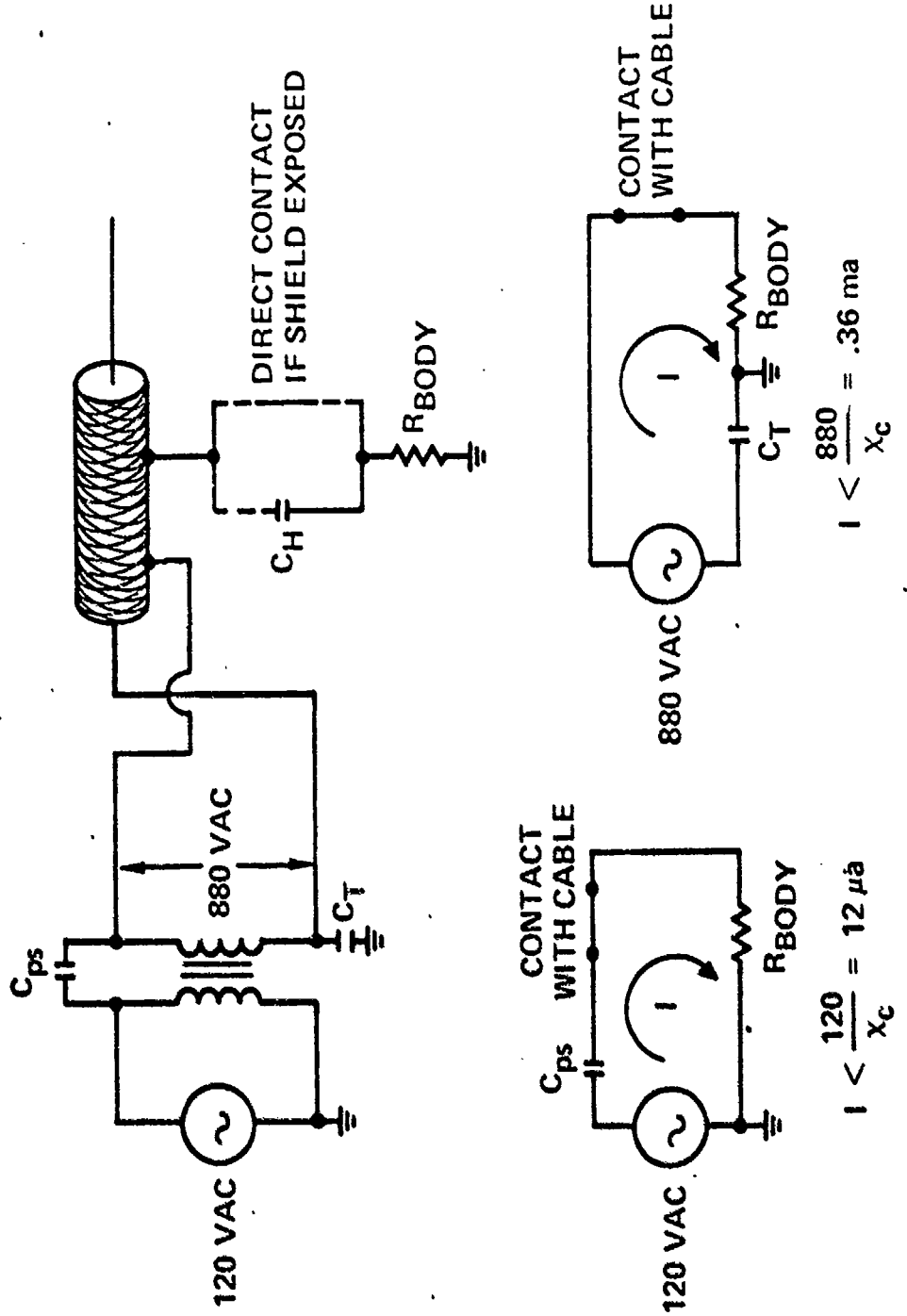


Figure 21:

# CABLE HANDLING LEAKAGE CURRENTS



7155

**nuc**

Figure 22:

# POWER CIRCUIT LEAKAGE CURRENTS

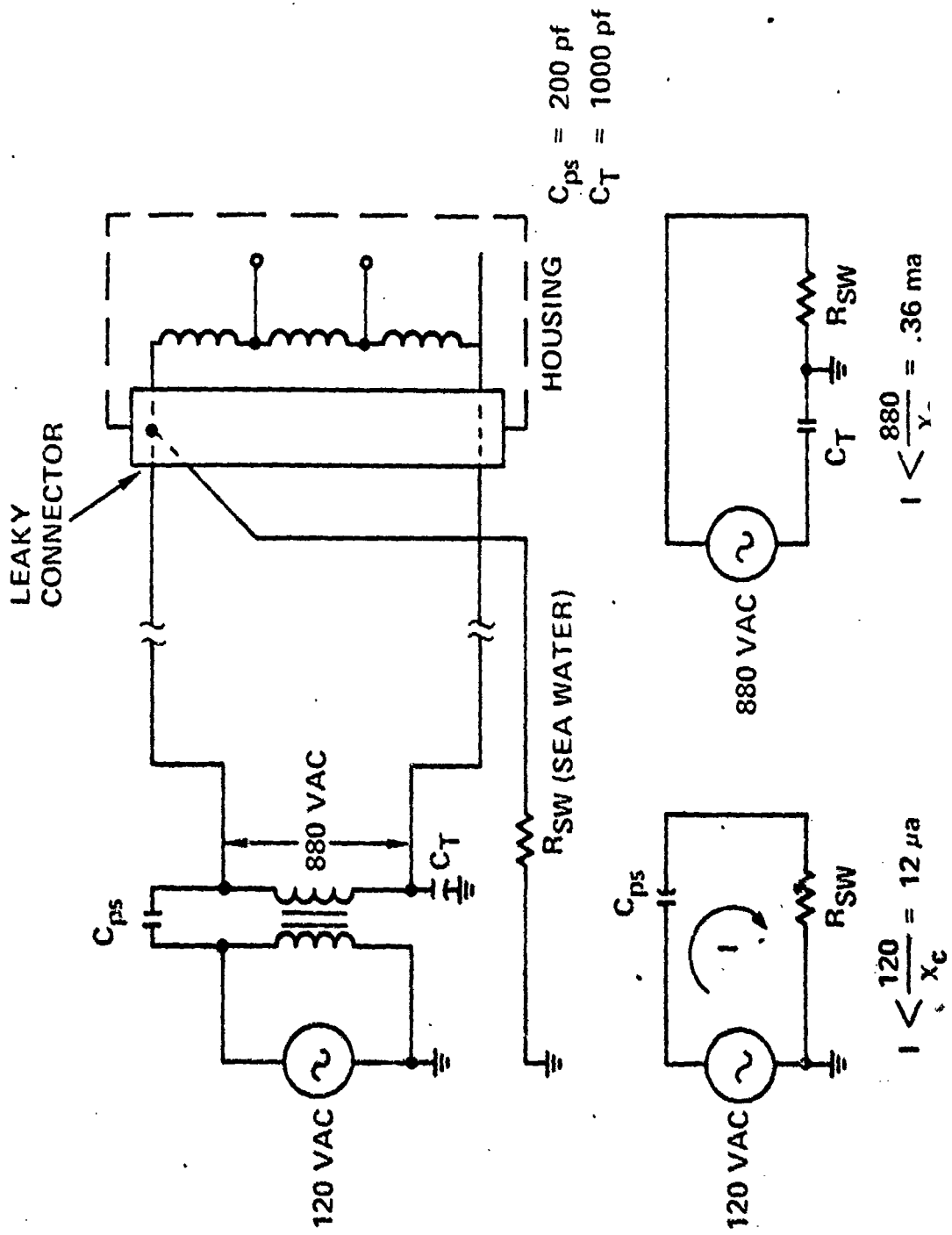
