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DEVELOPMENT OF NEW IMPROVED TECHNIQUES FOR UNDERWATER WELDING

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Chon-Liang Tsai
Hironori Ozaki
Arnold P. Moore
Lawrence M. Zanca
Subodh Prasad
Koichi Masubuchi

Massachusetts Institute of Technology

Cambridge, Massachusetts 02139

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Related Reports

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Brown, Alan J., Russell T. Brown, Chon-Liang Tsai, and Koichi Masubuchi. REPORT ON FUNDAMENTAL RESEARCH ON UNDERWATER WELDING. MITSG 74-29. Cambridge: Massachusetts Institute of Technology, September 1974. 282 pp. $5.00.

Masubuchi, Koichi. MATERIALS FOR OCEAN ENGINEERING. Cambridge: M.I.T. Press, February 1970. 542 pp. $14.50.

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Administrative Statement

This is the final report of a 2½-year research program conducted by researchers at the Massachusetts Institute of Technology. The purpose of the program was to develop new, improved techniques for underwater welding and cutting. It included both experimental and analytical investigations and also involved the compilation of all available technical information pertinent to the research.

During the time elapsed since the beginning of the 2½-year period (which began in July 1974), the interest in and enthusiasm about underwater welding and cutting on the part of the ocean engineering and welding industries has grown. The publication of this report should therefore be timely; it should quickly prove its usefulness in the development of the new, improved underwater welding techniques needed by the rapidly-expanding ocean engineering industries.

Funds for this research effort came in part from the Welding Research Council, a group of Japanese companies in shipbuilding and heavy industry, the NOAA Office of Sea Grant through grant number 04-6-158-44007, and the Massachusetts Institute of Technology. Several companies in the U.S. and the United Kingdom provided varying kinds of assistance, including the loaning of equipment, the providing of materials, and the willingness to participate in consultations. Assistance was also given by the MUST Office of NOAA.

Dean Horn
Director

March 1977

Acknowledgment

This program was carried out through the cooperation of a number of government agencies and companies in the U.S.A., the Federal Republic of Germany, Japan, and the United Kingdom. The authors wish to thank the many people who helped M.I.T. researchers in various phases of the work.

The authors are grateful to those many people in NOAA, the U.S. Navy, and GKSS who provided various kinds of assistance, especially during the underwater welding experiments in the Baltic Sea. Among these are:

NOAA: Dr. D. C. Beaumariage, Dr. D. B. Duane, Mr. E. A. Finkle, Mr. J. R. Vadus, and Dr. J. M. Wells.

U.S. Navy: Mr. J. Bladh and Mr. H. Harper.

GKSS: Dr. H. G. Schafstal, Mr. H. Victor, Mr. G. Luther, Mr. B. Donker, Mr. P. R. Kipp, Mr. R. Neukrich, and Mr. K. Szlinski.

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The authors also wish to thank a number of people at M.I.T., especially Mr. D. A. Horn, Mr. J. E. Grayson and Mr. N. Doelling for their administrative help, Mr. A. J. Zona for welding, and Mrs. June McLean and Mr. J. Morrow for typing and editing.

Several graduate and undergraduate students including Mr. J. Chiba, Mr. M. N. Greer, Mr. C. Dalvi, Mr. J. Naiman, and Mr. A. R. Mehta made their varying contributionsto this program. The authors are especially grateful to Mr. Chiba and Mr. Greer for their efforts in the Baltic Sea experiment.

Abstract

This is a final report coming out of a 2½-year research program focused on the development of new, improved techniques for underwater welding.

The offshore industry's need for underwater welding technology is re-examined in order to focus the project along practical lines. A previous M.I.T. study that generated a great deal of fundamental knowledge about underwater welding (July 1971 to June 1974) is used to define the significant areas of interest. A literature survey is also taken to assess the information on underwater welding processes currently available.

Two underwater welding processes, stud welding and flux-shielded welding, are made the focus of the program: the stud-welding process because it is simple in application and the flux-shielded process because, through direct flux covering, it minimizes water contact in the arc zone. The experimental results are discussed in terms of microhardness distribution, ultimate tensile strength, and weld ductility.

Several important factors that must be taken into consideration when developing a capacity to join metals in a deep-sea environment are discussed. The formulation and evaluation of a conceptual design for an underwater deep-sea welding system is presented (Chapter 6).

During the summer 1976, a series of underwater welding experiments were conducted in the Baltic Sea near Travemunde,

Federal Republic of Germany. The experiments were conducted as a part of the U.S.-German cooperative effort supported jointly by the Manned Undersea Science and Technology Office of NOAA and GKSS. This program was an extension of the current research effort. Phenomena observed during the undersea project are described, explained and discussed (Chapter 5).

Several research programs designed to systematically advance underwater welding technology are proposed in the final chapter of this report. Several appendices included in this report provide useful reference information that should prove helpful to anyone continuing research along these lines.

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CHAPTER 1: INTRODUCTION

A three-year program, "Fundamental Research on Underwater Welding," conducted from 1971 to 1974 by M.I.T., generated much new and valuable data on underwater welding. The objective of the program was to develop a fundamental understanding of what goes on during underwater welding. The final project report was published in September 1974.(1)

In July of 1974, a new, two-year program was initiated. It was hoped that with the understanding of the basic mechanisms of underwater welding gained from the earlier program the techniques could be further improved. This program was conducted primarily at the M.I.T. welding laboratory, but in the summer of 1976 a series of underwater welding experiments were conducted under actual diving conditions in the Baltic Sea in West Germany, and the program was extended for six months (until December 1976).

This program was supported by the National Sea Grant Office of the National Oceanic and Atmospheric Administration (NOAA). The Baltic Sea welding experiment was conducted as a part of the U.S.-German cooperative effort supported jointly by the Manned Undersea Science and Technology (MUST) Office of NOAA and the Gesselschaft für Kernenergieverwertung in Schiffbau und Schiffahrt (GKSS) mbH. Assistance was provided by the Diving Operations Branch of the Naval Sea Systems Command of the U.S. Navy. Matching funds were provided by the Welding Research Council and a group of Japanese companies including Hitachi Shipbuilding

and Engineering Company, Ishikawajima Harima Heavy Industries, Kawasaki Heavy Industries, Kobe Steel Works, Misubushi Heavy Industries, Mitsui Engineering and Shipbuilding Company, Nippon Kokan K. K., Nippon Steel Corporation, Sasebo Heavy Industries, and Sumitomo Heavy Industries. Some other companies including the Arcair Company and SubOcean Services have also assisted in providing consultations and loaning tools and equipment.

This final report on the 2½-year research program presents the important findings to come out of this program and summarizes the present state of underwater welding technology.

1.1 A Review of the Need for Underwater Welding Technology by the Offshore Industry.

Since the early 1900's there has been a demand for underwater welding techniques. But until recently they were still expensive and unreliable. The welds were more brittle than those done in air. The environment was hazardous, the mobility limited, and the visibility poor. Usually it was restricted to temporary repair or salvage operations.

The development of an advanced underwater welding technology has started to change all of this. A substantial amount of both academic and industrial research on underwater welding is in progress. This is in response to needs that can be classified into three different categories of application.

Category 1: Underwater construction of structures including pipelines.

Category 2: Permanent repair of underwater structures including oil rigs.

Category 3: Emergency repair of structures including the rescue and salvage of sunken ships.

Undersea construction (Category 1) requires high-quality welds and the relatively expensive dry chamber system may still be the only answer. Permanent repairs (Category 2) can be done using a reliable wet shielded metal arc process or, if better quality is needed, a movable dry chamber. A wet shielded metal arc technique is usually used for emergency repairs (Category 3), at least in shallow sea applications.

Offshore platforms have traditionally been fabricated on land, towed to the site, and submerged into place, a procedure that is risky and that severely limits the size and geometric complexity of the structure. If the appropriate underwater techniques were available, sub-assemblies of convenient size and shape could be prefabricated on shore and assembled at the site.

The conventional methods of laying offshore pipelines become increasingly expensive as the distance from the shore, the water depth, or the pipe diameter increases. The appropriate underwater techniques could bring down these costs.

Dry-dock time is expensive and ship repairs could be done for much less cost if the appropriate underwater techniques were available, if "code-quality" welding could be done underwater.

Current underwater welding technology can produce "code-quality" welding if a dry chamber system is used. But the large pressurized air (or inert gas) chambers used to exclude water from the work area have a high operational cost, and for this reason the process is not economically feasible. But the economically feasible wet process produces welds of an inferior quality. And this illustrates the crucial issue: operational cost vs. weld quality.

Though doubtless there is an economic limit to what can presently be accomplished in underwater welding technology, the current expansion in ocean engineering activities has brought with it an overwhelming demand that this development take place. Joining techniques in particular are needed.

In order for this and other related developments to take place, both theoretical study (technical and economic) and practical developmental work need to be done by researchers. The ocean-oriented industries have indicated their overwhelming concern that this development take place.

One clear indication of this interest is the recent surge of articles on underwater welding. APPENDIX A is a bibliography of underwater welding literature published since 1930. In one year, 1973, 26 significant articles were published in the world on underwater welding. Figure 1-1 is a survey of such articles published since 1930.

Figure 1-2 is a statistical survey of the field use of underwater welding processes by the various offshore companies. There was no significant use of underwater welding before 1967. In 1973, over 25 underwater welding services were completed by these companies, according to our information.

During one year (1975), the number of marine drilling rigs completed or under construction increased from 408 to 443. Of the 443 units, 23 (5%) were submersibles; 101 (22%) were drill-ships or drillbarges; 192 (43%) were jack-ups; and 127 (30%) were semi-submersibles. 304 of these units were operating by

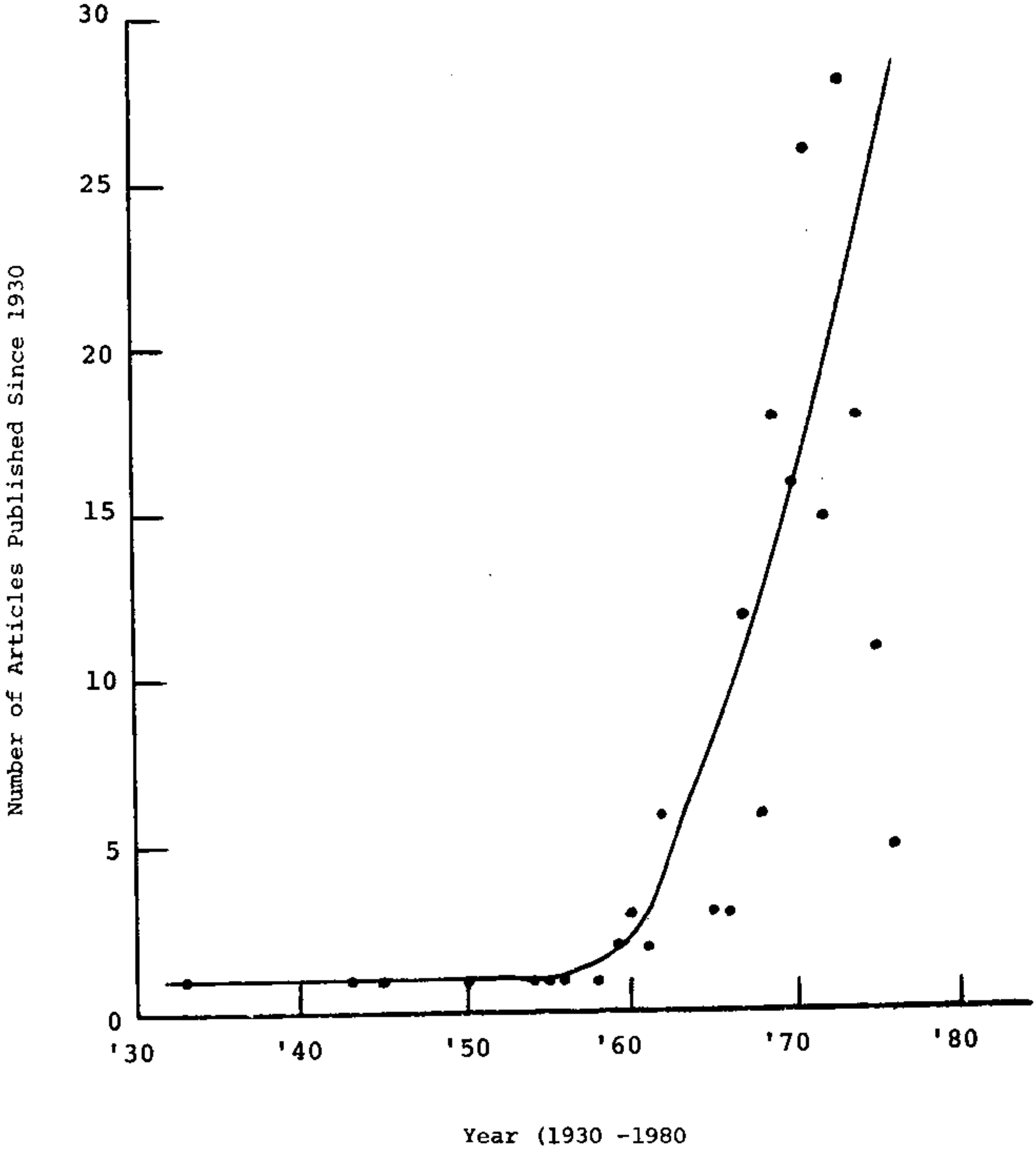


Fig. 1-1 Articles on Underwater Welding Published Since 1930

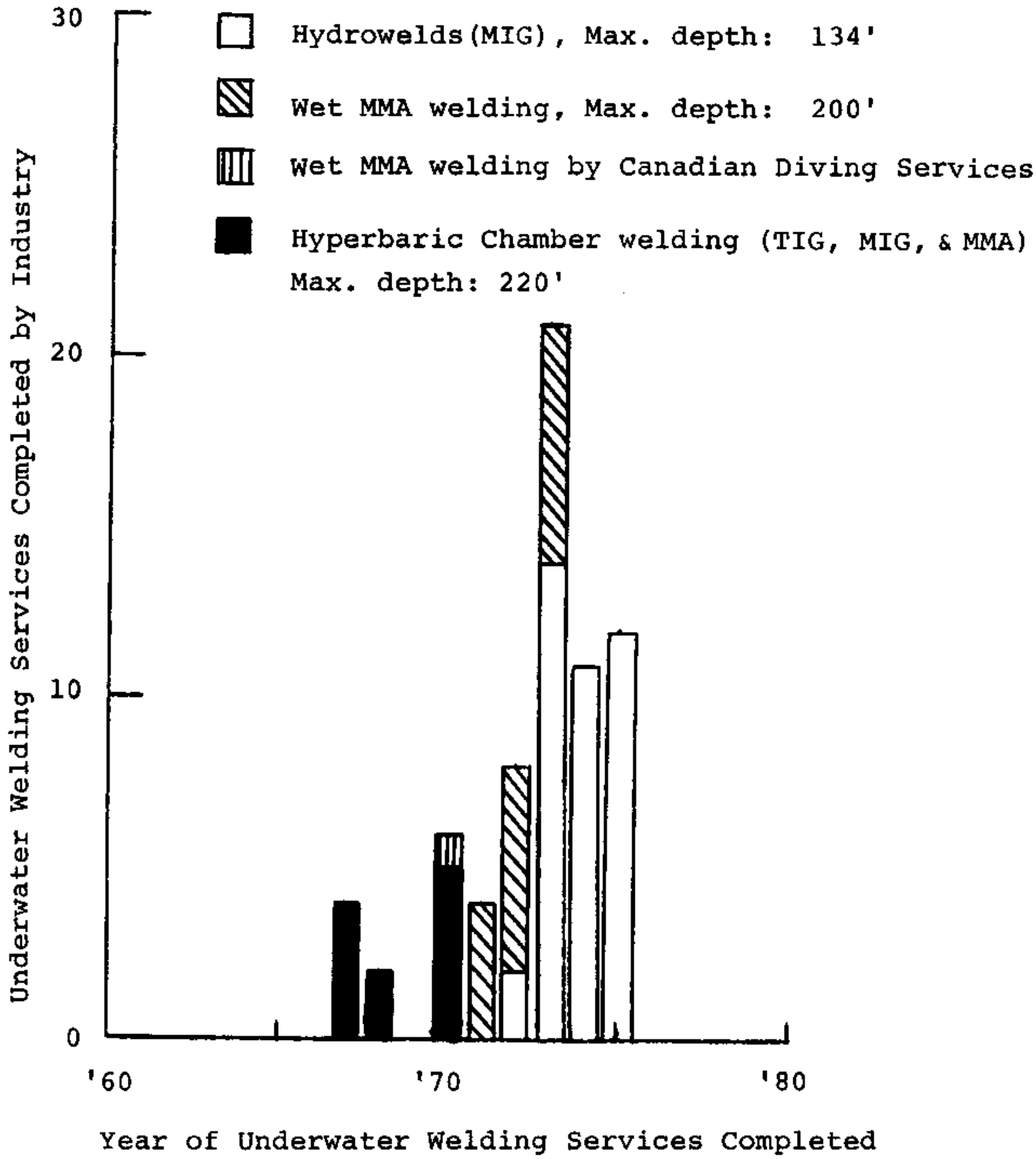


Fig. 1-2 Statistical Survey of the Field Use of Underwater Welding Processes by the Various Offshore Companies

the end of the year; the remaining 139 were either under construction or in the planning stage.[2]

Offshore structures are being built in deeper and deeper water environments of increasing hostility. This is a clear indication of the commitment on the part of the commercial interests involved. As these activities are extended into this environment, the need for high-quality underwater joining techniques in sub-sea environments will continue to grow.

1.2 Present Status of Underwater Welding Research and Development

Research and Development in underwater welding is now in progress in Germany, Holland, Japan, Norway, the Soviet Union, the United Kingdom, and the United States. More than half of the papers mentioned in Part 3 of the M.I.T. Sea Grant Report ("State-of-the-Art of the Technical Aspects of Underwater Welding") are recent publications (since 1970).

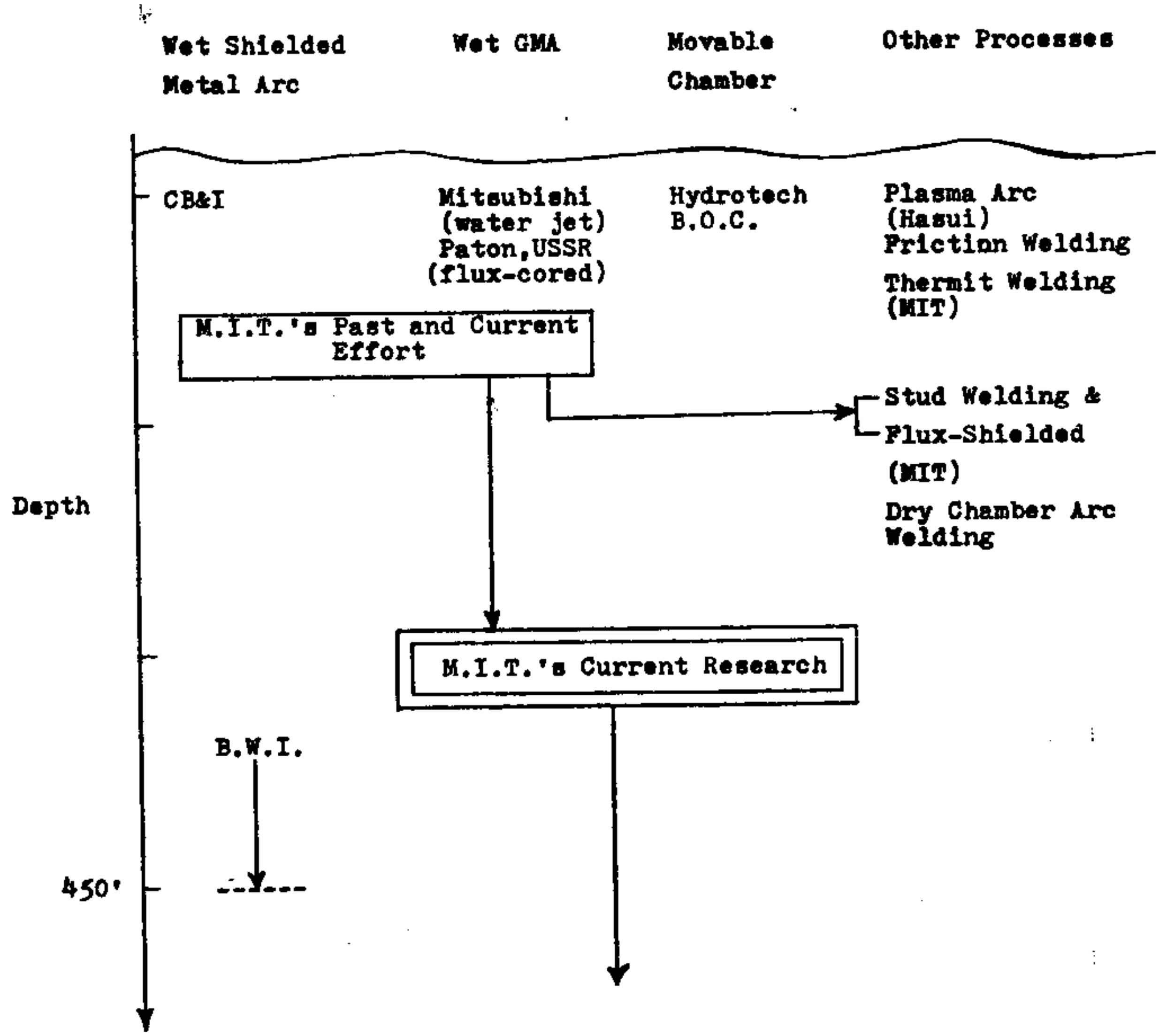
Although recently studies have also been published about other joining techniques including friction welding, plasma welding and thermit welding, most current studies deal with the various arc welding processes. Table 1-1 summarizes the underwater welding processes that are either being used or in the final stages of development.

Figure 1-3 illustrates recent activities in underwater welding on the part of various organizations. The Chicago Bridge and Iron Company, an organization that has done more actual underwater construction work than any other, uses a covered

TABLE 1-1

SUMMARY OF UNDERWATER WELDING PROCESSES

	Process	APPLICATIONS	Limitations
I	WET WELDING TECHNIQUES		
	A. Shielded Metal-Arc	Complex lap, tee or butt welds. Very maneuverable. Single or multipass.	Visibility-positioning, diver stability, rapid cooling, hydrogen, discontinuities from changing electrodes.
	B. Shrouded Metal-Arc	Fairly uniform joints. Single-pass. Fair maneuverability.	Visibility-positioning, diver stability, non-uniform joints, hydrogen, cooling rate. Discontinuities from changing electrode.
	C. Plasma Arc	Butt, lap, tee joints. Very good weld bead shape and penetration. (Experimental stage only).	Slow speed, visibility-positioning, moderate complexity of equipment, rapid cooling, diver stability.
	D. Gas Metal-Arc (continuous wire electrode)	Butt, tee, lap joints. Moderate maneuverability. Multipass. Superior quality to metal arc.	Visibility-positioning, maintenance, complexity hydrogen (without shielding), rapid cooling, diver stability.
II	DRY WELDING TECHNIQUES		
	E. Movable Chamber	Uniform joint design. Butt and fillet joints, pipelines possible. Multipass. Very high quality.	Visibility-positioning, diver stability, complex equip. maintenance (need wide area adjacent to joint for chamber)
	F. Fixed Chamber (complete enclosure) Gas Tungsten-Arc Process	Pipelines, simple enclosable structures. Very high quality.	Expense, complexity of chamber & equip., explosion. Elaborate support crews.



Various Underwater Welding Processes

Fig. 1-3 Recent Activities in Underwater Welding electrode process that was developed by its own engineers. Although the Arcair Company is not directly involved in construction work, it produces covered electrodes for underwater welding as well as underwater cutting torches.

Underwater wet welding using the gas metal-arc process has been studied by several investigators in an attempt to make it possible to use continuous electrodes and to eliminate some of the discontinuities involved in changing covered electrodes. For example, Mitsubishi Heavy Industries recently developed a wet GMA process using a jet of water to create a stable gaseous atmosphere surrounding the welding arc.

Hydrotech Incorporated has developed a GMA process for underwater welding that is enclosed in a small movable chamber. British Oxygen Company had a licensing agreement with Hydrotech, the owner of the patent on the process. These companies had subsidaries that were involved in underwater construction and repair work.

Recently the British Welding Institute conducted a large scale research program on underwater welding sponsored by the British government. The objective of the program was to develop techniques for joining low-carbon and some high-strength steels (up to a carbon equivalent of about 0.45%) in sea water up to 450 feet deep. They have selected the shielded metal-arc process over the GMA process.

Unfortunately, much of the technical information collected by these companies is kept secret for commercial reasons. The results of the research done by the British Welding Institute may also remain unpublished due to restrictions placed on it by the sponsor.

Underwater welds are plagued by the rapid quenching effect of the surrounding water and by a susceptibility to hydrogen embrittlement. The current trend in underwater welding research is to improve the weld quality be removing the wet conditions around the arc zone using direct shielding or mechanical devices.

In his study of the effects of water quenching and hydrogen embrittlement, D. Lythall of British Oxygen Company, Limited[3] carried out a series of wet shielded metal arc welds in which he eliminated first one effect and then the other. The results lead him to the following conclusions:

1. It is unlikely that code ductility can be produced underwater without some form of gas coverage or pre-heat treatment to recover the properties lost in welding.

2. Low-hydrogen electrodes are a significant improvement over rutile coated electrodes because hydrogen is eliminated from the shielding gas, as indicated by an improvement in Charpy test results.

Advanced underwater welding techniques are still pretty much in the theoretical development stage and investigators disagree about their present-day adequacy for construction or repair. Economic limits on the weld technology and a lack of hard data about off-shore structure reliability are partial causes of this.

M.I.T. has developed a theoretical foundation for underwater welding research that involves an understanding of the basic physics and metallurgy of the process. On this foundation the development of welding technologies can proceed in a more systematic and coordinated fashion. Recent efforts in this theoretical study has included a consideration of:

1. Bubble dynamics
2. Welding heat transfer
3. Hydrogen diffusion
4. Pressure effects

1.3 The M.I.T. Effort and the Research Programs

M.I.T.'s active involvement in research on underwater welding and cutting began in 1968 when Professor Koichi Masubuchi, an expert on welding fabrication, joined the faculty. His paper on "Underwater Welding and Cutting" describes M.I.T.'s past and present efforts in underwater welding research, summarized below (see Figure 1-4).

In 1970, Professor Masubuchi published a textbook, "Materials for Ocean Engineering," which contains as its appendix a state-of-the-art report on underwater cutting and welding.[4] During the 1970-71 academic year, two theses were prepared on underwater welding.[5, 6] A research program on underwater thermit welding* was conducted for the Office of the Navy Supervisor of

*LCDR A. Anderssen continued this study during the 1971-72 academic year and wrote a Master's thesis on underwater exothermic welding.(7)

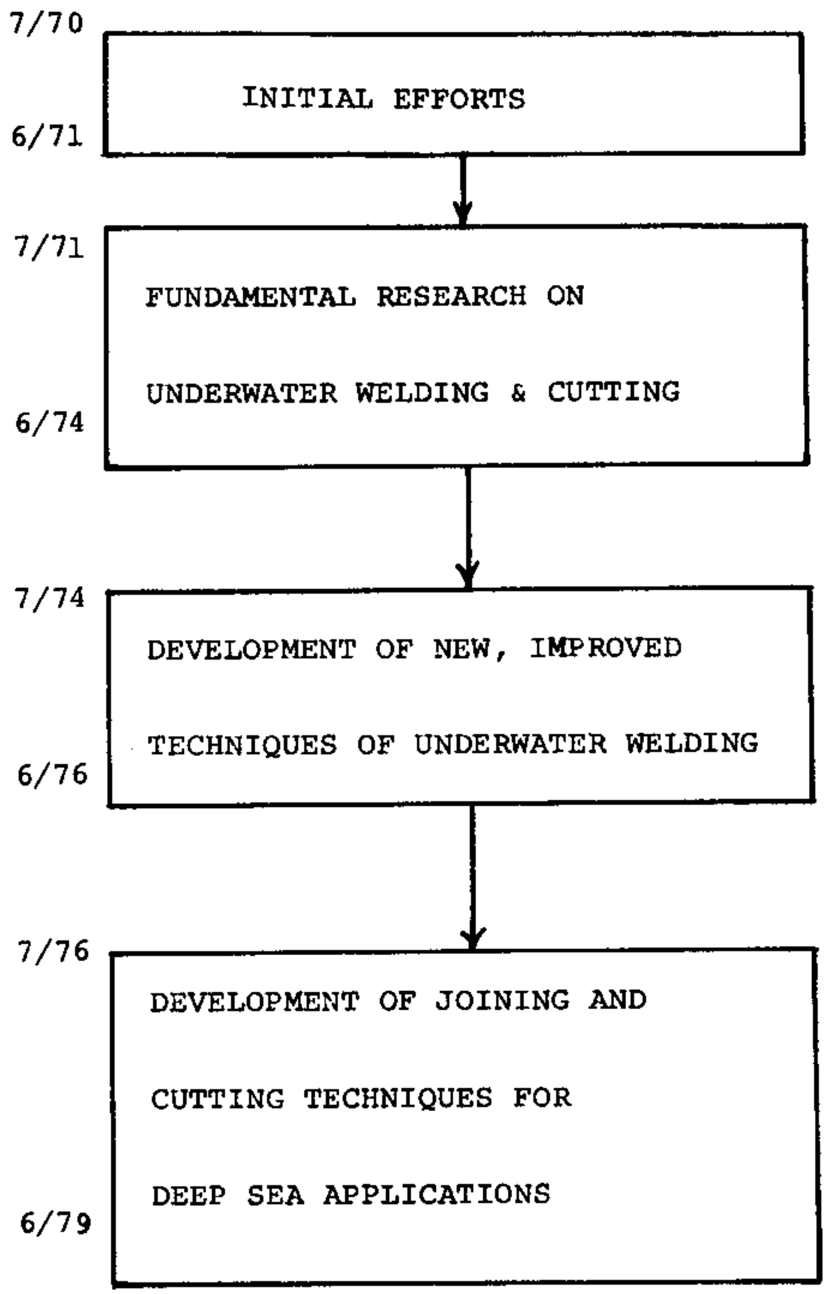


Fig. 1-4
DEVELOPMENT OF RESEARCH ACTIVITIES ON UNDERWATER WELDING AND CUTTING AT M.I.T.

Diving, Salvage, and Ocean Engineering.

The three-year program on "Fundamental Research on Underwater Welding" was initiated on July 1, 1971. The program covered the following phases:

Phase 1. A survey of fundamental information on underwater welding and cutting.

Phase 2. A study of heat flow during underwater welding.

Phase 3. A study of the mechanisms of metal transfer in underwater welding.

Phase 4. A study of the effects of water environment on metallurgical structures and properties of welds.

Phase 5. The development of improved underwater welding methods.

The program was supported by the National Sea Grant Office. The Welding Research Council and several Japanese companies provided matching funds during the second and third years. Some U.S. companies also contributed funds.

The program was completed in June 1974, and the final report,[1] probably the most comprehensive document on the science and technology of underwater welding ever published, is now available. Several theses and papers have also been written to cover the various phases of the program,[8-11] and an arrangement has been made with the Welding Research Council to prepare an interpretive report.*

This M.I.T. study has generated new and valuable scientific information on underwater welding and has increased our under-

*The final draft has already been prepared.

standing of what occurs during welding. M.I.T. researchers now know what should be done to systematically improve the techniques.

In July of 1974, a new, two-year program was initiated. It was hoped that with the understanding of the basic mechanisms of underwater welding gained from the earlier program the techniques could be further improved. This program was conducted primarily at the M.I.T. welding laboratory, but in the summer of 1976 a series of underwater welding experiments were conducted under actual diving conditions in the Baltic Sea in West Germany. Thus the program was extended for six months until December, 1976. The program covered the following phases:

Phase 1. The development of the conceptual designs of several new, improved underwater welding and cutting techniques.

- A. The possible uses of various welding and cutting techniques.
- B. The improvement of arc welding processes.

Phase 2. Further study of one or several of the most promising techniques.

Phase 3. Further tests and improvement of tools and/or machines.

Phase 4. A study of a total operation system for underwater welding and cutting.

Phase 5. Experiments under the Baltic Sea, as a part of MUST program, to evaluate several underwater welding processes including shielded metal arc and flux-shielded arc welding processes.

This program was supported by the National Sea Grant Office with matching funds provided by the Welding Research Council and a group of Japanese companies including Hitachi Shipbuilding and Engineering Company, Ishikawajima Harima Heavy Industries, Kawasaki Heavy Industries, Kobe Steel Works, Mitsubushi Heavy Industries, Mitsui Engineering and Shipbuilding Company, Nippon Kokan K. K., Nippon Steel Corporation, Sasebo Heavy Industries, and Sumitomo Heavy Industries. Some other companies including the Arcair Company and SubOcean Services have also assisted in providing consultations and loaning tools and equipment.

The study has been completed and this report is a summary of the results.

July 1976 marked the beginning of a new three-year program to generate data about various aspects of joining and cutting techniques in deep-sea applications and to develop some protatype tools appropriate to these techniques. The program includes the following tasks:

Task 1. The evaluation of various joining and cutting techniques with an eye to their possible use in deep sea applications.

Task 2. The construction of a pressure tank (using matching funds).

Task 3. Experiments are conducted on arc welding and cutting in deep-sea conditions.

Task 4. The experiments on arc welding and cutting in deep-sea conditions are continued.

Task 5. Prototype tools suitable for deep-sea welding and cutting are designed.

Task 6. The prototype units are tested and improved.

Task 7. Preparation of the final report.

It is expected that during the first year Tasks 1 through 3 will be completed, during the second Tasks 4 and 5, and during the third Tasks 6 and 7.

Personnel Involved. The programs have attracted a number of students in light of the rather modest funding level of $20,000 to $30,000 per year. Since the beginning of the project in July 1970, a total of 13 graduate students and one undergraduate have worked on theses:*

LT J. A. Staub, M.S. and Ocean Engineer in June 1971

Mr. A. J. Brown, B.S. in June 1971 and M.S. in June 1973

LCDR A. H. Anderssen, M.S. and Ocean Engineer in June 1972

Mr. R. T. Brown, B.S. in June 1971 and M.S. in June 1973

LT M. B. Meloney, M.S. and Ocean Engineer in June 1973

LT S. L. Renneker, M.S. and Ocean Engineer in June 1974

Mr. C. L. Tsai, Ph.D. candidate

LT A. P. Moore, M.S. and Ocean Engineer in June 1975

Mr. L. M. Zanca, M.S. in August 1975

Mr. S. Prasad, M.S. candidate

Mr. C. Dalvi, M.S. in June 1976

Mr. J. Naiman, B.S. in June 1976

Mr. A. R. Mehta, M.S. in January 1977

Mr. J. Chiba, M.S. candidate

Among those listed above, Messrs. Tsai, Moore, Zanca, Prasad, Dalvi, Naiman, Mehta, and Chiba contributed to this research program in varying degrees.

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*Ranks of students from the U.S. Navy and Coast Guard are those held when they were at M.I.T. Most of them have been promoted.

Mr. M. N. Greer, a graduate student under the joint program between M.I.T. and Woods Hole Oceanographic Institute also participated in the Baltic Sea welding experiment.

In addition, Dr. M. Kutsuna, a visiting research associate from Kawasaki Heavy Industries participated in the program during the 1974-75 academic year. Dr. H. Ozaki, also a visiting research associate from Kawasaki Heavy Industries, is working on the current program. Dr. Ozaki plans to stay at M.I.T. for at least two more years. The services of Dr. Kutsuna and Dr. Ozaki have been made available at no cost to the research contract.

1.4 Summary of This Research Program

This program was initiated on July 1, 1974, and completed on December 31, 1976. The program covered the following phases:

Phase 1. The development of the conceptual designs of several new, improved underwater welding and cutting techniques.

- A. The possible uses of various welding and cutting techniques.
- B. The improvement of arc welding processes.

Phase 2. Further study of one or several of the most promising techniques.

Phase 3. Further tests and improvement of tools and/or machines.

Phase 4. A study of a total operation system for underwater welding and cutting.

Phase 5. Experiments under the Baltic Sea, as a part of MUST program, to evaluate several underwater welding processes including shielded metal arc and flux-shielded arc welding processes.

Phase 1, Task A. The results are given in Chapter 2 of this report. The purpose of this study was to explore the possible uses of various existing welding processes that might have the potential for further development. Initially a careful literature study on various underwater welding processes such as shielded metal arc welding, gas metal arc welding, thermit welding, stud welding and plasma arc welding was conducted. Some modified gas metal arc welding processes, such as water shielded gas metal arc welding and hydrotech welding techniques also were studied. Experimental results of determining the feasibility of such welding processes as well as the results obtained by other investigators are discussed in Chapter 2. Advantages and disadvantages of these techniques are evaluated in the same chapter.

Phase 1, Task B. Three welding processes, water shielded gas metal arc welding, stud welding and flux-shielded metal arc welding, were selected for further study. The details about the water shielded gas metal arc welding process are given in Chapter 2 and those about the stud welding and the flux shielded metal arc welding processes in Chapter 3 of this report. As a part of this task, underwater stud-welding guns have been developed. A patent application was filed and a news story of this invention appeared in the Los Angeles Times (June 22, 1975). The patent was granted by the United States Patent Office on November 2, 1976 (Appendix C). A patent application for the flux-shielded metal arc underwater welding process was filed in June 1976.

Phase 2 and 3. Stud welding and flux-shielded arc welding were selected for further study. The processes, the capabilities and limitations of the processes, the application of the processes, the experimental results and the evaluation and redesign of the underwater stud and flux-shielded welding tools are discussed in Chapter 3 of this report.

Phase 4. The study covered the following subjects:

1. Present and projected needs
2. Diving system limitations
3. Depth-related technical problems
4. Conceptual design of deep-ocean welding systems

A paper on this subject was presented at the 1975 national meeting of the Marine Technology Society in San Diego, California in September 1975 (see Chapter 4).

Phase 5. In the spring of 1976 the research program was modified to add Phase 5, a series of welding experiments under the Baltic Sea near Travemünde, West Germany in July 1976. The experiment was conducted as a part of the MUST program. We are grateful that we had the opportunity to conduct underwater welding experiments in actual diving conditions. Mechanical and metallurgical examinations of the welds were conducted in the fall of 1976. This field experiment is discussed in Chapter 5 of this report.

For a comprehensive overview of research and development in underwater welding techniques, see Chapter 6. The results obtained in the M.I.T. program, in both the laboratory phase and the Baltic Sea phase, as well as those obtained in other programs by other researchers are integrated in this overview and in its conclusions.

Chapter 7 suggests several possible future investigations and developments in underwater welding, including several that have been suggested by the offshore industry itself.

CHAPTER 2: AN EVALUATION OF CURRENT UNDERWATER WELDING PROCESSES

2.1 Operational Characteristics.

Welding processes that have been tried underwater include the following: shielded metal arc welding, gravity welding, firecracker welding, gas tungsten arc (GTA), gas metal arc (GMA), flux-cored arc welding, plasma arc welding, electron beam welding, thermit welding, friction welding, and explosion welding. There are basically two underwater welding systems: "wet" and "dry."

The operational characteristics of most of these processes and both of these systems were discussed in the previous report[(1)]. Table 1-1 summarizes these processes and systems. It is obvious that once a process is jigged, mechanized or systematized, it loses its versatility.

2.1.1 Characteristics of Various Electrode Types.

Several reports are available in which the running characteristics of covered electrodes used in air welding are discussed[(12)]. According to these reports, the acid, iron oxide, and rutile coated electrodes give the best running characteristics. The currents required underwater are 20 to 25 percent higher than those normally employed in air welding[(13, 14, 15, 16)].

The cellulosic electrode produces an irregular bead prone to porosity and undercut. The basic electrode has been found to be difficult to manipulate in underwater manual operations[(12)].

The opposite was found to be true by Bouwman and Haverhals[(17)].

They claim that the inferior running characteristics of the basic electrodes are attributable to the absorption of water by the flux coating and hence can be improved through the use of waterproofing. The advantages of electrode coatings containing iron powder have also been demonstrated.[13, 14, 15, 16, 18, 19] These electrodes form a stable cup on the end of the electrode and thus lend themselves to a touch welding technique that minimizes the degree of welding skill required in low visibility situations. It is relatively easy to start the arc with this type of electrode, and the deposition rate is high; these characteristics help to minimize bottom time.

Detailed information on underwater welding electrodes is given in references 15, 20 and 21.

2.1.2 Effect of Pressure on the Operational Characteristics.

The British Welding Institute[22] has investigated how certain welding processes, including shielded metal arc, GTA, and GMA are affected by pressure (up to 32 bars--about 32 atmospheres). D. J. Lythall et al[23] recently studied how depth affects the operational characteristics of the TIG, MIG, and plasma welding processes. From these two studies, the following conclusions can be drawn:

1. Increased pressure does not significantly affect the arc characteristics in shielded metal arc welding. Unlike

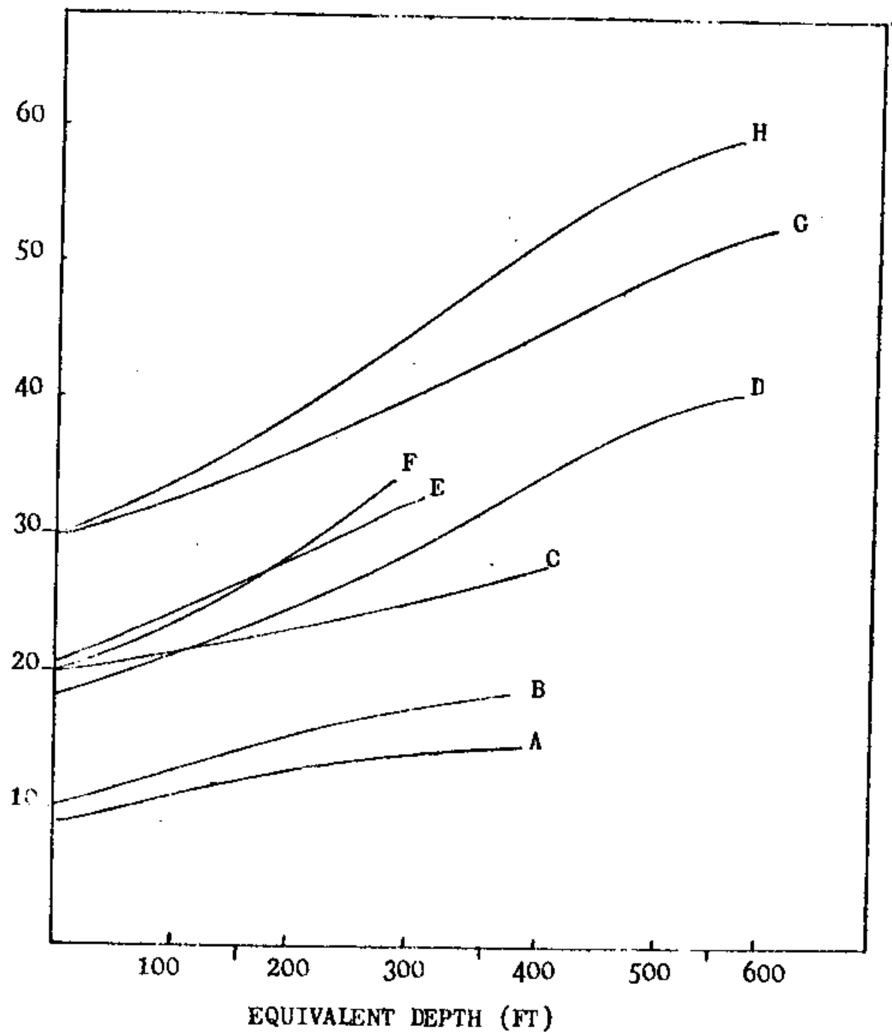
the characteristic results of "wet" welding, the basic electrode produced a sound weld and a good bead appearance, and the rutile electrode produced beads with gross open porosity.

2. Erosion of the electrode tip in TIG welding beyond 8-9 bars (240-300 feet depth) causes arc deflections which become serious at a pressure of 12-16 bars. Arc initiation can be a problem when using TIG under pressure.

3. The MIG process can be used in up to 32 bars. However, weld quality deteriorates rapidly beyond 6 bars. This process at high pressure is characterized by arc instability and stubbing, a marked increase in spatter, and a considerable increase in the fume-levels. These effects seriously limit the manual use of this process beyond a certain depth.

4. The plasma arc was extremely stable at high pressure.

5. In the GTA, GMA, and plasma welding processes, if the arc length is kept constant, the arc voltage will tend to increase with the pressure (Figure 2-1). Because of this, the plasma arc process might be a better choice for deep sea application. Though there are safety problems that need to be taken care of, the more stable arc produced makes this process worth the time spent in development. Dispite the fact that there may be severe fume production problems, the flux cored arc process may be well worth investigating.



Curve A : TIG Welding; 1/16-inch arc length; flat position.
Curve B : TIG Welding; 1/8-inch arc length; flat position.
Curve C : Dip Transfer MIG Welding; HV Position; argon in pressure vessel A/5% CO_2 shield.
Curve D : Dip Transfer MIG welding; HV Position; nitrogen in pressure vessel A/5% CO_2 shield.
Curve E : Pulsed MIG welding; HV position, argon/5% CO_2 shield, special source.
Curve F : Pulsed MIG welding; HV position; argon/5% CO_2 shield, Airco PA3.
Curve G : Plasma welding; 1/8-inch orifice; 3/8-inch stand-off, HV position.
Curve H : Plasma welding; 1/8-inch orifice; 3/8-inch stand-off; flat position.

Figure 2-1 Comparative Plot of Effect of Depth on Arc Voltage for Constant Arc Length for Various Arc Welding Processes

2.2 Hydrogen Cracking in Underwater Welds.

Hydrogen cracking in the weld metal and the HAZ is induced by the water environment. A detailed discussion of hydrogen induced cracking is given in reference 25.