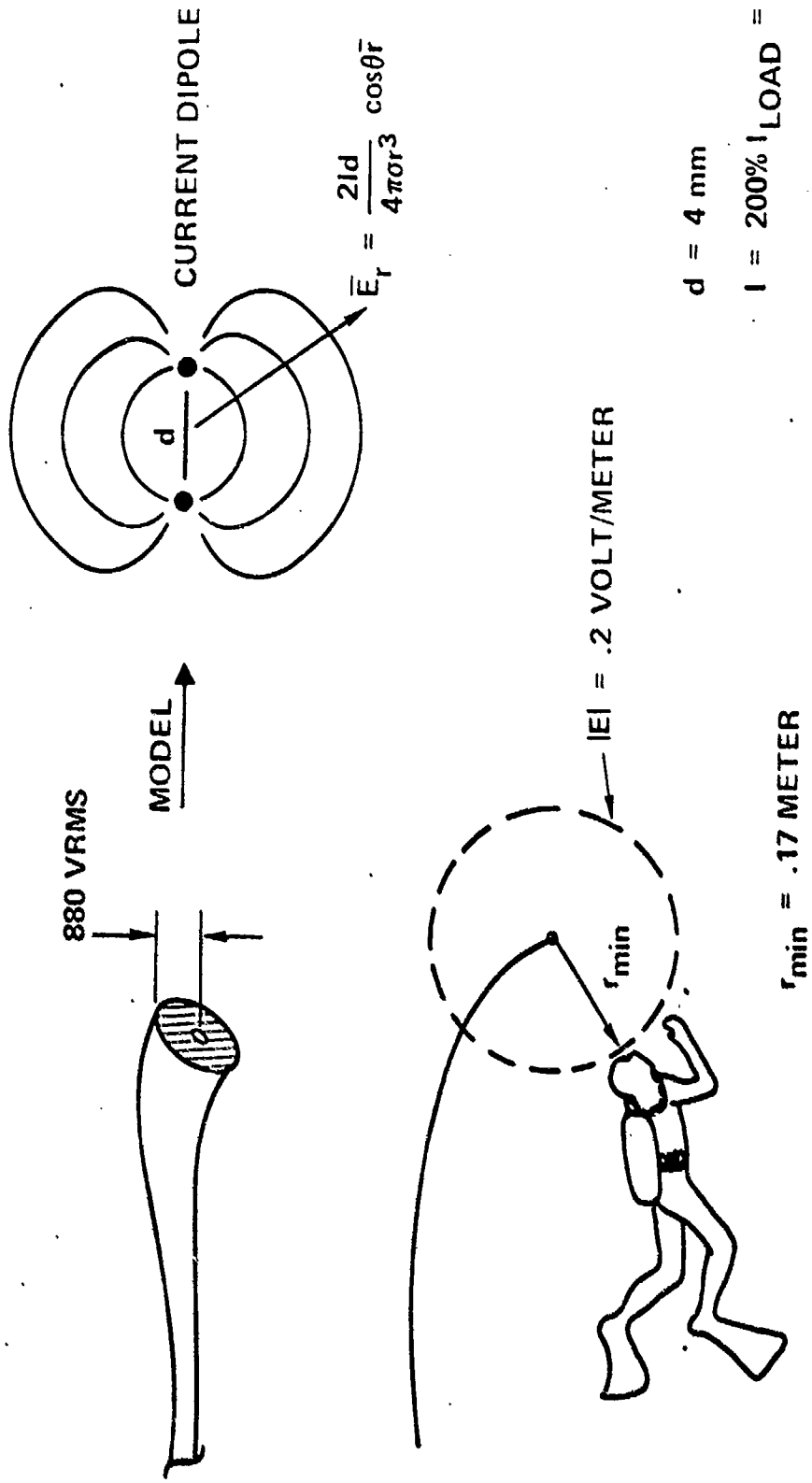


Figure 23:

# ELECTRIC FIELD INTENSITY ABOUT A SEVERED TETHER

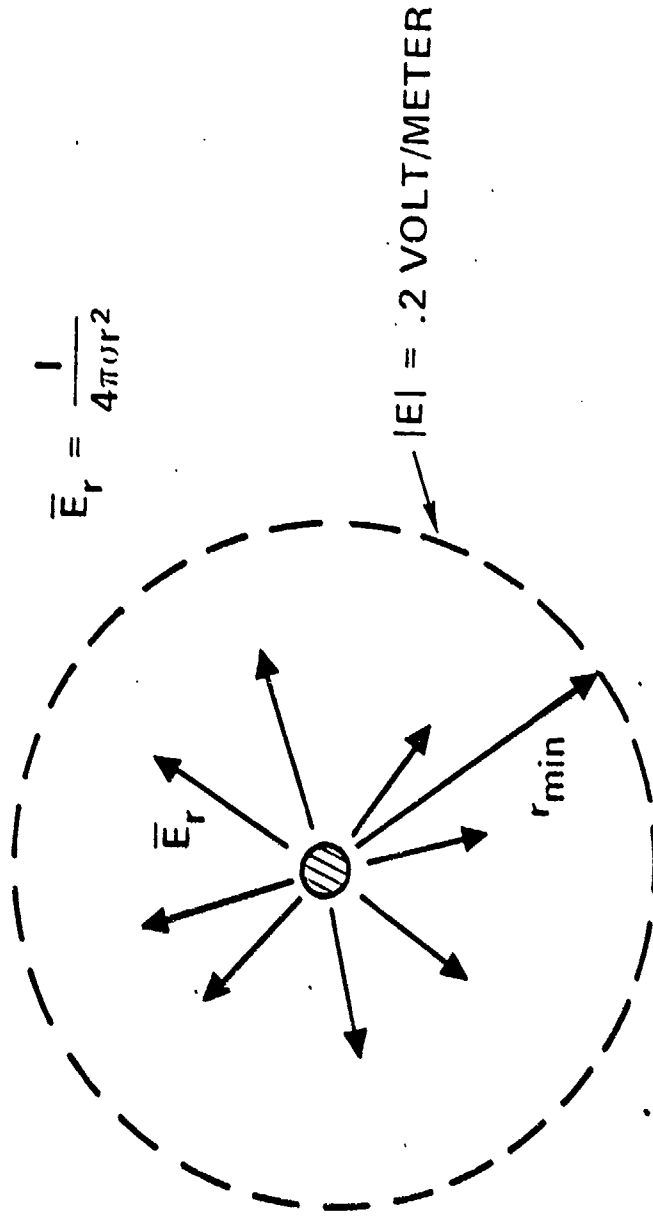
4516



**NBC**

Figure 24:

# ELECTRIC FIELD INTENSITY ABOUT A CURRENT MONOPOLE



$r_{min} = .55 \text{ METER}$

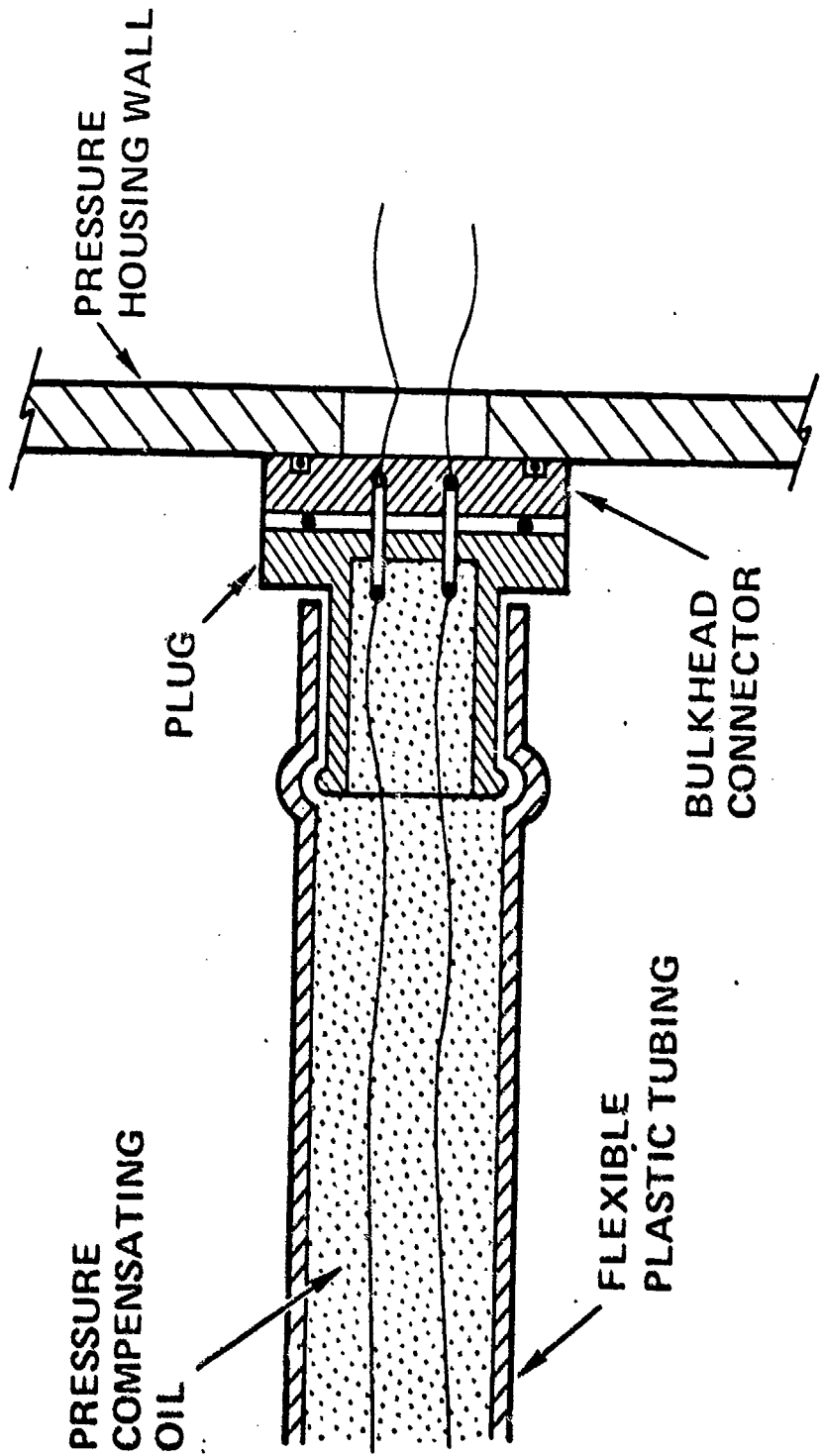
FOR  $I = 100\% I_{LOAD} = 3A$



**NGC**

Figure 25:

# OIL FILLED PRESSURE - BALANCED CONNECTOR



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ADDENDUM TO THE REPORT  
UNDERWATER ELECTRICAL SAFETY PRACTICES  
of the  
Panel on Underwater Electrical Safety Practices  
Marine Board  
Assembly of Engineering, National Research Council  
March 14, 1978

In the light of recent industrial experience and technical developments in connection with the use of alternating current (AC) welding and direct current (DC) rectifiers in underwater welding operations, an ad hoc group was convened by the Marine Board to review the following conclusions and recommendations on pages 61-62 of the report, Underwater Electrical Safety Practices, issued in 1976. Members of the ad hoc group are listed at the end of this addendum.

Conclusion: AC power, when used in water or other conductive environments, is lethally hazardous to a submerged diver.

Recommendation: Because of the lethal electrical hazards, AC cutting and welding equipment should not be used in underwater operations. Further, when an AC motor is used to drive the DC welding generator on deck, the AC motor should be equipped with ground-fault detection and interruption devices. Welding systems using AC-to-DC static rectifiers should not be used for underwater work.

Conclusion: AC ancillary equipment requires careful grounding and other devices for shock protection.

Recommendation: All AC-powered ancillary equipment and systems for use under water should be safety-checked through the use of systems analysis techniques and should include GFD or GFI circuitry, as appropriate.