The water environment charges the arc atmosphere and gas bubbles with high levels of hydrogen. The weld is rapidly quenched to a temperature where cold cracking can occur and where hydrogen diffusion from the joint is negligible. Furthermore, such a rapid cooling rate produces microstructures susceptible to cracking.

Two theoretical analyses have been done of the thermal situation in underwater welding, one by the authors and the other by Bouwman et al. The work done by the authors was described in the previous report.[1]

The analysis done by Bouwman and Hoverhals[17] using a modified form of Rykalin's Equations is shown in Figure 2-2. In the figure the empirical results done by the British Welding Institute are also shown. In the data produced by Bouwman et al, the maximum values of the cooling time from 800°C to 500°C are given; the empirically obtained values appear to be linear.

The cooling rate of a underwater weld is generally several times that of an air weld (see Figure 2-3). Figure 2-4 illustrates the relationship between the critical cooling time (from 800°C to 500°C) and the strength of various steels. The definition of the critical cooling time is the required cooling time from 800°C to 500°C to produce a fully martensitic structure

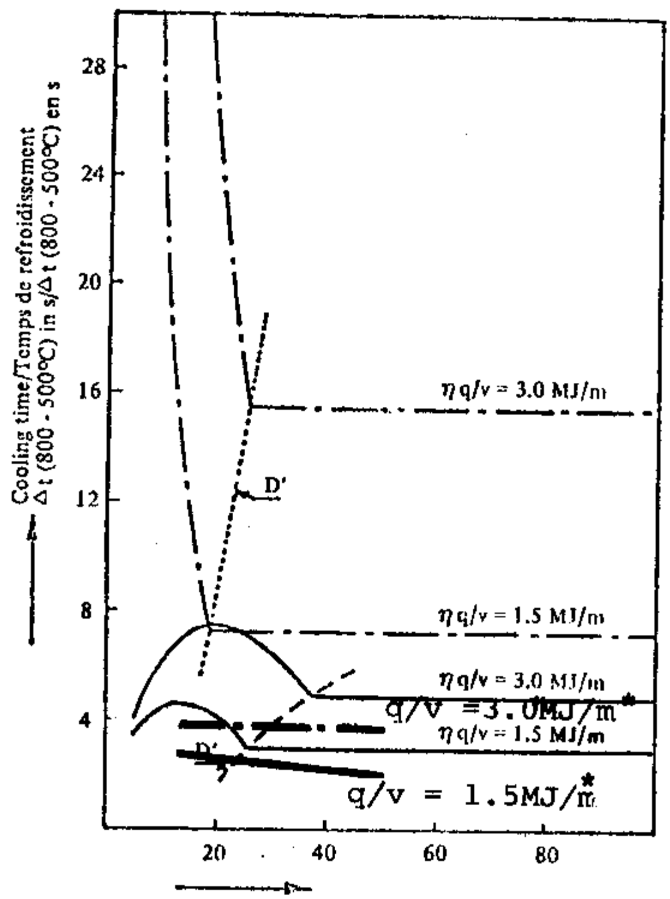
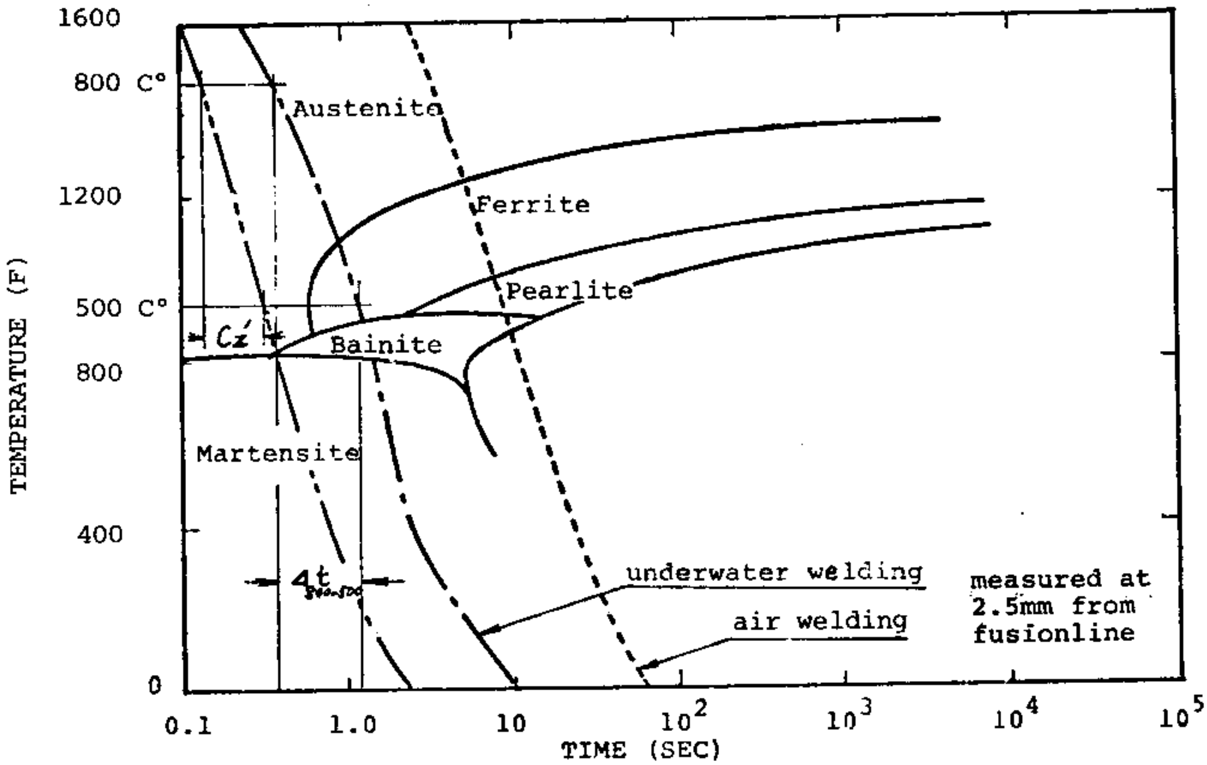


Plate thickness D in mm/Epaisseur de la tôle D en mm
*taken from the reference 27.
———— Underwater welding/Soudage sous l'eau
— - — Welding in the air/Soudage dans l'air

Figure 2-2 Cooling time vs. plate thickness during welding



Cooling curves of underwater and air welds superimposed on the CCT diagram of 0.2% C steel

$\Delta t_{800\sim500}$ cooling time from 800 C to 500 C

Cz critical cooling time from 800 C to 500 C

Fig. 2-3 Cooling curves of underwater and air welds superimposed on the CCT diagram of 0.2% C steel

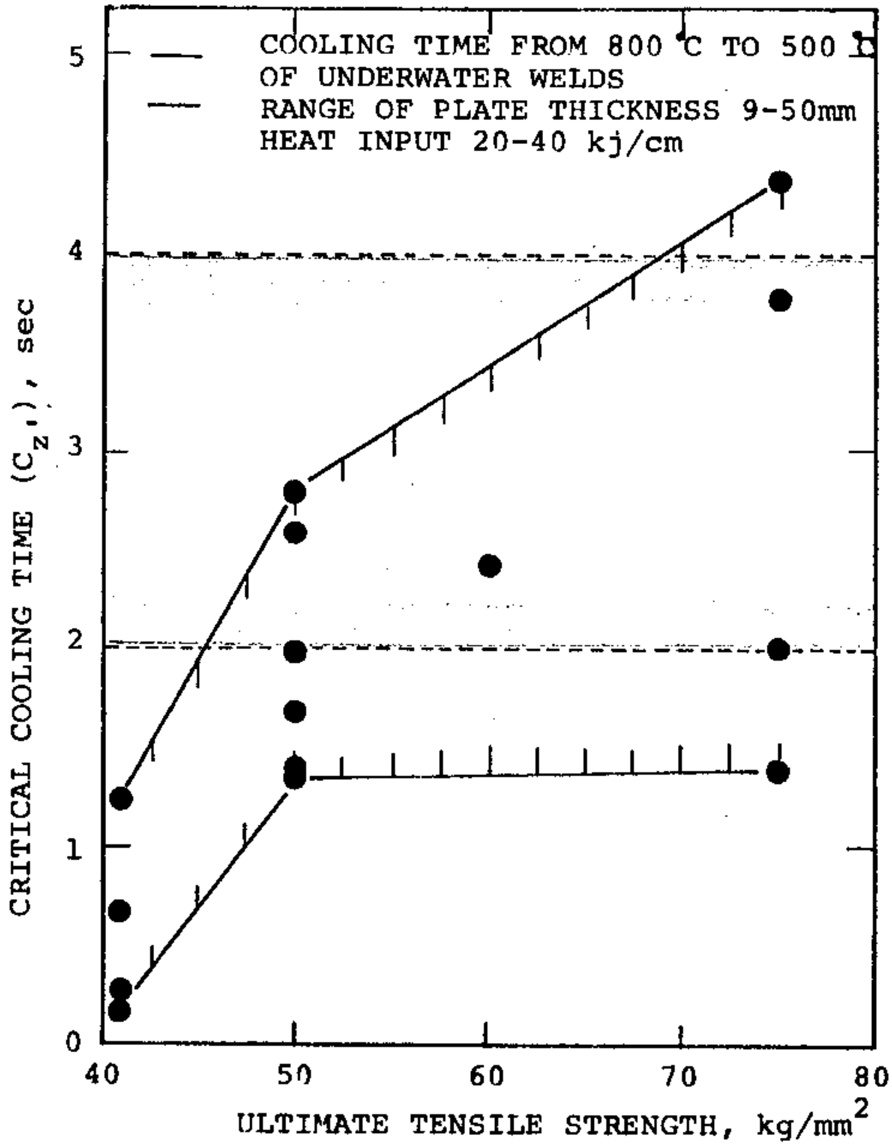


Fig. 2-4 Critical cooling times of various steels for producing full martensite structure

(see Figure 2-3). In the figure, the probable critical cooling time is shown to be in the range of 2-4 seconds.

In underwater welding, steels with more than 50kg/mm^2 (71 KSI) are likely to produce a fully martensitic structure. Only mild steel can be welded underwater without producing a martensitic structure. This data correlates with the results by Bouwman et al, (17) which indicated that ST52 steel (UTS, 50kg/mm^2 [70 KSI] class steel) was a borderline case for hydrogen cracking. Figure 2-5 shows the relationship between the maximum hardness values in underwater welds and the strength of various steels.

The maximum hardness increase is linear with respect to the increasing strength of the steels in both underwater and air welds. The difference in maximum hardness between the two is much less at higher strength levels. At 80kg/mm^2 (114 KSI) the difference is minimal. Note that the maximum hardness of underwater welds of mild steel can nearly equal that of air welds of high tensile strength steel. Figure 2-6 shows the relationship between the carbon equivalent of steels and the maximum hardness values of underwater welds.

Table 2-1 shows the relationship between the diffusible hydrogen content of shielded metal arc weld metals and the different coating fluxes. The iron oxide-iron powder type electrode appears to give the lowest diffusible hydrogen content (24cc/100g). The diffusible hydrogen content with a low hydrogen electrode is about 32cc/100g, which is lower than those

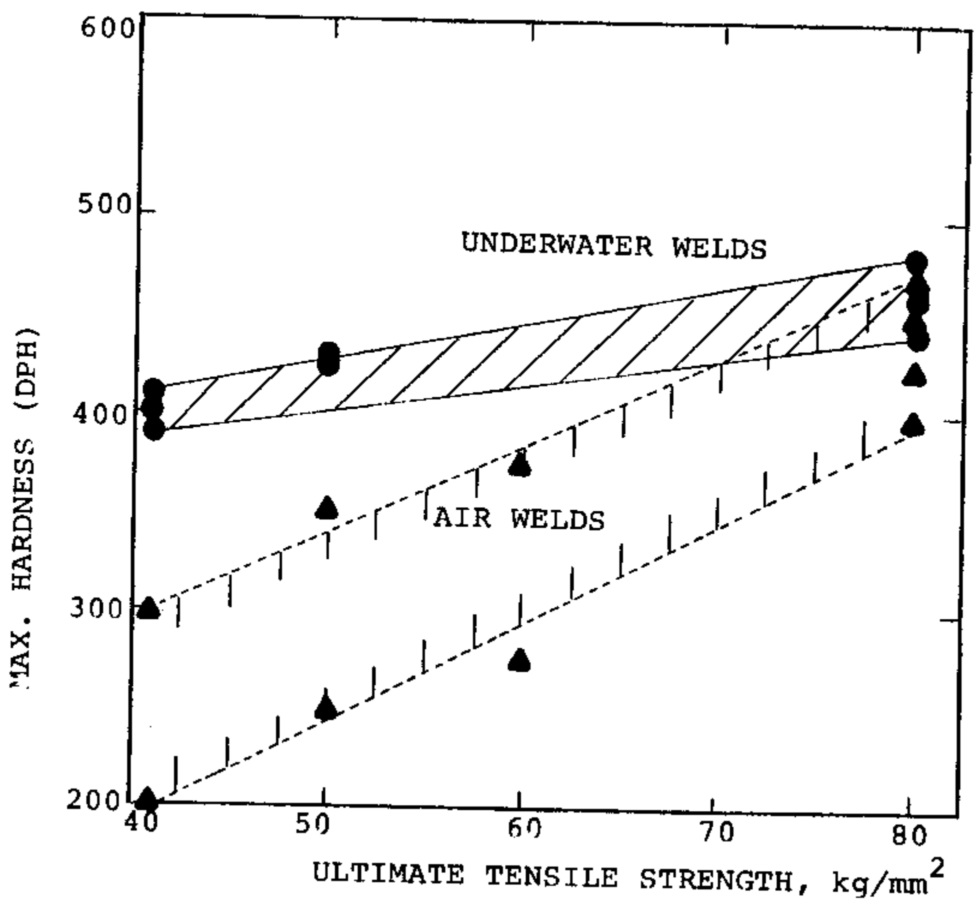


Fig. 2-5 Relationship between maximum hardness of underwater welds and ultimate tensile strength of steels

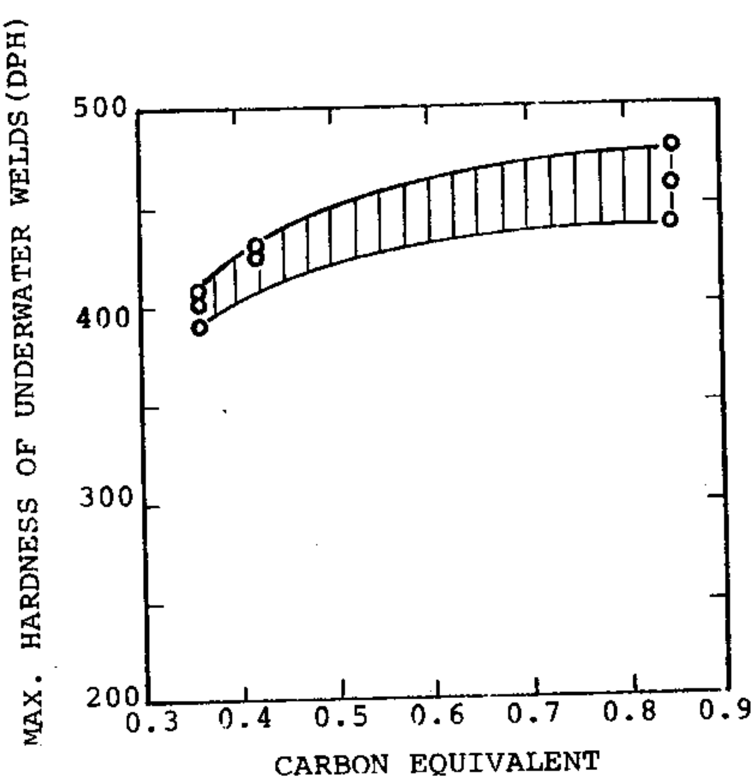


Fig. 2-6 Relationship between carbon equivalent of steels and maximum hardness in underwater welds

Table 2-1 Comparison of diffusible hydrogen content and mechanical properties of shielded metal arc weld metals made with different flux coatings

type of electrode	UTS kg/mm^2	elongation %	Max. hardness DPH *1	charpy impact value kg.m	diffusible hydrogen content cc/100g
rutile iron powder (7014)	53.6	8.5 *2	390	2.4 (4.0) [0 C]	53.5 *3
cellulosic (6010)	50.5	7.4 *2	378	(5.0)	
rutile iron powder (7024)			387	1.29 (4.0) [0 C]	43.0 *3
iron powder iron oxide (7027)	54.3	10.9 *2	360	1.07 (5.0) [0 C]	24.0 *3
low hydrogen (7018)				(12.0) [0 C]	32 *4
(8018)					32 *4
(11018)					32 *4

*1 : measurement was done including HAZ
*2 : result of notch tensile test
*3 : IIW method
*4 : JIS method (glycerine method) conversion was made using the following equation

$$H_{IIW} = 1.266\ H_{JIS} + 2.19$$

Values in parentheses () are obtained in the air.
The temperature of charpy test is shown in the parentheses[].
Mild steel was used as base metal.
1 kg.m = 7.25 ft.lb   0 C = 32 F

of rutile-iron powder or rutile type electrodes. Table 2-2 compares the amount of diffusible hydrogen of the various welding processes.

The GMA process using a water curtain, developed by Mitsubishi Heavy Industries Ltd,[26] and the flux-cored arc welding process using a special electrode developed in the U.S.S.R. give better results than those of shielded metal arc welding processes. GMA and shielded metal arc welding with iron oxide electrodes show a 22-24cc/100g hydrogen content. The hydrogen contents of air welds, shown in the parentheses, are usually much lower than those of underwater welds. Austenitic electrodes are probably best for welding steels with a carbon equivalent exceeding 0.40, because they have a high capacity for hydrogen and tend to keep it away from the crack-sensitive base metal (see Table 2-3).[27]

Although austenitic electrodes can reduce hydrogen cracking, many types of austenitic electrode tend to produce welds containing martensitic structures along the fusion boundaries due to the high parent metal dilution achieved underwater and this results in weld metal hydrogen cracking.[27]

Table 2-4 gives the results of the study, where the effect of austenitic electrodes (25 Cr--20 Ni) on the hydrogen cracking susceptibility of HY-80 underwater welds was investigated. As far as the hydrogen cracking is concerned, the use of austenitic electrodes can reduce the cracking ratio. It should be noted,

Table 2-2 Comparison of diffusible hydrogen content, cooling rate from 800 C to 500 C and mechanical properties of various underwater weld metals

process	UTS		Elongation % *7	Max. Hardness DPH *1	charpy impact value				diffusible hydrogen content cc/100g	$t_{800-500\ C}$ sec.
	kg/mm	ksi			kg.m.	ft.lb	Tem. C	Tem. F		
SMA (rutile)	53.6	119	8.5*2	390	2.4 (4.0)	17.9 (29.0)	0	32	53.5*3 (25.0)	2-8
(iron oxide)	54.3	121	10.9*2	360	1.07 (4.0)	7.8 (29.0)	0	32	24.0*3	
TIG										(15)
MIG									24*8 (2.5)	
with water curtain	73.3 (63.5)	164 (142)	23.5 (31.3)	325 (220)	6.7 (10.8)	48.6 (78.3)	R.T		10*5	
MAG (CO_2)				390	6 (13)	43.4 (94.3)	*6		22*8	(8)
FC (non shield)	46.1	103	17.4		11.1 (13)	80.5 (94.3)	20	68		
(CO_2)	42.8	95	11.9						(22)	
USSR	40	90	31.5		12.3	89.2	20	68	11.9*8	
with water curtain	53	119	13	280						
Plasma	54	120	7	400	8.2	59.5	15	59		3
FS *9				375 (250)					56*4	

*1-4 : see the note of Table , *5 : oral information, *6 : not specified
*7 : guage length is not same, *8 : measuring method was not specified
Values in the parentheses are obtained in the air.
*9 : Flux shield process see chapter 3.

Table 2-3 Welded metal hydrogen contents

Average of three determinations

Electrode no.	Electrode type	Diffusible content*	Residual content** $mlH_2/100g$ deposited metal	Total content
7	Rutile iron powder	43.0	3.3	46.3
3	Rutile	53.5	3.3	56.8
27	29/9 Austenitic	40.0	39.5	79.5
11	Oxidising iron oxide	24.0	13.5	37.5

* After 20days at 20°C

** At 650°C

Table 2-4 Effect of the use of austenitic electrode on hydrogen cracking in underwater welds of HY-80 steel

type of electrode	atmosphere	hydrogen cracking ratio (%)	total cracking ratio (%)
E11018	air	95	100
	underwater	100	100
E310-16 (25Cr-20Ni)	air	1	10
	underwater	21	100

however, that hot cracks were observed.

It is a well-known fact that the use of undermatched electrodes (the weld metal strength being lower than that of the parent metal) effectively lessens hydrogen cracking.

In addition, since the strength of underwater weld metal tends to be higher than that of air weld metal, due to the quench effect of water (see Table 2-2), it seems to be unnecessary to use so-called "matched electrodes" in underwater welding. Figure 2-7 shows the effect of undermatched electrodes on the hydrogen-cracking susceptibility of HY-80 steel. In air welding, the cracking ratio can be noticeably decreased by using E7018 electrodes, but undermatched electrodes seem to have no significant effect.

Insulating the surface of the plate to be welded is another way of reducing the cooling rate of underwater welds.

Bouwman and Haverhals[17] attempted to increase $\Delta t_{800-500}$ by using an unspecified layer. This had the effect of increasing $\tilde{\Delta} t$ by approximately 20%.

The authors investigated the insulating effect of asbestos. Only a marginal decrease in cooling rate was observed when the asbestos was placed on the top surface of the plate.

When it was placed on the back surface, no noticeable effect was observed.

Hasui et al has stated that waterglass insulation effectively reduces the $\Delta t_{800-500\,°C}$ of plasma-arc welding. With no shielding

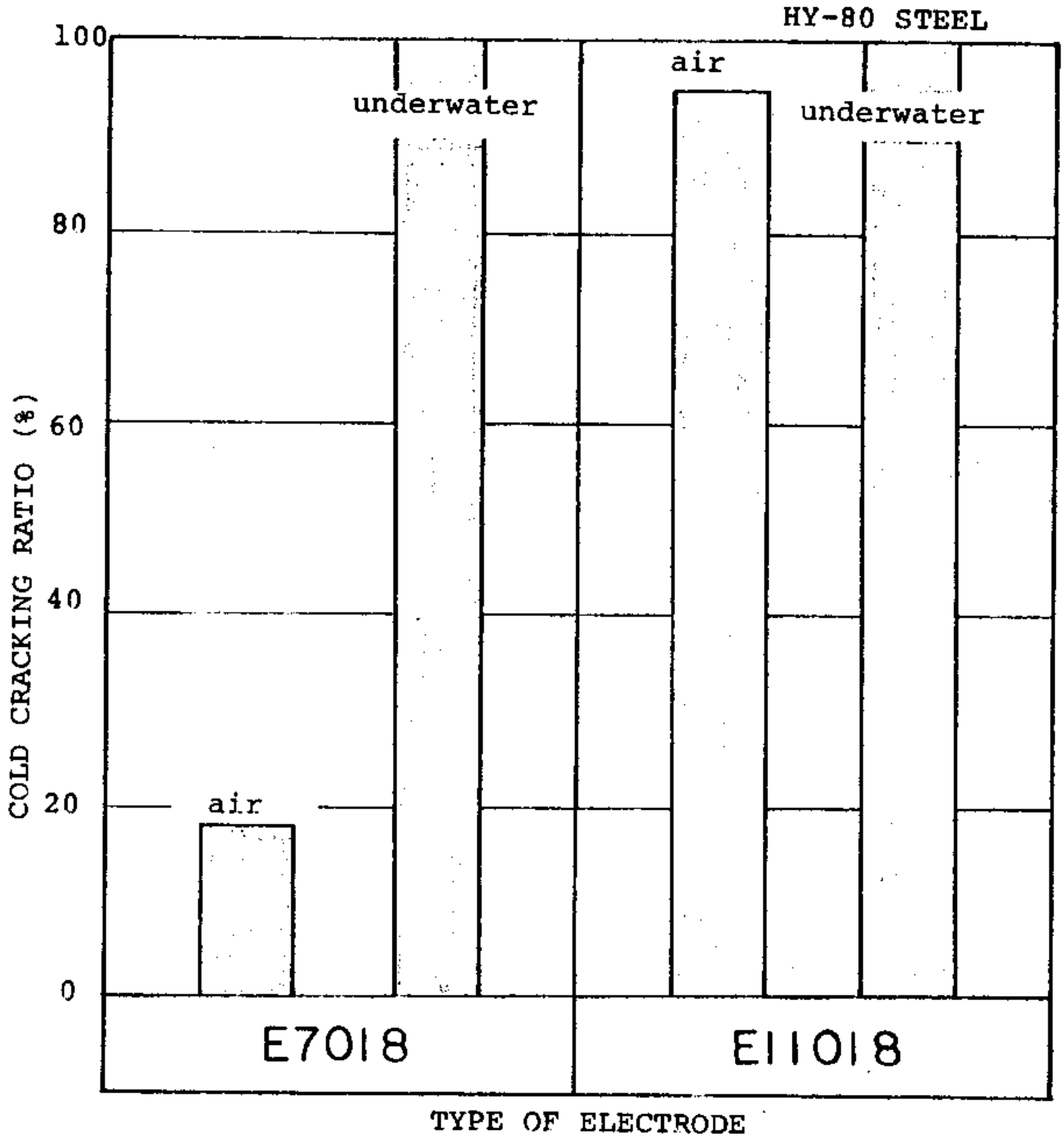


Fig. 2-7 Effect of low strength weld metal on hydrogen cracking

or with argon shielding gas, Δt was about 3 seconds; when a water-glass shielding medium was used, Δt was increased to 5 seconds.

Flux can also be a medium of insulation. The reduction of the hardness values using flux has been demonstrated (see Chapter 3)

2.3 Mechanical Properties of Underwater Welds.

2.3.1 Mechanical Properties of "Wet" Welds.

According to Madatov and Potapevski[28] the tensile strength of underwater welds is approximately 80% of those in air and the ductility approximately 50% of those in air.

Table 2-1 shows the mechanical properties of underwater shielded metal arc weld metals made using various types of electrodes. The base plates used were various mild steels.

The tensile strength of these weld metals was over 50 kg/mm^2 (71 KSI), higher than that of mild steel. Their ductility is apparently low, although these results were obtained from notch tensile tests. The Charpy impact values do not meet the appropriate requirements for air welds of the American Bureau of Shipping. The highest value, 2.4 kgm, was obtained from the weld metal made with rutile type electrodes and is in dispute. Silva reported that the Charpy impact value of the weld metal with rutile type electrodes showed only 1.0 kgm (7.3 ft lbs).

In Table 2-2, the mechanical properties of the weld

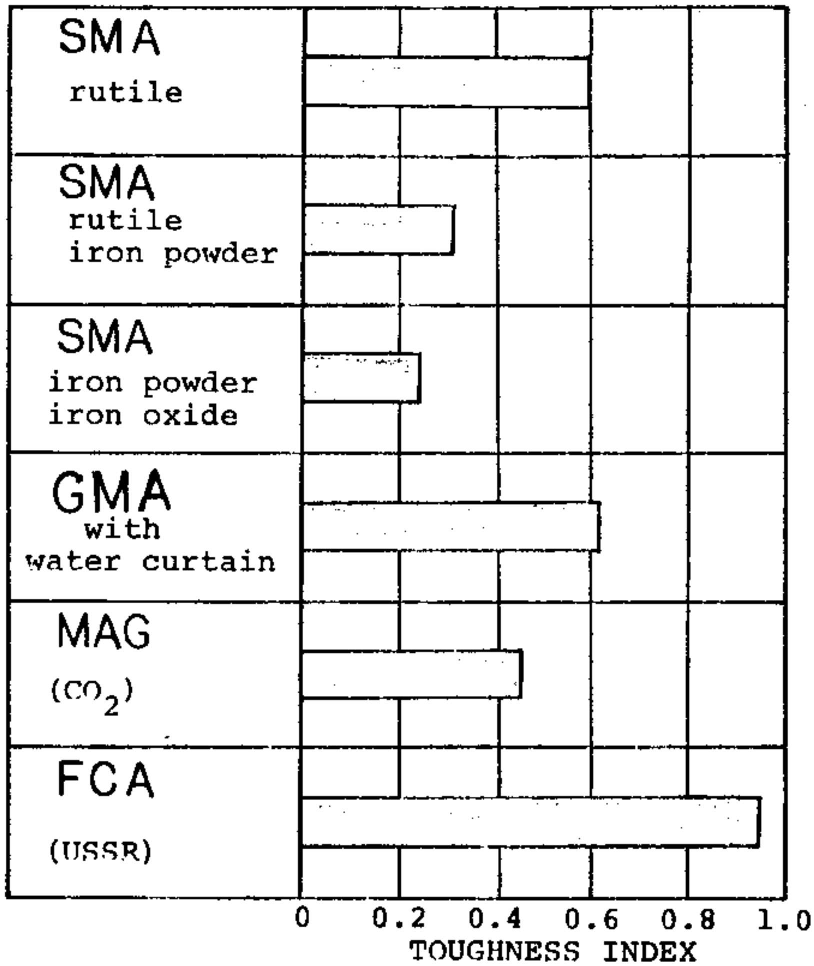


Fig. 2-8 Toughness of underwater weld metals compared to air weld metal
Toughness Index : charpy impact value of underwater weld metal/ charpy impact value of air weld metal at the same temperature

metals made by various processes are given.

The tensile strength of the weld metal using an GMA with a water curtain (solid wire) tends to increase. The use of a flux-cored wire appears to result in a relatively low-strength weld metal.

The Toughness of Weld Metals Made by GMA, MAG. According to Russian investigators, flux-cored arc (FCA) welding is superior to shielded metal arc welding and can meet ABS requirements. Toughness of flux-cored arc weld metals was good (all of the toughness data on flux-cored arc welding was given by Savitch, U.S.S.R.).

Figure 2-8 compares the toughness of underwater weld metal and air weld metal for various welding processes. The FCA process produces the best results, the toughness of the underwater weld being nearly equal to that of the air weld. Shielded metal arc underwater weld metals with rutile-iron powder or iron powder-iron oxide have low toughness indices, less than 0.32.

The weld metals made using the SMA process with rutile electrodes or the GMA process with a water curtain show a toughness index of about 0.6.

2.3.2 Mechanical Properties of Underwater Welds Made Using a "Dry" System.

The mechanical properties of underwater welds made using a "dry" system and with a careful welding sequence can equal those of air welds. But the water environment has its effect, even in a "dry" system: the welding atmosphere is much more humid than in air welding, making the welds more susceptible to hydrogen cracking, especially when the steel is high-strength. Tables 2-5, 2-6, and 2-7 and Figure 2-9 give the typical weld properties of MIG welds using solid wire and a dry welding chamber.

Table 2-7 shows the results using flux-cored wire. In every instance the mechanical properties of "dry system" welds are better than those of "wet" welds. But the use of flux-cored wire resulted in even better ductility and toughness in these "dry system" welds.

2.4 Steel Suitable for Underwater Use.

Steels for underwater use should be less sensitive to hydrogen cracking and have a high toughness value, even when the cooling rate is rapid. The low-carbon microalloyed steel that has been developed for low-temperature undersea pipelines might prove to be suitable in underwater welding. The typical chemical composition and mechanical properties of this metal are given in reference 29. The weld metal transit in properties are given in reference 30 and the hydrogen sensitivity of the bare metal is given in reference 31.

Table 2-5 Deep MIG trials in open fresh water (Mechanical test results)

BUTT WELDS CARRIED OUT ON LLOYDS E-GRADE STEEL (½-INCH THICKNESS) TECHNIQUE USED–PORTABLE DRY SPOT

DEPTH	POSITION	RADIOGRAPH	BENDS OVER 3T			MEAN CHARPY IMPACT VALUES (FT LBS AT –10°C)	ULTIMATE TENSILE STRENGTH OF JOINT (TPSI)
			FACE	SIDE	ROOT		
65 feet	Downhand	Very good	180° 180°	180°	–	35·0	31·4 Failed in plate
65 feet	Vertical	Very good	180° 180°	145°	–	28·0	30·75 Failed in plate
90 feet	Downhand	Very good	180° 180°	180°	180°	30·5	30·65 Failed in plate
90 feet	Vertical	Very good	180° 180°	180°	–	29·0	31·00 Failed in plate
120 feet	Downhand	Good	180°	180°		38·0	–
120 feet	Vertical	Good	180° 180°	180°		29·0	-

Table 2-6 Underwater butt weld properties, 1 inch EH steel (0.46 carbon equivalent)

Single 'U' Edge Preparation, Hydrobox Technique, MIG Process

POSITION	ELECTRODE WIRE	SHIELD GAS	WELD METAL PROPERTIES	BENDS (3T)	CHARPY VALUES (FT LBS) MEAN
Vertical	BOC LW1 MILD STEEL	A/5% CO_2	NA	FACE	UPPER LEVEL
				180° 180°	+20°C : 67 0°C : 36 −20°C : 20
				ROOT	LOWER LEVEL
				180° 180°	+20°C : 57 0°C : 33 −20°C : 23
Vertical (Approval Test)	Inconel	Argon	Weld: 34·40 tsi UTS: 53·28 tsi Elongation: 23%	FACE	UPPER LEVEL
				180° 180° 180° 180°	+20°C : 54 0°C : 53 −20°C : 54
				ROOT	LOWER LEVEL
				180° 180°	+20°C : 46 0°C : 45 −20°C : 42
Downhand (Approval Test)	Inconel	Argon	Weld: – UTS: 48·96 Elongation: 22%	FACE	UPPER LEVEL
				180° 180° 180°	+20°C : 47 0°C : 49 −20°C : 43
				ROOT	LOWER LEVEL
				180° 180°	+20°C : 39 0°C : 37 −20°C : 36

Table 2-7

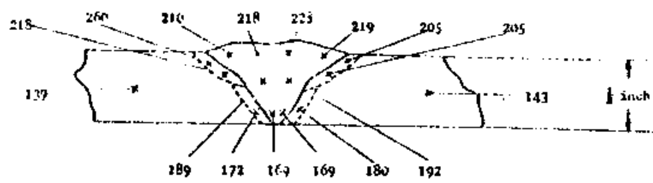
FLUX-CORED WIRE WELDING UNDERWATER

ALL-WELD-METAL PROPERTIES

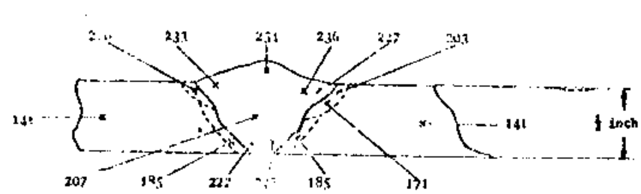
(RESULTS FROM ALL-WELD-METAL TEST WELD ASSEMBLIES AS SPECIFIED IN BS 639.
WELDING CARRIED OUT IN DRY WELDING CHAMBER)

			WATER DEPTH (FEET)		
			0	70	260
YIELD STRENGTH		TONS / IN^2	33•73	32•76	
		KG / MM^2	53•14	51•61	
ULTIMATE TENSILE STRENGTH		TONS / IN^2	38•01	38•91	
		KG / MM^2	59•87	61•30	
ELONGATION (%)			29	27	
REDUCTION OF AREA (%)			72	66	
CHARPY IMPACT STRENGTH	0°C	FT-LBS	112,137,149 / 133	103,120,128 / 117	
		KG-M	18•4	16•2	
	−30°C	FT-LBS	108,112,124 / 115	62,68,74 / 68	
		KG-M	15•9	9•4	
WELD METAL HARDNESS (DPN 10KG)			209 − 163 / 187	238 − 187 / 207	

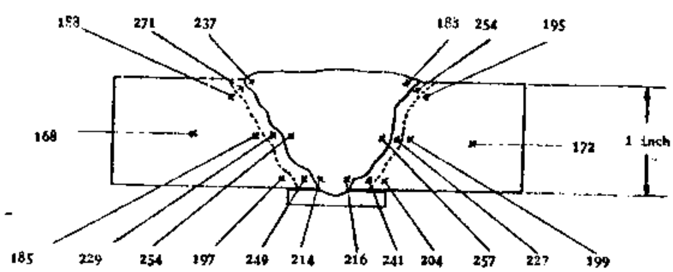
MATERIAL: E GRADE STEEL THICKNESS: 1/2 INCH
HARDNESS VALUES IN VPN MEASURED WITH 10 KG LOAD
MILD STEEL ELECTRODE WIRE. DEPTH: 90 FEET WATER



A. Downhand Butt Weld



B. Vertical Butt Weld



C. Hardness Survey - Inconel Butt Weld

HARDNESS VALUES IN VPN MEASURED WITH 5 KG LOAD
DOWNHAND BUTT WELD MATERIAL: EH2 STEEL
DEPTH: 90 FEET OF WATER THICKNESS: 1 INCH

Figure 2-9 Butt Weld Hardness Surveys

CHAPTER 3: UNDERWATER STUD WELDING AND FLUX-SHIELDED WELDING

The underwater welding processes currently in use were discussed in the last chapter. After a careful examination of these, the stud welding and flux-shielded welding processes were chosen to be the focus of this particular research program. The reasons for this decision are as follows:

1. Extensive training and experience are not required in order to do stud welding. This makes it an ideal diver's tool. Although stud welding is an arc welding process, it is simple and can be used in a variety of ways.

2. Flux-shielded welding does not require a gas supply, making it ideal for deep-sea use. The arc is submerged in the molten flux and the water expelled by direct flux covering. An automated form of the process could be used for such deep-sea applications as pipeline welding.

Underwater joining processes are relatively new and have not been tested in large scale underwater construction. But due to the leveling off of the economy and the necessity for new kinds of expansion in the offshore development industry, the advanced technological development of underwater joining processes is in the beginning stages, but accelerating. At present this development is in response to certain specific needs, among which include:

1. Automatic or mechanized equipment so that divers with

specialized manual skills will not be required.

2. Equipment versatile enough to be used in a variety of different applications.

3. Operating depth and efficiency must be improved so that costs can be reduced.

4. The auxiliary equipment that supplies the electrodes, holds and guides the welding apparatus, aligns the parts to be joined and prepares the joints for welding must be improved.

5. More presently-available joining processes need to be evaluated for possible underwater use.

This study is in specific response to needs #1 and #5.

3.1 The Processes.

3.1.1 Stud Welding Process.

Stud welding is an arc welding process in which metal studs (or similar part) and a workpiece are heated and melted by an electric arc drawn between them. Then the two pieces are brought together under pressure to form a strong, welded joint. This simple joint replaces drilled-and-tapped studs, reduces the number of required operations, and saves time and money.

The two basic techniques of stud welding are defined by their method of power supply. A motor generator, a transformer rectifier, or a storage battery must be used as a power supply for the first method, arc stud welding. The power supply for the second method, capacitor-discharge stud welding, is a low-voltage electrostatic storage system, and the arc is produced by a rapid discharge of stored electrical energy. Both methods involve direct current and arcing and in both cases the stud serves as the electrode and a "stud gun" as the electrode holder.

3.1.1.1 Arc Stud Welding.[32, 33]

Above water, the arc stud welding process is the most widely used of the two basic types of stud welding and is similar in many respects to manual shielded metal-arc welding. The heat for end welding of the studs is developed by passage of current through an arc from the stud (electrode) to the plate (workpiece). Automatic controls determine the welding time and the plunging of the stud into the molten metal to complete the weld. The weld is usually completed in less than one second, the actual duration of the weld cycle depending upon the diameter of the stud and the particular equipment used. By using a ceramic arc shield (ferrule) around the stud, substantial shielding is obtained while retaining the molten weld metal to form a fillet weld. Apart from shaping the fillet, the ferrule shields the operator from the glare of the welding arc and when preplaced in jigs, it helps in the positioning of the stud.

Flux is generally used for arc stud welding; it provides a cleaning action and acts as an arc stabilizer and deoxidizing agent. As shown in Figure 3.1, the flux is either within or permanently affixed to the end of the stud. This fluxing action

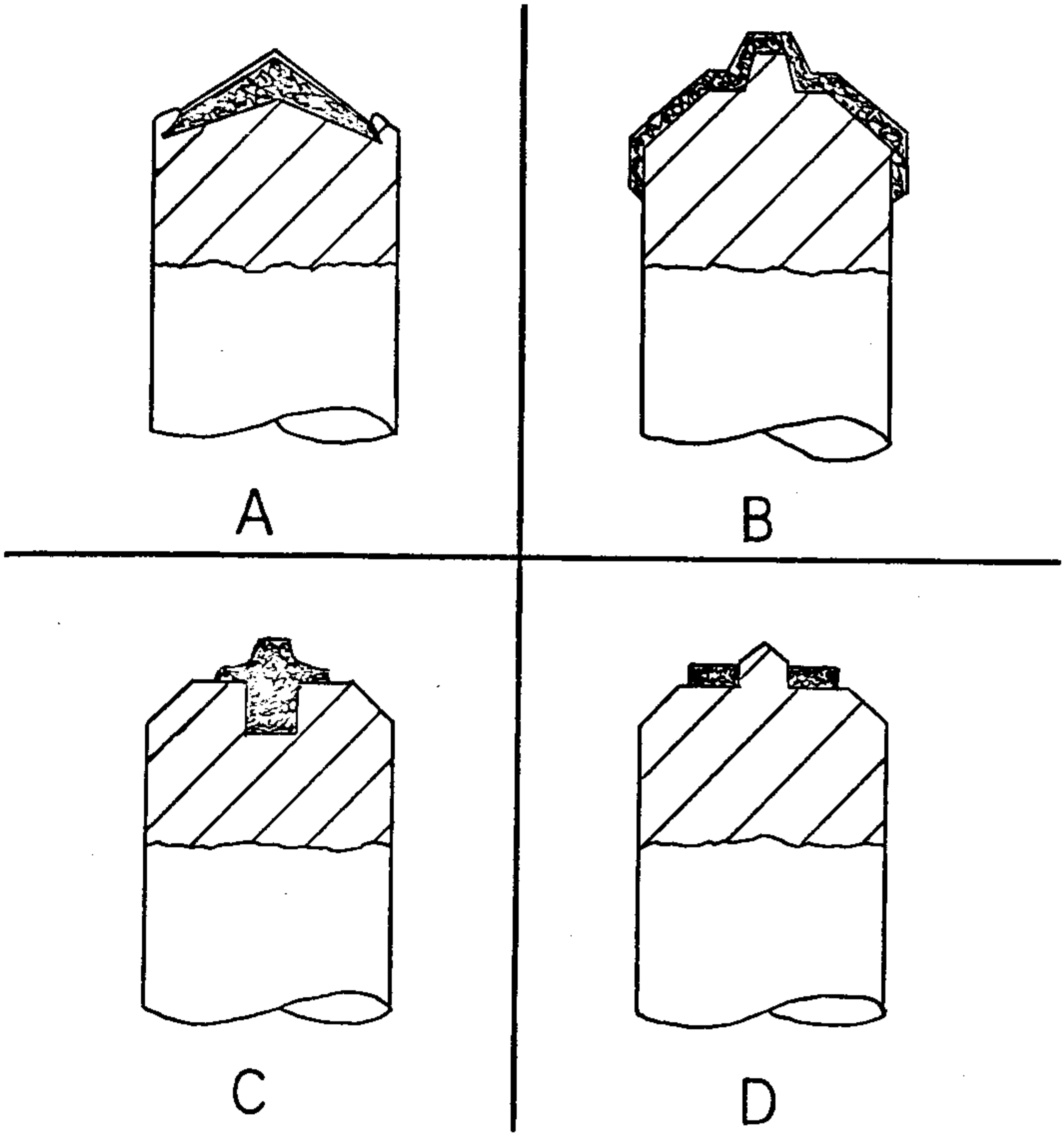


Fig. 3-1[32] Methods of containing flux on stud end; (A) Granular flux, (B) Flux coating, (C) and (D) Solid flux inserts combines with the shielding effect of the ferrule to protect the molten metal from oxidation during welding.

The mechanics of the arc stud welding process are illustrated schematically in Figure 3.2. The stud is loaded into the chuck of the stud gun, the ferrule is placed in position over the end of the stud, and the gun is properly positioned for welding (Figure 3.2A). The trigger is depressed, starting the automatic welding cycle (Figure 3.2B). The stud is lifted by a solenoid within the body of the gun, creating an arc and forming a molten pool on the workpiece and the stud end. A controlling device limits the arc period automatically, according to a predetermined setting. At the end of the arcing period, the welding current is shut off, de-energizing the solenoid, allowing the mainspring of the gun to plunge the end of the stud into the small volume of molten metal to complete the weld cycle (Figure 3.2C). The gun is lifted from the stud and the ferrule is knocked off since the weld solidifies almost instantly (Figure 3.2D). A shielding gas is sometimes used when nonferrous alloys are being arc stud welded.

The arc stud welding process is used to best advantage when the base metal is thick enough to enable the weld to be made without burn-through and allowing the full strength of the welded stud to be developed. For low-carbon steels, the weld base diameter of the stud should be at least one-third the base metal thickness, and, to avoid burn-through, the weld base diameter should be at least one-fifth the base metal thickness.

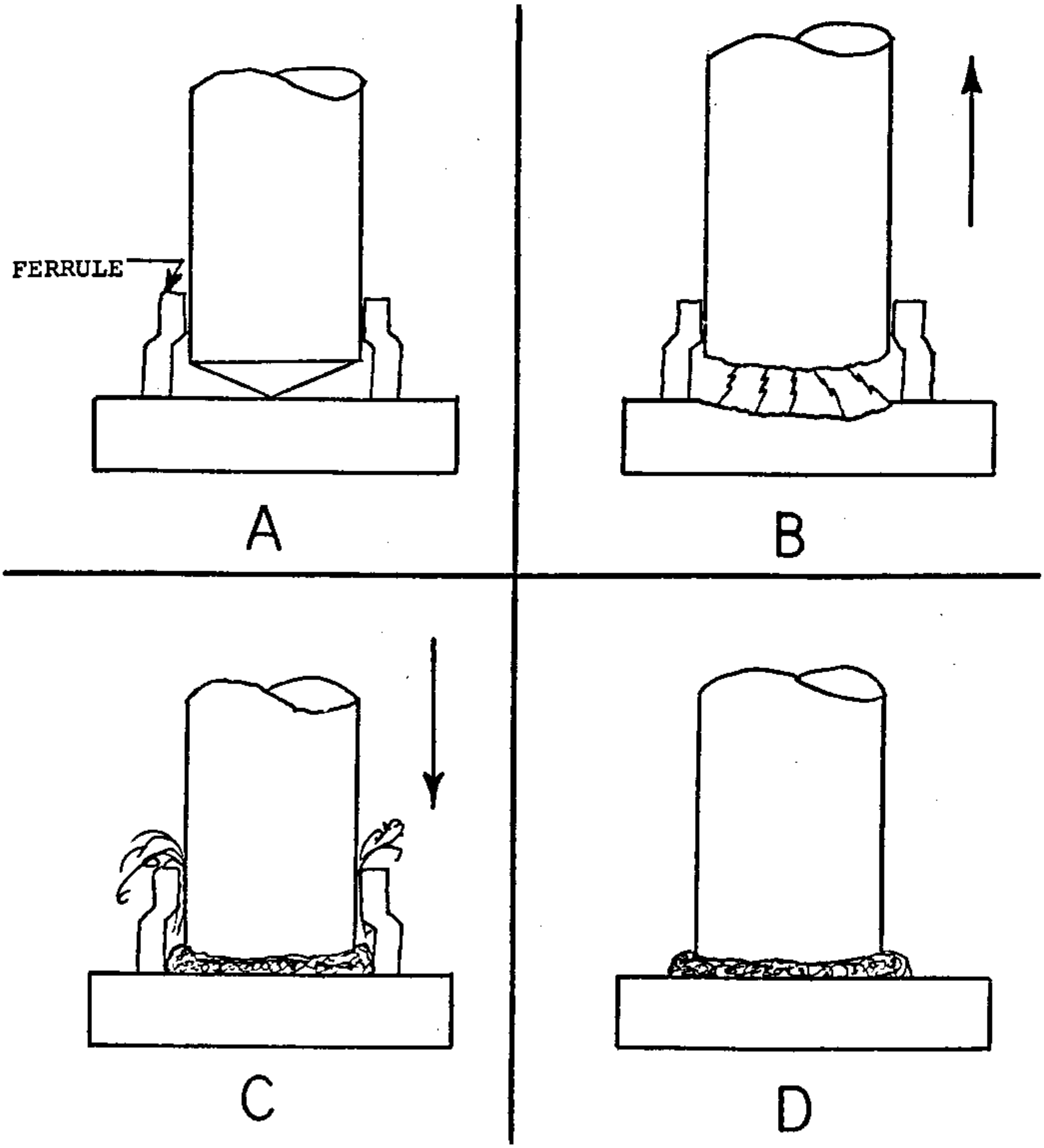


Fig. 3-2[32] Schematic of arc stud welding; (A) Stud placed against work, (B) Gun lifts stud drawing arc, (C) Stud plunged into molten pool of metal, (D) Gun and ferrule removed for completed weld

3.1.1.2 Capacitor Discharge Stud Welding.[32, 33]

The second basic stud welding process derives its heat for welding from an arc produced by a rapid discharge of stored electrical energy, with pressure applied to the stud during or immediately following the electrical discharge. The arc is established either by rapid resistance heating of a projection on the stud weld base with a resulting weld time of 3 to 6 milliseconds, or by drawing the arc in a similar manner to that of arc stud welding by lifting the stud away from the plate. The latter procedure results in a 6 to 15 millisecond weld time. In either case, no ceramic ferrule or flux is used due to the speed of welding.

Another consequence of the extremely short welding time in capacitor discharge stud welding is the absence of heat build-up. This allows welding of studs to thin materials without pronounced distortion, burn-through, or discoloration. Weld penetration is slight, which permits many dissimilar metals to be welded with acceptable strength and metallurgical structure.

There are three different capacitor discharge stud welding systems: initial contact, initial gap, and drawn arc. These processes vary primarily in the manner of arc initiation. Initial contact and initial gap utilize studs with small, specially engineered tips on the stud end, while the drawn arc method uses studs that have rounded tips on the stud end. Most of the studs used in capacitor discharge stud welding have a flanged or enlarged base.

In Figure 3.3 the procedure of initial contact capacitor discharge stud welding is shown schematically. The stud is first placed against the work (Figure 3.3A). The stored energy is next discharged through the projection at the base of the stud. This small tip presents a high resistance to the stroed electrical energy and rapidly disintegrates, creating an arc that heats the surfaces to be joined (Figure 3.3B). During arcing (Figure 3.3C), the stud and the workpiece are in the process of being brought together by the action of a spring in the stud gun. When the two surfaces are in contact, fusion takes place to complete the weld (Figure 3.3D). The melted surface layer on each part is only a few thousandths of an inch thick. There is very little weld spatter, producing a smooth clean weld.

The sequence of operation in initial gap capacitor discharge stud welding is shown in Figure 3.4. The stud is positioned away from the surface of the workpiece leaving a small gap between the stud and the work. When the gun is triggered, a solenoid brings the stud in contact with the work (Figure 3.4B) causing current to flow and flashing off the tip. The arc formed heats the metal on the stud end and the work, causing them to become molten (Figure 3.4C). Continued movement of the stud onto the work extinguishes the arc and forges the stud into the workpiece as shown in Figure 3.4D. The weld is completed with little or no reverse side marking.

The drawn arc capacitor discharge stud welding method is best

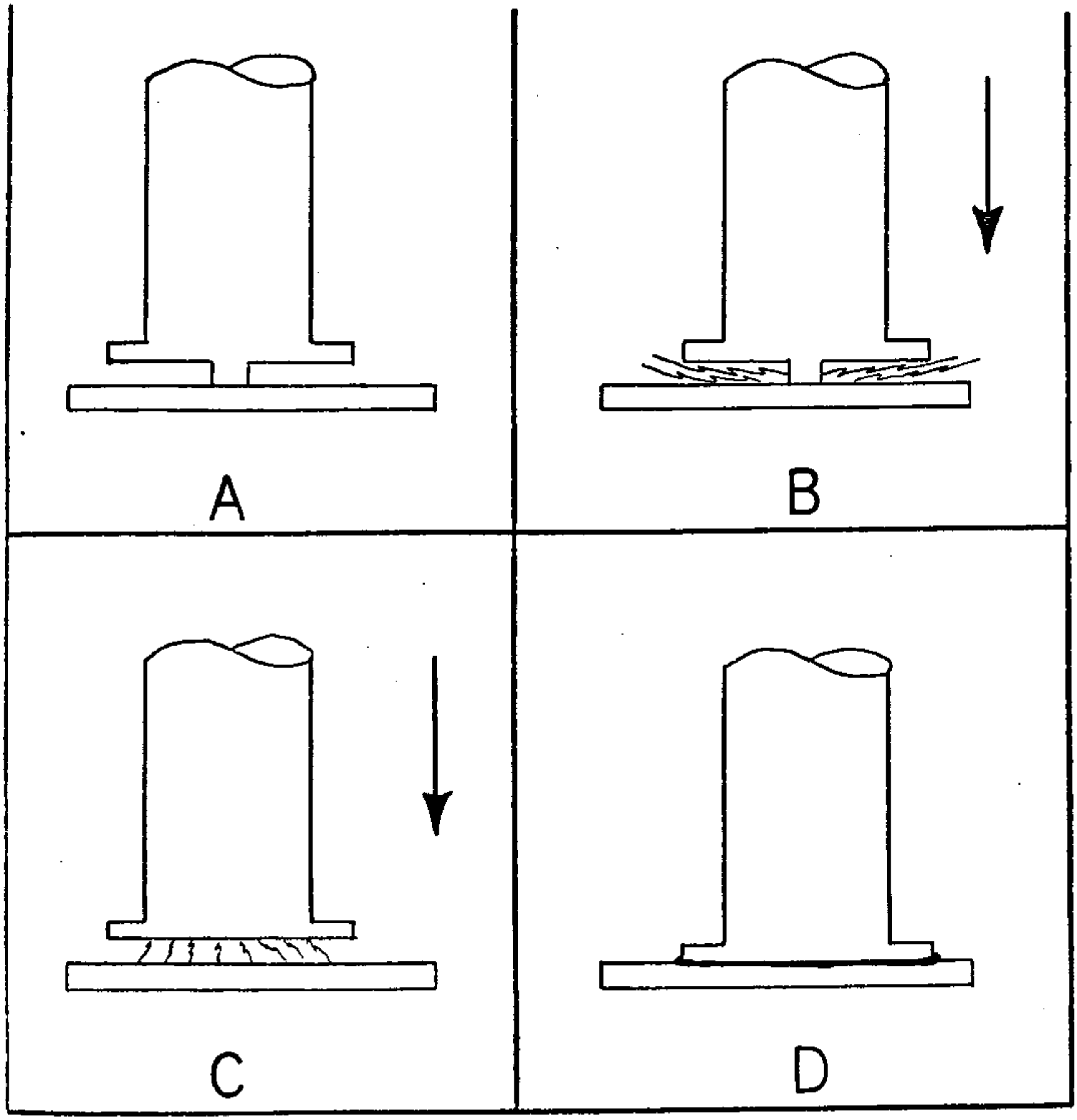


Fig. 3-3[32] Schematic of initial contact capacitor discharge stud welding; (A) Stud placed against work, (B) Stored energy creates arc at stud tip, (C) Tip flashes off as stud plunges into molten metal, (D) Completed weld

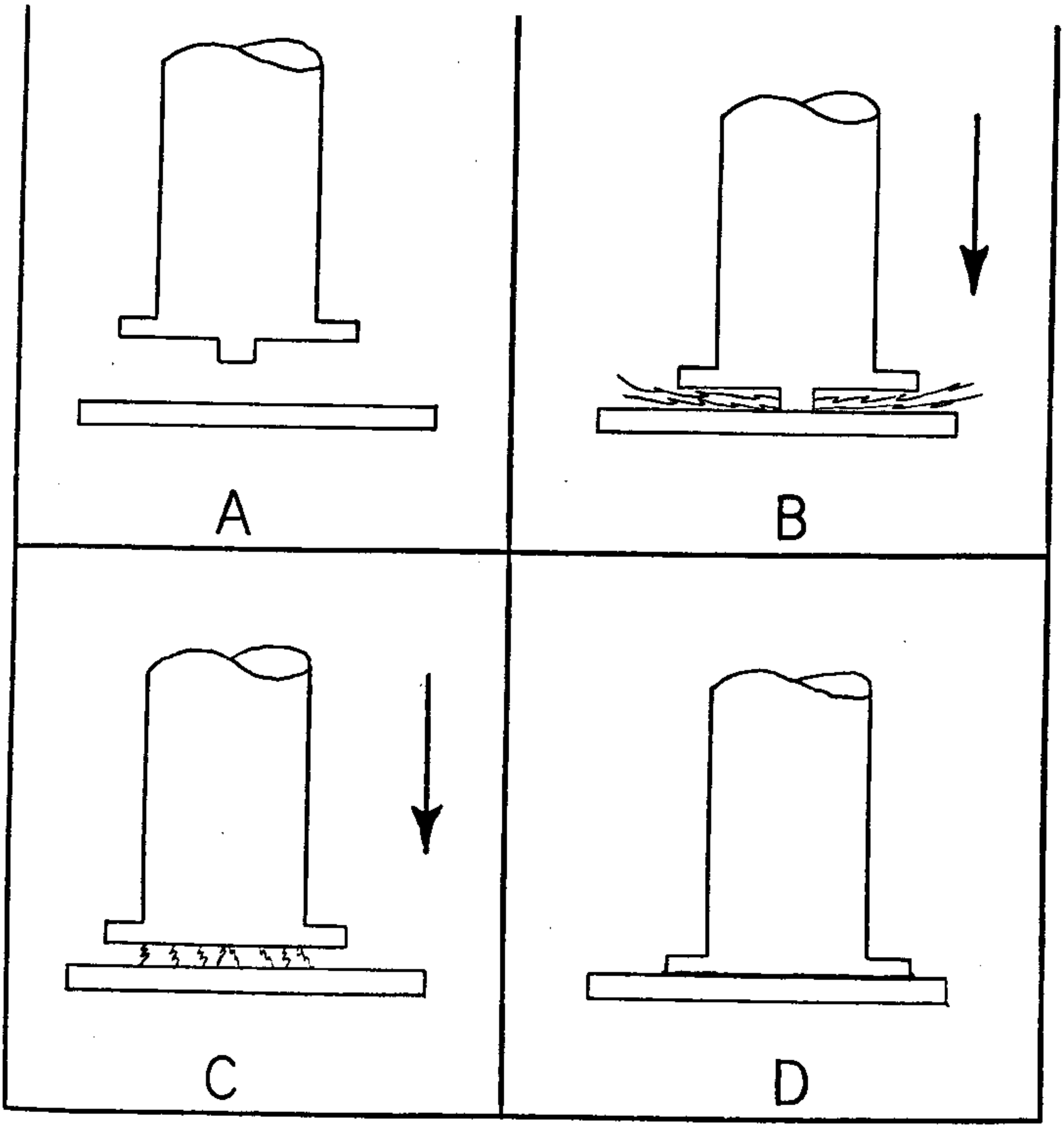


Fig. 3-4[32] Schematic of initial gap capacitor discharge stud welding; (A) Stud positioned away from work leaving gap, (B) Stud tip contacts work creating arc, (C) Tip flashes off as stud plunges into molten metal, (D) Completed weld suited for base metals that have light rust, millscale, or surface irregularities. As shown in Figure 3.5A, this method positions the stud against the work. The trigger switch is actuated, energizing a solenoid coil in the stud gun body. The stud is lifted from the work (Figure 3.5B) drawing a low-amperage pilot arc. As the lifting coil is de-energized, the stud starts to return to the work. The welding capacitors are discharged, creating the welding arc, melting the end of the stud and the adjacent workpiece. The stud then plunges into the puddle of molten metal (Figure 3.5C) to finish the weld, leaving little or no fillet.

The capacitor discharge system of stud welding offers amazing versatility, due to the almost limitless variety of stud sizes, shapes, and materials, the inherent speed of application, the ability to fasten light gage and dissimilar materials without distortion or burn-through, and the elimination of postweld cleaning or finishing operations. Because of these factors, capacitor discharge stud welding has earned a unique place in production welding, taking full advantage of its economic nature.

3.1.2 The Flux-Shielded Welding Process.

In this process a consumable electrode is fed into a weld zone at a controlled rate while a continuous blanket of molten flux shields the weld zone from contamination, enabling the use of this process underwater. Because water is eliminated from the arc area during welding, the water quenching rate is reduced.

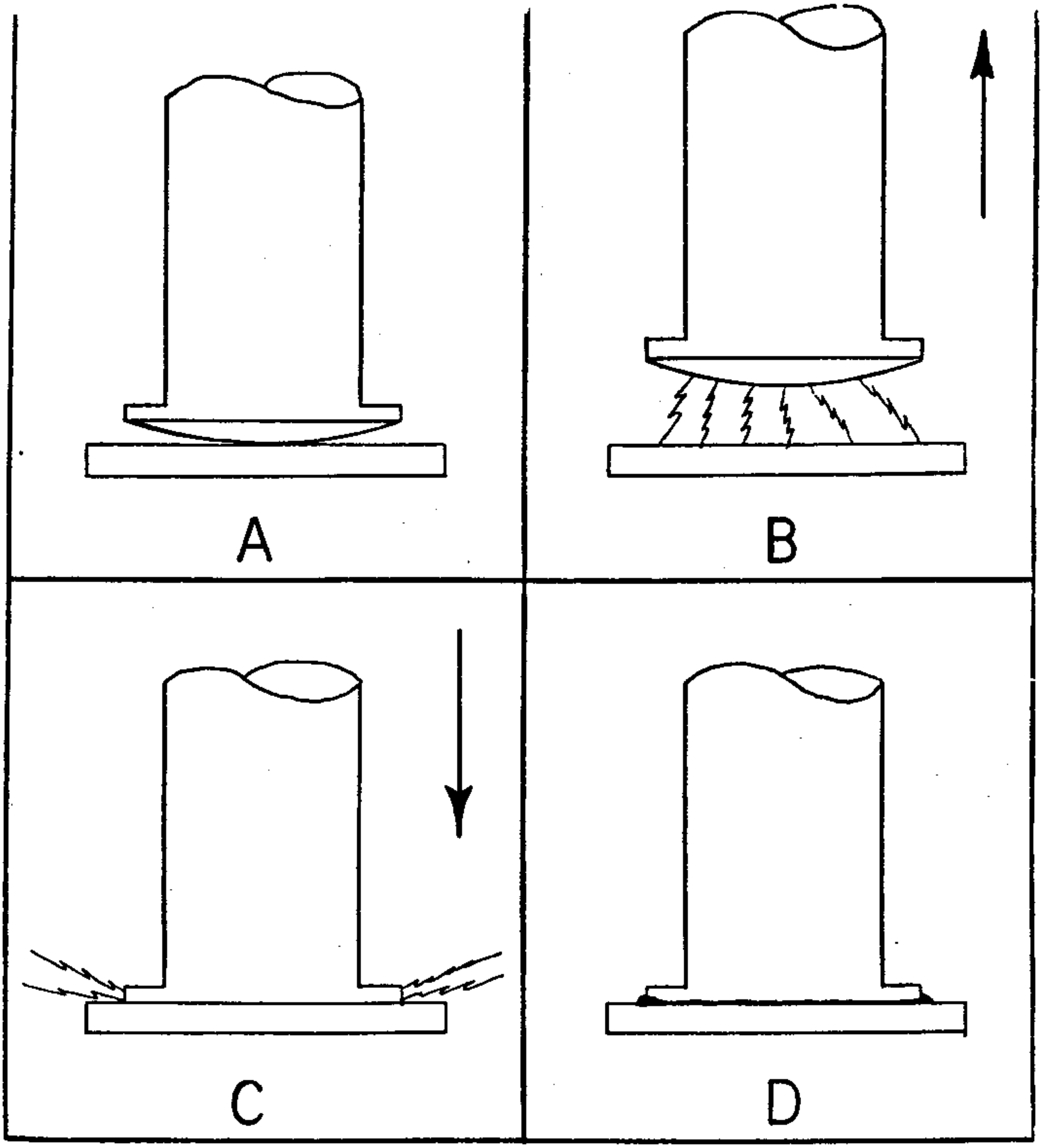


Fig. 3-5[32] Schematic of drawn arc capacitor discharge stud welding; (A) Stud placed against work, (B) Gun lifts stud drawing arc, (C) Stud plunged into molten pool of metal, (D) Completed weld

The two basic techniques of flux-shielded welding are defined by their method of flux utilization. A flux-feed system supplies liquid flux to the weld area and protects the arc from water contact. This approach has not been too successful because of difficulties associated with developing a liquid flux that feeds properly. In the flux-stuffed enclosure system, welding flux and other chemicals are packed in a prefabricated enclosure that is then aligned with the joint of the plate to be welded by means of an alignment guide. When the enclosure is in place, a resilient sealing member of suitable material on the bottom sheet (preferably near its periphery) provides a water seal. A suitable clamping device such as an electromagnet is used to hold the enclosure. The electrode penetrates the flux layers and is energized when it touches the bottom sheet. The electrical arc melts the sheet, the electrode, the base metal, and the flux into a common pool. The molten flux acts as a cleaning agent and floats to the top of the weld as protective slag while the weld solidifies (see Figure 3.6A and B).

Our study of the flux-shielded processes started one year ago; many problems still remain unsolved. Experiments were conducted on simplified specimens to determine how much a flux covering reduces the cooling rate.

3.2 Capabilities and Limitations of the Process.

It is extremely important to make sure the welding process selected for a given situation is the most appropriate one

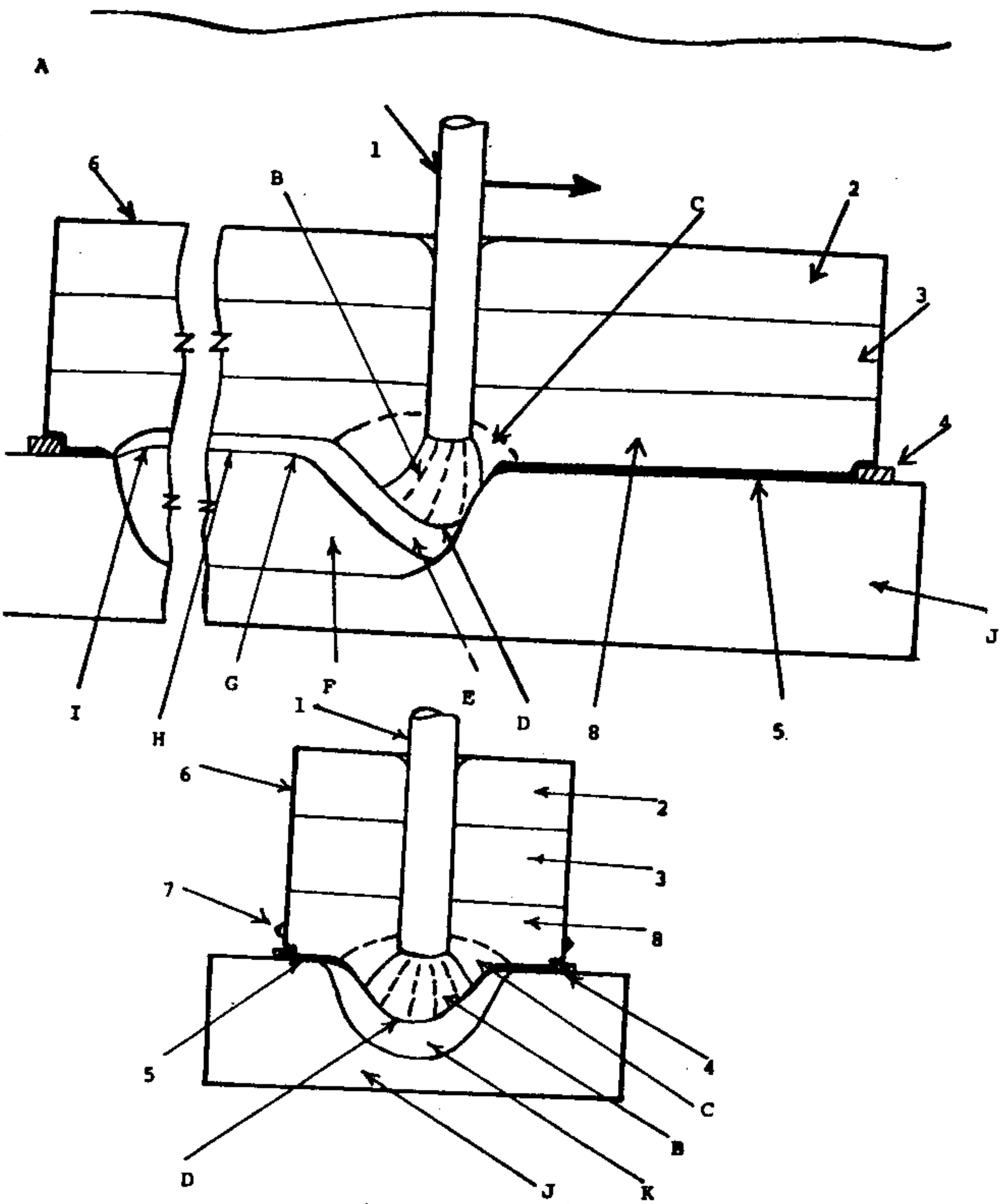


Figure 3-6a,b An Underwater Submerged Arc Welding Process

List of Symbols

A Water
B Welding Arc
C Molten Flux
D Molten Pool of Fillet Metal, Metal Sheet, Base Metal and Flux
E Freezing Weld Metal
F Solid Weld Metal
G Molten Slag
H Freezing Slag
I Solid Slag
J Base Metal
K Heat Affected Zone
L Polymer Corn

1 Electrode
2 Polymer
3 Powder Insulation Material
4 Bottom Seal
5 Thin Metal Sheet
6 Enclosure
7 Check Valve
8 Flux
9 Joint Fit-Up Guidance
10 Slut Cover

Figure 3-6a, b (continued)

available. There are several basic considerations pertinent to this process selection, including the following:

Base Metal. Low-carbon steel and austenitic stainless steel can be welded using either stud welding process. Aluminum alloys, copper, brass and galvanized sheet are welded using the capacitor-discharge method. The flux-shielded process has been tested on low-carbon steel and medium high-strength steel. The weld cracks produced using conventional shielded metal arc welding methods on medium high-strength steel do not appear when a flux-shielded welding method is used (see Chapter 5). The flux-shielded process may also be suitable for low-carbon, high-alloy steels. The effectiveness of the flux-shielded cooling reduction when welding high-strength steels is yet to be determined; more experimentation is needed.

Working Depth. Its simplicity of operation makes stud welding suitable for deep ocean use. Capacitor-discharge welding can be used on studs ranging from 1/16 to 3/8 inch in diameter. Arc stud welding must be used on diameters greater than 3/8 inch and can be used on diameters of 1/4 inch. The arc stud process promises to be most useful in the deep-sea welding of large diameter studs. The flux-shielded process is also suitable for deep-sea use because it does not require shielding gas. Due to its invisible arc motion, the system must be automated, and this enables it to be operated by a diver.

Base Metal Thickness. The capacitor discharge method can be used only for parent metals less than 20 gage (0.036 inch) thickness. Arc stud welding results in a much larger weld fillet and deeper penetration than the capacitor-discharge method and therefore can be used on thicker plate.

Shape of Joint. Stud welding is simply attaching a stud to a plate. In capacitor-discharge stud welding, stud bases are nearly always round, though the shank may be any shape. In arc stud welding, square, rectangular, or any odd shape of small stud may be used. Flux-shielded welding can be used to weld tee-joints or lap-joints. The enclosure system is suitable for welding a closed contour such as a pipeline.

Quality Requirement. Metallurgical problems are encountered in arc welding, both in stud welding and flux-shielded welding. Satisfactory welds do not have inclusion, porosity, cracks, and other defects that show up in macroscopic and microscopic examinations. Arc stud welding gives a larger fillet and a deeper penetration, but also a much larger heat affected zone than the capacitor discharge method. Reduction of impact strength in the heat affected zone may turn out to be a problem in underwater welding. The flux-shielded process, though it reduces the cooling rate during welding, has not successfully eliminated water from the weld area completely, and the diffusible hydrogen content in the weld is about the same as that in underwater shielded metal-arc methods. Improving the water seal may reduce the amount of hydrogen dissolved in the molten puddle during underwater welding.

Since stud penetration into the base metal is slight, many different combinations of stud and base metals are capable of producing quality stud welds. If both parts are electrical conductors, the melting point and the electrical resistivity of the parts to be welded have little effect on the weld.

The limitations to stud welding, although not strict when compared to the ease and economy of this process, must be considered when replacing other means of studding or designing for a particular application. The basic faults are as follows:

1. Studs must be of a size and shape that permit chucking, and the cross-sectional area of the weld base must be within the range of the welding equipment.

2. Studs for arc stud welding usually must permit the use of a ceramic ferrule around the weld base. The weld base often must accommodate flux.

3. Studs for capacitor discharge stud welding require a carefully designed, close tolerance projection on the weld base used to make initial contact with the work and initiate the welding arc.

4. Areas to be welded must be clean and free from paint, scale, rust, grease, oil, dirt, zinc plating, or cadmium plating. Aluminum surfaces require oxide removal if badly oxidized.

5. Only one end of the stud can be welded to the workpiece.

Studs are secured to only one side of the workpiece. If a stud is required on both sides, a second stud must be welded to the opposite side.

Flux-shielded welding limits the joint geometry. A change of joint geometry necessitates a redesigning of the enclosure to fit the joint. If a reliable flux-fed system could be developed, joint geometry would no longer be a problem.

An automated flux-shielded weld system would utilize a flux cartridge that would be replaced between each welding operation. In addition to the problems inherent in any system's development, there are several special problems:

1. Joint preparation is an important consideration in fitting the predesigned flux-stuffed cartridge. In multipass welding, reshaping the joint after each pass becomes mandatory.

2. In multipass welding, precise control of the metal deposition during each pass is necessary. A proper enclosure must make this control possible.

3. Automated welding itself is fast and easy, but joint preparation may be time-consuming.

4. Finely distributed slag inclusions were found in most of the samples welded using the flux-shielded process. The effect of these inclusions on the mechanical strength of the weld has not yet been determined.

3.3 Applications of the Processes.

3.3.1 Application of Stud Welding.

Of the fifty or so years that stud welding has been around, only in the last 15 has there been a upsurge in the variety of applications of this welding process. Stud welding outdates the traditional method used to attach a fastener, normally accomplished by drilling and tapping a hole and screwing in the stud. It will also compete with or replace other methods of studding including hand arc welding, resistance welding, and brazing.

New applications quickly are being found for stud welding. An example of this involves the fixing problems associated with non-metallically clad metals; a Teflon coated aluminum frying pan being a prime user of stud welding.

Capacitor discharge stud welding is the fast production process used in light engineering, while arc stud welding is the more general purpose process used in widely diverse fields. Some of the fields that utilize stud welding include: appliances, automotive, construction, industrial equipment, and shipbuilding. The following list is a few specific examples of stud welding use in each field and is not intended to be complete, but just provide the reader with an idea of stud welding's versatility.

Appliances. Studs are used to attach plastic handles, legs, and drawer pulls; radio and TV chassis mountings; insulation for dryers, water heaters, air conditioners, refrigerators, and space heaters.

Automotive. Studs are used to secure bumpers and bumper guards; shock absorbers; trim and emblems; wood liners and wood floorings in trucks; fire wall insulation; hydraulic line fastenings.

Construction. Shear connectors, cometimes called concrete anchors, used to secure door framing, expansion joints, truck doors, are welded studs; reinforcing rod and mesh, and composite beams for bridges, highways, and buildings are attached by stud welding. The sheet metal industry uses studs to attach cork, fiberglass, and glass wool insulation for heat and air conditioning ducts; secure hatch covers, inspection ports and the like.

Industrial Equipment. Studs are used for textile equipment; furnaces of all types; tanks and pressure vessels; securing wire, conduit, and cables; clean-out or access doors and water feed coils for ASME-approved boilers and unfired vessels.

Shipbuilding. Stud welding is approved by the Navy for securing wood deckings; electrical wireways and control panels; cable and pipe hangers; furniture and galley equipment. Studs are used by shipyards in fitting-up plates for ship hulls before welding.

From the above examples, it can be seen that stud welding could easily find a place as an underwater welding process. In salvage work an attachment point for a padeye or similar part could be done by using stud welding. In repair work studs could be used to secure cover plates or patches over holes in pipelines or other vessels which must remain intact and watertight. And in underwater construction shear connectors could be used for concrete structures and again the need for a quick and handy attachment point for fitting-up could be handled by stud welding. It is on the premise that an underwater stud welding gun could be a useful tool, that the experimental study is based.

3.3.2 Application of Flux-Shielded Welding.

Submerged arc welding is widely used in the shipbuilding industry because of its high deposition rate and deep penetration. The flux-shielded process used underwater has a special function: it keeps water away from the arc area by direct flux covering.

Since underwater flux-shielded welding is a newly developed process, all the possible applications of the technique have not as yet been tested. But its tremendous potential in several different underwater applications is clear.

Welding a Plate to an Underwater Structure. Instead of attaching a small stud to a structure, a relatively large plate such as a stiffener can be attached as a part of either a repair or construction project. Since a plate has a simple geometry, designing the flux cartridge would not be difficult.

Automatic Underwater Pipe Welding. A pipe is a structure that is symmetrical about its axis, and the joining of two pipes requires a motion of the arc around the circumference. Because of this symmetry, the design of a flux cartridge and welding system for pipe welding would be relatively simple.

Repair or Construction of Offshore Platforms. Fortunately, almost all the existing offshore platforms have underwater joints that are tubular. As in pipe welding, the geometrical symmetry allows the use of the flux-shielded welding process in order to achieve a better quality weld.

3.4 Results of Mechanical and Metallurgical Tests.

In order to determine the suitability of a welded joint for a given application, two points must be considered:

1. The mechanical strength of the weld, and
2. The welding metallurgy including the composition and soundness of the weld metal and the microstructure of the weldment.

Success in underwater welding depends upon a careful consideration of these points, and their relationship to the drastic quenching effect of the weld zone by the surrounding water environment. The microstructure present in an underwater weld will be a consequence of the composition of the base metal and the filler metal used, as well as the thermal history of the welded joint. The mcaroscopic properties of the weld such as tensile strength, hardness, ductility, fatigue life, and notch toughness can be directly related to the weld microstructure.

3.4.1 Experimental Results on Stud Welding.

An experimental approach was used to determine whether the stud welding process could produce satisfactory welds in a wet environment, without an enclosure or shielding gas system and to verify the analytical heat flow model. Since the basic welding metallurgical patterns in air have been well documented, we felt that comparing air and underwater welds would help us to better understand underwater welding metallurgy.

Using the accepted assumption that "dry" underwater welding is better than "wet" underwater welding, a portable chamber was constructed for the stud welding gun. The basic objective was to determine what, if any, advantages occur when stud welding is carried out in air as opposed to underwater. Also the premise that dry welding is better than wet welding underwater is tested to verify the intuitive guess that it is better.

Throughout the study the following identification system was utilized to identify the welding environment of each stud specimen.

CONDITION	ENVIRONMENT
1	Weld made in air without shielding.
2	Weld made in the wet without any chamber or shielding provided.
3	Weld made in dry underwater chamber with inert shielding gas (Argon).

The parameters involved in this investigation were selected with the stud welding process in mind. The arc length, welding speed, welding polarity, and electrode coating are all dictated by the stud welding process. Since the initial contact capacitor discharge method is used the arc length and welding cycle are preset for a particular stud size. With capacitor discharge stud welding there is no flux coating on the studs, but there is a thin copper flashing on the steel studs to prevent corrosion during storage of the studs. When welding steel studs to low-carbon steel plate, straight polarity (electrode negative) must be used with the particular stud welding system involved in this study.

The variables which were investigated in this program include:

Welding Voltage. Which relates directly to the heat input. Four different voltages were used ranging from 125 to 170 volts. Throughout the study they are designated

C = 125 volts
D = 140 volts
E = 155 volts
F = 170 volts

Welding Position. Both flat and vertical positions were tested. Welding in the overhead position was unfeasible due to the small size of the water tank used for underwater welds.

Base Plate Preparation. Due to the shallowness of penetration of the stud the base metal condition was thought to have an effect on weld quality. Therefore for condition G- (GROUND) the mill scale of the base plate was ground down to bare metal to test its effect on weldment reliability.

Weld Environment. Welds were made both in air and underwater according to conditions 1, 2, and 3. For condition 2 fresh tap water (Cambridge, Massachusetts) was used. Also to simulate sea water 3.4% NaCl (by weight) solution was used in condition 3.

Equipment and materials used in the experimental procedure are outlined in Table 3-1. The basic experimental setup is shown schematically in Figure 3-7. For "wet" stud welding, a similar equipment arrangement was used but without the dry chamber.

Experimentation began with welds made in air (condition 1); for each of the four voltages thirteen (13) studs were welded onto the base plate (8 studs for tensile test, 5 for bend test). Since voltage E (155 volts) was the recommended setting for the combination of stud and base plate used, each variable (welding position, base plate preparation, water environment) was tested at voltage E by again welding 13 studs to the base plate in the appropriate condition.

Next the stud gun was waterproofed with a silicone sealer and the trigger was replaced with a knife switch, and then studs were welded underwater without any shielding (condition 2). Safety precautions against electric shock required that the operator wear rubber gloves and stand on a rubber mat while holding the stud gun underwater. An assistant threw the knife switch on command to complete the underwater "wet" weld. Again for each condition 13 studs were welded. Then to simulate sea water a 3.4% NaCl solution was made by the addition of a measured amount of salt to the water tank and welding was carried out as previously mentioned.

The final phase of stud welding required that the stud gun

Table 3-1

Outline of equipment and materials

1. Omark model DS-G capacitor-discharge stud gun
2. Omark model SS-6 Twin Pack power unit
3. 1008 steel studs with cooper flashing
4. 1/4 inch low carbon steel plate (SAE 1018)
5. 27 gage low carbon steel sheet
6. Plexiglass water tank
7. Rubber gloves and mat
8. Thermometer (mercury in glass)
9. Tempilaq temperature indicating liquid
10. Instron Universal Testing Instrument, Model TTC
11. Wilson Tukon Microhardness Tester, Model LL

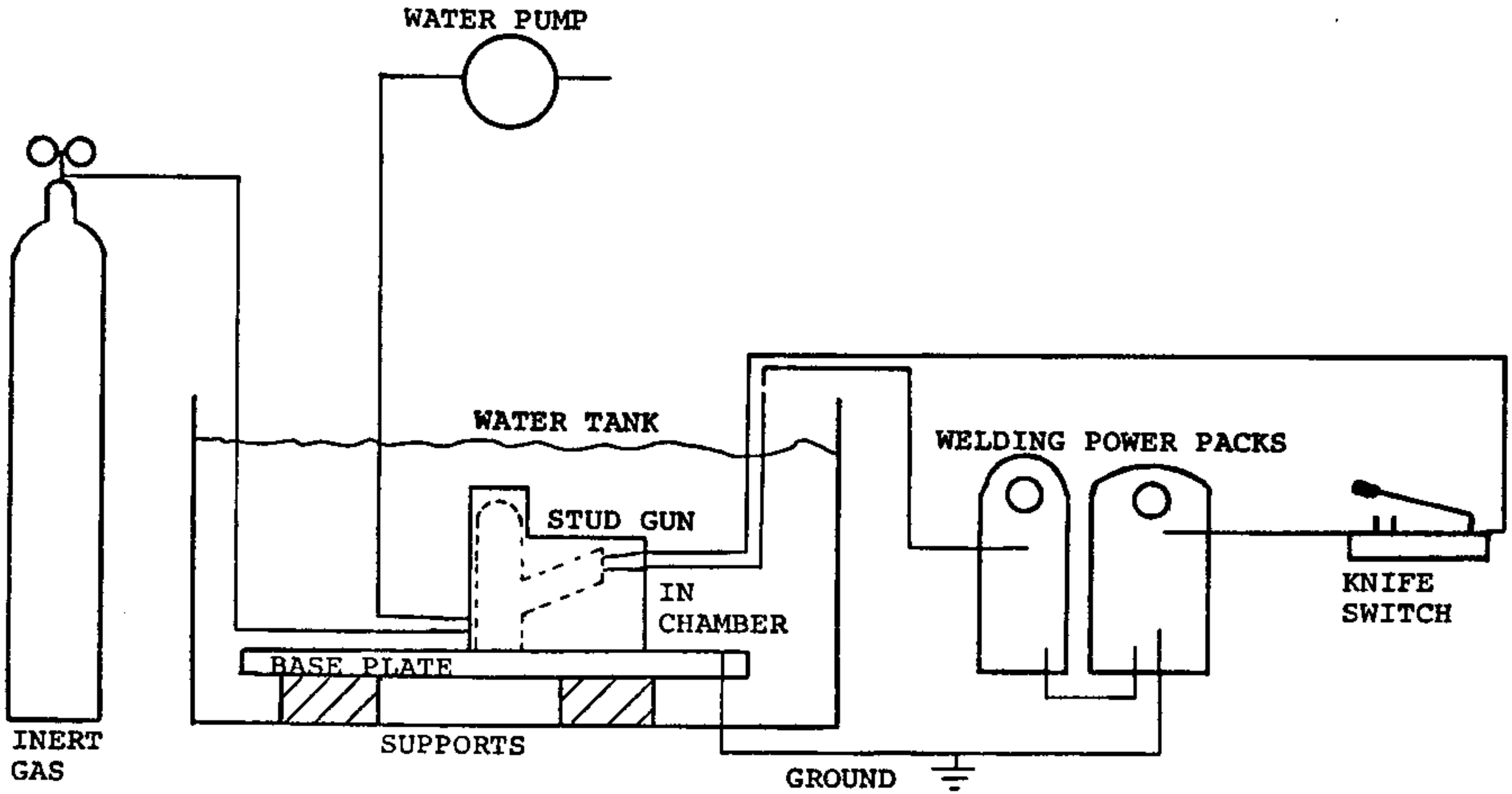


Fig. 3-7 Schematic of underwater dry chamber stud welding apparatus

be positioned in the small steel chamber. Hoses for shielding gas and water removal were attached to the chamber then the stud gun was aligned to allow studs to be welded perpendicular to the plate. The chamber was provided with a small Lexan window to aid in positioning the stud. A sponge rubber gasket allowed the chamber to become "watertight", by compressing over any irregularities in the base plate. Once the operator was satisfied with the stud's position the water pump removed the water with help from the flow of the shielding gas. Once the weld area was dry (within 5-10 seconds) the command to trigger the switch was given allowing the weld to be made in a dry chamber underwater process (condition 3).

With the completed welds for each specific condition completed, 8 specimens were cut from the base plate into one inch square pieces as tensile specimens, while the remaining studs were left for the bend test. After the specimens were tested to failure in the tensile test, representative studs were selected for metallographic examinations.

Using the American Welding Society Structural Welding Code Requirements[34] as a guideline, simple mechanical tests were devised for the stud welded specimens. The AWS requires that test specimens be welded at both optimum current and at 10% above and below optimum, a procedure that is followed in this study. Studs failing to qualify by the AWS guidelines shall be considered inadequate for the particular welding service in which they were prepared.

The mechanical tests involved in this program include a typical tensile test (yielding quantitative data) and a simple bend test (yielding qualitative data).

3.4.1.1 Summary of Mechanical Tests.

The tensile test results obtained by Mr. Zanca and Mr. Moore are shown in Tables 3-2 and 3-3 separately.[35,36] As seen in Table 3-2 , the studs that were welded in conditions 2 (wet underwater welding) experienced more weld failures than either condition 1 or 3 stud specimens. This is strong evidence that "dry" is better than "wet" underwater welding. Also from the tensile test results, a comparison of the other experimental variables yields some interesting details. Some of these details are easily predictable while a few of the others are difficult to explain.

It appears that base plate preparation has little, if any, effect on stud weld reliability. All of the stud specimens that were welded on a polished base plate (condition G) had similar ultimate strength to those that were welded directly to the mill scale of the base plate. And only for condition 3 did the ground condition produce more weld failures--one more weld failure--than the regularly prepared specimens. This is puzzling since the stud penetration in capacitor discharge stud welding is so small, it is thought that the mill scale on the base plate would effect the integrity of the welded joint. Based on the tensile results there is little advantage gained in grinding the base plate down to the bare metal.

TABLE 3-2 TENSILE TEST RESULTS OF WELDED STUD SPECIMENS; ULTIMATE STRENGTH OF WELDED JOINT

CONDITION	NUMBER OF WELD BREAKS	MEAN VALUE OF ULTIMATE STRENGTH (LBS)	STANDARD DEVIATION (LBS)
C 1	-	903.0	52.6
D 1	-	882.5	8.1
E 1	-	877.3	13.7
E 1 G	-	869.1	7.4
E 1 V	2	875.6	18.1
F 1	1	787.5	257.8
C 2	4	649.5	280.3
D 2	2	850.3	66.8
E 2	2	815.9	161.4
E 2 G	2	824.1	126.8
E 2 V	7	561.0	183.8
E 2 SW	1	850.0	72.2
F 2	1	866.4	26.1
C 3	-	872.1	14.6
D 3	-	881.5	9.6
E 3	-	875.4	6.4
E 3 G	1	819.5	163.3
E 3 V	6	597.0	269.0
F 3	1	866.4	26.1

EIGHT (8) STUDS WERE TESTED FOR EACH CONDITION

AVERAGE STUD ELONGATION AT FAILURE = 18.8%

AVERAGE ULTIMATE STRENGTH OF STUDS = 883.2 LBS

Table 3-3

Stud Weld Tensile Test Results

Voltage	Condition	No. of Studs Tested	No. of Weld Failures	Failure Percentage
C (125)	Dry	5	0	0
	Wet	8	4	50
D (140)	Dry	4	0	0
	Wet	5	0	0
E (155)	Dry	4	0	0
	Wet	8	2	25
F (170)	Dry	4	0	0
	Wet	8	1	12.5

The comparison of the vertical welding position to the normal flat welding position illustrates that for each condition 1, 2, or 3, vertically welded studs are less reliable and have less strength than comparable welded joints made in the normal welding position. In air, although the vertically welded studs had 2 weld failures--with 0 weld failures for the flat position--the ultimate strength of the welded joint was 875.6 lb. or almost equal to the average ultimate strength of the studs. But when welding was done underwater the ultimate strength and the reliability decreased drastically for the vertical welding position.

It appears that studs welded in salt water (condition SW) in a wet underwater process will produce better results than when welded in plain tap water. This increase in strength and reliability is probably due to the high ion concentration in the salt water, which leads to a better distribution of the welding arc over the surface of the stud base because of the increased electrical conductivity of the salt solution.

The other variable tested, the welding voltage, seemed to have little effect on the strength of the welded joint, except for wet underwater welds. As could be predicted, the higher voltage (voltage F) produced less weld failures than any of the other voltages in wet underwater welding. This is due to the increase in welding energy which was able to vaporize the water surrounding the stud tip, allowing a sound weld to be made. But when welding was carried out in a dry environment, both in air and underwater, this higher voltage was not as good as the recommended voltage (voltage E).