In its review of these statements, the ad hoc group considered:

1. The use of AC for underwater cutting or welding;
2. The use of static rectifier systems as a source of direct current for underwater cutting or welding; and,
3. The use of ground-fault detectors (GFD) and ground-fault interrupters (GFI) in underwater alternating current electrical equipment not used for welding or cutting.

° The use of AC for underwater cutting or welding.

In the Underwater Electrical Safety Practices report, AC is considered to be more hazardous to the human body than DC. Therefore, the report recommends that AC welding and cutting operations should be prohibited among Navy divers in the underwater environment. This recommendation is still valid, primarily because of the limited training and experience of Navy divers in underwater welding and cutting.

On the other hand, several industrial underwater welding and cutting groups have successfully used AC for welding, particularly for restoring weld quality when work-piece magnetization occurs. However, the divers employed by industry usually receive extensive training in its use and are most likely to observe the strictest safety standards and procedures. Therefore, as there may be occasions when technical requirements or operational considerations require the use of AC by commercial divers working for the Navy, it is unrealistic and impractical to prohibit the divers from employing conventional techniques.

° The use of static rectifier systems as a source of DC for underwater cutting or welding.

The Marine Board concludes that the recommendation in the report Underwater Electrical Safety Practices against the use of rectifier-supplied DC welding sources by Navy divers is no longer valid. This conclusion is based on a review of the experiences of several industrial groups with thousands of hours of underwater welding and cutting experience, using rectifier-type welders as DC welding power sources. The Marine Board's review revealed no increase in the frequency of electric shock as a result of using DC rectifiers in underwater work. Furthermore, the welding current supplied by rectifiers appear to be more stable than rotating-machine-supplied DC, resulting in improved weld quality and faster cutting operation.

According to information brought to the Marine Board's attention since publication of the report Underwater Electrical Safety Practices, (1) the mean time between failure of silicon-type rectifiers is very long (on the order of 10,000 hours), (2) failure of currently used silicon diodes normally results in a short circuit, with subsequent circuit interruption, and (3) no injuries to commercial divers have been reported in the past seven years as a result of the use of rectifiers.

Diode failure causes a decrease in the available DC power supply and an increase in peak-to-peak ripple voltages. Such failure degrades the performance of the welding machine and causes interruption of the operation until the malfunctioning component is replaced. Occasionally (possibly one in two thousand diode failures) a diode fails "open;" again, such a failure greatly degrades the performance of the welding machinery and forces an interruption of the operation until the malfunctioning component is replaced.

- The use of ground-fault detectors (GFD) and ground-fault interrupters (GFI) in underwater alternating current electrical equipment not used for welding or cutting.

The report recommended that "...all AC-powered ancillary equipment and systems for use under water should be safety-checked through the use of systems analysis techniques and should include GFD or GFI circuitry as appropriate." In view of subsequent experience with the use of GFD or GFI circuitry, this recommendation needs to be clarified. An inappropriate application, for example, would be the use of an interrupter in conjunction with diver life-support equipment. Depending on the circuits that may be protected, an accidental power cut-off could interrupt the flow of vital breathing gases and/or prevent the recovery of a submerged diver.

In order to use GFD/GFI devices to protect the diver from the possibility of faulty electrical equipment, either new GFD/GFI techniques need to be developed for specific application to underwater equipment, or improvements are required in the insulation of submerged cables and/or operating procedures. The existing GFI devices have been designed primarily for dry environments rather than the undersea environment. The insulation of cables used at sea may be degraded over time by prolonged use and by the underwater environment. Such degradation may not necessarily constitute a hazard to the diver or cause equipment failure. However, slight internal leakage of electrical current may result. This may be sufficient to trigger alarms unnecessarily and/or to cause interruption of vital power. Such susceptibility may render the GFD or GFI circuitry impractical for some underwater use.

This addendum to the report, Underwater Electrical Safety Practices, was reviewed and approved by the Marine Board, Assembly of Engineering, National Research Council at its meeting on January 12-13, 1978.

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Underwater Electrical Safety Practices

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