The performance of all the successful welded stud joints compares favorable to manufacturer's standards and the AWS specifications for stud welding. For the 10-24 threaded studs, the manufacturer predicts an ultimate strength of 900 lb. which is close to the average ultimate strength found in the tensile test of 883.2 lb. The AWS requires that steel studs have an ultimate tensile strength of 55 ksi with an elongation of 20% in a 2 inch gage length. The results found in these tests gave an ultimate tensile strength of 39.4 ksi while the approximate elongation at failure was 18.8%.

Similar results are shown in Table 3-3 . No failures were noted for any of the air welds. At the lowest setting, 125 volts, 50 percent of the wet welds failed. However, at higher settings much better results were obtained. At 140 volts no failures occurred; at 155 volts a 25 percent failure rate was produced and at 170 volts 12.5 percent of the underwater welds failed.

Table 3-4 details the bend test results and again these appear to follow the same trends found in the tensile tests. Although this test did not record any numerical data, the fact that a stud weld failed along the weld line is sufficient reason for predicting poor weld performance for that particular welding condiditon. There was a problem in obtaining perpendicular welded

TABLE 3-4 BEND TEST RESULTS OF WELDED STUD SPECIMENS

CONDITION	NUMBER OF WELD FAILURES	CONDITION	NUMBER OF WELD FAILURES
C 1	-	E 2 SW	-
D 1	-	F 2	1
E 1	-	C 3	1
E 1 G	-	D 3	-
E 1 V	-	E 3	1
F 1	-	E 3 G	1
C 2	-	E 3 V	3*
D 2	1	F 3	-
E 2	4		
E 2 G	5		
E 2 V	-		

FIVE (5) STUDS WERE TESTED FOR EACH WELDING CONDITION
* STUD SPECIMENS WERE NOT PERPENDICULAR

studs for the vertical underwater dry condition (condition E 3V). Due to the weight of the steel chamber, placing and holding the stud gun was difficult and therefore stud specimens were not at right angles to the base plate. This problem was also noticed in some of the tensile specimens and it was the major cause of weld failure for these particular studs.

The poorest performance in the bend tests was again found in wet underwater welded specimens. The other experimental veriables seemed to have little effect on weld reliability, except for the condition 2 welds. An interesting detail is that the vertical welding position used on underwater wet welded studs produced no weld failures in the bend test, and this is contradictory to previous results found in the tensile tests. The bend test used was a simple and quick means of determining weld quality and when compared to the tensile test results it seems to be an accurate indicator of weld reliability. It is because of this that the standard industrial practice of striking welded studs with a hammer until they fail is still successfully used to predict weld quality.

By plotting the percentage of stud failures against the welding voltage, a measure of weld reliability is found. Since the studs were tested to failure, this percentage of stud failures is a measure of weld failures and therefore the quality of the weld for each voltage used. Figure 3-8 illustrates this stud weld reliability using the results from the tensile test. In Figure 3-9 , the bend test results are utilized to make a similar curve illustrating weld reliability. Both of these figures reveal the

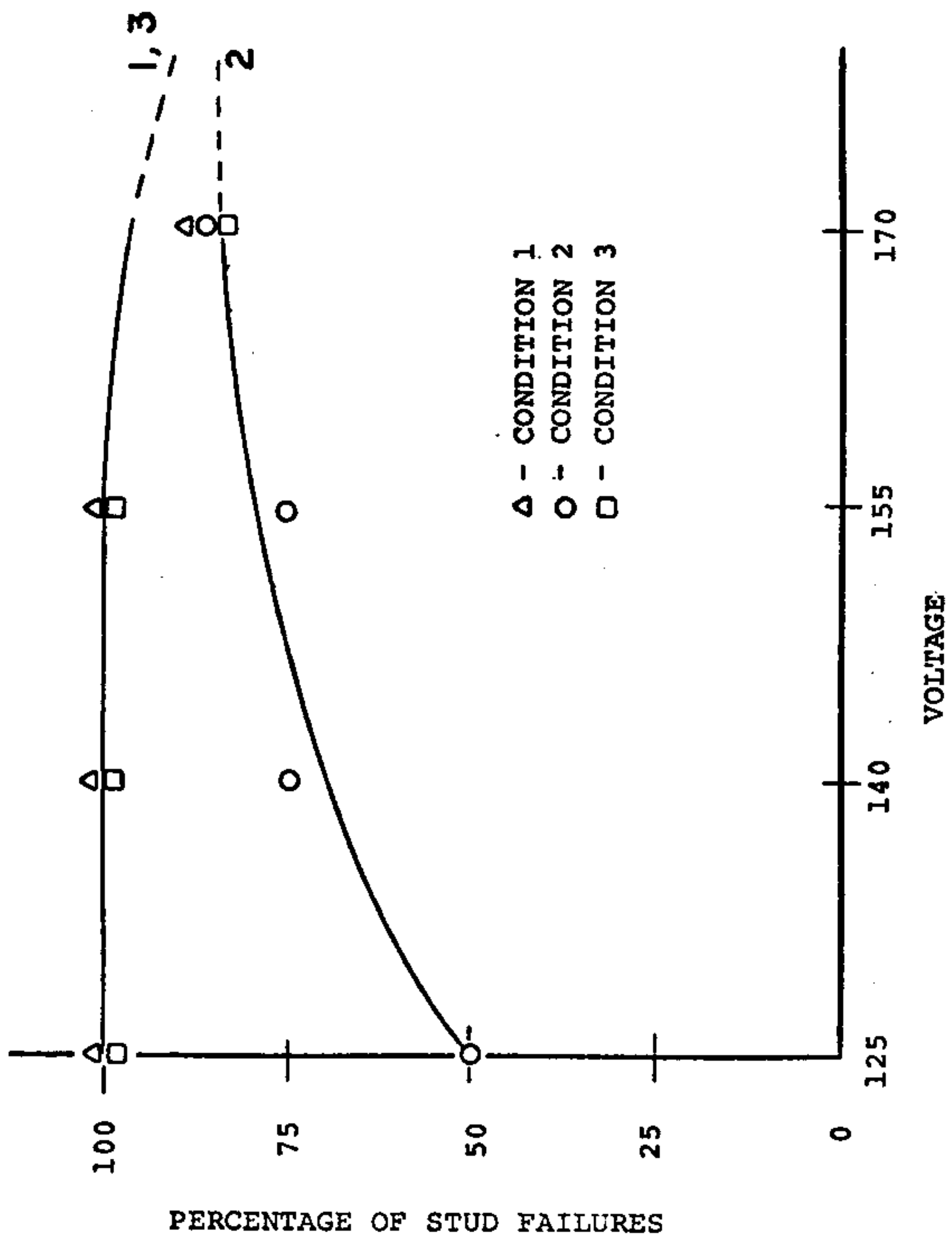


FIGURE 3-8 STUD WELD RELIABILITY FROM TENSILE TEST RESULTS

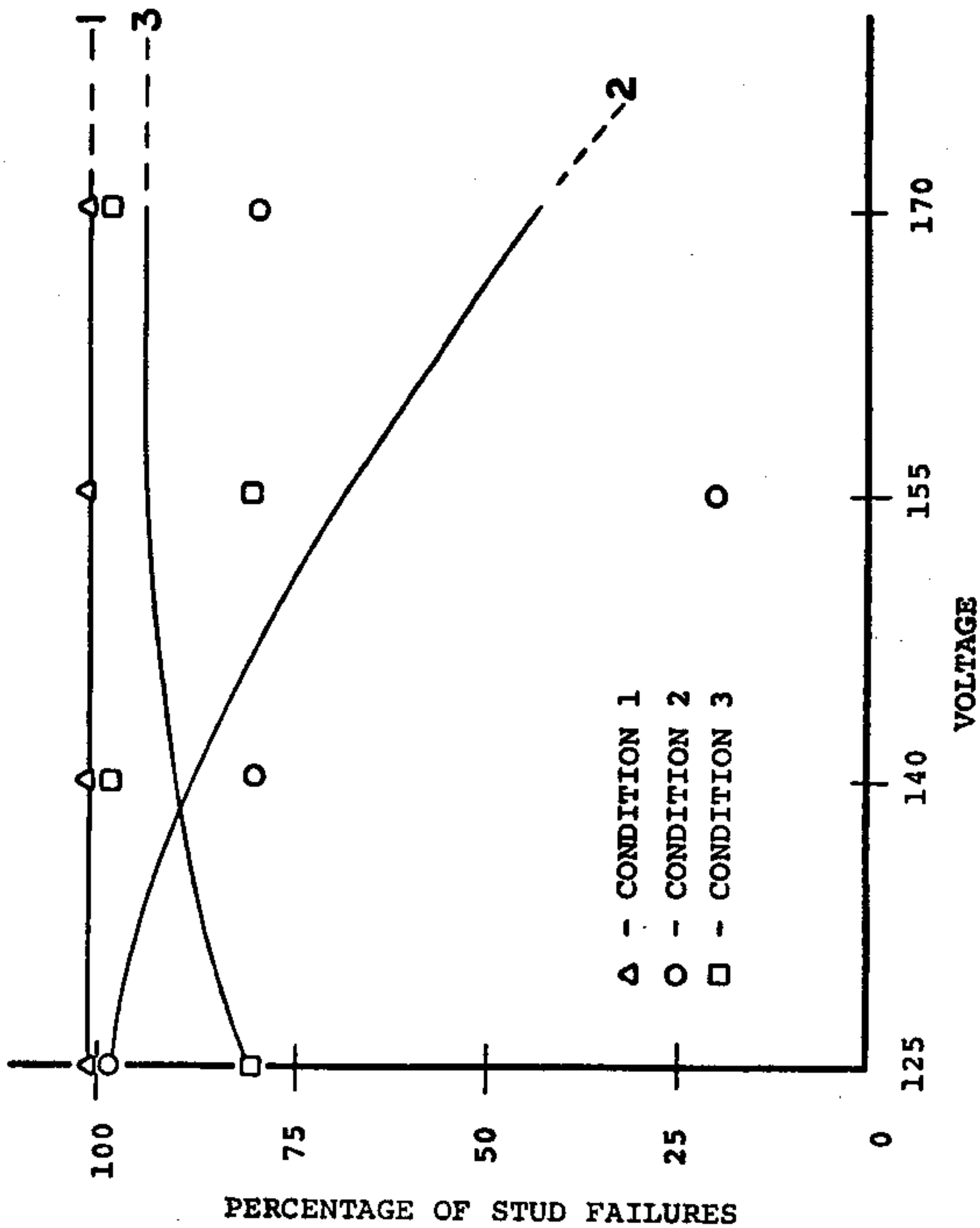


FIGURE 3-9 STUD WELD RELIABILITY FROM BEND TEST RESULTS

fact that dry underwater welding is better than wet underwater welding, but not quite as good as stud welding done in air.

From all of the mechanical test results it is found that the underwater stud welding system is capable of producing quality underwater stud welds. And, more important, the dry underwater welding process is better than the wet underwater technique as far as stud welding is concerned. Although this premise was first assumed at the beginning of this study, the test results are proof that such an assumption was correct.

3.4.1.2 Summary of Metallographic Tests.

In order to determine the soundness of a welded stud joint and the microstructural phases present in the weldment, several metallographic tests were conducted on stud specimens for each welding condition. The simplest test involved the macroscopic examination of the stud specimens along the vertical plane through the centerline of the stud. A low magnification photograph was taken to determine the presence of large defects in the weld or the absence of fusion between the stud and the base plate.

Macrographs (9X) of the stud specimens that were welded in air, were used for the measurements of the fusion zone of the weld and the heat-affected zones of the stud and base metals. Upon careful examination of these pictures, voids or inclusions in the weld area become apparent. It can be seen that for all of the specimens except E lV and E l, there is complete fusion of the stud with no visible defects present. In conditions E lV and E l the presence of a defect at the tip of the stud leads to the conclusion that the welding arc did not make a complete excursion over the base of the stud before fusion was achieved. But since the mechanical test results for condition E 1 were above average, this may not be the total explanation for these defects.

The macrographs of the wet underwater stud welds reveal some interesting details. Except for the vertical welding position, all of the studs show good fusion of the stud to the base metal. In fact a few of these specimens, D 2 and E 2 seem to be equal in soundness to those studs of the same voltage that were welded in air. It is obvious that with the vertical welding position there is poor fusion at the edge of the stud, with no fillet present. This could account for the bad performance of this welding condition in the mechanical tests. Another interesting feature is that the various widths of the weld zones are smaller for wet welds than is the case for dry welds. This is intuitive because of the quenching effect of the water environment. Base plate preparation seems to have little effect on the weld quality, if anything the stud with the millscale intact has a better weld appearance with no defects present.

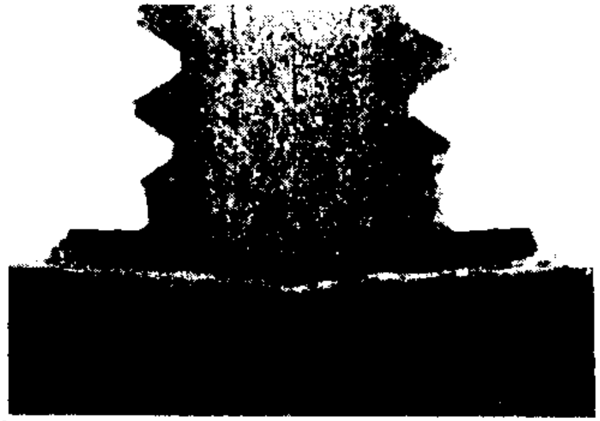
In the macrographs of condition 3 stud welds, there appears to be a large number of defects at the weld line for this group of specimens as a whole when compared to condition 2 specimens. But there is a larger weld fillet in the condition 3 specimens which creates a strengthening effect on the stud joint. Notice the large asymmetrical weld fillet of the vertical welding condition, illustrating the effect of gravity on the flow of the molten weld metal. The various widths for the fusion zone and the heat-affected zones of the stud and base metals are greater than those of condition 2 specimens, demonstrating the fact that there is a slower cooling rate attained in the dry underwater welding process. These widths appear to coincide with those of air welded specimens, varifying the fact that the small chamber is effective in reducing the large cooling rates experienced in underwater welding.

The last set of macrographs in Figure 3-10 shows the results of studs welded in salt water as compared to the smae voltage in fresh water and the best of the specimens of the wet welds of condition 2. Also shown is the specimen that was prepared with the light portable underwater stud gun. The rather poor results obtained with this new design will be discussed further in the next section. The picture demonstrates the lack of strength of this particular welded joint, and since the weld failed in the tensile test it was impossible to record any information on the weld joint, including the vertical microhardness survey. This figure is effective in showing the good fusion attained when wet welding is carried out in salt water, which could be worth further investigation since wet stud welding would require no supportive chamber or gas shielding.

After the visual examination for gross structural defects, the specimens were subjected to a microhardness survey to determine

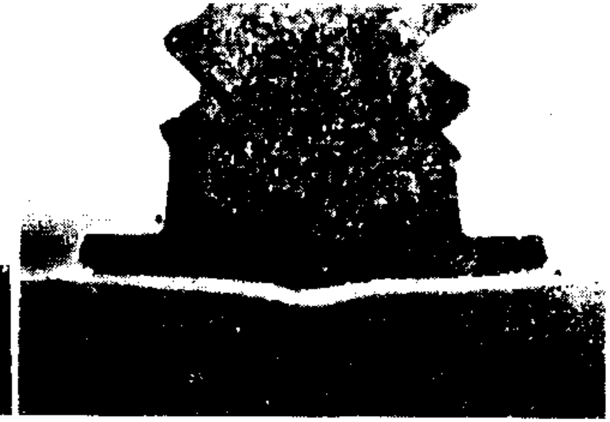
VOLTAGE E-SALT WATER (2)

WIDTHS (mm)	CENTER	EDGE
Stud HAZ	.115	.100
Fusion Zone	.140	.075
Base HAZ	.100	.090



VOLTAGE E (2)

WIDTHS (mm)	CENTER	EDGE
Stud HAZ	.110	.050
Fusion Zone	.100	.075
Base HAZ	.075	.060



VOLTAGE D (2)

WIDTHS (mm)	CENTER	EDGE
Stud HAZ	.100	.060
Fusion Zone	.200	.125
Base HAZ	.100	.075

VOLTAGE E-PORTABLE STUD GUN

WIDTHS (mm)	CENTER	EDGE
Stud HAZ	.050	.040
Fusion Zone	----	----
Base HAZ	.075	.060

VOLTAGE E (3)

WIDTHS (mm)	CENTER	EDGE
Stud HAZ	.065	.085
Fusion Zone	.200	.160
Base HAZ	.090	.075

VOLTAGE F (3)

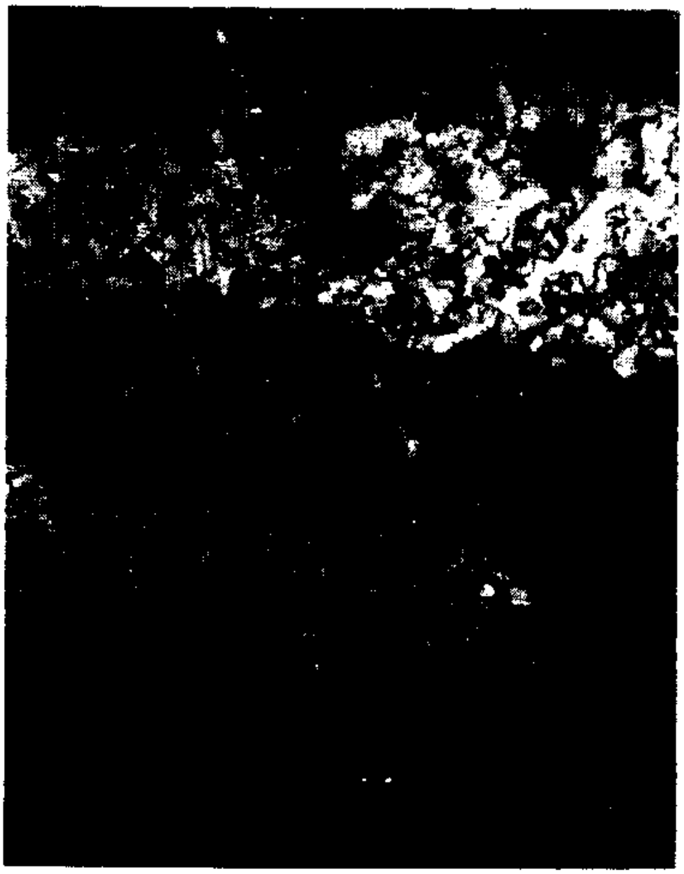
WIDTHS (mm)	CENTER	EDGE
Stud HAZ	.080	.075
Fusion Zone	.200	.170
Base HAZ	.075	.070

FIGURE 3-10 MACROGRAPHS OF STUD WELDS: SALT WATER AND PORTABLE STUD GUN (9X)

the presence of verious structural phases and predict the various cooling rates encountered by the welded studs. Figure 3-11 is a micrograph detailing a wet underwater welded specimen that was subjected to a vertical microhardness survey. The Knoop Hardness Numbers (100 g.) given correspond to the impression in the specimen surface and relate to the different zones of the weldment. The horizontal microhardness traverse is featured in Figure 3-12, and again the corresponding hardness numbers for each zone of the weld are given. It can be seen from these figures that the unaffected stud and base metal reveal the common pearlite and ferrite structure found in low-carbon steels. Since the base plate has a higher carbon content (.18% C), there are more dark areas present than are found in the stud metal. When the heat-affected zones are reached, a slightly refined structure of ferrite and some pearlite is observed. The fusion zone is a conglomeration of martensite, bainite areas with a few grains of retained austenite due to the drastic quenching effect of the water on the already fast cooling rate of stud welding.

The final metallographic test performed on the stud specimens involved the microscopic examination of the welded joint. The micrograph of a wet underwater welded stud taken at the centerline of the stud was studied. Most of the stud specimens had the same basic structures present, but with minor differences depending on the welding environment. As seen in this figure, the fusion zone is a combination of various structural phases, all present due to the rapid quenching from the austenite range. The

SPECIMEN D2 AT CENTERLINE OF STUD



KHN (100 g)

175 STUD METAL

220 STUD HAZ

430

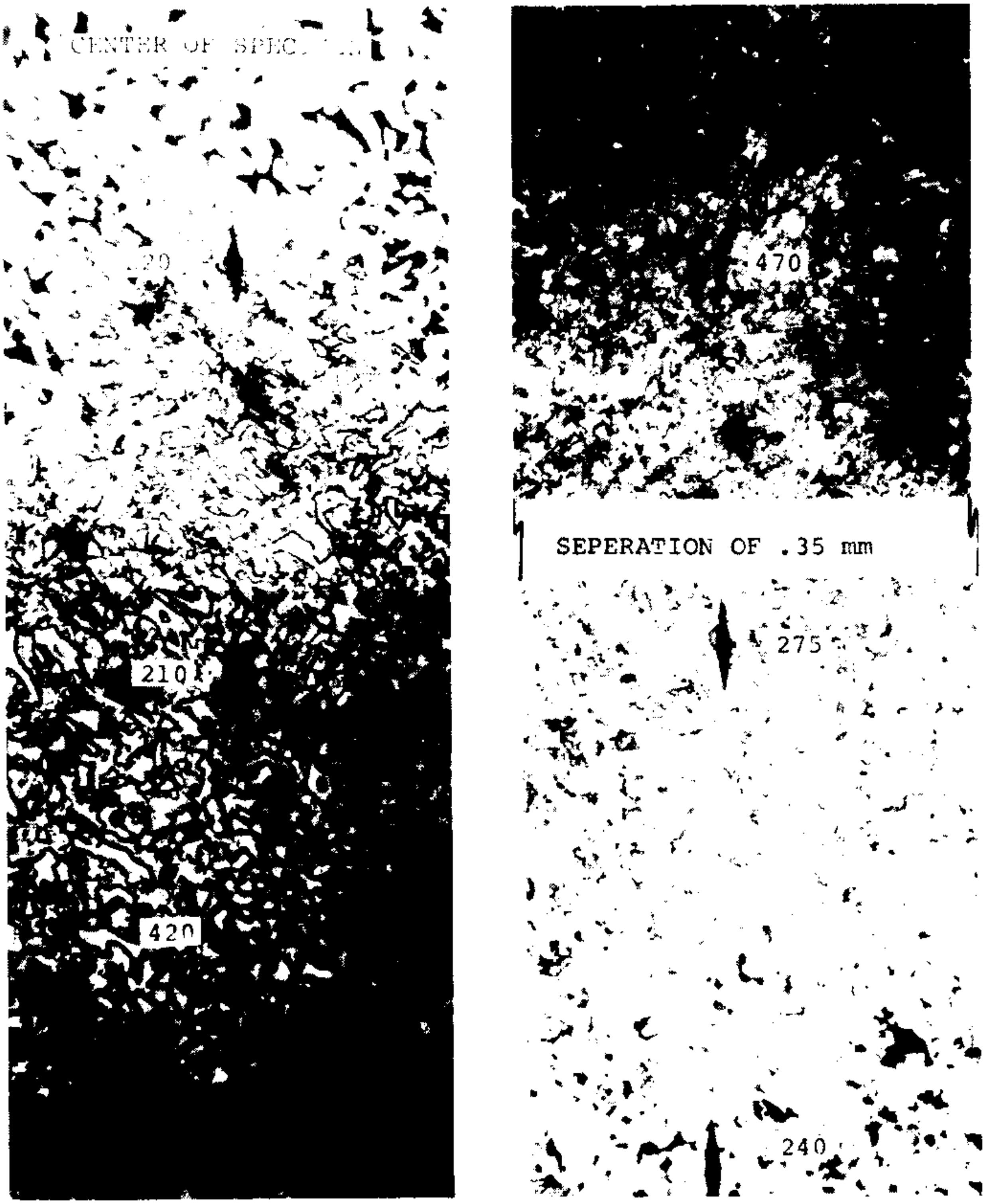
FUSION ZONE

536

310 BASE HAZ

240 BASE METAL

Fig. 3-11 Micrograph of vertical microhardness traverse (200 X)



FUSION ZONE   BASE METAL

SPECIMEN E 2 FROM CENTER OF WELD TO EDGE
NUMBERS ARE KNOOP MICROHARDNESS NUMBERS (100 g)

Fig. 3-12 Micrograph of horizontal microhardness traverse (200 X) enlarged area (1000 X) shows the characteristic needlelike structure of martensite, which is formed with either 60° or 120° angles between the grains due to its tetragonal crystal structure. Also present are a few grains of retained austenite which did not have time to transform upon cooling. There appears to be some bainite grains along with a possible Widmanstätten structure completing the fusion zone.

Both air and underwater welded specimens seem to have the same basic type of structural phases present. An interesting fact is noted when comparing wet and dry under water welded specimens. The heat-affected zones of both the stud and base metals of the wet welded stud have larger, coarser grains than are found in both conditions 1 and 3. This is due again to the large heat sink of water causing a drastic cooling rate from the austenite range. It appears that recrystallization has not been completed, due to the speed of the welding process and the huge cooling rate in the water environment.

Probably the most significant feature of the microhardness surveys is the fact that condition 2 welds have higher hardness values on the average than those specimens of conditions 1 and 3. Another interest point is that with the vertical microhardness surveys, usually the centerline has a higher hardness value due to the larger heat input to the tip of the stud. But this effect is sometimes reversed and is more unpredictable with condition 2 specimens. The higher cooling rates experienced in wet underwater welded specimens can explain all of these hardening effects and these microhardness profiles verify the already documented fact that cooling rates are much more pronounced in the water environment.

Another predictable result is that for greater heat input (higher voltage) the maximum hardness is larger along with the apparent increase in weld size. The greatest hardness is obtained with voltage F (170 volts) in conditon 1 and was a value of 720 KHN (100 g.).

It is difficult to discern any significant differences between condition 1 and 3 stud welds on the basis of the microhardness profiles. There does not seem to be any predictable trend when comparing these welding conditions, which again verifies the assumption that dry underwater welding is effective in producing air quality welds.

3.4.1.3 Summary of Temperature Analysis.

Verification of the computer heat flow model is completed using maximum temperature data for points in the plate, rather than temperature histories for these points. This is done because the small size of the studs welded in these experiments (base diameter, 0.25 inch) precluded the installation of thermocouples.

Figure 3-13 presents the maximum temperature attained at various distances form the stud centerline. Results predicted by the analystical heat flow model as well as results obtained from experimental efforts are included. This figure suggests that a reasonably close correlation between theoretical precictions and experimental results exists. Insulation assumptions included in

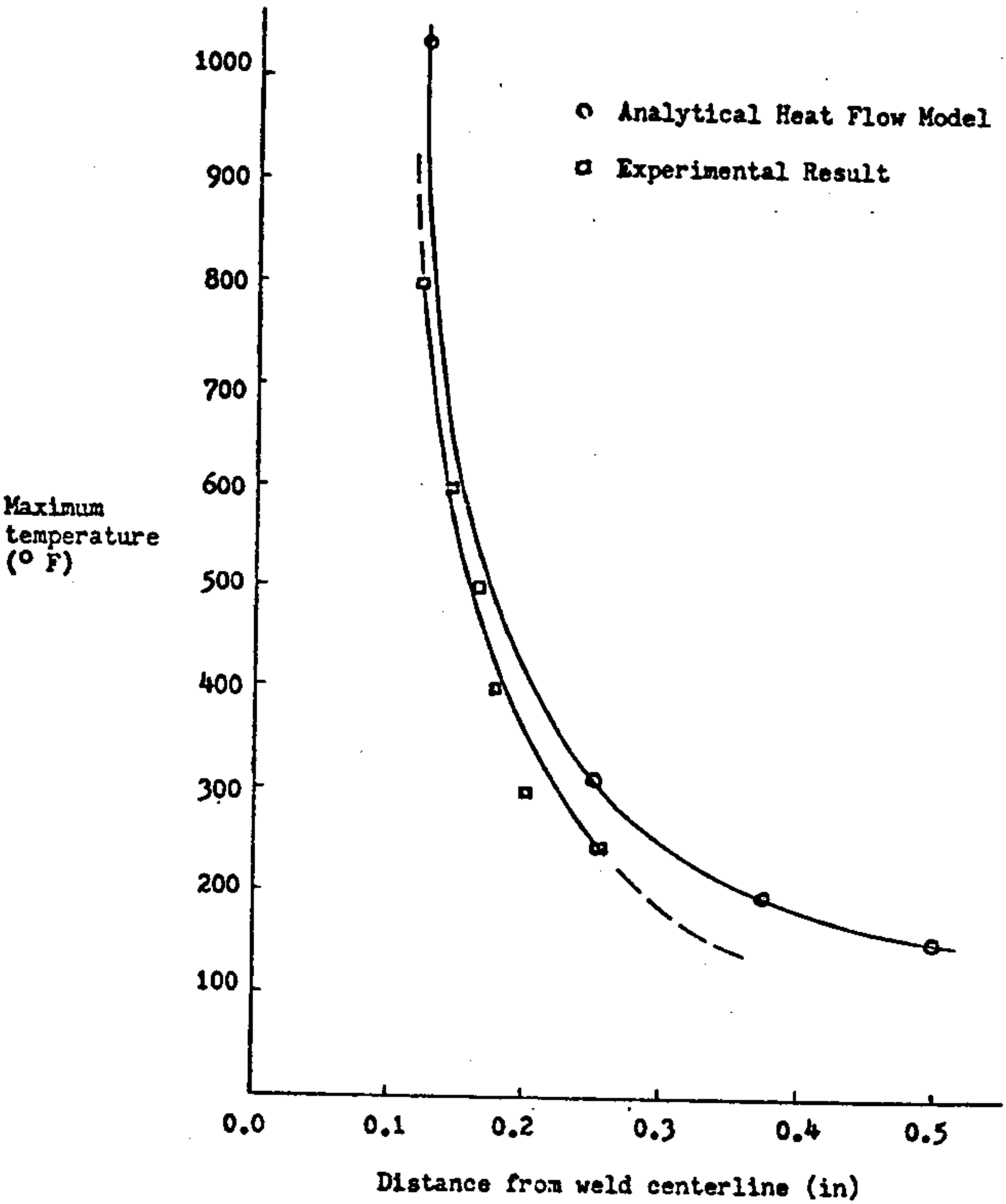


Figure 3-13 Heat Flow Model Verification.

the analytical heat flow model shift that curve to the right, compared to experimental results which are derived form a non-insulated capacitor-discharge stud weld.

Figure 3-14 presents the cooling rate curve for the center of the stud weld superimposed on the CCT diagram for low-carbon steel. From this illustration, it can be seen that the relatively large quantities of martensite and the bainite found in micrograph can be predicted by the heat flow model.

In summary these results indicate that satisfactory stud welds can be made in a wet environment and that no enclosure or gas supply system is necessary. These results also indicate that a computer heat flow model can be used to predict temperature histories in the weld areas. This knowledge can be used to predict microstructure and weld properties.

3.4.2 Experimental Results on Flux-Shielded Welding.

An experimental approach was used to determine whether the flux-shielded welding process could produce better quality welds as predicted. Since a better system would be required to function properly in an actual field operation, we decided to test only simple underwater flux-shielded weldings under simulated conditions in our laboratory.

By studying the microhardness values of welds made using several different processes, we were able to determine how much the flux-shielded process slowed the cooling rate as compared to the other processes. In addition to the data available in the

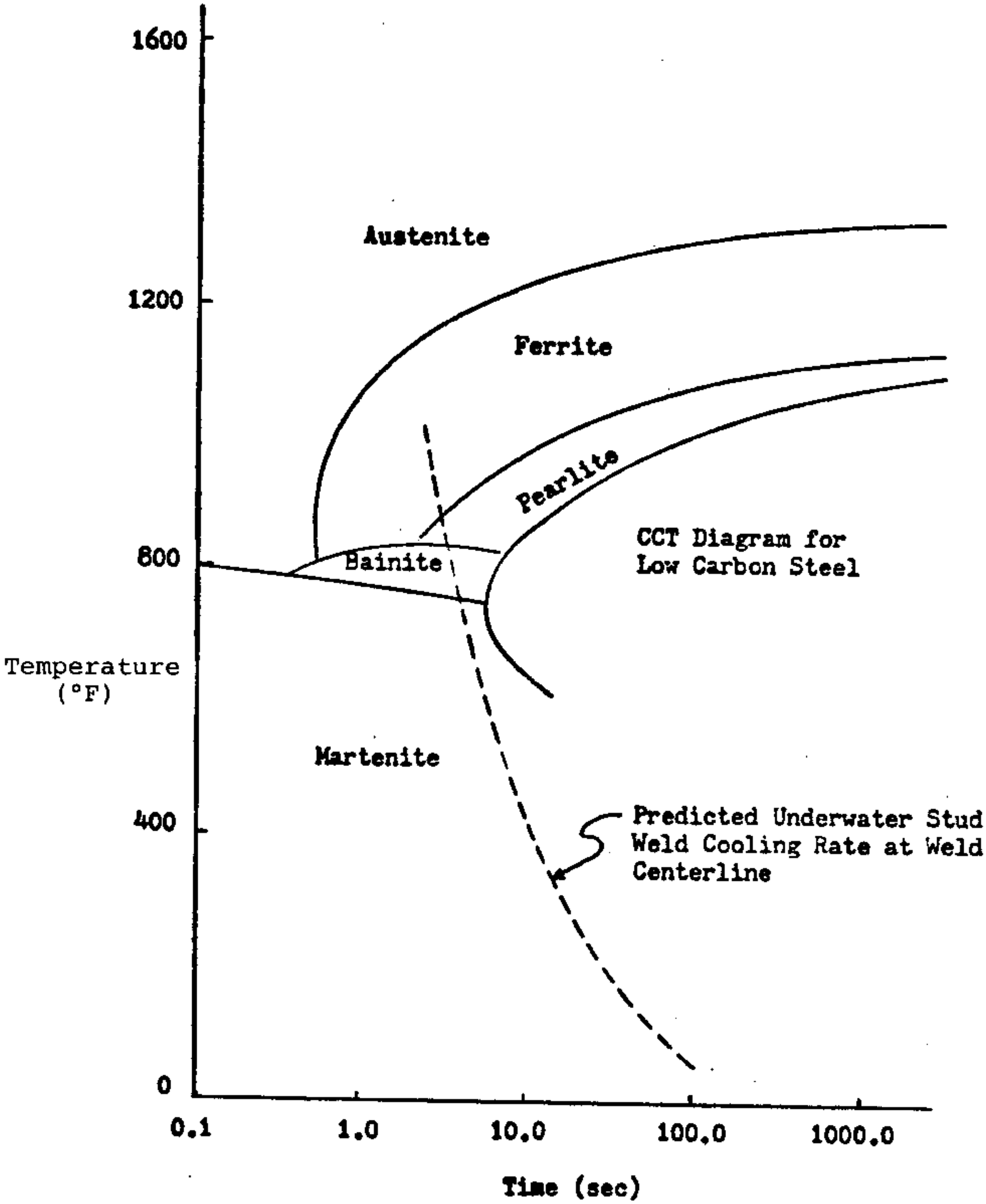


Fig. 3-14 Predicted stud welding cooling rate

published literature (see Chapter 2), the following is provided as an outline of the results of our series of bead-on-plate welds:

SERIES	WELDING PROCESS
S	Shielded metal-arc welding process.
G	Gas metal-arc welding process.
F	Flux-shielded metal-arc welding process.
W	Water-shielded gas metal-arc welding process.

3.4.2.1 Shielded Metal-Arc Welding Process.

1. Weld made underwater using waterproofed E7014 (3/16" ϕ) electrode (designated S-1).

2. Weld made underwater using waterproofed neutral electrode (designated S-2).

3.4.2.2 Gas Metal-Arc Welding Process.

Weld made underwater using AWS E70S-6 (1/16" ϕ) wire shielded with 75% argon plus 25% CO_2 gas (designated G).

3.4.2.3 Flux-Shielded Metal-Arc Welding Process.

1. Weld made underwater using waterproofed neutral electrode shielded with #761 Lincoln flux (designated FE-1).

2. Weld made underwater using waterproofed neutral electrode shielded with #761 Lincoln flux mixed with Kasil #6 Potassium Silicate (K_2SiO_4, 1:1 ratio by volume)(designated FE-2).

3. Weld made underwater using waterproofed neutral electrode shielded with #761 Lincoln flux mixed with Kasil #6 Potassium Silicate (K_2SiO_4, 1:1 ratio by volume), insulated

at the bottom of the plate, and minimum water contact in the arc zone by rubber seal between the bottom of the flux coverage and the top of the plate (designated FE-3).

4. Weld made underwater using AWS E70S-6 (1/16" ϕ) wire shielded with #761 Lincoln flux (designated FS-1).

5. Weld made under using AWS E70S-6 (1/16" ϕ) wire shielded with #761 Lincoln flux mixed with Kasil #6 Potassium Silicate (K_2SiO_4, 1:1 ratio by volume), insulated at the bottom of the plate and minimum water contact in the arc zone by rubber seal between the bottom of the flux coverage and the top of the plate (designated FS-2).

6. Weld made underwater using AWS E70S-6 (1/16" ϕ) wire shielded with Kasil #6 Potassium Silicate Paste (K_2SiO_4), insulated at the bottom of the plate, and minimum water contact in the arc zone by rubber seal between the bottom of the flux coverage and the top of the plate (designated FS-3).

<u>3.4.2.4 Water-Shielded Gas Metal-Arc Welding Process</u>.

1. Weld made underwater using waterproofed neutral electrode shielded with water jet (designated WE-1).

2. Weld made underwater using waterproofed neutral electrode shielded with argon gas and water jet (designated WE-2).

3. Weld made underwater using AWS E70S-6 (1/16" ϕ) wire shielded with water jet (designated WS-1).

4. Weld made underwater using AWS E70S-6 (1/16" ϕ) wire shielded with argon gas and water jet (designated WS-2).

Table 3-5 summarizes the welding conditions and weld shapes of each group of welds. Arc stability was analyzed using chart recordings of current-voltage traces. Arcs were stable for all welds using the coated electrode. For GMA and water shielded GMA processes, arc stability depended on gas flow rate. 60 SCFH for GMA and 5 to 10 SCFH for water shielded GMA were considered optimum. When welding using the flux-shielded process underwater, the arc was very difficult to maintain using bare wire. The addition of potassium silicate would probably smooth the arc somewhat. The trial welding using potassium silicate paste shielding did not succeed. Because submerged arc flux powder loses its arc stabilizing property when it get wet, new arc flux materials that do not lose their original properties when submerged are needed.

Current used for bare wire welding (GMA, FSMA, WGMA) ranges between 300 and 350 amperes. High penetrations are the result of lower shape-factor values (weld bead width/penetration) on the order of 2-2.5. Welds produced using stick electrodes resulted in shallow penetrations (shape factor ≈ 6.5). Additional shielding around the stick electrode with a water jet and with gas reduced the bead width 10% and increased the penetration 15%. This results in a 25% reduction in the shape factor (≈ 4.5). The reasons for such a phenomenon have not been determined.

Figures 3-15 to 3-18 show the microhardness distribution along the weld center line. Air weld data is plotted as a reference for comparison with data obtained from the various underwater

Table 3-5 Summary of the welding conditions and weld appearance

Welding experiment	Current (Amps. DCRP)	Voltage (Volts)	Speed (ipm)	Feed (ipm)	Arc stability	Weld Appearance: Smoothness	Weld Appearance: Regularity	Weld Appearance: Shape factor ($S = \frac{\text{Bead width}}{\text{Penetration}}$)
Air	140	40	---	---	stable	excellent	excellent	6.36
SMA	185	30	---	---	stable	good	good	4.37
GMA	320	35 - 40	25	200	stable*	good**	good	2.38
FE-1	185	30	---	---	stable	good	good	3.33
FE-2	185	30	---	---	stable	good	good	6.45
FE-3	320	40	---	---	stable	excellent	excellent	6.45
WE-1	185	35	---	---	stable	fair	fair	5.0
WE-2	185	35	---	---	stable	fair	fair	3.16
WE-3	185	35	---	---	stable	fair	fair	4.24
FS-1	350	35	15	150	unstable	poor	poor	1.9
FS-2	350	35	15	150	interm.	fair	fair	2.24
WS-1	260 - 300	40	25	200	stable	fair	fair	2.04
WS-2	320	35 - 40	25	200	stable***	good**	good	2.77

* Stability depends on gas flow rate. 60SCFH is optimum.

** Good but porous.

*** Stability depends on gas flow rate. 5 - 10 SCFH is optimum.

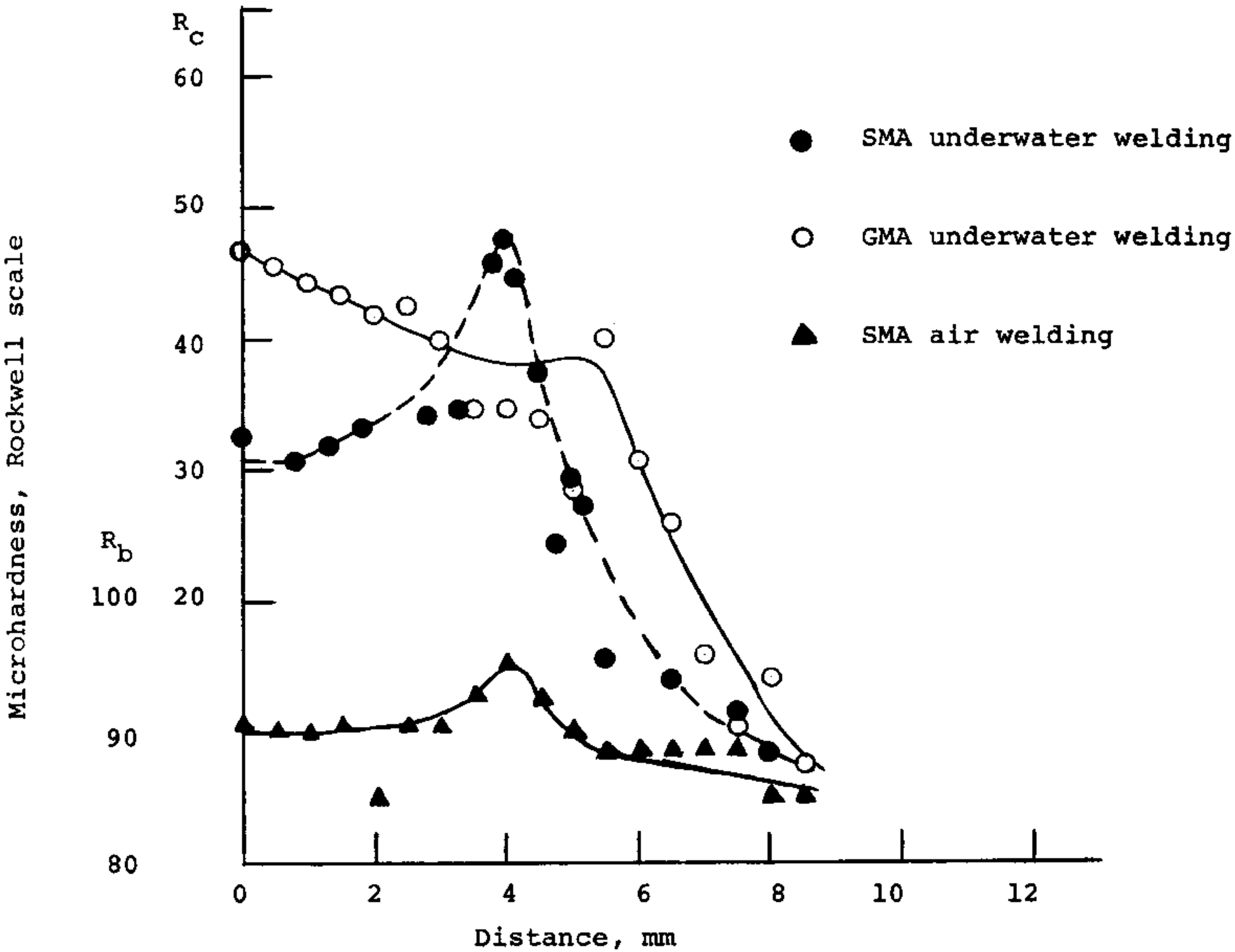


Fig. 3-15 Microhardness distribution along the weld center line (Measurement started from water-weld interface)

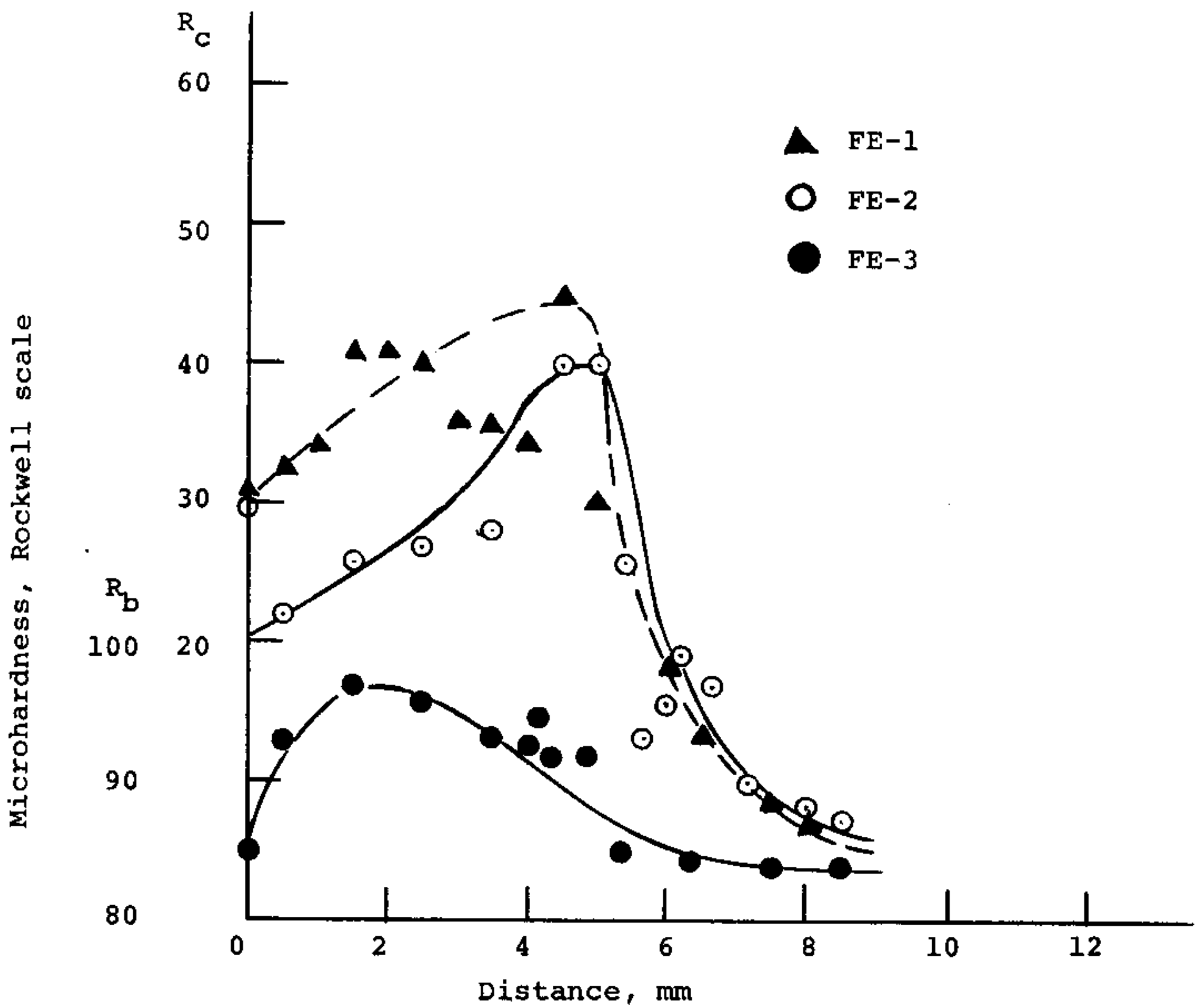


Fig. 3-16 Microhardness distribution along the weld center line (measurement started from water-weld interface)

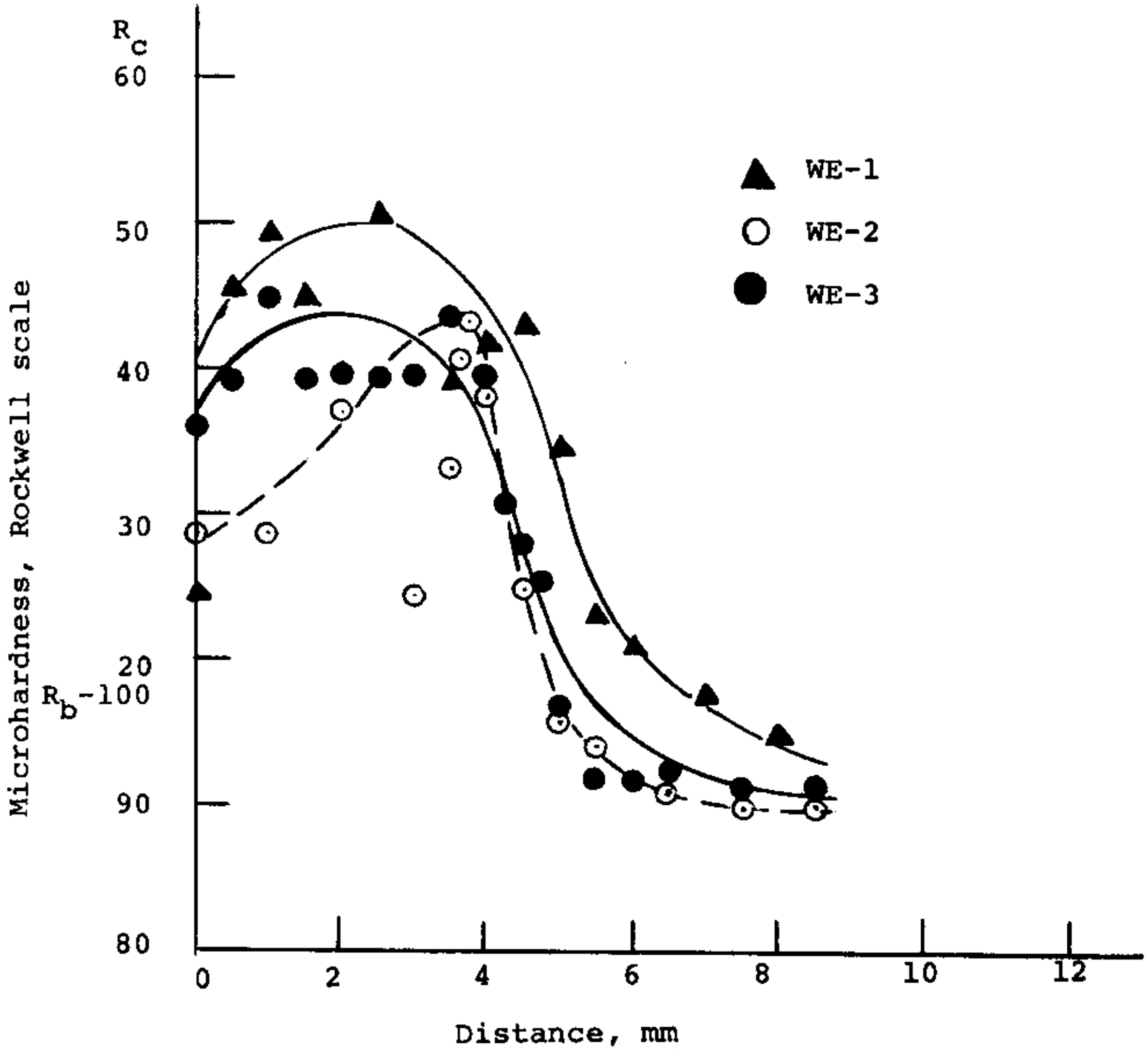


Fig. 3-17 Microhardness distribution along the weld center line (measurement started from water-weld interface)

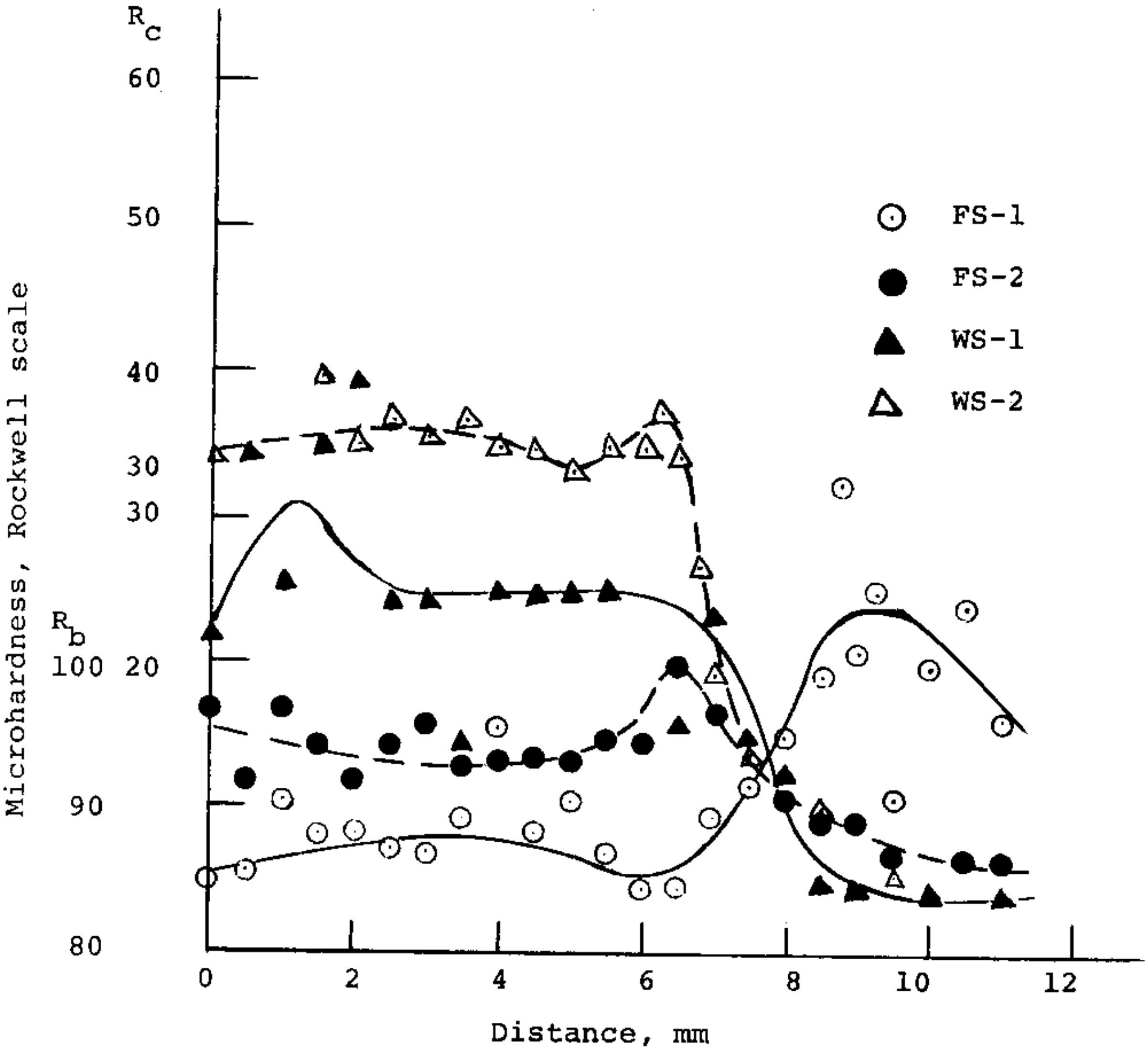


Fig. 3-13 Microhardness distribution along the weld center line (measurement started from water-weld interface)

processes. Figures 3-19 to 3-22 show the average magnitude of microhardness of the welds in each of the four series.

Although often the hardness is reduced significantly in flux-shielded welds (see figures 3-21 and 3-25), this was not always the case in our series of experiments. The flux covering and the welding set-up had to be carefully prepared before satisfactory results could be obtained.

Figure 3-23 shows the microstructure of a weld made using the flux-shielded process (FE-3). Finely distributed inclusions are shown in the weld metal. The effect of such inclusions on the mechanical strength has not been determined.

In order to determine the importance of heat loss during underwater welding, a series of experiments was done. The experiments dealt with the physical and metallurgical properties of underwater welds in mild steel in which asbestoes was used as an insulating material against heat loss.

Cold rolled, ASTM-242 steel plate was used in the bead-on-plate welding. The welding was carried out on a 10" x 6" x 1/4" plate at the mid-length across the face. The plates were insulated using 1/8" thick asbestoes cloth. Five methods of insulation were investigated (see Figure 3-24). Figures 3-25a to 25e show the macrostructure of the welds. The size of the heat affected zone, which depends on the maximum temperature reached in the base metal during welding, may be a good indicator of the thermal penetration from the fusion line. It increased 20% when the back was insulated and 28% when the face was insulated. In the

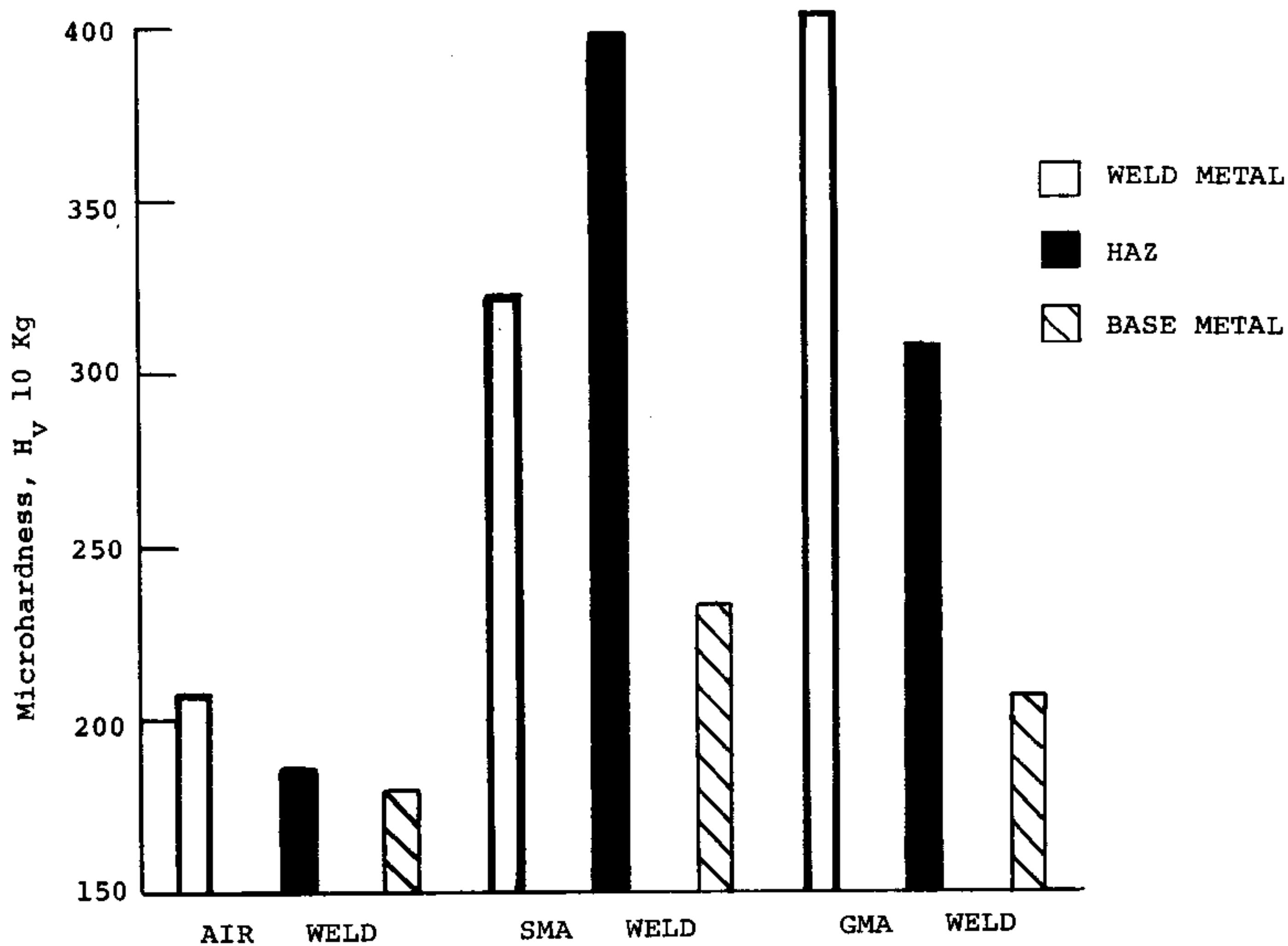


Fig. 3-19 Average magnitude of microhardness of welds

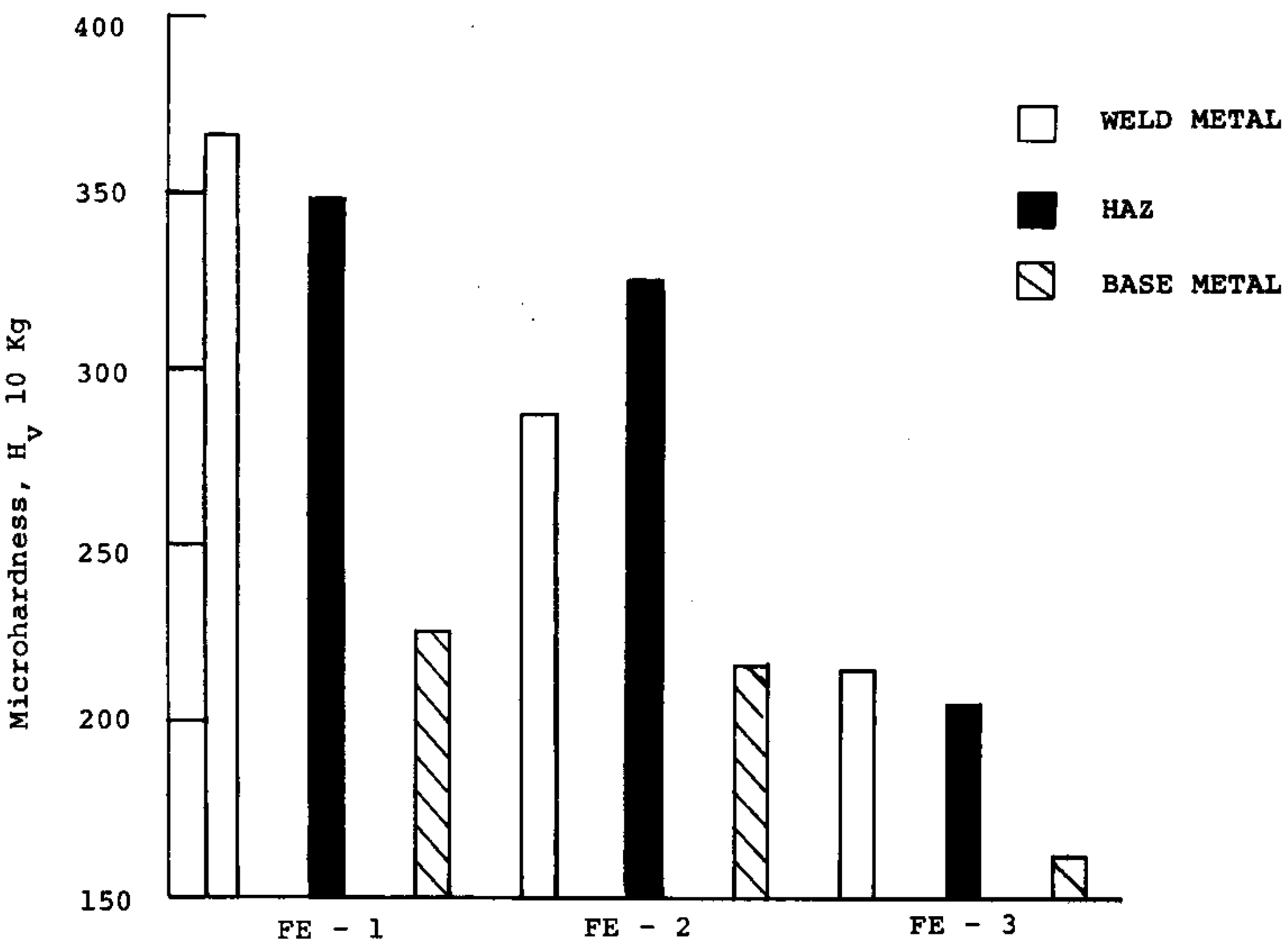


Fig. 3-20 Average magnitude of microhardness of welds

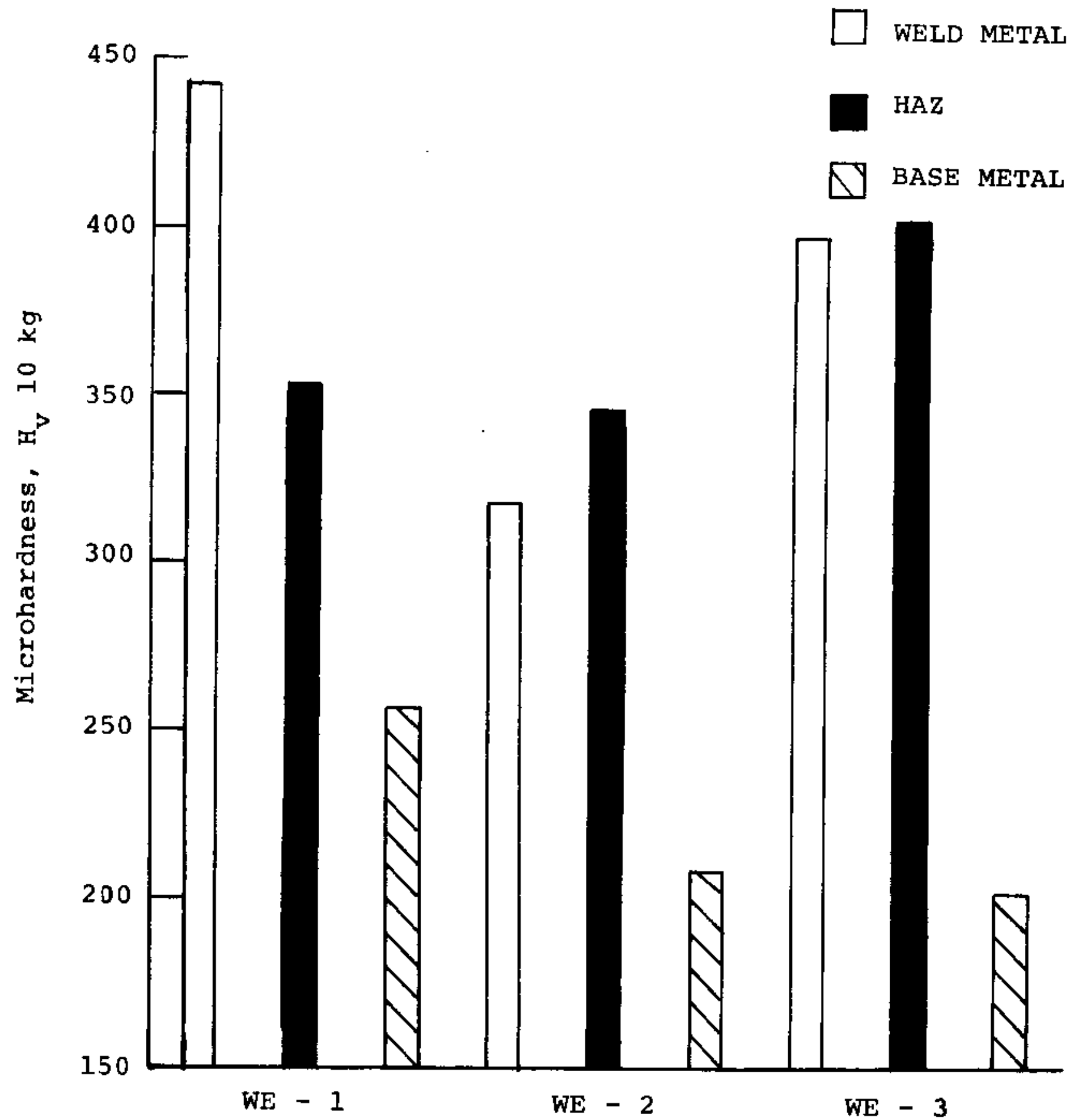


Fig. 3-21 Average magnitude of microhardness of welds

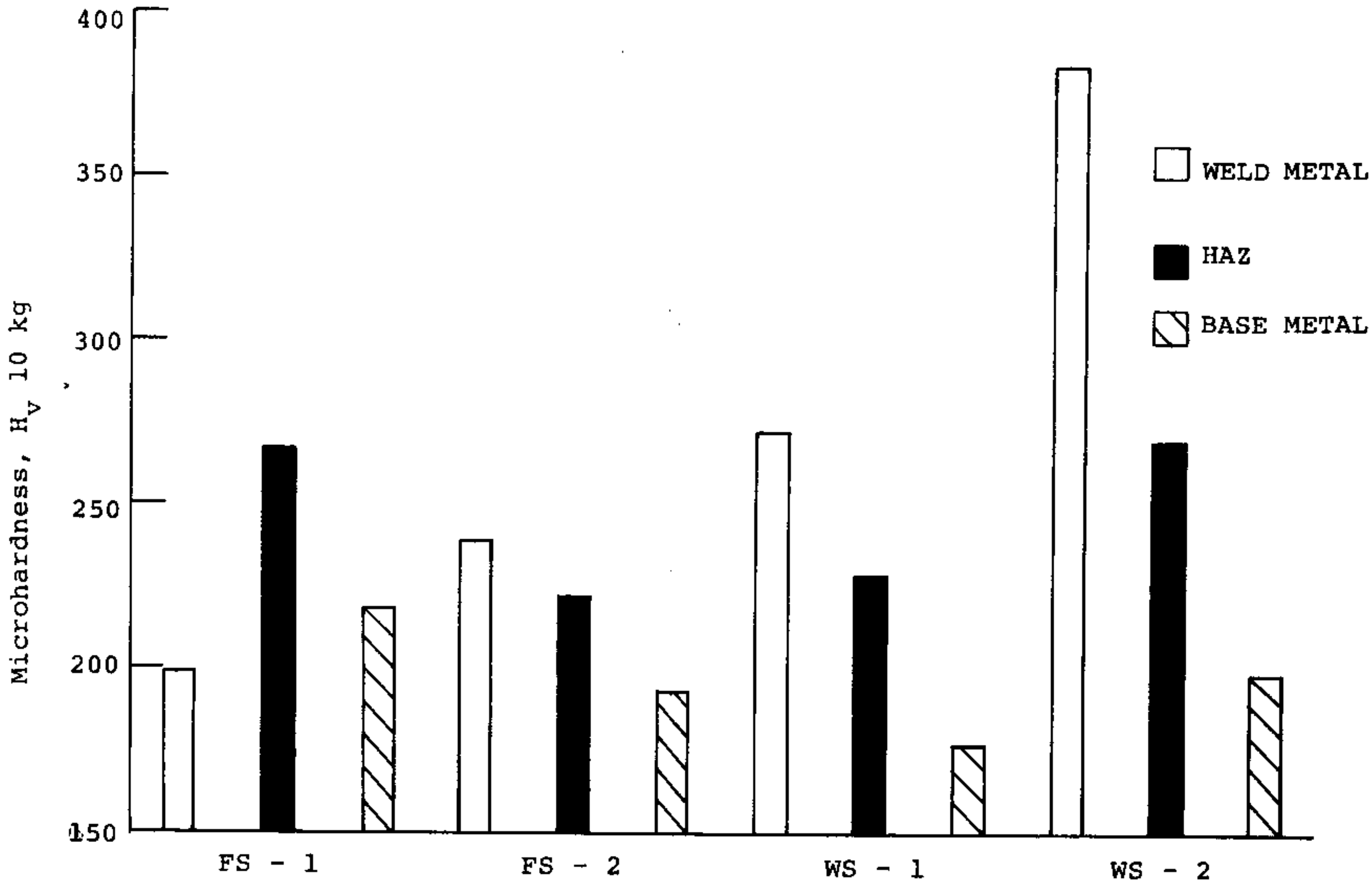
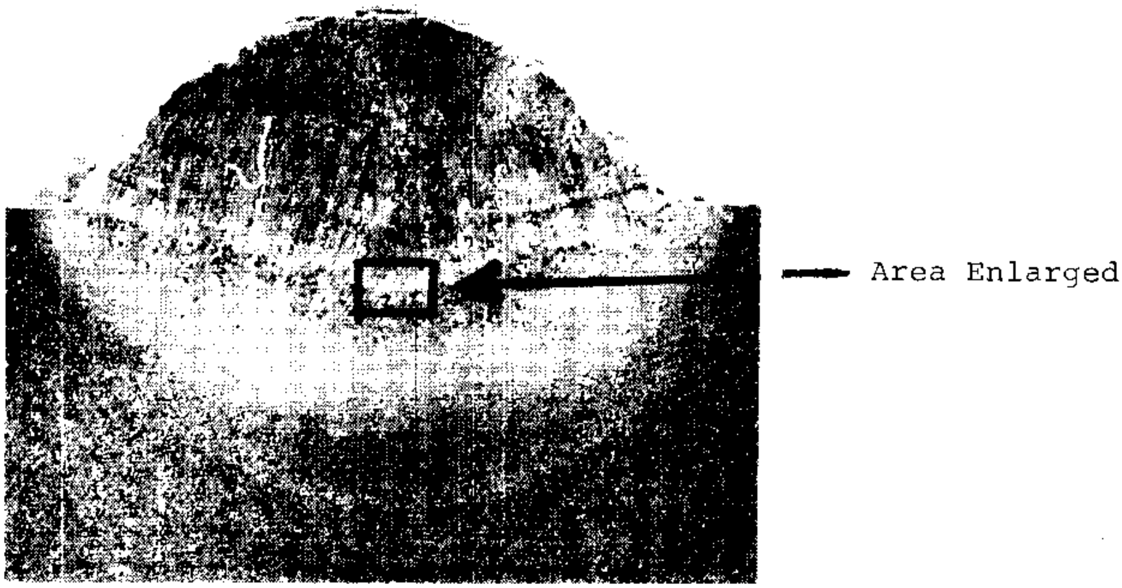
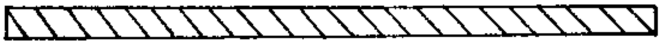


Fig. 3-22 Average magnitude of microhardness of welds



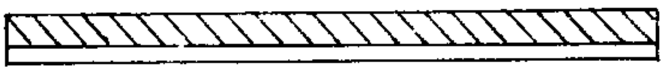
(Magnification X100, etched with 1% Nital)

Figure 3-23 Microstructure of a weld using the flux-shielded process. (FE - 3)

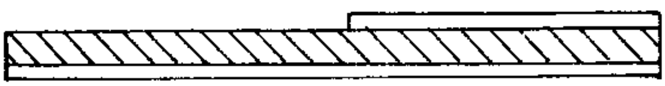


UN-INSULATED PLATE

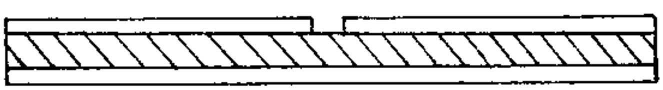
TOP INSULATED PLATE



BOTTOM INSULATED PLATE



HALF TOP & BOTTOM INSULATED PLATE



FULLY INSULATED PLATE

Figure 3-24 Five methods of insulation used for underwater welding plates.

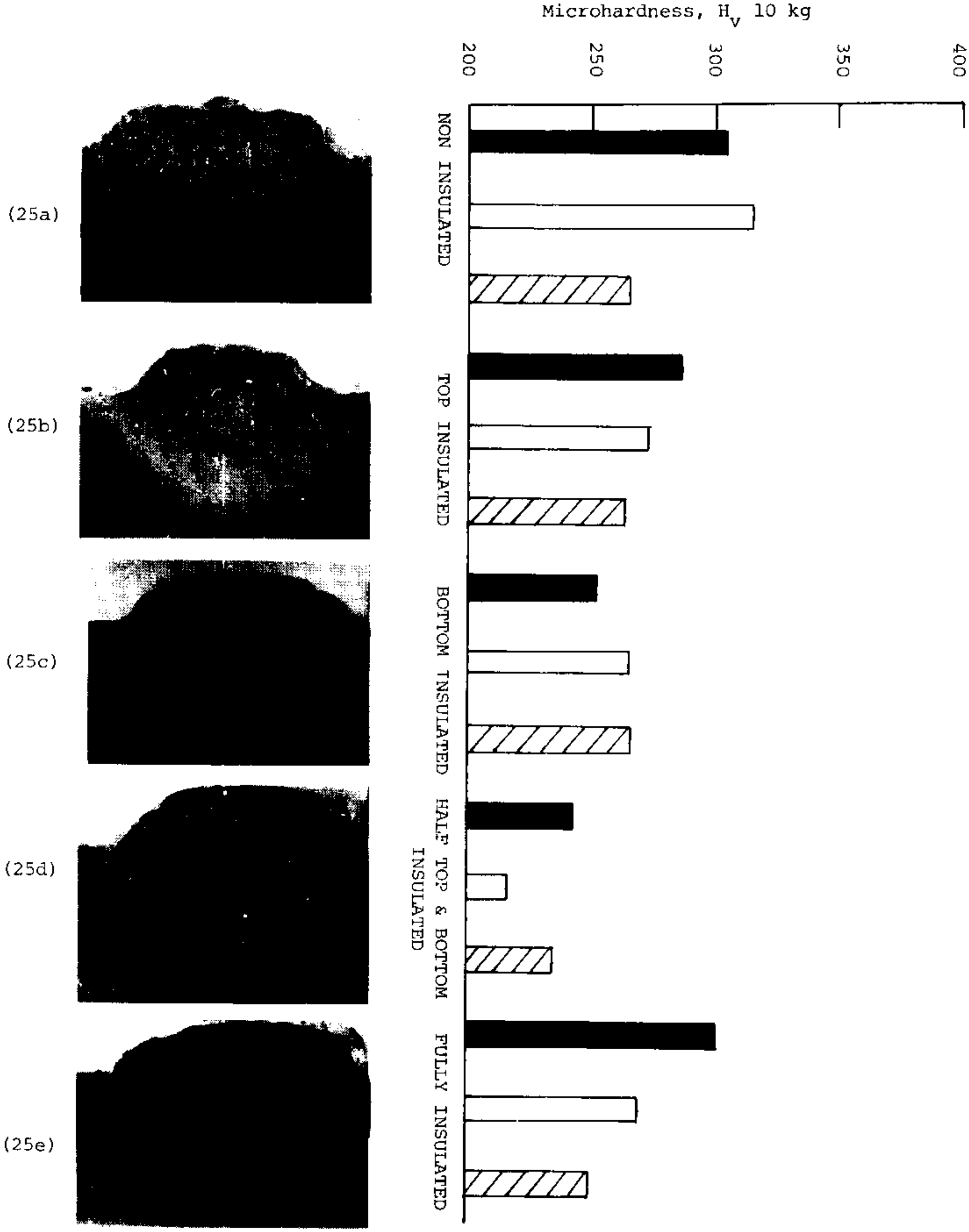


Fig. 3-25a-e Microstructure and microhardness of underwater welds in the half-insulated top and half-insulated bottom sample, only a 10% increase was observed. No change in the fully insulated sample was found. Figure 3-30 shows the microhardness measurement in the sample welds.

The effect of flux shielding was also investigated. 3-26a to 26d show the macrostructure and Figure 3-26 shows the microhardness measurements of the welds.

It was found that the hardness of the weld metal was reduced about 10 to 30% when flux shielding was used, but the hardness of the HAZ increased about 6 to 30%. The reasons for this are not clear.

From these limited number of experiments, the following observations can be made.

1. The insulation slows the cooling rate.
2. Insulation is better used on the face of the material to be welded than on the back.
3. Fully insulating the plate produced marginally improved results over the face-insulated plate.
4. The penetration was greater when face insulation was used than when back insulation was used.
5. The hardness of the weld metal is reduced by flux shielding. It is not clear why flux shielding increases the hardness in the HAZ.

It can therefore be concluded that most of the heat loss during underwater welding is from the face of the plate. This is in accordance with the heat transfer theory in which nucleate boiling on the face and film boiling on the bottom of the plate are assumed. The difference in the heat transfer coefficient is

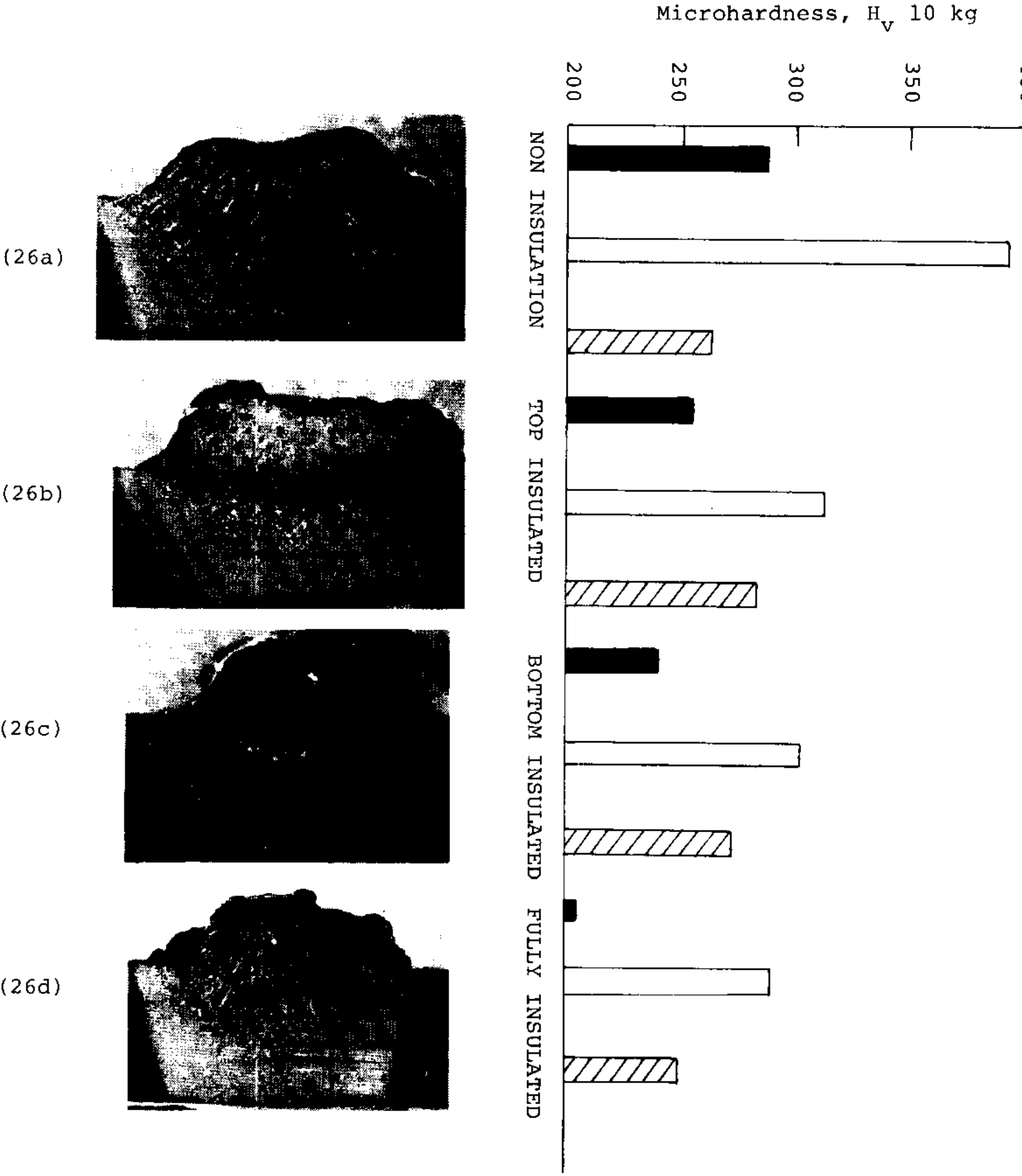


Fig. 3-26a-d Microstructure and microhardness of underwater flux-shielded welds on the order of 10^6. The same conclusions can be drawn about any plate thicker than 1/4".

The mechanical strength of flux-shielded welds was compared with that of underwater welds produced by the SMA, the GMA and the WSGMA processes. Figure 3-27 shows the ultimate tensile strength and Figure 3-28 the percentage of elongation obtained in a free bend test when different processes are used. Table 3-6 shows the tension test results and Table 3-7 shows the bend test results. The data show that the ultimate tensile strength is increased about 6% and the percentage of elongation due to uni-axial tension is increased about 45% by flux shielding compared with the E7014 SMA process. For the flux-shielded process, the ductility obtained by the bend test is also increased about 45% and no cracks were found.

The effect of insulation on the mechanical strength of the flux-shielded welds is shown in Table 3-8 . The ultimate strength did not seem to have been significantly improved. Any kind of insulation increased the ductility about 50%.

3.5 Design of Underwater Stud and Flux-Shielded Welding Tools.

Since it was found that underwater stud welds made with a dry chamber process had a quality equivalent to that of air welds, we feel that the development of a light portable stud welding

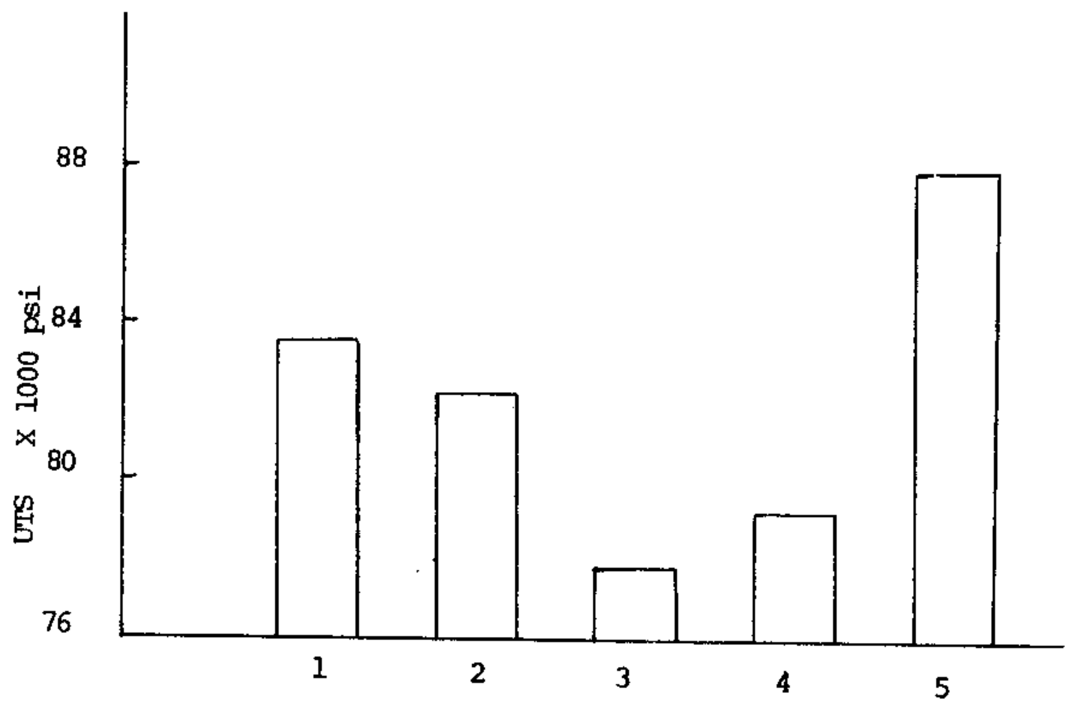


Fig. 3-27 Ultimate tensile strength obtained by following processes

1. SMA
2. SMA (Insulated Base Plate)
3. GMA
4. Waterjet GMA
5. Flux Shielded Metal Arc

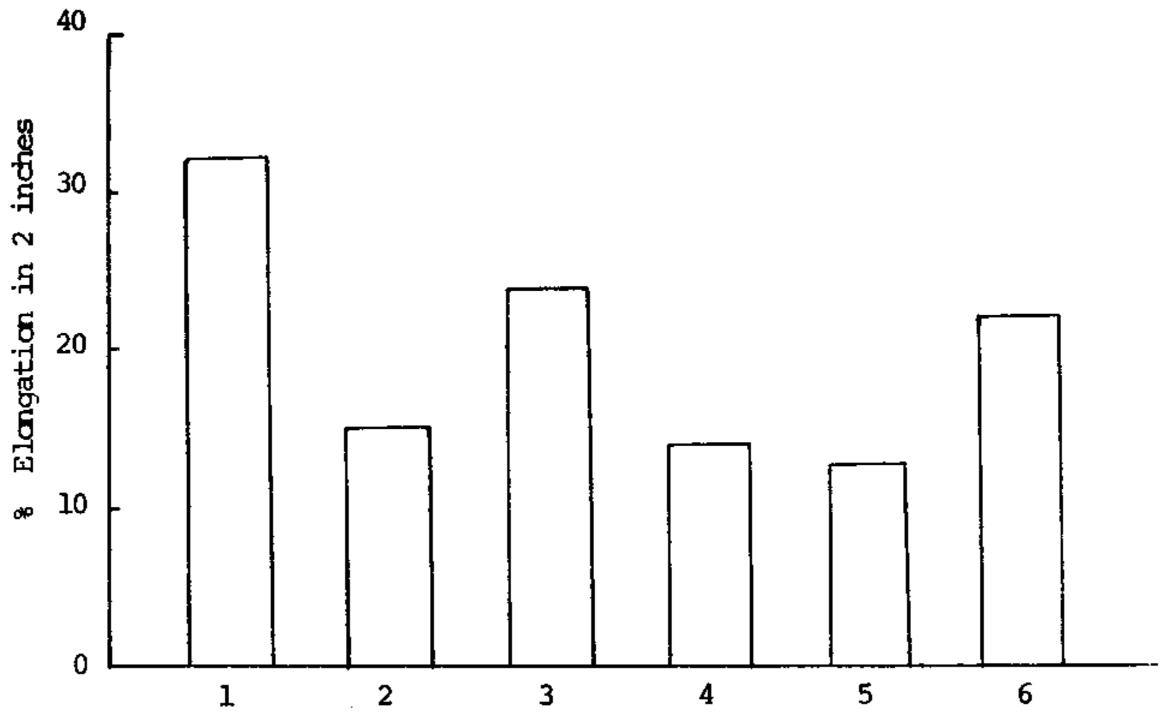


Fig. 3-28 Comparison of elongation obtained by bend test for specimen welded by different methods

1. Welded in air
2. SMA Welded
3. SMA (Base Plate Insulated)
4. GMA
5. Waterjet GMA
6. Flux Shielded Metal Arc Process

Table 3-6 Tension Test Results

Process	Specimen No.	Ultimate Tensile Strength (psi)	% Elongation in 2 in	Fracture location
SMA E7014	D1	82,555	9.2	B.M.
	D2	83,400	9.4	B.M.
Neutral Electrode (Insulated Plate)	E1	81,666	6.7	W.M.
	E2	82,370	6.5	B.M.
Neutral Electrode (Bare Plate)	G1	83,288	6.2	B.M.
	G2	83,644	7.1	B.M.
GMA AG75	K1	70,311	4.2	W.M.
ARCO	K2	77,955	4.5	W.M.
Waterjet GMA AG75 ARCO	N1	78,335	6.3	B.M.
	N2	79,285	6.4	W.M.
Flux Shielded Metal Arc	X1	87,911	14.0	B.M.
	X2	87,550	13.0	B.M.

B.M. = Base Metal

W.M. = Weld Metal

Table 3-7 Percentage Elongation From Bend Test

Process	Specimen No.	T (in.)	X (in.)	% Elongation E=(x-T) 100	Average E	Conditions after bend	Crack Initiation Angle
Air	A1	0.36	0.49	36.0	32.4	no crack	-----
	A2	0.38	0.49	28.9	32.4	no crack	-----
SMA	D1	0.55	0.64	16.4	15.3	crack	70
	D2	0.57	0.64	14.0	15.3	crack	65
	E1	0.43	0.53	23.2	23.8	no crack	-----
	E2	0.45	0.56	24.4	23.8	no crack	-----
	G1	0.49	0.58	18.3	17.45	crack	79
	G2	0.42	0.49	16.6	17.45	crack	70
GMA	K1	0.43	0.48	11.6	14.1	crack	52
	K2	0.48	0.56	16.6	14.1	crack	46
Waterjet GMA	N1	0.40	0.45	12.5	12.5	crack	35
	N2	0.45	----	----	12.5	failed	35
Flux Shielded	X1	0.37	0.46	24.3	21.9	no crack	-----
	X2	0.41	0.49	19.5	21.9	no crack	-----

Table 3-8 Tension Test Results - Flux Shielded Welds

Welded Sample	Ultimate Tensile Strength (psi)	% Elongation in 2 inches	Reduction of Area (%)	Fracture Location
No Insulation	92,400	12.5	31.25	B.M.
Top Insulated	89,066	18.75	23.44	W.M.
Bottom Insulated	88,533	17.74	32.81	HAZ
Top & Bottom Insulated	87,600	18.75	37.50	HAZ

B.M. = Base Metal

HAZ = Heat Affected Zone

Base Plate Material = ASTM-242

Electrode Material = Waterproofed E7014

Current = 240 Amps.

tool usable by divers in underwater joining should be a priority task in a future program.

Since it was also found that the mechanical strength and ductility of welds made with proper flux shielding could be greatly improved (the ductility up to 45%), the design of a flux-shielded welding unit should also be a priority task.

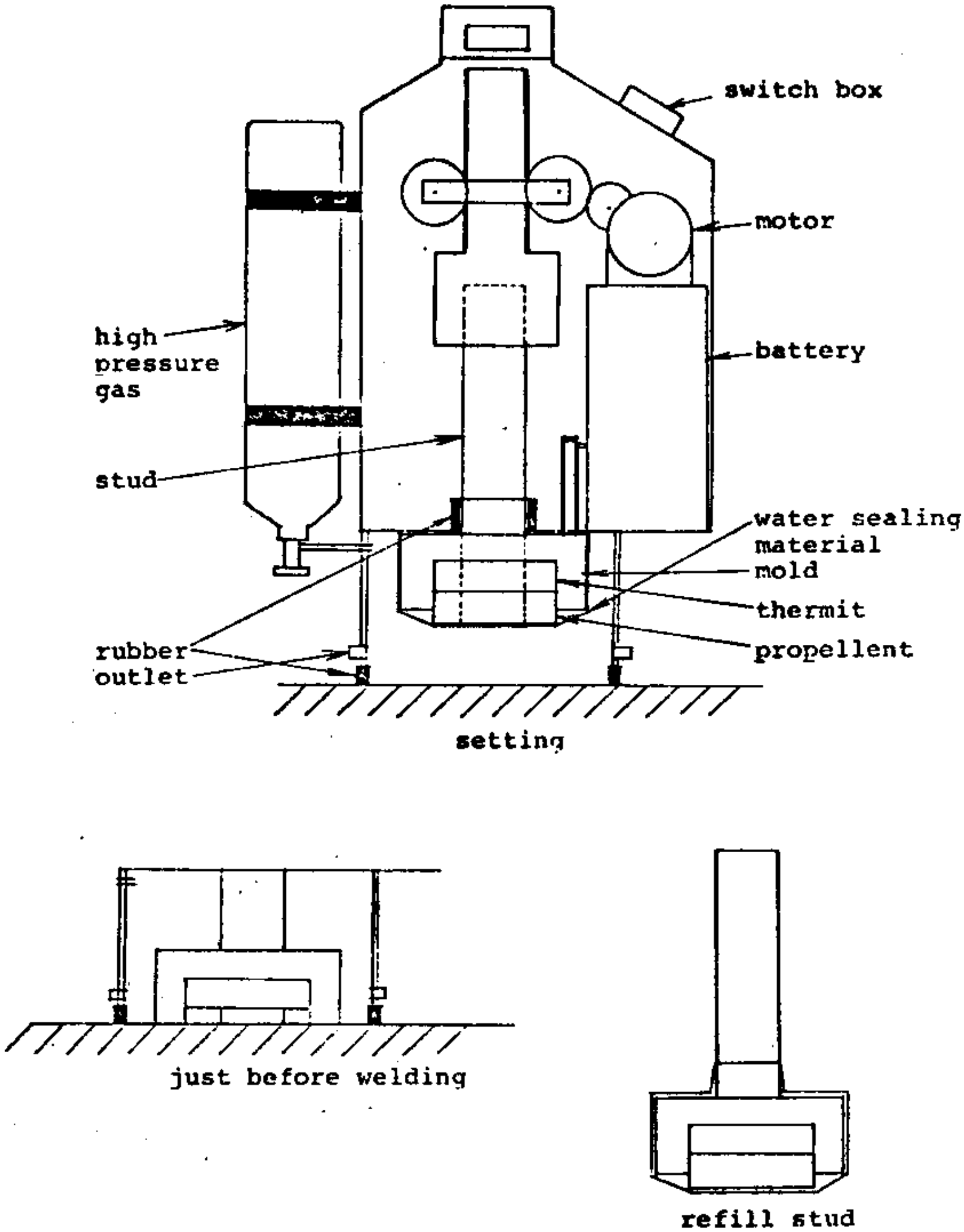
As we can see by a review of underwater welding technology as it has been carried out thus far (see Chapter 2), most underwater processes are adaptations of techniques that were originally designed for air use. In the GMA process, for example, the argon or helium stream does remove the oxygen or nitrogen from the arc atmosphere, but it, or a similar gas-stream method, could probably never be successfully adapted to remove water, especially in deep-sea situations. Flux in a powder or liquid-solid form is probably more promising as an arc-protector.

What we need are techniques specifically suited to underwater welding, not just underwater applicatons of air welding processes. Figures 3-29 and 3-30 are conceptual designs for two new units:

1. A unit for welding a stud to a plate.
2. A unit for fillet welding a plate to a plate.

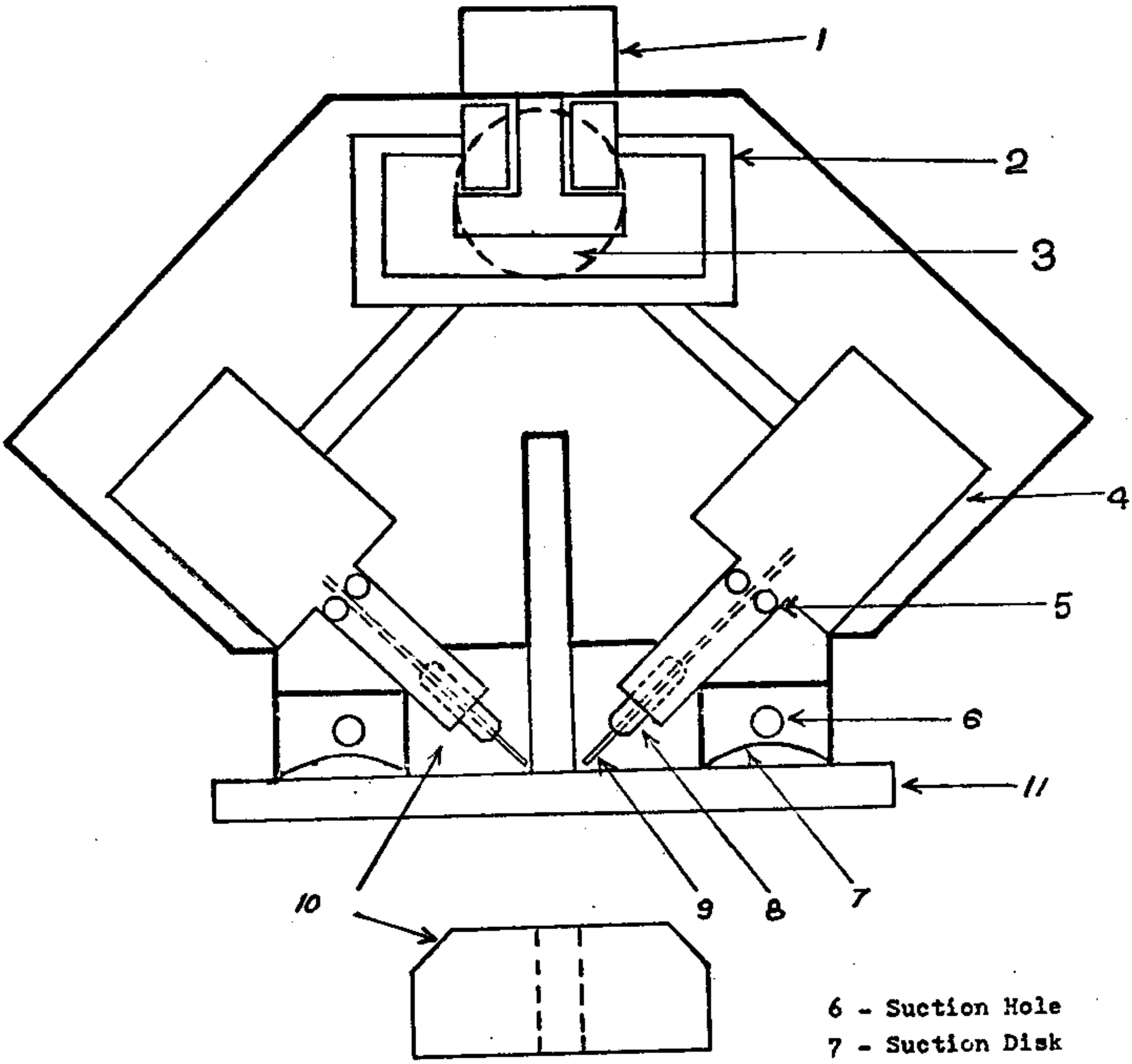
These units have the following unique characteristics:

1. The units are completely enclosed. The only portion that is exposed to water is the area to be welded. The welding reaction takes place in a dry atmosphere.



A refill stud contains a stud, a mold, propellent and thermit.

Figure 3-29 Underwater Welding Unit for Joining a Stud to a Flat Object



1 - Control Box
2 - Travel System
3 - Motor
4 - Wire Box & Feed System
5 - Roller
6 - Suction Hole
7 - Suction Disk
8 - Directional Tip
9 - Wire
10- Flux Filled Cartridge
11- Base Plate

Figure 3-30 Underwater Welding Unit for Fillet Welding a Plate to a Flat Object

2. No welding skill is required. The diver places the unit to the object to be welded and either activates the unit or informs someone on the support ship to activate the unit.

These units would be similar to an SX-70 Polaroid camera in that the only thing that the operator would have to do to complete the process would be to press a button. The results would be guarenteed.

CHAPTER 4: TOTAL OPERATIONAL SYSTEMS FOR UNDERWATER WELDING

This study will examine those factors that must be considered when developing a capacity to join metals in a deep-sea environment: Why is such a process needed? How do we know when it is needed? How is its success dependent on diving system capability? What technical problems are caused by pressure effects?

Figure 4-1 shows how these factors interact.

1. A need must exist that can be met either fully or partially by the employment of some underwater metal joining process.

2. Selection:

(a) The process most suitable for meeting the requirements must be indentified and any technical problems associated with working at the intended depth must be solved.

(b) A diving system must be selected that is capable of delivering and employing the joining process. (In a complete underwater repair or fabrication system, additional elements may also be selected and worked into the design.)

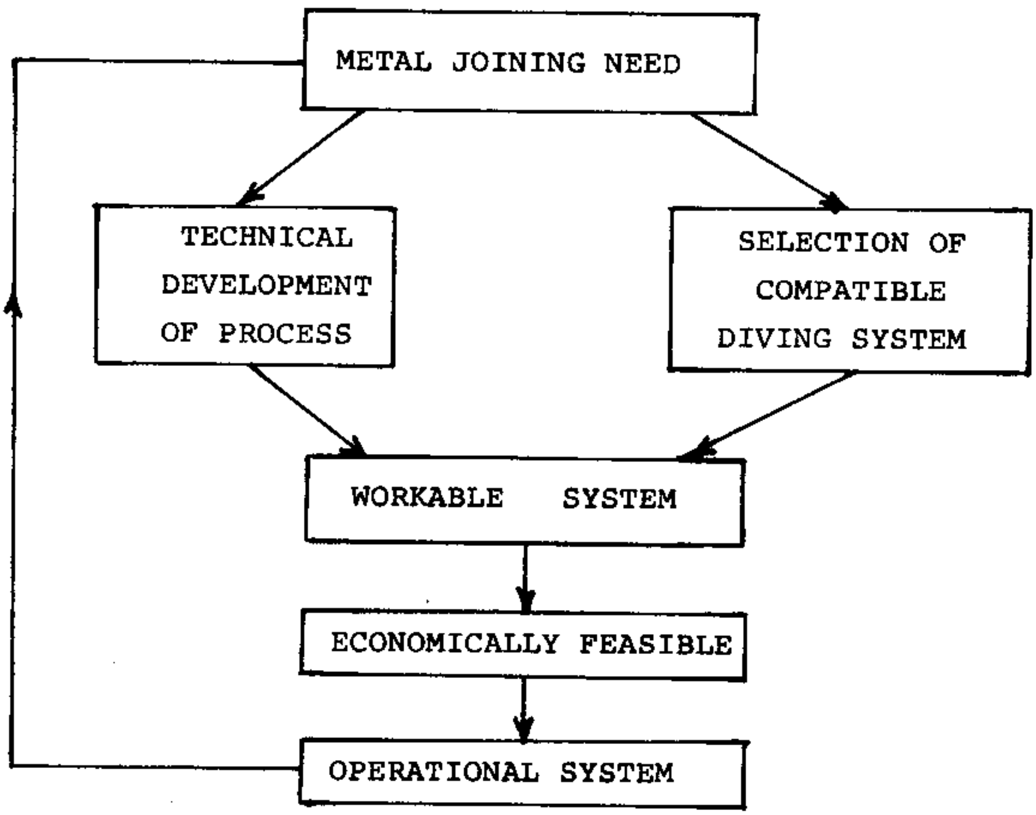


Figure 4-1 Development of a Deep Ocean Joining System

3. The individual elements are integrated into a workable overall system.

4. The economic feasibility is demonstrated.

The feedback loop from operational system to need indicates that the development of a workable system where none previously existed often leads to the identification of other similar needs.

4.1 Present and Projected Needs.

The purpose of our study is to examine why deep-sea metal-joining processes are needed. We will survey those industries and other interests which either presently operate in the deep ocean or are expected to operate there in the near future. In this manner two objectives can be met.

1. The processes that appear to be most promising for practical application can be identified and the technical and diving-related problems worthy of more detailed study pinpointed.

2. The industries or governmental agencies that provide the driving force behind the development of underwater joining processes can be identified and the incentives that determine the direction of technical development examined.

Technology is a product of both incentive and time. The rate of technical development depends on the economic and political incentive to invest the required capital. Incentive, however, can be whetted or dampened by previous technology. As a result, a closed cycle is often observed wherein economic needs motivate the development of technology and advancing technology points the way for potential economic gain. The direction of new technology is determined also by previous developments, because economic factors generally favor the development of processes that seem to offer the quickest solutions with the least technical risk.

Ocean industries are in their infancy. It is difficult to predict future needs from the scant activity now observed in the shallower portions of the world's oceans. However, some idea of potential technical needs can be gained by examining a profile of the ocean bottom such as that depicted in Figure 4-2. At the present time, most, if not all, activities requiring the capability to fabricate metals take place on the continental shelf. As its name implies, the continental shelf, occupying only about ten per cnet of the seabed, is a gently sloping terrace gradually increasing in depth from the shore to where the sharp incline of the continental slope begins. The dividing line between shelf and slope varies throughout the world, averaging about 400 feet, but angling down to a maximum of 2000 feet in a few areas. The width of the continental shelf ranges from a minimum of less than one mile to a maximum of about 800 miles.[38]

Activity in offshore waters is moving now primarily into the deeper waters of the continental shelf itself. As long as such moves are confined to the shelf, depth requirements for fabrication processes will stretch only a small amount. However, serious activity on the continental slope and beyond is expected

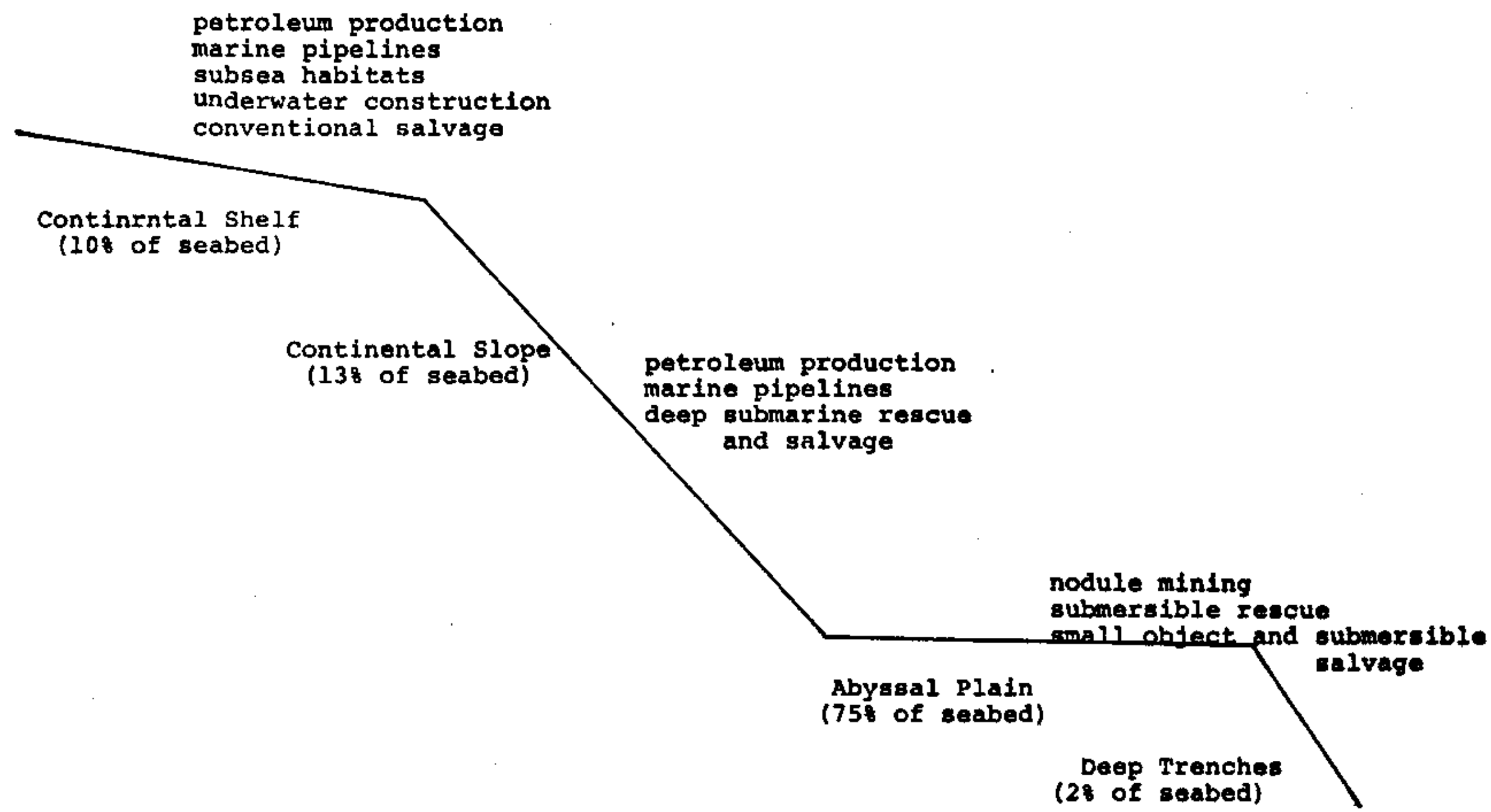


Figure 4-2 Present and Future Ocean Activity

to begin very shortly. Seismic petroleum exploration is being conducted actively on the slope and plans are being advanced and equipment tested to conduct mining operations on the abyssal plain. This type of activity means that depth needs for fabrication equipment may increase drastically in a relatively few years.

4.1.1 Needs of the Offshore Petroleum Industry

The primary economic impetus to extend metals joining technology deeper into the ocean comes from the offshore petroleum industry. Petroleum is by far the most important marine resource with approximately 19 per cent of the world's current crude oil production coming from subsea deposits.(39) More than 80 nations around the world are engaged in some sort of offshore petroleum activity and proven offshore reserves in the free world total more than 500 billion barrels. The United States Geologic Survey's estimate for deposits off the coast of the United States is from 65 to 130 billion barrels of oil and from 395 to 790 trillion cubic feet of gas. The National Petroleum Coucil estimates that the area out from shore to a water depth of 200 meters (656 feet) probably contains from 55 to 70 per cent of potential reserves; the area between 200 meters and 2500 meters (8200 feet) water depth from 20 to 35 per cent; the area between a water depth of 2500 meters and the seaward edge of the continental rise from 1 to 15 percent and the deep ocean seabed only up to 2 percent.(40)

Most actual production offshore comes from waters of less than 200 feet with very little production at depths greater than 400 feet. However, exploratory drilling is going on in water depths in excess of 2000 feet and Exxon has completed a well in 1,400 feet of water in the Santa Barbara Channel.[41] The trend is clearly to drill and produce in deeper waters when increased costs are justified by the potential return from sizable deposits.

Underwater metals joining techniques are required for the repair of both surface and subsea production sites and in the repair of undersea pipelines. In addition, underwater joining processes may be required in the initial fabrication of pipelines in depths beyond the capability of surface laying barges.[42, 43]

1 Fixed platforms. To date, all but a few offshore wells have involved the construction of fixed bottom platforms to serve as drilling or production bases. Fixed platforms have been installed in waters in excess of 400 feet and are being designed for use in water up to 1000 feet in depth.[39] The cost of these structures increases rapidly with depth. In 100 feet of water, the cost of the platform alone exceeds $1.5 million; in 350 feet, $4 million; and in 600 feet, $12 million.[38] These structures are constructed in shipyards and towed to the well site where they are deballasted and fastened into place with pilings. No underwater fabrication processes are necessary for their construction or placement.

In several cases, however, platforms have been damaged during towing or installation and in these cases underwater repair techniques have proven valuable since the cost of refloating and towing these structures back to dry dock was saved. In addition, these structures may be damaged in service by wave action, fire or other operational accidents, as well as the corrosive action of the marine environment over a period of years.[44, 45]

For a number of years, from 1947 when the first platform was put in service, until the late 1960's, operators were reluctant to order underwater repair of these structures since single pass, drag type welds made underwater using the SMA process were low in strength and notch toughness and suffered from cracking problems.[46]

Offshore platforms are complex structures and joining systems used in their repair must be able to overcome several constraints in addition to those encountered in all underwater fabrication processes. Since platforms are constructed of a combination of vertical, horizontal and diagonal members of varying sizes, any repair technique should be flexible, capable of repairing any member of any platform. High cost habitats designed for one configuration, such as those used in the repair of undersea pipelines are virtually ruled out by this requirement. Since welding operations conducted in an actual marine environment require expensive diving and surface support, any underwater repair process must be relatively quick. This eliminates processes with extremely slow deposition rates such as plasma-arc welding. Since offshore production and drilling platforms are critical structures subject to extreme loading conditions, weld quality is especially important. Cracking and low notch toughness cannot be accepted. Thus the conventional single pass underwater SMA process cannot be considered satisfactory.

Possible candidate processes for platform repair are thus considerably reduced. Small fixed and movable chambers employing the GMA process have been used with some success in the repair of tubular offshore structures. Although repairs that can be made to some joint designs are limited by the size of the head, this process appears to be sufficiently versatile for most platform repairs. Presently used mostly in depths of less than 200 feet, this process seems to be a good candidate to be developed for use at the greater depths required for the repair of future platforms.

Another process, the multi-pass SMA technique developed and practiced by CBI has proven extremely reliable in actual service. Depth related capability seems to hinge on electrode composition and practical diving limits. E6013 electrodes have proved to be effective at depths exceeding 200 feet for materials with a carbon equivalent of less than 0.40. Austenetic electrodes are reliable in service to 80 feet for materials with a carbon equivalent greater than 0.40 but less than 0.60 and these electrodes are presently being modified for greater depth capability. The greatest disadvantage of the multipass technique is the extremely exacting, time consuming and expensive training procedure needed to train welder-divers. It appears unlikely that personnel can be trained in the numbers required by a rapidly expanding petroleum industry.

Two other processes, shrouded metal-arc welding and wet GMA welding, both in the experimental stage, exhibit promise but require much more developmental work before they can be considered operational.[47]

All of the processes mentioned as suitable for platform repair are highly diver dependent and thus are limited by depth and cost considerations as discussed in the next chapter. Mechanical joining is the only technique suitable for platform repair which is capable of employment by a manned submersible or remotely operated manipulator.

2 Subsea Production Systems. As the search for gas and oil progresses into deeper waters new production sites are required. Although the deepest fixed production platform now under consideration is planned for water depths of 1000 feet it is expected that a technical need to produce in 2000 to 3000 feet of water will soon exist. In fact, the record water depth for conventional gas and oil drilling is 2150 feet and rigs are now available that are capable of drilling in 3000 feet of water. Subsea production systems are now being developed and tested in order to meet the need for deep production facilities. In areas with rough weather conditions, subsea production sites are also expected to be more economical than platforms in waters as shallow as 400 to 500 feet.[39]

Underwater completions have been made for more than 30 years in shallow water and at low pressure. More than 300 have been made in Lake Erie alone and at least 106 have been completed on offshore continental shelves. However, the deepest of all these completions was made in only 375 feet of water, well within diver range. In all cases but one, divers were required to complete connection of flowlines even though attempts were made to connect remotely. In addition, most production functions for these completions were performed on land or on nearby platforms.[39]

Subsea wellhead equipment or "X-mas trees" can be divided into "wet" and "dry" types. The wet type has all components exposed to the sea and must be reapired and serviced by either recovering the tree to the surface, employing conventional divers, or using specially designed manipulators. The dry type has all components housed in a chamber isolated from the sea. This system can be serviced by men working on the seafloor in a one atmosphere environment. Though othersare being constructed, only one dry system has been installed on a real subsea well.[41, 48]

The wet tree is usually completely assembled and tested prior to installation. It can be run down to the seafloor casing housing and latched on with a remotely operated hydraulic connector. Flowlines can next be connected by divers or, at least theoretically, by remotely controlled manipulators. The dry chamber system is run down and connected to the seafloor casing housing in the same manner. However, all components are dismantled and stowed inside until after connection to the casing. A specially designed one atmosphere capsule is used to transport men down to the chamber to make the flowline connection and assemble and test the X-mas tree.[39, 48]

Four companies are constructing or testing complete subsea production systems with design depths ranging from 1500 to 3000 feet. It is estimated that one of these, Exxon's submerged production system (SPS), will cost about $29 million. Two of the four have already been installed at test depth and the other two are scheduled to begin testing in 1975. Test depths range from 170 to 250 feet. Each of these four systems is designed so that repair or replacement of well head components can be easily completed. In the wet systems all components are mechanically connected so that remotely operated manipulators or manned submersibles can replace faulty components. In the dry systems, men working in one atmosphere chambers can effect repairs using conventional surface techniques.[39, 48]

Although each of these systems contains structural protective members and other components which cannot be mechanically replaced or serviced from work chambers, the incidence of damage to, or deterioration of, these parts is expected to be very small. If some critical member should be damaged, it may be possible to reinforce it using a sleeve or other mechanical connector placed using a submersible or remotely operated manipulator, since water depths of 2000 feet and deepter are well beyond practical diving limits. If damage is severe enough to warrant closing down production, the entire structure must be retrieved and repaired on the surface or in drydock. Underwater welding systems capable of reliable repair work at ambient pressure on a structure 2000 feet below the surface are still quite a few years in the future. The need to design around technical gaps such as this one is the reason that deep subsea production systems are such complex and expensive projects.

3 Undersea Pipelines. Any offshore petroleum production system requires pipelines to bring any oil or gas recovered to some central collection point. Flowlines, transfer lines, trunklines and risers are all needed. In addition, underwater pipelines have become integral parts of transport pipeline networks used to route liquids to markets. A $475 million undersea pipeline system is presently being planned which will carry crude oil produced in five North Sea fields to a terminal in the Shetland Islands. Called the Brent System, this pipeline will stretch 96 miles through waters over 500 feet deep and will eventually fill over one half of Great Britain's petroleum needs.(49)

Since the 1940's in the Gulf of Mexico, offshore pipelines have been constructed and laid from barges. In very shallow water, pipe sections are joined on the barge and passed directly over the stern to the bottom. As depth increases, rigid "stingers" or slides are used to support the pipe between the barge and the seafloor. In 1963, Shell Oil Company developed a method where the pipe is held in tension at the barge and allowed to hang in a suspended span from the end of a short stinger to the bottom. Articulated stingers, an improvement developed in 1967, are sufficiently flexible to absorb lay barge motion and conform to suspended pipe span profiles.(39)

The largest pipeline laid in deepwater to date is the 32 inch diameter Forties Field pipeline, constructed for British Petroleum in the North Sea at water depths to 420 feet. It is thought that a dynamically positioned lay barge, using the tension technique, can lay pipe up to 24 inches in diameter in 3000 feet of water. With further development of tensioning equipment, laying 30 inch pipe at 3000 feet may eventually be possible. In order for oil to be economically produced in waters exceeding 3000 feet, sizable quantities must be present. In such a case, floating risers might be employed to bring the oil directly to the surface and the need for bottom laid pipe eliminated. If underwater fabrication processes can be developed to join pipe at extreme pressures without the need for divers, these techniques might prove to be less costly than riser systems.

The problems associated with construction of deep undersea production systems and pipelines are complex and difficult. However, the repair of pipelines in water depths beyond the reach of divers may be the single most difficult problem in extending oil and gas production into deep water. At present, the system used for most underwater pipeline work is the hyperbaric chamber. Since a pipeline has a very simple configuration, it is possible to construct dry chambers which can be fitted over and sealed to pipes of many different diameters. Second generation chambers can be mated with alignment devices and used to join sections, to effect tie-ins and to replace sections of pipe in addition to performing simple repairs. Pipelines can be repaired, tested and coated, all within these chambers. Since water is displaced from these chambers by a mixture of pressurized gases, men within these chambers are subject to a pressure corresponding to water depth. This method is thus limited to depths equivalent to practical diving depths.[47, 50]

An alternative repair method has been proposed by Shell. This system is called the Seafloor Pipeline Repair System (SPRS) and its development is being supported by other companies as well as Shell. The concept entails constructing an entire system, unmanned and remote controlled, which would replace entire sections of damaged pipe in a single dive. The system contains tools and manipulators necessary to uncover, inspect, clean, cut and remove damaged pipe and to insert and join replacement pipe, which is carried onboard. Mechanical couplings would be used for the joining of the replacement pipe to the pipeline.[51]

4.1.2 Deep Marine Salvage Needs

The requirements for metals joining processes in deep marine salvage are somewhat limited in scope. To begin with, salvage operations in waters deeper than 200 feet are rare and can be expected only in somewhat unusual circumstances. In such deep waters no attempt is likely to be made to salvage conventional ship types since required lift capacity would be prohibitive and structural integrity of the sunken vessel questionable. In addition, few vessels are expensive enough to justify the tremendous salvage costs involved and valuable cargo from a sunken vessel can be recovered by itself.

Deep marine salvage can then be expected to be limited to small objects except for two special types of cases. The first of these is the case of a fairly large object which possesses a great deal of structural strength and is very expensive. The second case is that of an object which has generated a great deal of international political interest. One example, the nuclear submarine, falls into both of these categories. It is conceivable that a submarine could be sunk on a continental shelf or other location at a depth shallower than its crush depth. Salvage would then be desirable for several reasons. First the submarine might be restored to service condition saving several hundreds of millions of dollars in replacement cost. Next, it is possible that if the submarine were sunk on the continental shelf of another nation its nuclear powerplant might stir up diplomatic reactions. Finally, it might be desirable to salvage the submarine to preclude the possibility of its recovery by another nation.

The establishment of an attachment point on a sunken object constitutes the main need for underwater joining technology in deep marine salvage. This can be a difficult problem in deep salvage operations. Low visibility, diver stability, short bottom time and the problems inherent in the conventional manual SMA process can make the welding of a padeye, even in depths within the range of a diver, a difficult matter. In depths beyond practical diving limits, an entirely different approach must be taken.

The U. S. Navy is currently interested in developing a process capable of remotely attaching a 50 ton padeye to a metal structure underwater. Several devices are presently being developed to meet this and other deep sea attachment needs. These include exothermic welding devices, explosive bonding devices, velocity powered stud guns and automatically activated metal-arc processes. The velocity powered stud gun, in particular, has proved useful in various underwater tasks and is being used in multiple groupings to provide a lifting point in the Navy's Large Object Salvage System (LOSS). However, none of these devices has yet proved successful in providing heavy loading capacity using only one attachment point.

4.1.3 Other Needs.

Industries other than the petroleum industry are just beginning to develop marine resources. Probably much of the technology required by these industries will be adopted from the petroleum industry and newly emerging marine industries will not exert a large driving force on new technology.

The mining of manganese nodules from the seabed is receiving a great deal of publicity. Several large corporations have invested millions of dollars in the development and testing of recovery techniques and processing plants. Surveys indicate that these nodules, which contain nickel, copper, and cobalt in addition to manganese, are most plentiful on the deep abyssal plain in depths ranging from 10,000 to 20,000 feet. At the present time, however, the legal status of mining these deposits is in doubt, depending on the outcome of complex international negotiations in the continuing Law of the Sea Conferences. This legal uncertainty has inhibited capital investment in recovery equipment. In addition, these nodules, which form from mineral deposits in the water column, are spread in a fairly shallow layer over the seabed, although they are more concentrated in certain areas than in others. Because of this scattering, it is unlikely that any permanent seafloor structures will be erected to aid in the collection of nodules. All recovery is expected to be undertaken from surface based air-lift dredges and continuous line buckets possibly combined with bottom crawlers. As a result, equipment is expected to be easily recoverable to the surface for repair and it appears unlikely underwater metal joining processes will be required.[52]

Phosphorites are another important hard mineral mined from subsea deposites. However, land and shallow water deposits are sufficient to provide for world demand for some time so that deep water mining is not contemplated.[38]

One other conceivable need for metals joining in the deep ocean is the construction and repair of manned habitats used for scientific or military purposes. Although some far-sighted individuals have predicted the eventual construction of undersea cities, present activity in this field is somewhat more limited. Most if not all habitats are constructed on the surface and are recoverable for reuse. Since most are used as bases for saturation diving, repairs can be made using the diver operated techniques described for use in the repair of oil platforms. Any habitats constructed in deeper waters in the near future are likely to be small portable structures designed for missions of limited duration and, as a result, will require few, if any, repairs.

4.1.4 Summary of Needs

In summarizing those processes that appear to have potential for deep sea application, it is useful to divide processes into two groups. The first group encompasses those techniques oriented toward general repair or fabrication usage. Processes in this group normally require manned operation, either in the form of a diver or a welder within a dry habitat. The second group includes processes most useful in establishing single attachments on underwater bodies, such as the welding of a padeye underwater. Techniques in this group lend themselves much more easily to remote operation by a manned or unmanned submersible with manipulators.

Promising joining techniques are outlined in Table 4-1. In the first group, joining processes identified are all electric-arc welding processes, with one exception. In order to adapt these processes for deeper application, technical problems associated with pressure effects on the arc must be studied. In addition these processes require very precise manipulative ability and are thus not readily adaptable to remote operation. Both of these topics will be discussed in detail in later chapters. The one technique in this group that is not a welding process is mechanical joining. Since mechanical methods are compatible with remotely operated systems and are not affected by pressure, their use is being planned in several deep water systems.

Table 4-1

Joining Processes with Potential for Deep Ocean Application

Process	Possible Deep Ocean Application
I. Processes Suitable for General Repair and Fabrication	
wet shielded metal atc	
single-pass	temporary repair; padeye attachment
multi-pass	platform, habitat, pipeline repair possible underwater fabrication
hyperbaric chamber (enclosing diver and work)	pipeline repair and hot-tap work fabrication of deep pipelines
small fixed or movable chamber (enclosing only work)	platform and other repair work
shrouded metal arc	presently under development
wet plasma arc	presently under development
wet gas metal arc	presently under development
mechanical joining techniques	platform, submerged production system, pipeline repair
II. Processes Suitable Primarily for Establishing Attachment Points	
exothermic welding/brazing	attachment point; possible pipeline repair
explosive welding	attachment point
velocity power tool	attachment point

Processes in the second group are more diverse in character. Each is technically different and must be studied separately. Little trouble is expected in matching these techniques with remotely operated diving systems.

The offshore petroleum industry is the driving force propelling the development of processes in the first category. Although there are certainly political forces acting on the industry, incentives motivating the development and employment of underwater joining devices are strictly economic. Operating costs offshore are so huge that the cost of developing and operating a joining process is completely subordinate to the goal of keeping hugely expensive capital equipment in operation.

Processes in the second category are most useful in deep salvage systems. The U.S. Navy is the primary organization conducting developmental work in this area. In a normal funding climate, money available for the development and operation of salvage systems can be expected to be modest. However, as is the case with all defense funds, spending can be subject to political pressures in response to international events. Operations such as the salvage of nuclear weapons off Palomares, Spain, in 1966 or the salvage of a portion of a Russian submarine off Hawaii in 1974 can trigger the expenditure of vast amounts of funds for salvage systems.

4.2 Diving System Limitations

Underwater joining techniques depend on the diving systems with which they are used. In shallow water, many problems such as low visibility and a lack of stability are imposed by diver limitations. As water depths increase, diving systems impose even stricter constraints on joining processes. The next few paragraphs outline the most important of these limitations, which will be discussed in detail in the remainder of the chapter.

Topics of key importance include manipulative and depth limitations. Most of the processes that appear to have potential in meeting broad deep ocean repair and fabrication needs require manipulative abilities which can only be met by a trained welder. Thus, these processes can only be employed with a diving system which directly interfaces the man and the work. Unfortunately, the most useful of these diving methods exposes the operator to ambient pressure that severely restricts depth capability. Automatic processes such as those used to establish attachment points are much more versatile in this respect. Less manipulative ability is demanded and, as a result, these techniques can be employed with remotely operated manipulators as well as with divers.

As the distance from the surface increases, providing support functions for underwater tasks becomes more difficult. In shallow water, cables and hoses can be used to provide power and shielding gases for joining processes. At depths of several thousand feet, other solutions may become necessary.

The primary costs associated with actual underwater repair and fabrication operations are generated by the expense of diving and surface support. In addition, economic factors may determine the selection between different diving systems at some depths.

Cost versus depth relationships for the various diving methods are thus necessary in gaining an understanding of the economic constraints acting on the total system.

A summary of diving system limitations is given in Table 4-2.

4.2.1 Diving System Classification and Description

Since it is the purpose of this section to study diving systems as they affect the joining of metals underwater, it is appropriate to classify them in a mannner which is compatible with the classification of underwater joining processes. Diving systems of interest here can be divided into two groups. The first group is composed of those systems that have a direct man-work interface, that is those in which the diver/operator can get his hands on the work. In the second group are those systems in which extra links have been added in the form of manipulators, TV cameras or other similar devices. These systems have a remote man-work interface.

In the remainder of this section the following diving systems will be discussed:

Direct Man-Work Interface	Remote Man-Work Interface
Conventional Diving	Manned Submersibles
Saturation Diving	Remotely Operated Work Vehicles
Ambient Pressure Chambers	
Constant Pressure Chambers	

1 Conventional Diving. A conventional diving system is one in which a man is exposed to ambient water pressure, but

Table 4-2

Summary of Diving System Limitations

Diving System	Manipulative Ability	Depth Capability	Flexibility	Support Capacity	Risk to Life
Conventional Diving	3	1	5	3	6
Saturation Diving	4	3	6	4	5
Ambient Pressure Chambers	5	2	2	5	4
Constant Pressure Chambers	6	4	1	6	2
Manned Submersibles	2	5	4	1	3
Remotely Operated Work Vehicles	1	6	3	2	1

6 greatest

1 least

not for a period long enough for his body tissue to become saturated with inert gas. The man may be tethered to the surface and receive his breathing gas through a hose from the surface or he may be free swimming, carrying compressed gas in tanks. For work projects in one location, the tethered arrangement is by far the most common. The diver's range of vision and manual dexterity are often poor, suffering substantial performance degradation compared to his counterpart on dry land. Short mission capability and generally shallow depths characterize conventional diving, with decompression required after only a few minutes of work below 100 feet. When air is used, a safe depth limit is just under 200 feet, with a helium-oxygen mixture it is less than 400 feet. At these limits, working time is extremely short if massive decompression times are to be avoided. Surface support required is minimal, consisting of a breathing gas supply, a line tender, a backup diver and a decompression chamber.[53]

2 Saturation Diving. The tissues of a man who has been exposed to an inert gas under pressure for 25 hours have taken up practically all the inert gas they can hold at that pressure. The man is then said to be saturated at that pressure and his decompression time is unaffected by further bottom time at that depth. A total saturation diving system permits the diver to live and work at pressure continuously for the entire time the job may take, requiring only decompression when the diver leaves the system. In this manner, a much larger percentage of the time under pressure is spent working and a much smaller percentage is spent undergoing decompression.[53, 54]

A given job often can be completed more quickly and with fewer divers if saturation techniques are used rather than multiple conventional dives. However, surface support requirements are increased both in cost and complexity due to the requirements for a large pressurized living chamber and a heavy lift capability. These increased costs must be balanced against any advantage gained by an increase in depth capability or time saved when choosing between conventional and saturation methods.

An actual undersea test project was conducted to determine if men could work at a depth of 840 feet effectively. Using saturation techniques, divers were kept in a living chamber at 660 feet and deployed to the work site for periods of up to three hours, where they conducted work simulating that which might be required at a subsea wellhead.[55] From this test it can be concluded that men can now work in waters in excess of 800 feet safely, at least in ideal conditions. Although men have recently undergone pressurization in dry chambers to pressures corresponding to 2000 feet of water, the jump from experimental to practical working conditions is a large one. It is widely predicted that men will work almost routinely in waters of 1000 to 1200 feet by 1980 but, at the present time, tests under ideal conditions not withstanding, 600 feet is a pretty good estimate of a practical working limit in a severe marine environment.[53,54,56]

3 Ambient Pressure Chambers. Several commercial diving companies, engaged in the support of offshore oil production,

use underwater welding chambers to provide a dry environment for the repair of damaged sections of undersea pipelines. The forward and aft bulkheads of the chamber, perpendicular to the pipeline direction, are designed with large grooved penetrations and the bell is lowered so as to fit these directly over the pipe. Below the pipeline, once it is straddled by the bell, the grooves are closed with watertight doors. Next, water is displaced from the chamber by pressurized gases and divers enter from the bottom and fold down gratings for a work platform.(53)

The gas mixture used in these chambers must be non-explosive and able to sustain life for brief periods in case of diver life support system malfunction. A helium-oxygen mixture with an oxygen partial pressure of 6-8 psi has been found suitable. The welders breathe through a mask using a separate system of gases more suitable for sustaining life. Because the chamber is extremely humid, hydrogen cannot be removed from the chamber atmosphere and shielding gases must be used with the welding arc itself.(50)

Entire pipeline repair and fabrication systems can be built around the basic chamber. These systems include fine positioning and alignment equipment so that large sections can be joined without intermediate short sections called "pup joints."(50)

Since welders are at ambient pressure in these chambers, safe diving depth limits must be observed. The Taylor Diving Company has utilized one of these chambers at 540 feet in the Gulf of Mexico, which is the deepest known use. Support requirements for these systems are complex and costly and are quite similar to those for saturation diving.[42, 50]

4 Constant Pressure Chambers. Subsea chambers maintained at a constant internal pressure of one atmosphere are one solution to the problem of working on underwater producing systems in deep water. These chambers can be constructed to enclose clusters of conventional oil field equipment on the sea floor, including manifold centers, separation stations and pumping stations as well as wellhead X-mas trees. Designed to mate with personnel transfers capsules, these chambers can be used by petroleum company work crews to complete welds and perform on site maintenance. Because personnel are not exposed to pressure or other diving hazards, workmen specially trained in oilfield skills but not in diving can be employed. Surface repair techniques and welding processes can be employed with little problem. Special equipment within the chamber need not be developed since men can work on the equipment directly. This ability to work directly on production systems also means that response to unexpected problems within the chamber can be more flexible and imaginative.[48]

The one atmosphere chamber is the only diving system with a direct man-work interface which is not severely limited in depth capability. Its primary disadvantage is that it is extremely limited in application. Work can only be performed in very small areas enclosed by a specially designed work chamber which can only be mated with a custom designed transfer capsule. The system is also expensive, considering its limited application, and surface support equipments are heavy, similar to those for ambient pressure chambers and saturation diving. At the present time, three companies are designing and testing this type of system. Two test models have been deployed in waters of 240 to 250 feet. Present chambers are desinged for depths of up to 1200 feet but with design modifications these systems can be extended to 3000 to 4000 feet water depths.(39)

5 Manned Submersibles. The word submersible, as it is used today, connotes no precisely defined vehicle. For the purposes of this study, a manned submersible will be considered any undersea vehicle capable of transporting a man or men at a constant pressure and capable of performing some degree of manipulative work underwater. A great deal of literature has been generated describing these vehicles, so only the briefest of remarks will be noted here. There are a great many such devices of varying complexity in sevice today and more are being designed and built. Submersibles are being used to complete a variety of underwater tasks in governmental, commercial and scientific service and are indispensible to expansion into the deep ocean. These work vehicles are important here because they represent a means by which joining processes can be deployed and operated in a number of situations in the deep ocean. Actual operation must be conducted remotely through manipulators, but men can directly observe and control such actions from within the submersible. Submersibles can be designed for use at any depth. In fact, several can reach into even the deepest ocean trenches. Submersibles with manipulative ability are being built for use on the abyssal plain at depths of 15,000 to 20,000 feet.(53)

Limits, as they affect joining techniques, are not depth-related but rather determined by the manipulative devices incorporated into submersibles. This is the subject of a later section. Present working submersibles have limited mission durations and require extensive support from an accompanying surface vessel.[53, 57]

6 Remotely Operated Work Vehicles. Remotely operated work vehicles may be used effectively underwater in a number of situations. Manipulators can be operated from the surface as well as from within a submersible and television cameras and sonar systems can go a long way toward replacing a man's eyes underwater. Although the advantage of having a man, particularly one with special skills, present at an undersea work site may be useful or even essential, that advantage still has its price in terms of risk to life, money, and mission flexibility. Manned undersea vehicles must incorporate extensive life support systems that are not only costly but also limit mission duration.[58, 59]

Several remotely operated maintenance systems intended to perform predesignated functions on underwater structures are being designed. These include Shell's Seafloor Pipeline Repair System (SPRS) and Exxon's Submerged Production System (SPS) maintenance unit. The SPRS is designed to replace a section of pipeline, and action which might remedy a number of problems. The SPS maintenance unit is designed to remotely replace removable components on the production system. Remotely controlled devices may also prove useful in several phases of deep salvage work, such as attaching lifting points and lines to sunken objects.

The use of remotely operated vessels to recover weaponry underwater is now well advanced. Remotely operated work vehicles may not be as flexible in unusual situations as manned submersibles, but they should prove useful in a number of tasks, saving the high costs and personnel risks associated with the use of manned vehicles. These devices can be built to operate at any desired depth, but require a surface platform for control and power supply.

4.2.2 Manipulative Ability [57, 58, 60, 61]

The ability of a diving system to perform its intended task, in this case the operation of a joining process, is the key issue under examination in this chapter. There is a sharp difference in the manipulative ability of systems with direct man-work interfaces and those with remote interfaces. Direct interface systems are capable of operating any of the joining processes listed in Table 4-1. Remote interface systems are, at present, capable of deploying only those systems in part II of this table as well as mechanical joining devices. All of the direct interface systems but one are severely depth limited, however, and the one not depth limited is restricted to use only in very limited circumstances. The logical question one must then ask is: What are the chances of developing manipulative systems capable of performing advanced underwater joining techniques?

Manipulator systems, whether manned or operated from the surface, must contain four integrated subsystems: locomotion, sensory, command and manipulation. A diver, in fact, can be thought of as an extremely well integrated model of such a system.

In order for the overall system to function properly, each of the components must do its part. The locomotion subsystem must maintain the position of the larger system with respect to the workpiece. The sensory subsystem must relay an accurate picture of the operation as it progresses to the command subsystem, which must control the manipulator itself. The more fully integrated the overall system, the greater the underwater efficiency. A study of the relative productivity of alternative diving systems illustrates this point. A man performing a task on land is given an index value of 1.0 for relative productive capacity and other representative values are as follows:

Saturation diver	0.6
Conventional diver	0.5
Manned submersible	0.05 - 0.25
Remotely operated vehicle	0.01 - 0.05

Values follow the degree of subsystem integration. Human divers are extremely well integrated. In manned submersibles, sensory and command systems are both incorporated within the operator but these subsystems are more loosely joined to the locomotive and manipulative subsystems. In fully remote vehicles, subsystems are least tightly integrated and manipulative ability suffers accordingly.

In another study, overall performance rations for a series of eight underwater tasks indicated a 4:1 advantage for divers over submersible-type manipulators during tests in which the operators could see the work. For tasks requiring particularly exacting manipulations the advantage for divers rose as high as 30:1.

There has been much work on perfecting underwater manipulators in recent years and technology from aerospace and nuclear handling has been incorporated into the effort. In spite of this fact, manipulative systems still lag far behind men in their overall work ability. This point is well documented by experimental tests, both on land and in water environments. It seems unlikely, then, that these techniques will become sufficiently advanced in the near future to perform delicate arc-welding processes underwater. This is emphasized by the fact that only the most well-trained, experienced divers are presently able to perform joining techniques of the quality necessary for permanent repair and fabrication usage.

If devices with remote man-work interfaces cannot be used to arc-weld underwater, of what use are they in joining metals in the deep sea? Can their virtually unlimited depth capability be used to advantage? These devices have tremendous potential for application in the deep ocean, but suitable joining techniques must be designed especially for these systems, exploiting their advantages and minimizing the effects of their limitations. Remotely operated work vehicles and submersibles are being used in the design of systems for the maintenance of submerged production systems and pipelines underwater. Joining is being accomplished in these systems by the use of mechanical connectors designed to be compatible with both the work vehicle and the system to be repaired. Submersibles and work vehicles could prove very useful in placing and activating automatic welding devices which may be designed to fill certain underwater requirements. Several examples illustrate this possibility. First, devices are under development which may prove suitable for providing necessary attachment points for salvage purposes. These include exothermic, explosive bonding and velocity powered techniques. Other conceivable possibilities inlude semi-automatic shielded metal-arc techniques, which might be used for attaching padeyes or applying temporary patches, and exothermic welding or brazing techniques that might be used to seal repair sleeves to underwater pipelines. More detailed descreptions of these examples are included in a later chapter.

4.2.3 Support Systems [46, 53, 59, 62]

Many underwater joining processes require a source of electrical power and some of these processes require shielding gases as well. In relatively shallow waters, these items can be provided by cables and hoses from the surface. As dpeths increase, however, these simple solutions may no longer be feasible.

Most manned submersibles are designed to operate without a tether leading to the surface. Much more maneuvering freedom is gained in this way and undesirable surface coupling effects are eliminated. These vessels are presently powered by batteries with very low power densities. Both weight and volume are at a premium on the majority of these vessels as well. If joining processes are to be employed with presently available manned submersibles, they must either have small self-contained power sources or only modest requirements from the submersible itself. In the future, such power sources as fuel cells, radioisotope systems, and small nuclear power plants may increase the power available to untethered submersibles somewhat. Joining systems with fairly small power requirements will still be most desirable, however, because any power gained will be largely absorbed into submersible propulsion and auxiliary systems. Small quantities of shielding gas may be carried by these submersibles in cylinders mounted outside the pressure hull, but joining processes must use these gases only sparingly.

The majority of remotely operated work vehicles in use today are tethered to the surface and power as well as guidance is provided through this tether or umbilical. Power requirements for joining processes are therefore much less restrictive if remote vehicles are employed, even though cable losses are significant as illustrated in Figure 4-3. It is still more practical to carry shielding gas in cylinders on remote work vehicles due to the pumping head required at extreme depths for a hose system.

4.2.4 Cost-Depth Relationships [53, 54, 57, 58, 59, 62]

The major operational cost components of any total underwater joining system are the expenses associated with diving. Costs incurred by the operation of the joining process itself are normally quite small. This is particularly true for deep water systems since diving costs increase rapidly with depth while process costs increase only slightly, if at all.

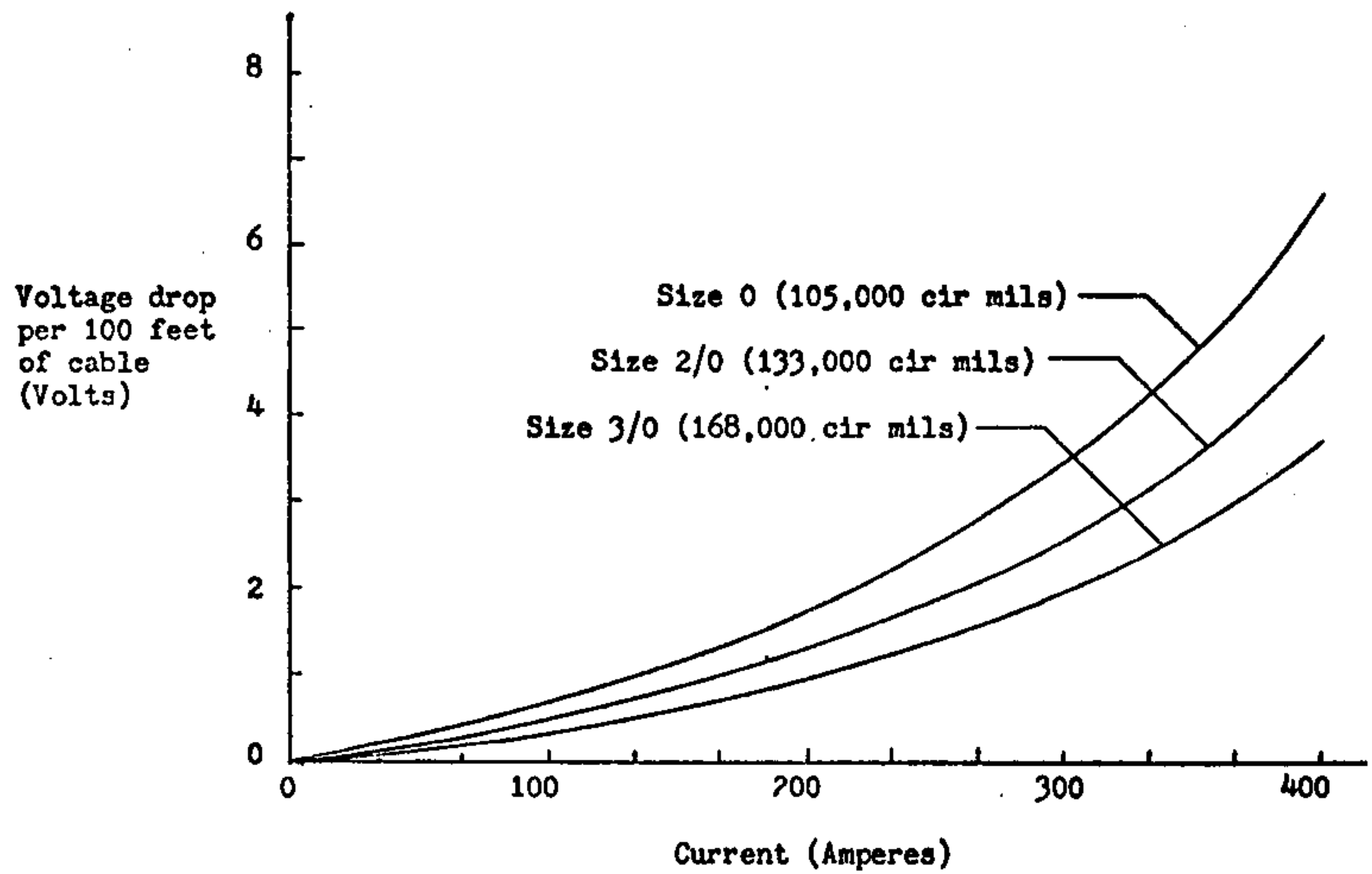


Figure 4-3 Voltage Drop in Power Supply Cables[46]

In many cases, selection of a diving system must be based on performance considerations alone. Depth constraints and manipulative limitations act to narrow the choice of diving systems considerably. However, cost considerations will enter into the choice in a great many cases so that a knowledge of cost-depth relationships is essential. It should be emphasized that data presented here necessarily represents only general trends and that specific trade-offs should be based on precise data for individual systems.

Figure 4-4 presents cost relations for depths of up to 1000 feet and Figure 4-5 presents similar information for depths of up to 20,000 feet. Hyperbaric chamber costs, which are not shown, are somewhat higher than those of saturation systems operating at the same depths. One atmosphere chamber costs are largely undetermined at this time but should approximate those of manned submersibles. One major factor affecting the relative position of the curves is the cost of surface support equipment. This figure is highly variable, depending upon the particular support vessel chosen. In interpreting these figure it must be remembered that no attempt has been made to adjust the curves to account for the relative efficiencies of the systems compared. As a result, both cost per work hour and hours required to complete the job must be considered in determining the most economical diving system for a particular job. Supporting data and calculations for Figure 4-3 and 4-5 appear in Appendix C.

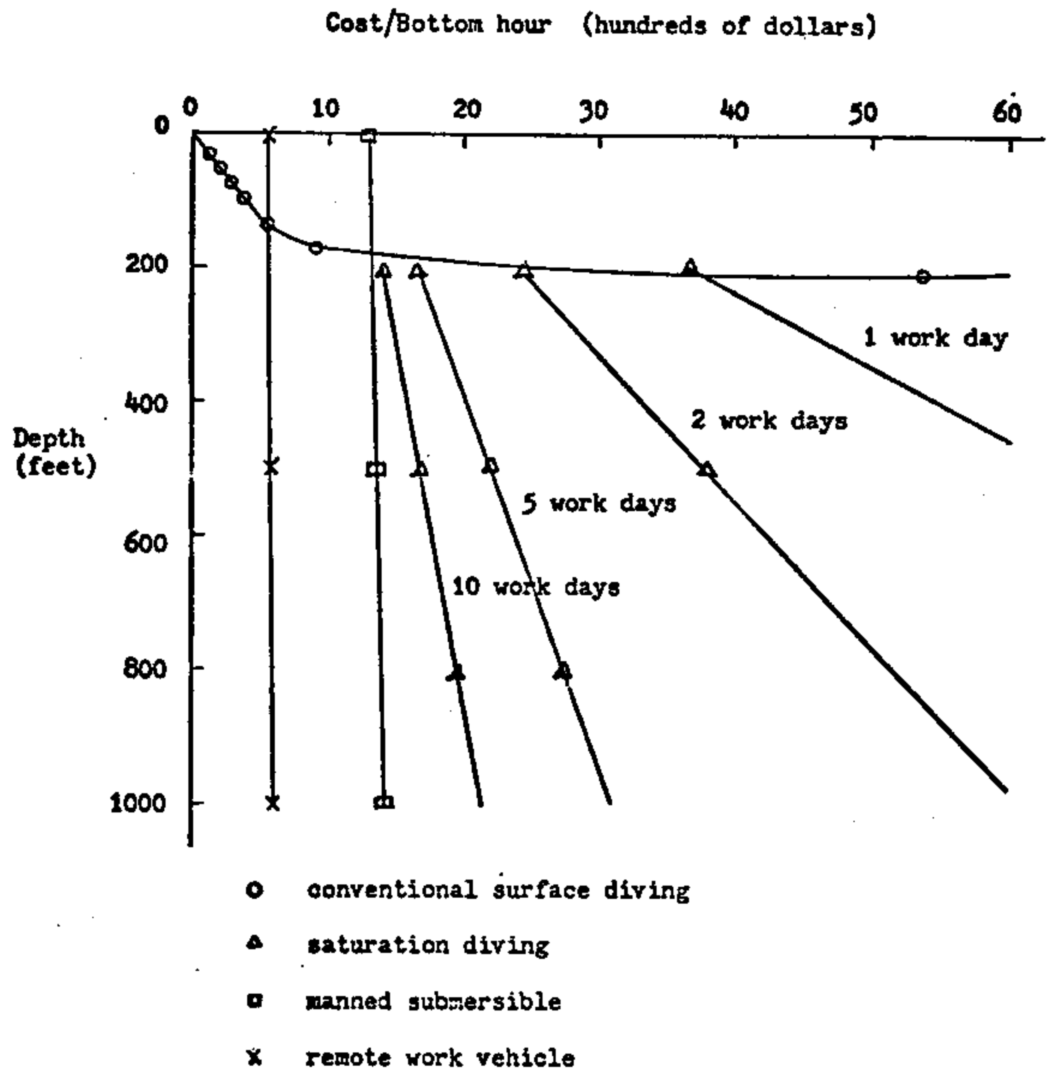


Figure 4-4 Cost vs. Depth for Diving Systems (0-1000 feet)

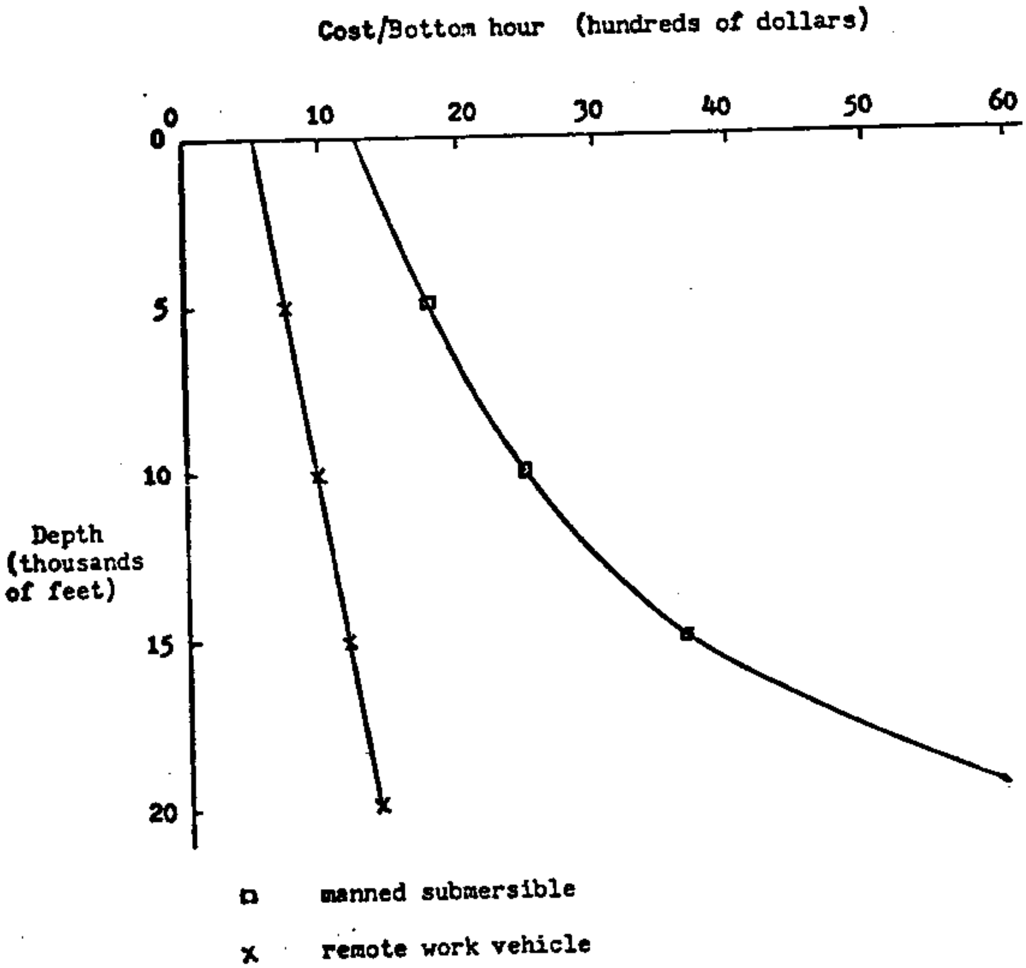


Figure 4-5 Cost vs. Depth for Diving Systems (0-20,000 feet)

In Figure 4-4 it can be seen that conventional surface diving techniques have no real competition in shallow water, at least for tasks of short duration. This is due to the fact that support and capital costs for conventional systems are small. However, as depth or bottom time increases, larger decompression debts are incurred and the conventional diver efficiency also decreases with depth. Depth does not, however, make as much difference in the efficiency or work cycle of a saturation diver. He needs to orient himself to depth and the job at hand only once so his overall efficiency is higher. The number or work hours per day in a saturation system is largely unaffected by depth. At 300 feet, the saturation diver can spend approximately three times as long working, per unit time under pressure, as can the conventional diver and his efficiency will be 25-50 percent more at this depth. This increase in working time and efficiency makes up for increased support costs for jobs of longer duration.

Due to a marked difference in capability, manned submersibles and remote work vehicles are rarely in competition with conventional and saturation diving systems. As both Figures 4-4 and 4-5 illustrate, cost increases with depth are much less dramatic for these systems. Several "standard" submersibles for relatively shallow depths can be purchased, but remote systems and many submersibles are one-of-a-kind models and are still more expensive than they would be if they were more widely produced. This accounts for the relative closeness of the two curves. As remote work vehicles become more standardized their cost in comparison with submersibles should drop.

Manned submersibles are most economical for mission lasting a few hours because performance and time on bttom are limited by on-board power. Remote vehicles are particularly valuable for long missions in very deep water and in the performance of tasks inherently dangerous to divers and submariners. No price tag can be put on human life.

4.3 Depth-related Technical Problems

As operating depths are increased, the effects of pressure on joining processes become of far greater importance. Although a certain amount of work on this topic has been done, a great deal more must be completed if greater joining deoths are to be achieved. In this section, technical problems anticipated in extending the depth capacity of those techniques outlined in Table 4-1 will be reviewed. An assessment of possible corrective measures as well as an identification of practical future developmental work will be made.

Many of the arc-welding processes which appear in Table 4-1 are subject to the same depth-related problems due to the characteristics of the underwater arc itself. These common problems will be dealt with first. Following this, the other processes noted in Table 4-1 will be examined in order to define technical problems that must be solved in expanding operational depth limits.

4.3.1 Electric Arc Processes[13, 28, 45, 47, 57, 63-76]

The special characteristics of an underwater arc create a number of depth-related effects that must be considered in the development of any electric arc joining process for the deep sea. These effects are discussed in the following sections.

1 Penetration and Weld Bead Shape. The very high arc core temperatures found at greater depths greatly increase arc penetration. This can have both beneficial and detrimental effects. Increased penetration, accompanied by more rapid metal transfer, can lead to higher, more efficient deposition rates. On the other hand, at the high pressures found on the deep ocean floor, increased penetration can lead to burnthrough.

In laboratory research, Madatov reported an increase in penetration with depth for shielded metal arc (SMA) welds, as well as widening of the penetration shape factor (W/P) from 5 to 3. De Saw et al. found that reverse polarity SMA welds were shallower, wider and less porous than straight polarity welds. This reversal of arc characteristics at depth was not explained. However, during extensive commercial repair work at sea, Grubbs has noted that excessive penetration is not a problem in multi-pass SMA welding, even at depths in excess of 200 feet.

SMA weld bead characteristics have been found to be quite satisfactory in actual service when the sophisticated multipass technique is employed. Developmental work in extending the depth capability of this process centers around electrode coatings and has resulted in the development of satisfactory electrodes for low carbon steel (carbon equivalent less than 0.4) welding in depths exceeding 200 feet. At present, austenitic electrodes may be satisfactorily employed for steels with higher carbon equivalents in depths up to 80 feet and work is underway to extend this capacity to over 300 feet.

A number of investigators have studied the effects of pressure on the gas metal arc (GMA) welding process. Pilia found that welds made at 60 feet were peaked and thin and that burn-through was a problem at 80-100 feet because of excessive penetration. In dry welds made under pressure on aluminum, Brandon noted that the weld cross-sectional area, the weld depth to width ratio and penetration all increased with increased pressure. Careful control of filler metal feed speed was the single most important factor available to offset or control these effects. Arc voltage and welding travel speed were less influential in their effects on weld penetration and shape. In underwater chamber welding, the diver-welder must manipulate the arc differently than in surface welding in order to offset the more narrowly concentrated heat of the constricted arc. It is more difficult to initiate the arc, to maintain a stable arc and to obtain good fusion across the width of the weld joint. The welding arc becomes more intense and the electrode wire melts at a faster rate as the pressure increases. This causes a larger weld pool and control difficulties, and can lead to such weld defects as overlap and improper fusion.

As welding pressure increases, the only significant change in the characteristics of a gas tungsten arc (GTA) is a constriction of the arc column leading to an increase in arc voltage. This causes an effect not unlike that of a plasma arc weld and results in greater weld bead penetration, often as much as 50 percent at 20 bar.

2 Current and Voltage. Compressive forces acting on the underwater arc make voltage-amperage curves concave or rising. Thus, though the voltage needed to strike the arc is higher than the voltage needed to maintain it, the amperage grows as the voltage decreases once the arc has been established. As depths increase and greater constriction due to water pressure is experienced, the current density continues to increase. At great depths, Madatov found the large concentration of heat from the increased current density acted to limit welding currents to 180-240 amps.

Although, at one time, apparent increases in current requirements for SMA welding were attributed to heat losses through thermal conduction, some researchers now believe that increased current demands are primarily due to the constriction of the arc and increased resistance heating of the rod as greater pressure are encountered. Arc length must also be considered, since longer arc lengths result in greater hydrogen cooling and hydrostatic effects, which combine to cause greater constriction and current density. To compensate for these factors, it has been suggested that the welding current be increased by 10 percent per atmosphere of additional pressure in order to maintain similar arc conditions. This suggestion has not been confirmed by practical experience, however. During multipass SMA repair welding at various depths up to and exceeding 200 feet, Grubbs has found no need to increase current drastically with depth. He has found that it is necessary to increase current approximately 10 percent over that required for air welds and to increase current as cable length is increased but has noted that there is no need for a current increase with depth.

Several reports have been issued on the effects of pressure on the GMA welding process. From them, much information concerning the effects of depth upon current and voltage can be gained.

Arc power consumption is a meaningful measure of welding performance, which complements voltage and heat input data. An idea of the arc power consumed in any region can be gained by measuring the voltage consumed and remembering that the same current flows through all elements in a welding circuit. These distinct voltages, which are shown in Figure 4-6, are the IR drop in the electrode stickout, the anode voltage, the positive column voltage and the cathode voltage. Since total arc voltage will be divided differently among these regions depending on welding conditions, these distinct voltages must be considered. Figure 4-7 illustrates arc length vs. voltage. The IR voltage drop can be expected to remain constant and not vary with minor current variations. Extrapolating the curves to zero length eliminates the contribution to total voltage of the column voltage. These zero arc length voltages, which represent the sum of anode and cathode voltages, increase with pressure by differing amounts as shown by the varying slopes of the constant pressure curves. Similar results were reported for underwater arcs by Avilov in earlier work.

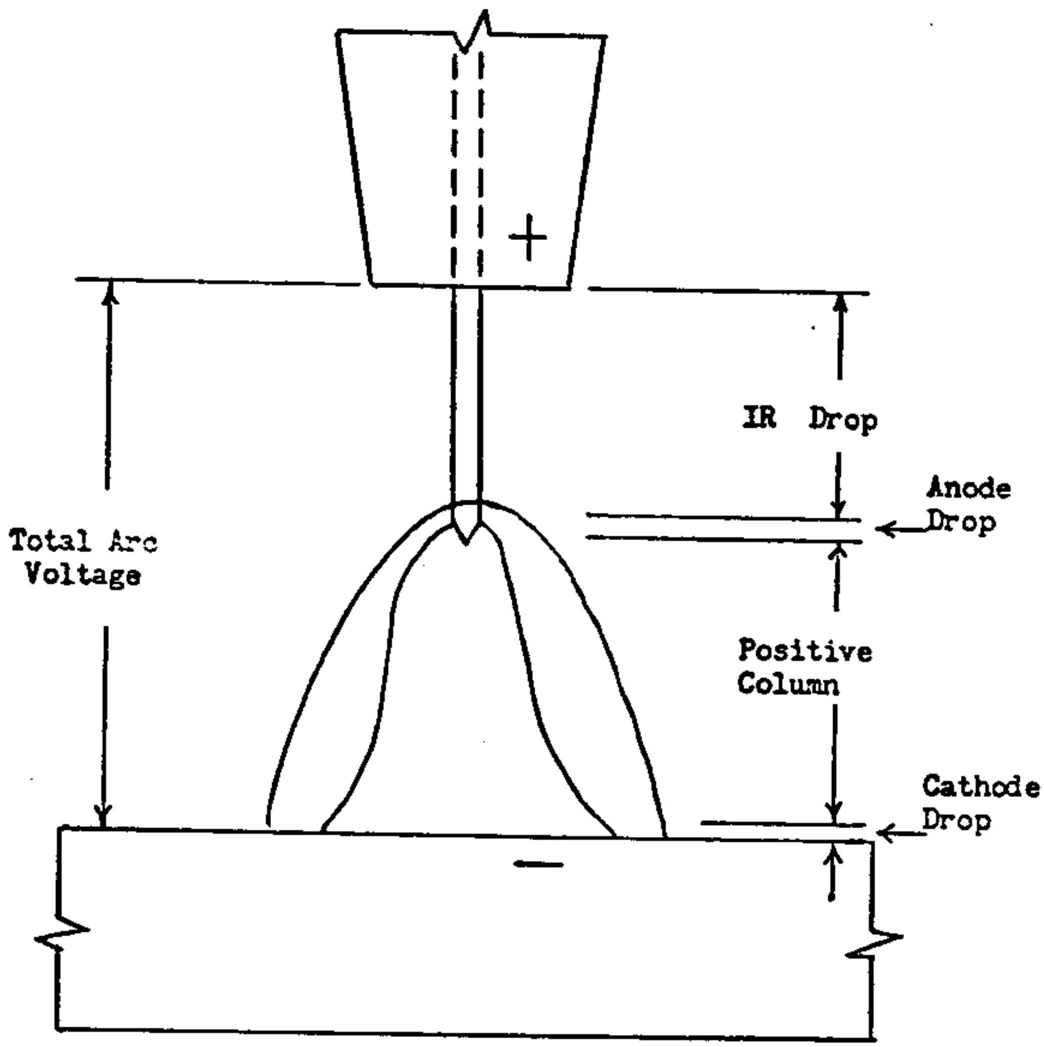


Figure 4-6 Arc Voltage Division[69]

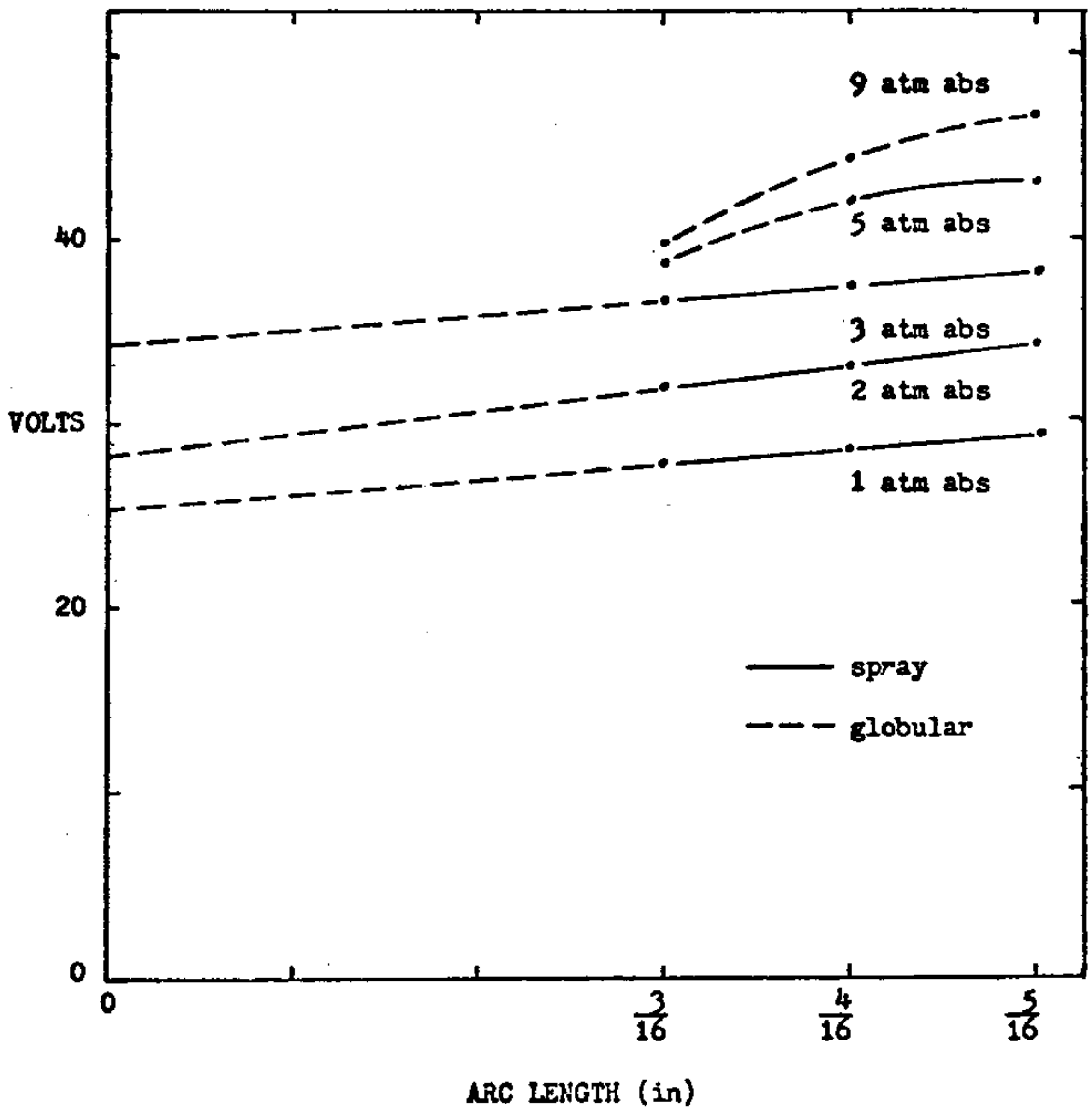


Figure 4-7 Arc Length vs. Voltage[69]

This increase is probably due to anode voltage, as can be explained by using the following formula for direct current reverse polarity melting rate:

$$M = aI + bLI^2$$

where: a is a constant dependent upon anode size and material

b is a constant dependent on electrode diameter and resistivity

L is the electrode strickout distance

The first term on the right represents the anode melting contribution and the second, resistance melting. In this equation, the electrode voltage drop is independent of the temperature at the end of the electrode. Experimentally, more current is required to maintain the melting rate than would be predicted by the melting rate equation. Since no change can be expected in the resistance heating term, the anode melting term must increase. This conclusion is supported by Maecker's analysis of plasma jets. Entrained cold gas has to flow over the electrode to be heated and accelerated. This energy requirement should result in an increase in the anode voltage drop with pressure.

Figure 4-8 presents voltage and pressure data for the same arc length values in a different manner. Figure 4-9 is the power vs pressure relation claculated from measurements of arc voltage. Brandon, in his report, noted that increased pressure is detrimental to arc stability, but that increased voltage promotes stability. At low pressures, near atmospheric, arc

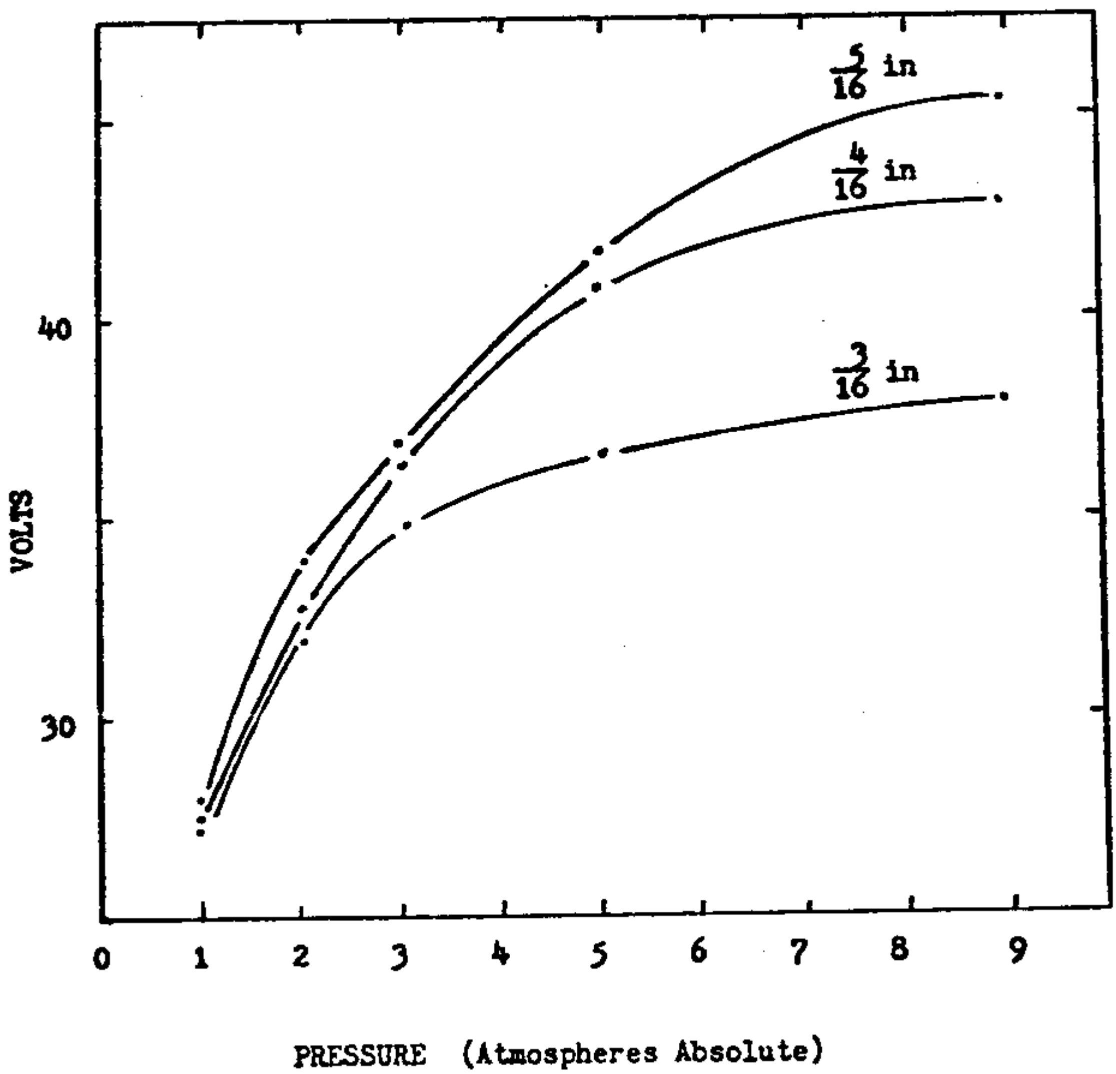


Figure 4-8 Arc Voltage vs. Pressure[69]

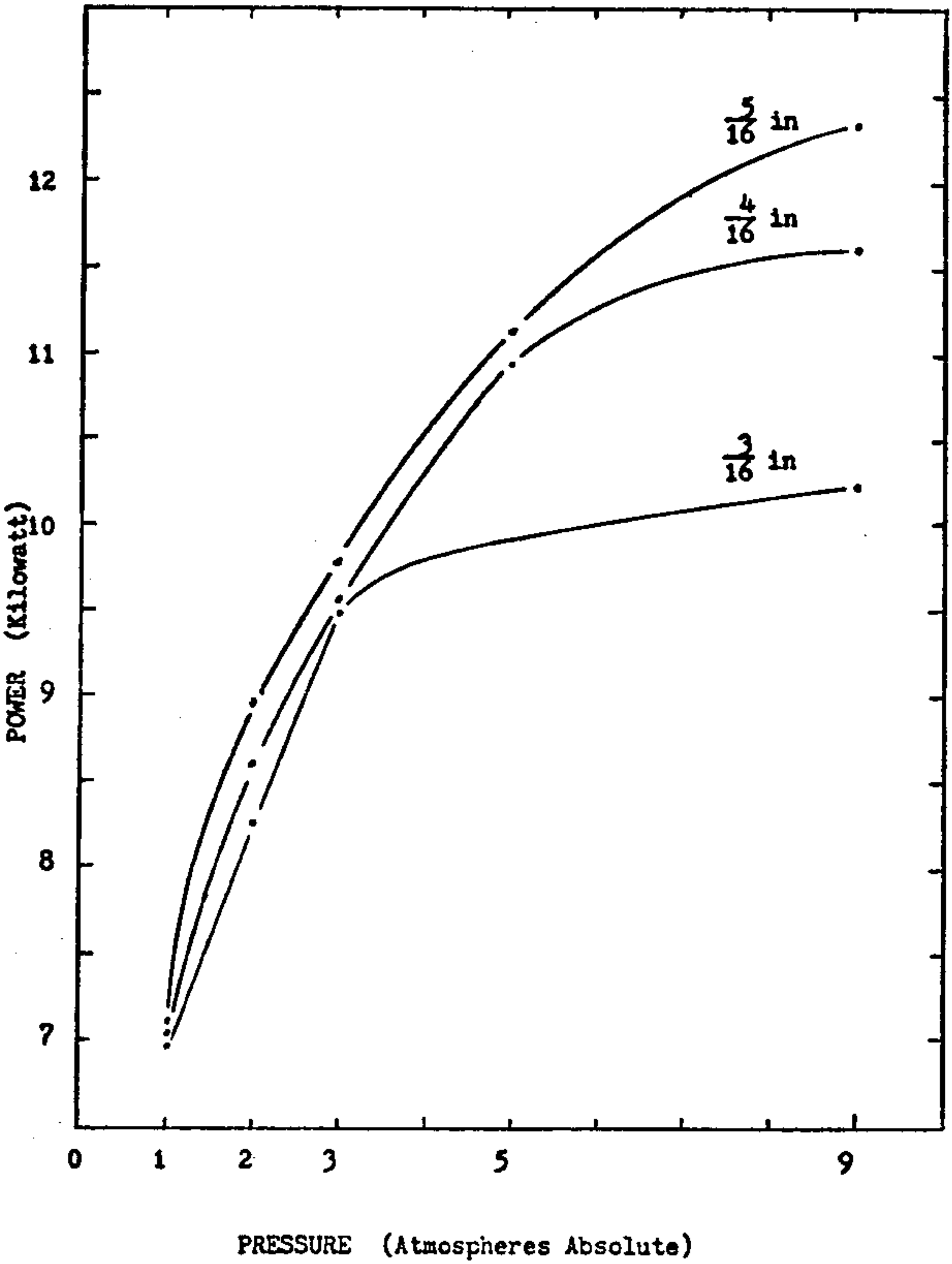


Figure 4-9 Arc Power vs. Pressure[69]

stability is relatively insensitive to voltage, but at high pressures, increased voltage greatly increased stability. This reinforces previous work suggesting that increasing voltage when ambient pressure rises may be a useful technique.

Several experimentors discovered that constant potential power sources were not adequate for work at higher pressures. Drooping power sources were used at pressures greater than about 8 bar to provide the necessary open circuit voltage for high pressure welds.

In summarizing current and voltage relations found in welding under pressure, the following points should be noted:

1. As hydrostatic pressure adds to electromagnetic and cooling constricting forces, the current density increases and a higher voltage is required to maintain a constant arc length.

2. Power requirements increase with depth.

3. Current requirements may increase somewhat with depth but the magnitude of this increase is in question.

Further work is needed to clear up areas where confusion exists as well as to verify previous work. Whenever possible, such work should be undertaken in an actual ocean environment, over a wide range of actual undersea projects. Results which appear to be significant in laboratory tests conducted under carefully controlled conditions are often not important factors in actual marine work.

3 Metal Transfer. There are three basic modes by which metal from the electrode can be transferred across to the weld

pool. The one that occurs at the lowest current level is dip or short circuit transfer. In this mode, electrode feed rate, current, and power source dynamics are such that the metal transfers across during the short circuit and, in the remainder of the cycle, the arc is maintained without metal transfer. As the current is increased, other parameters remaining the same, the transfer mode shifts to globular or drop transfer and the metal is transferred in large drops that travel slowly to the workpiece. This shift occurs because the ohmic heating of the electrode and the anodic heat developed at the tip generate enough heat to permit large globules of metal to detach without short circuiting. As current is increased further, rapid melting of the electrode occurs and droplets are ejected as a fine stream or spray by the action of plasma jets. In globular transfer, gravity is the dominant force, in spray transfer, the strength of the plasma jets is dominant. These modes may undergo transformations from one to another as parameters are altered or may occur in combination.

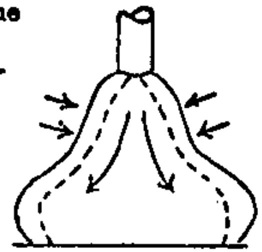
Maecker's plasma jet theory is useful in explaining the effects of pressure upon transfer in the spray mode. As the arc is constricted, radial pressures increase. Pressure equalization causes a flow along the axis toward larger cross sections and lower current densities. This flow draws cold gases into the arc and further constricts the discharge cross-section at the electrode, increasing the pumping action. This process continues until the temperature gradient becomes steep enough for a steady state to exist. The steady plasma jet attracts current paths by its good conductivity. These paths supply enough joule heat to offset the conductive cooling of the plasma jet and the balance is maintained.

As ambient pressure rises, the thermal conductivity of the gases increases. This increased conductivity causes a constriction of the arc and a new, higher velocity steady state is attained. This results in an increased drop transfer rate and deeper penetration, up to a certain level. At sufficiently high pressure levels the combined effects of the reflected vapor jet from the workpiece and a pressure induced squeeze effect on the bottom of the arc column begin to retard the plasma flow rate. This causes an eventual reversion to globular transfer. Figure 4-10 illustrates the balance between arc plasma and hydrostatic forces.

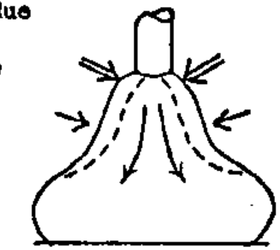
In studies of the effects of pressure on the GMA process, Billy and Perlman et al. found that a reversion from spray to globular transfer occurred at sufficiently high temperatures. The arc also became unstable resulting in an excessive amount of metal vapor and spatter as well as an uncontrollably large weld puddle. Poor, highly crowned weld beads were also formed after reversion to globular transfer. Burrill and Levin also found that there was a marked trend toward decreased metal deposition efficiency due to metal vapor formation and spatter. However, they could not confirm a change in the mode of transfer to globular. This may have been due to their use of a higher voltage power source.

Figure 4-11 illustrates the increase of spray transition

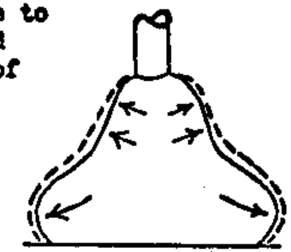
Constriction due to a rise in thermal conductivity.



Constriction due to cold gases drawn past the electrode.

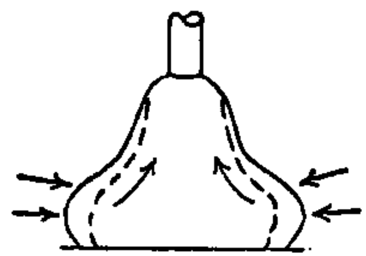


Expansion due to the increased temperature of the arc.

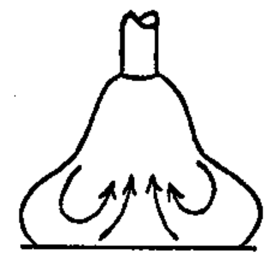


A. Forces acting on the top of the arc. The net result of these forces is a tendency for accelerated metal transfer and increased penetration.

Constriction due to ambient pressure effects.



Turbulence and reduction of flow caused by reflection of the plasma jet.



B. Forces acting on the bottom of the arc. The net result of these forces is a resistance to metal transfer and decreased penetration.

Forces A and B must be in equilibrium. When forces A predominate metal transfer is in the spray mode. As forces B become larger, the plasma jet is decreased until drop transfer replaces spray transfer.

Figure 4- 10

The Effects of Depth on Arc Characteristics

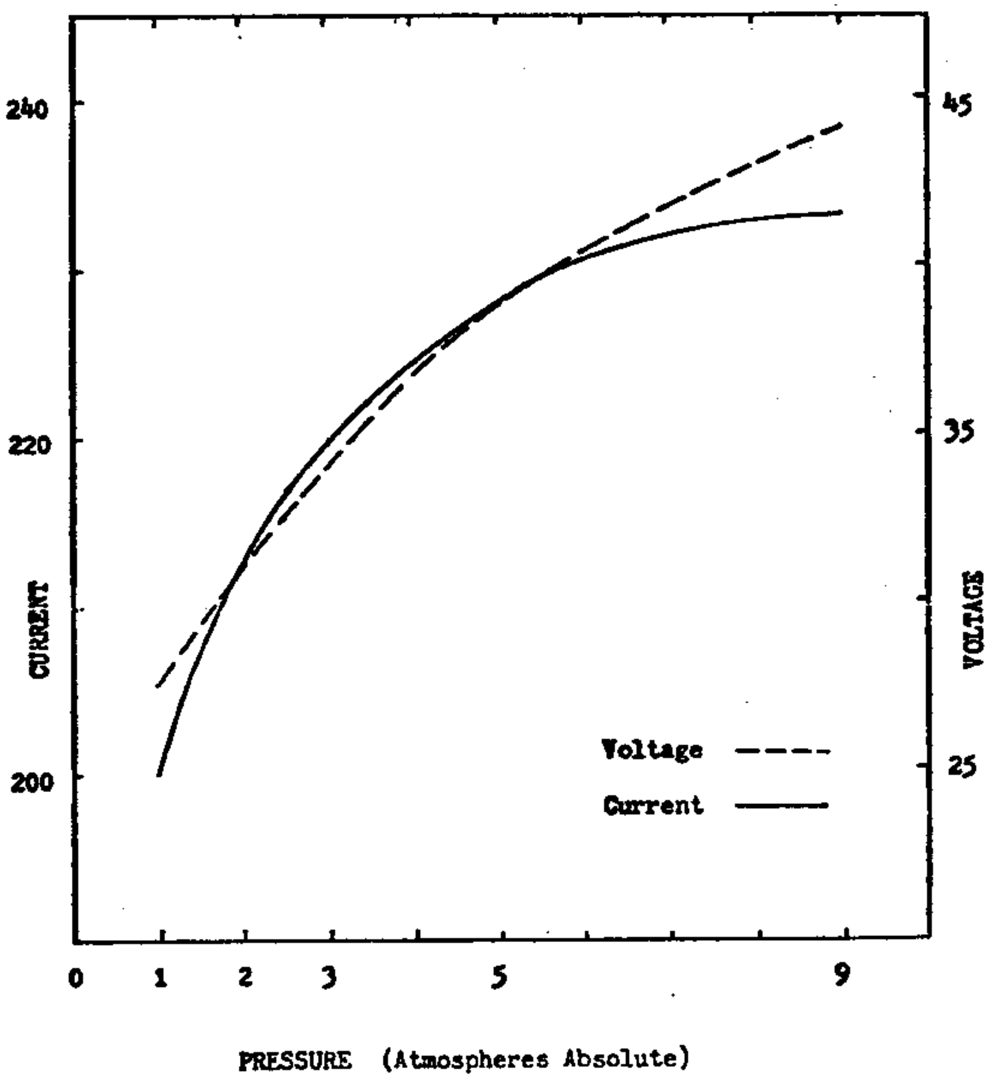


Figure 4-11 Spray Transition with Changing Pressure[69]

current and voltage with rising pressure for a GMA process.

With the GTA process, arc instability does not arise since the wire is not part of the arc system but is fed and melted directly in the weld pool. The only significant change in the GTA arc with increased pressure is a constriction of the arc column which leads to an increase in arc voltage and penetration. At higher pressures the GTA weld is similar to one made by the plasma-arc process. The increased penetration may make it possible to increase welding speed slightly, thus improving this process' chief shortcoming.

The normal metal transfer mode for SMA welding using the drag or touch method is small droplets, except for an occasional arc short circuit due to the formation of a large drop. Silva found that, even at shallow depths, SMA welding underwater resulted in globular rather than spray transfer. Madatov found that the time taken to form a drop on the electrode and the time that the drop spends in the arc bubble atmosphere were about the same for the SMA process. This is in contrast to thin wire welding processes in which the time spent in the bubble atmosphere often exceeds the time spent in drop formation. Madatov found that SMA drops transferred at a rate of 44 per second during his experiments.

In summary, increased pressure on the welding arc results in arc instability and a tendency to revert from spray to globular transfor. Increasing the voltage acts to prevent the revision to globular transfer, but does not prevent arc instability and the resultant loss of deposition efficiency due to spatter and vaporization. One suggested solution to this quandary is to employ lower heat input versions of the GMA process such as dip-transfer and the pulsed-arc technique. In the dip or short circuit mode, the filler wire first shorts out to the molten weld pool. Next, the current surges and the filler wire is melted off and the arc reestablished. These shorts occur 50-70 times a second with metal transfer taking place during each short. In pulsed-arc welding, the reverse effect occurs. The filler wire melted by the arc is projected across the arc by the current which is pulsed at 60 times per second. Both of these processes involve heat inputs 20-30 percent lower than conventional GMA welding.

A great deal of work has been done studying the mechanism of metal transfer in arc processes under pressure. It appears that many of the original questions in this field have been answered and the major problems isolated. Much work remains to be done, however, in solving these problems.

4 Bubble Dynamics and Shielding Gas. No results have been reported on the effects of depth on gas evolution rates. It has been suggested that this is an area that requires work in the future.

The effects of increased pressure upon the weld bubble are fairly easy to determine by assuming that the bubble atmosphere is an ideal gas. Since the bubble atmosphere is predominantly hydrogen this assumption is acceptable for pressures and temperatures of practical significance. The volume of a gas bubble containing a given mass is directly proportional to gas temperature and inversely proportional to pressure:

$$V \alpha \frac{T}{P}$$

As water depth increases, the pressure term increases. Increasing hydrostatic pressure also causes greater constrictuion of the arc resulting in higher current densities and greater arc temperature. This raises the temperature of the gas generated. Arc temperature does not increase as steeply as pressure, however, so the pressure term dominates and the volume of the bubble decreases as greater operating depths are reached. This means that the protection afforded a SMA weld made without supplementary gas shielding will decrease.

Silva has developed relations which link the velocity and diameter of a rising bubble to its depth:

$$V = \sqrt{\frac{4\ ghd(\rho_w - \rho_b) + 0.532d^2}{2\rho_b d + 3c\rho_w h}}$$

$$d = 3\sqrt{\frac{P + \rho_w gD}{P + \rho_w gh} \cdot d^3{}_D}$$

where V = upward velocity (ft/sec)

g = acceleration due to gravity (ft/sec^2)

h = depth of bubble being considered (ft)

D = dpeth of arc (ft)

P = atmospheric pressure (lb/ft^2)

C = coefficient of drag for a sphere (dimensionless)

d, d_D = diameter of bubbles at h or D (ft)

ρ_w, ρ_h = mass density of water or bubble (slug/ft^3)

Increased pressure also affected shielding gas behavior. The density of the gas is increased and higher flow rates are required. Figure 4-12 illustrates the increase required by Burrill and Levin in their experiments. Flow rates as great as ten times those used for surface welding have been required. Arc behavior may also change with depth and influence the selection of the shielding gas and the gas flow rate.

Liquification of shielding gases places a depth limit on their use, since the torch would cease to function. Of the gases suitable for shielding, argon and hydrogen remain gaseous at the greatest pressures. At 0°C, argon liquifies at 3570 meters and nitrogen at 5090 meters. Heating of a gas may extend its range slightly, but practical considerations limit this action.

5 Porosity and Chemical Composition. Porosity is caused by small gas bubbles becoming trapped in the weld metal. The small hole, or pore, in the welded joint is a mechanical defect and is not as serious as the chemical problem associated with the presence of the gas. Having oxygen or nitrogen present is harmful because oxides and nitrides formed from these gases cause embrittlement of the metal. The presence of hydrogen is even more critical but its effects will be considered separately in the next section.

Two possible causes of porosity in SMA welds made underwater have been suggested. The first, not a depth-related effect, is

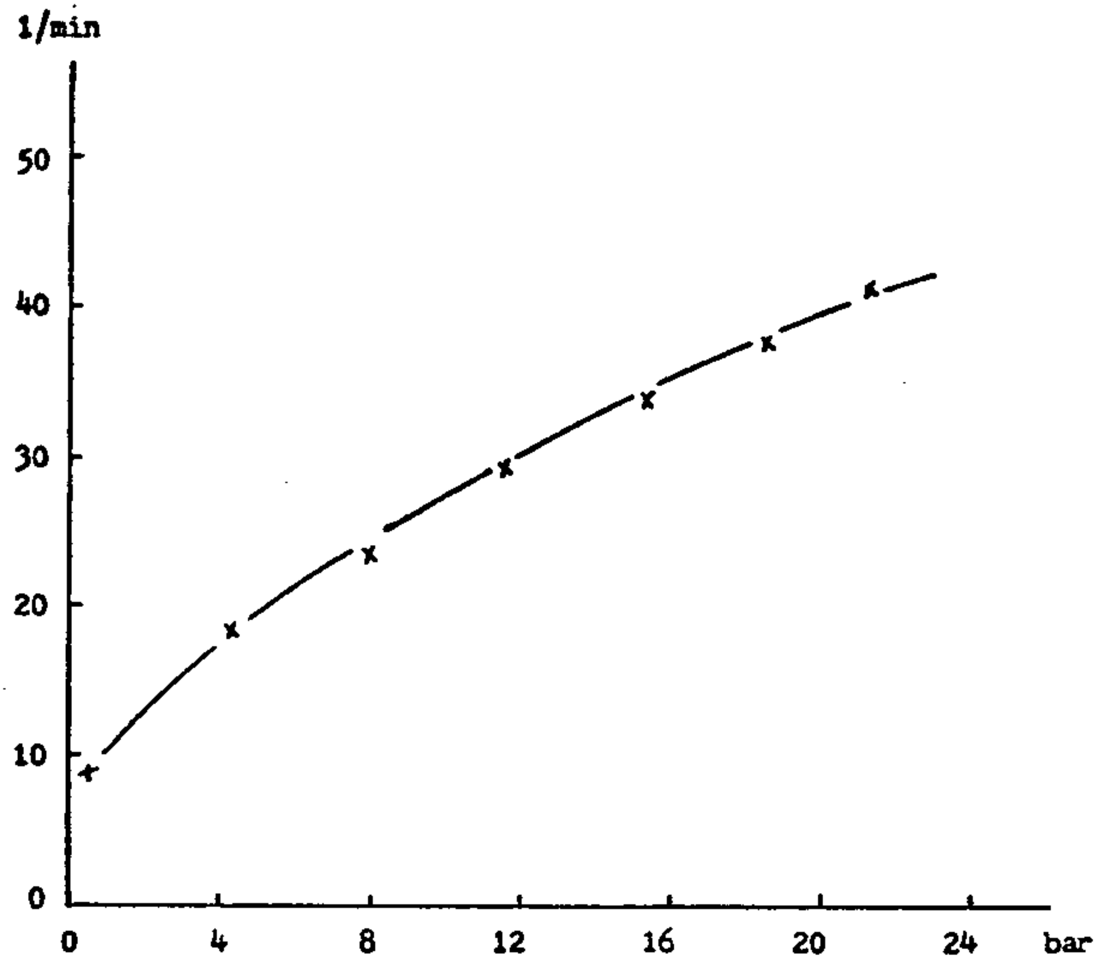


Figure 4-12 Increase of Shielding Gas Flow with Pressure[75]

that porosity is associated with wet electrode coatings. Chicago Bridge and Iron welders have found that keeping electrodes dry in a special underwater case until they are actually placed in the holder results in high quality, porosity free welds. Better coatings, which resist moisture penetration, also help to overcome this problem. There has been speculation that increased porosity found in SMA welds made at greater depths is related to the shrinking of the protective gas bubble under high pressures. It is though that protection of the arc and molten weld metal normally provided by the gas bubble breaks down. This problem might be solved by using a shroud to trap shielding gases generated or by the use of supplementary shielding gas.

In GMA welding tests made under pressure, porosity was found to be reduced when pressure was increased. This is believed to be due to the fact that the gas pressure in the bubble was lower than the sum of the hydrostatic pressure of the molten metal, the surface tension of the molten metal, and the ambient pressure of the chamber. If this is the case, chemical problems will remain unchanged since the amount of gas in the weld is not changed. Brandon noted a correlation between pore size and shape and turbulent arc and puddle action in GMA pressure welding. This might become a significant problem if pressures are sufficiently great to cause the welding arc to become unstable. In his tests, Brandon found that filler metal speed rate was the only parameter which affected weld soundness. Low filler metal feed rates with low levels of arc turbulence gave completely sound welds. High feed rates with a large amount of turbulence resulted in large voids.

In underwater welding there are many hydrogen and oxygen ions present and the possibility of substantial numbers of sodium, chlorine, magnesium, sulfur, potassium and calcium ions from the dissociation of sea water. In addition if nitrogen gas shielding is used, care must be taken to avoid welding steels containing aluminum, chromium, vanadium, or molybdenum since a brittle nitrided structure could result.

The presence of oxygen in a weld will reduce strength, hardness and notch toughness, especially if dissolved in quantities greater than 0.1 percent. Since oxygen from dissociated water is so prevalent in underwater welding, deoxidants in electrode coatings become of critical importance. As Table 4-3 indicates, a noticeable reduction in carbon, manganese and silicon is observed as welding is carried out at progressively greater depths. It is apparent that pressure increases the rate at which these deoxidants combine with the oxygen generated from the dissociation of water. This leads to their proportionate removal from the weld metal. It has also been reported that the chemical activity of silicon and manganese deoxidants increases with an increase in pressure. In welds made in aluminum under pressure, Rabkin et al. found that the concentration of the easily vaporized alloying elements, manganesium and zinc, increased as pressure was increased. This was due to the elevation of their boiling points and to a corresponding decrease in their rates of vaporization from the weld pool. An increase in zinc and magnesium concentra-

Table 4-3 Changes in Weld Composition with Depth

Depth (m)	Carbon (wt %)	Manganese (wt %)	Silicon (wt %)
20	0.26	0.63	0.16
40	0.19	0.21	0.08
60	0.09	0.12	0.03

tion resulted in the elimination of defects caused by oxide inclusions and in a reduction in porosity.

6 Hydrogen Embrittlement. The severe quenching effect of the underwater environment and the presence of hydrogen in the weld area cause the most severe problems encountered in wet underwater arc welding. Although the quenching problem can be solved for certain applications by removing the water through the use of dry chambers and shrouds, the remaining moist atmosphere is still high in hydrogen. Shielding gases are used to overcome this difficulty in chamber welding, but it remains a problem in shrouded SMA welding as well as in all wet techniques. The combined effects of hydrogen and the quenching action result in a severe cracking problem in the heat affected zone (HAZ) and in a loss of ductility and tensile strength.

The quenching of the weld due to the large heat sink of the water is not a depth-related problem, but there are indirect depth effects. In the deep ocean the water is likely to be much colder than at the surface and the quenching effect is more severe. Hydrogen embrittlement, which is depth-related, results in serious cracking only in hardened regions, such as those martensitic areas caused by quenching.

An underwater arc operates in a bubble atmosphere resulting largely from dissociation of the water by the extreme heat of the arc. This gaseous atmosphere may be up to 93 percent hydrogen. The hydrogen dissociated from water in the bubble dissolves into the weld puddle and the rapid quenching action which enhances the formation of brittle martensite by a precipitation process also acts to prevent the hydrogen's escape. As the temperature cools down, the solubility of hydrogen is reduced and the hydrogen begins to diffuse out of the weld metal into the surrounding water and into the HAZ. The presence of both hydrogen and a hard martensitic structure in the same region, the HAZ, is an important point since hydrogen will not induce cracking unless the region is hardened and contains residual stress concentrations. Faster cooling rates and resultant higher hardnesses give the HAZ a higher susceptibility to hydrogen cracking.

Hydrogen embrittlement is most apparent at temperatures just above those of the ductile to brittle transition of the hydrogen-free metal. Below the transition temperature, the metal is brittle regardless of the presence of hydrogen and above this temperature it is difficult for micro cracks to form and propagate before plastic deformation can occur.

Although many theories have been developed to explain the mechanism of hydrogen embrittlement, the one advanced by Morlett, Johnson and Troiano seems to be generally accepted today. This theory is based on diffused hydrogen localized at lattice inperfections known as voids. The severity of the embrittlement effect depends both upon the established stress system and the diffused hydrogen. The voids are regarded as micro notches about which a multiaxial stress system will be established when stress is applied to the steel. According to this theory, the stress system will be triaxial in nature in a region within the metal lattice near each void. It is suggested that it is the hydrogen concentration within this entire region of triaxial stress and not the concentration within the void alone that determines the degree of embrittlement.

During diffusion, hydrogen concentrates in those regions of the lattice that are highly stressed. This creates a hydrogen concentration gradient which corresponds to the multiaxial stress gradient of the region. However, once within the stressed region, equilibrium requirements cause the hydrogen to move from the lattice into the voids. The size of the hydrogen concentration gradient depends upon the original hydrogen concentration, the hydrogen diffusion rate and the time available for the diffusion of the hydrogen. One necessary condition for the diffusion of hydrogen through a metal is the dissociation of the hydrogen molecule to atomic hydrogen at the surface.

The diffusivity of hydrogen in metal can be expressed as an equation of the form:

$$D = D_o P \exp(-Q/2RT)$$

D = Diffusivity of hydrogen	Q = Heat of solution
D_o = Constant	R = Gas constant
P = Pressure of hydrogen	T = Absolute temperature

This equation, known as Sievert's Law, also governs the solubility of hydrogen in the weld metal.

It can be seen that diffusivity increases with temperature in accordance with the exponential law governing rate processes, and that diffusivity is also proportional to the square root of the hydrogen pressure. The hydrogen partial pressure in the arc bubble must be nearly as great as hydrostatic pressure since the bubble is more than 90 percent hydrogen and must have a total pressure equal to hydrostatic pressure. Thus, as Figure 4-13 illustrates, for a given temperature, the percentage of hydrogen in the HAZ increases as the pressure at which the weld is made is increased.

It has been suggested that the total amount of hydrogen that originally goes into solution in the weld metal must correspond to the maximum solubility of the metal. Since liquid metal has a greater gas solubility than solid, this results in greater initial absorption than would be expected using Sievert's Law. As a result, the diffusivity to the HAZ will increase over the values predicted by Sievert's Law. The rate controlling process for gas absorption proposed to replace Sievert's Law is the rate of gas ion supply to the metal surface. Additional study to determine which of these two diffusivity relations is most useful in predicting the extent of hydrogen embrittlement should be undertaken.

Once embrittlements has occurred, a brittle micro crack may initiate in the region of high triaxial stress. The exact manner by which the hydrogen concentration causes carck initiation is not known. In fact, it is not certain whether the initiation occurs prior to, or after, the introduction of hydrogen. Once the micro crack has been initiated, its propagation depends upon the hydrogen concentration, the triaxial stress field and the plastic flow at the crack tip. The initiation enlarges to the size of

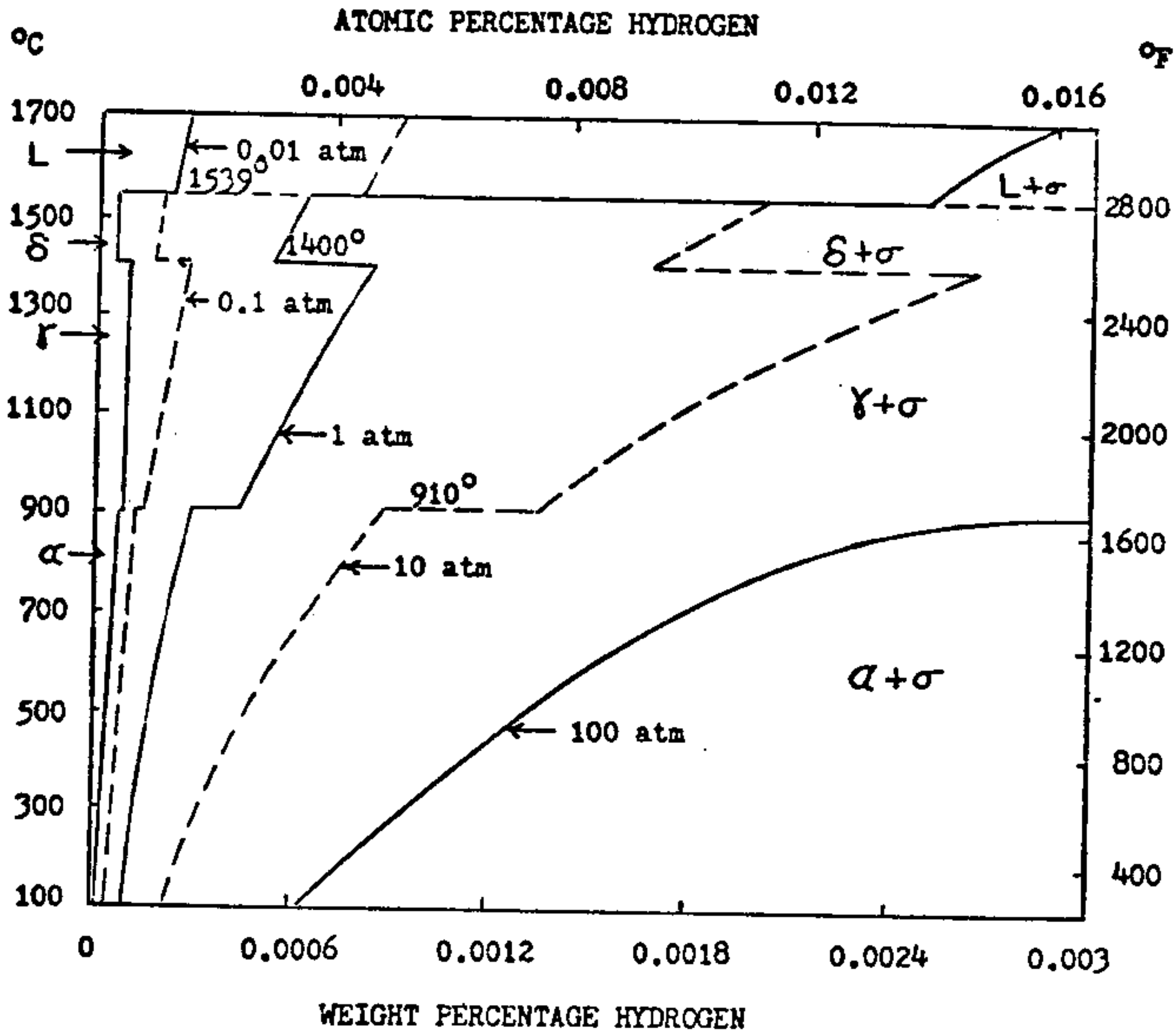


Figure 4-13 Iron - Hydrogen Equilibrium Diagram

a small crack which induces further stress on the carck tip, causing it to propagate. This carck may then grow in steps to critical size which can lead to brittle fracture and failure of the structure.

In most cases, of course, hydrogen-induced cracking does not lead to catastrophic failure. However, offshore structures made of higher strength steel have often suffered less dramatic cracking problems when repairs were attempted using single-pass wet welding techniques. It was not uncommon to be able to actually lift fillet welds made using wet processes out of the joint due to the severity of underbead cracking.

Porosity, due to hydrogen coming out of solution and forming small voids in the weld area, can also occur. It is not a major problems in reducing the quality of welds made underwater. It has been found in experimental studies that increased pressure acts to retard the formation of pores in welds. It is uncertain, however, whether this effect is due to the increased heat allowing the weld metal to remain molten longer, giving hydrogen additional time to escape, or to the increase in hydrogen solubility resulting from increased pressure.

Two approaches have been tried to lessen the effects of hydrogen embrittlement. In steels having a high carbon equivalent (greater than 0.4 but less than 0.6) the use of austenitic electrodes has resulted in the elimination of underbead cracking during multipass underwater welding. This technique has proven reliable down to a depth of 80 feet and research to extend this depth to the 300 feet mark is underway. An austenitic weld metal microstructure is capable of storing large quantities of hydrogen which, it appears, keeps the hydrogen away from the crack sensitive HAZ, avoiding underbead cracking. A certain degree of success has been noted using post heat treatments for underwater welds. Some welds shown significant improvement after two or three hours at 250°C but others required much higher temperatures. In another case, aging at ambient temperature for two days produced an improvement in dictility which was attributed to the escape of hydrogen from the weld area. Another form of post heat treatment, tempering previous passes with later passes using multipass techniques has resulted in CBI being able to consistently produce high quality welds underwater. It has also been suggested that preheating or insulating the work surface may help to reduce hydrogen related problems. Other possibilities include increasing the heat input to the weld arc without increasing weld size through the use of a wet GMA technique.

4.3.2 Exothermic Welding and Brazing [66, 77]

Exothermic processes exhibit several advantages which make them ideal candidates for deep-sea application. Small, inexpensive exothermic devices containing their own power source can be made, placed either by submersibles, remotely controlled vehicles, or by divers, and activated remotely. Several studies have been conducted on the feasibility of employing these devices for the placement of padeyes on objects prior to salvage. In addition, it is possible that several other practical applications may arise since the mold in which the reacted thermit is cast is not strictly size or shape limited. One such possible application is the attachment of repair sleeves to damage subsea pipelines.

Just as in the more common arc technique, cooling rates have a significant influence on the resulting hardness of a thermit fusion weld. Rockwell "B" hardness climbed considerably as the cooling rate was increased.

The underwater environment has other effects on thermit processes. Water must be removed from the weld area prior to tapping any molten metal into the area if a sound weld is to be achieved. This may be accmoplished by removing the water through displacement by a pressurized gas or by preheating the area through the use of a separate thermit reaction timed to ignite just prior to the primary reaction. It has been found that the flow of molten metal through the mold can effectively remove minor oxidation and dirt from the surfaces to be joined. Surface preparation may then be kept to a minimum.

One major depth-related problem, offsetting the pressure differential between reacting chamber and mold in order to provide for the flow of molten metal, must be solved before thermit processes can be considered practical alternatives for deep ocean application.

4.3.3 Explosive Welding[78]

Developmental work is now being conducted to develop an explosive welding technique suitable for the deep ocean. It is believed that this process may be useful in attaching padeyes to sunken objects to aid in salvage efforts. If development is successful, this device has several advantages which may be exploited for deep application. First little manipulative ability is demanded, in fact, only emplacement and remote detonation are required. Next, the power source for this device is small and self-contained. Finally, the process is simple and inexpensive.

In the particular technique employed underwater, a second charge timed to detonate a small fraction of a second prior to the main charge is placed in such a manner as to evacuate the water between the plates. However, as welding depths are increased, progressively larger secondary charges will be needed to evacuate the water since larger pressure forces will be acting to resist evacuation. This presents a real problem since the nearly incompressible water will transmit larger and larger shock waves to the plates as the size of the secondary charge is increased.

One final disadvantage common to both surface and underwater explosive welds should be noted. Welds with good bonding characteristics are difficult to produce consistently. This process appears to be highly sensitive to variations in welding conditions such as the plate separation distance and angle, the explosive standoff distance and the balance between the magnitude of the explosive force and the surrounding environment. Difficult to control precisely in laboratory conditions, these factors may become prohibitive in actual deep sea work.

4.3.4 Velocity Power Tools [79]

Several velocity power tools have been fully developed for use underwater in salvage and emergency repair work. These devices may be used to attach studs or lifting points, to provide fittings for gas or liquid transfer and to punch holes. Velocity power tools are small, inexpensive, flexible and have a self-contained energy source. Several models have been developed. Of these, two have been designed strictly as diver tools while a third has been designed for remote operation in conjunction with the Navy's LOSS program. These tools can be used on wood, concrete and sheet metal in addition to steel plate.

There are several types of ammunition available for each tool. These include several types of solid studs used for fastening, hollow studs used to transfer a gas or liquied through a bulkhead and a hole punch projectile used to punch a hole through a plate. Each type has a number of powder loads to accommodate plates of various thicknesses.

The primary disadvantage of the velocity power tool is its basically destructive nature. The projectile literally rips its way into the parent structure. Careful matching of powder loads for intended use minimizes the damage, but a stud or other fitting attached in this manner cannot be considered a permanent part of the structure. Crevices and discontinuities are created, and serve as sites for corrosion. This technique is thus limited to salvage and temporary repair. Even in certain salvage situations, the destructive nature of this tool is a disadvantage. If this device were used to provide an attachment point on a watertight compartment of a sunken submarine or submersible, it could cause leakage or even collapse of that compartment. This danger increases as salvage depth is increased.

4.3.5 Other Processes

There are several processes, other than those outlined above, that are being considered or may in the future be considered for deep ocean use. Because little technical information dealing with the effects of pressure on these techniques is available, they are listed below.

Mechanical Joining[51] - Mechanical joining techniques form the heart of several repair systems being developed for the deep sea. These are basicly for the use on pipeline based on devices developed for surface requirements where welding was not possible, such as, mechanical sleeves for bolting and sealing two pipe ends.

Gas Welding[28] - Attempts have been made to use gas welding with little success. Gases such as oxygen and hydrogen can be used up to the depth of 1,500 meters, after hydrogen lequifies.

Adhesive Bonding - The synthetic rasines developed for adhesive bonding for the aerospace industry may be used for underwater applications.

4.4 Conceptual Design of Deep Ocean Welding Systems

The current underwater welding processes are simply extensions of air welding processes. This approach is severely limited; this, the conceptual design of new underwater welding techniques is crucial.

The conceptual design should be approached from a total system viewpoint, with all of the factors outlined in Figure 4-1 considered. Several considerations in the development of deep ocean welding systems are discussed in this section.

4.4.1 Potential Use of the Possible Designs

There is a recognized need for devices capable of providing attachment points on sunken vessels to aid in salvage or rescue operations and there may soon be a requirement for techniques to make attachments on permanent sea floor structures. These requirements can be met in relatively shallow water using divers and hand-manipulated arc welding techniques. However, no divice has yet been developed which completely satisfies the need for a process capable of employment by a submersible or remote vehicles in waters beyond a diver's working depth.

Only one of the processes discussed in Section 4.3, the velocity power stud tool, has completed development and has been produced for operational usage. This device was successfully tested as part of the Navy's LOSS program, but it exhibits certain limitations that may inhibit wider application. Studs attached using this process can be heavily loaded in shear only, and multiple attachments are required for large loads. Discontinuities produced at the joining surface make this technique unsuitable for applications exposed to the corrosive marine environment for prolonged periods. In addition, the impact required to attach large studs may make the use of this device on submarines or other structures containing watertight compartments undesirable.

Studs arc-welded on the surface can be heavily loaded in tension and a single 1 1/4 inch diameter stud weld can withstand a static tensile load of over 60,000 pounds. Smooth weld fillets are produced and the low heat input of this process causes little damage to thick plates.[81]

Another design proposal involves is the development of an underwater automatic welding unit to attach a plate to a plate. Such a research effort might even be extended to include a realistic application, such as an automatic underwater pipe welding unit.

Figures 3-34 and 3-35 show the proposed design of an underwater stud welding gun and an automatic cartridge type welding unit.

4.4.2 Diving System Considerations

A number of considerations must be included in the choice of a diving system for the deployment of a marine stud welding device. Factors which enter into this decision include depth, cost and support requirements, as well as manipulative and maneuverability demands.

The requirement exists for a device for employment in depths well beyond diver range. An acceptable diving vehicle should have a depth capacity of from 1000 to 5000 feet and future requirements may even extend this to 20,000 feet, the depth of the abyssal plain.

Since vehicles employed in deep ocean operations are inherently very expensive, it is essential that this joining, system be mated to either an existing ocean vehicle, with modifications, or to a vehicle being designed to perform a variety of tasks.

1 Support Requirements. A device capable of welding a one inch diameter stud requires direct current electrical power with 2000 amps of current and an open circuit voltage of at least 65 volts. Options available for supplying power to existing deep sea vehicles are essentially limited to surface cables and storage batteries. However, power requirements for studs large enough to be useful in salvage operations effectively preclude storage batteries, due to weight and volume limitations. Any diving vehicles capable of employing a large stud welding device must, then, receive power through a surface umbilical.[82]

Cables capable of transmitting high levels of power, yet of sufficient structural strength and of reasonable size and weight, can be constructed for operations at 20,000 feet. A cable, able to transmit high, short duration loads of sfficient magnitude for arc welding of one inch diameter studs at 20,000 feet, requires a weight of only 2.0 pounds per foot and a diameter of about 1.25 inches.[83]

It is expected that a device which welds in the wet without the need for shielding gases can be constructed, such as the welding unit shown in Figure 3-35. However, shielding gas can be carried in small cylinders if it is needed. Since the actual welding of a stud occurs in a very short time period, just over one second for a one inch stud, only very small amounts of gas are required for adequate coverage. Argon can be used to 11,700 feet prior to liquification and nitrogen to 16,700 feet, so shielding can be achieved at all but the most severe depths.[28]

2 Manipulative and Maneuverability Requirements. The operation of a stud welding device requires that the device be placed squarely against the workpiece and held in position while welding takes place. The total time that the device must be held in position is on the order of a few seconds and depends more on the response time of the control system that on welding time. Positioning of the device may be accomplished easily by any one of a number of underwater manipulators now in service. Holding the device in position, however, will require either very fine maneuvering control of the work vehicle or some type of fixture or clamp.

Extensive surface preparation is not required for stud welding but marine growth and corrosion must be removed from the immediate area where the stud is to be attached. This can be accomplished by a rotary wire brush attached to a manipulator. Rotary movement is a very common feature on underwater manipulators.

Reloading a stud welding device in a high pressure environment may be a problem. Many small stud gunds used in industry are fed automatically, but none with studs longer than one inch. If a practical loading system cannot be developed, devices with multiple welding heads may be used.

4.4.3 Technical Feasibility

The next step in the conceptual design is the investigation of the technical feasibility of the proposal. Stated more simply, it must be determined if the stud welding processes can be used directly in a wet environment or if an enclosure and gas shielding system are required. From a total systems viewpoint, assuming both systems can produce satisfactory results, the wet system is preferable to the dry since the complications of a gas supply system and an enclosure can be avoided. Eliminating these features makes the overall system simpler, increasing reliability and decreasing cost. It also saves weight and volume, both valuable commodities in any deep sea system.

The approach to the question of technical feasibility is both experimental and analytical in nature. In the experimental portion, welds are made in a wet environment and samples are tested to determine tensile strength, hardness and metallurgical content. In the analytical portion, a computer heat flow model is employed to determine the temperature history of points near the weld. This is done because the large heat sink of the underwater environment changes the metallurgical structure of the weld and these changes can be predicted with a knowledge of temperature history. This model is verified experimentally.

The analytical and experimental results are discussed in Chapter 3 of this report.

CHAPTER 5: THE FIELD EXPERIMENT

During the summer of 1976, a series of underwater welding experiments were conducted under the Baltic Sea near Travemünde, the Federal Republic of Germany. The experiments were conducted as a part of the U.S.-German cooperative effort supported jointly by the Manned Undersea Science and Technology Office of NOAA and GKSS. Assistance were provided by the Diving Operations Branch of the Naval Sea Systems Command of the U.S. Navy.

We would like to express our sincere appreciation to all those people who have assisted us in so many different ways in this experimental program. The experience gained in applying our considerable theoretical data to an actual undersea welding situation has proven to be invaluable and will, among other things, make it possible for us to more rapidly develop the practical application techniques which are, after all, the goal of our efforts.

5.1 Brief Review of the Project

The underwater welding experiment was conducted in Travemünde, West Germany from June 14 to July 20, 1976. The objective of the program was to collect scientific data on underwater welding and to evaluate two welding processes under actual diving conditions.

The processes evaluated were (1) the shielded metal arc welding process, and (2) the flux-shielded metal arc welding process. The shielded metal arc welding process is widely used for underwater repair work. The flux-shielded metal arc welding process, developed recently at M.I.T., reduces water quenching around the arc zone by direct flux shielding.

The Subjects Studied. The study included the following Phases:

Phase 1. The study of an operational system that included cost analysis, electrical safety, diver's stability and fatigue rate.

Phase 2. The evaluation of two underwater welding processes with respect to (1) arc stability and metal transfer, (2) bubble formation, (3) heat flow, (4) metallurgy, and (5) mechanical properties.

The subjects studied included:

1. Type of flux coating of electrode (rutile, low hydrogen, and special coating for underwater application).

2. Type of water-proofing (duralic and epoxy).

3. Type of joint (butt and tee).

4. Welding positions (downhand and vertical).

5. Optimum welding current (D.C.R.P.) and voltage (drooping characteristic) with respect to each individual weld.

6. Base materials (primarily mild steel, although some work was done using ST52 high-strength steel).

Thicknesses: 6 mm and 15 mm.

The study included the following:

1. An examination of the metallurgical structures of the weld metal, the heat affected zone and the base metal.

2. An examination of a number of weld defects (porosity, undercut, slag inclusion, lack of fusion and lack of penetration, etc.).

3. The determination of certain mechanical properties (tensile strength, ductility, notch toughness, and microhardness).

4. An examination of several other qualities such as chemical composition and segregation of weld metal, arc stability and metal transfer, composition of gas bubbles and their generation rate, and heat flow in the weldment.

The Experimental Operations. The operations were conducted from July 4 through July 17, 1976.

During the welding operation a chart recorder was used to record the transient volt-ampere characteristics of all welds. Through the courtesy of the U.S. Navy, an underwater T.V. monitoring system was used to observe the welding operations. Photographs were also taken of the welding operations. Gas bubble specimens generated during welding were collected for chemical analysis.

X-ray films of all butt welds were prepared through the courtesy of GKSS. All butt welds were sent to M.I.T. for further mechanical and metallurgical testing. The chemical analysis of the gas bubbles was done through the courtesy of GKSS.

5.2 Underwater Welding Experiment

Two underwater welding processes, the "wet" manual metal-arc welding process and the "flux-shielded" manual metal-arc welding process, were studied in the experiment.

The underwater "wet" manual metal-arc welding process is already widely used. The underwater "flux-shielded" manual metal-arc welding process is a newly developed undersater welding process designed to reduce the cooling rate and the hydrogen pick-up around the arc zone through direct flux shielding. Figure 3-6 is a schematic diagram of this process.

A. Welding Arrangement.

The overall view of the experimental arrangement at the site is shown in Photograph 1. Figure 5-1 is a schematic diagram of the equipment arrangement for the underwater welding experiment and consists of the following:

1. The parent ship Tabasis
2. Power source
3. Current, voltage recorder
4. Underwater TV camera and monitoring system
5. Underwater electrode holder
6. Welding stand
7. Welding cable

Photo. 1

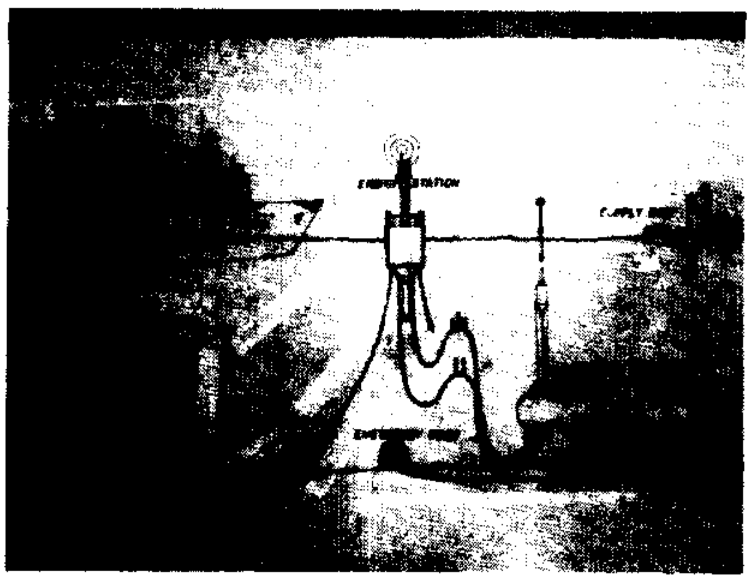


Photo. 1 The over all view of the experimental arrangement

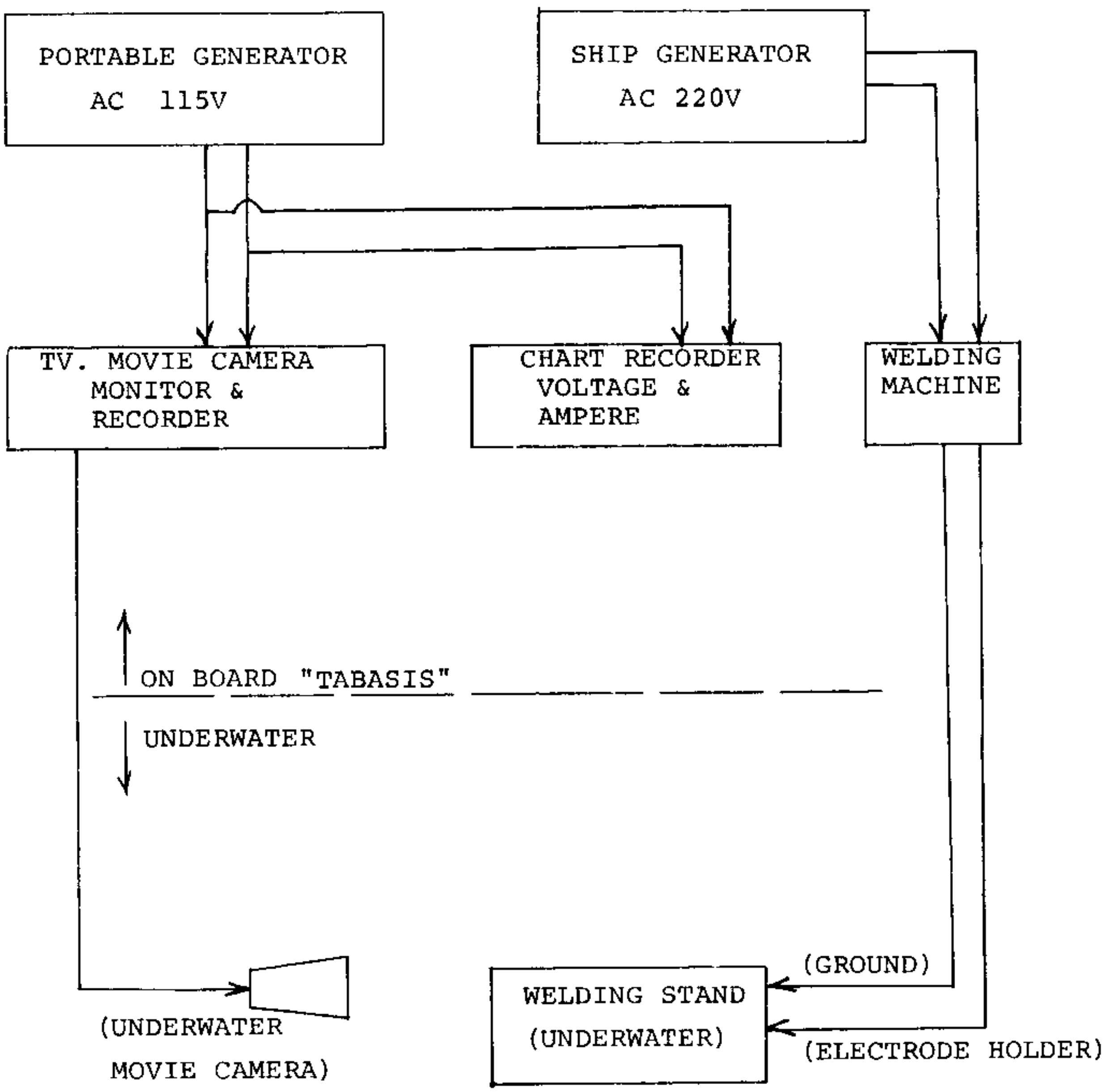


Figure 5-1 Diagram of Equipment Arrangement

<u>The Parent Ship: Tabasis</u>. The Tabasis provided all the supporting services for the experiment. All the control systems, including welding transformer, current and voltage recorder, TV monitoring system, and diving support systems, were located on the main deck. Welding preparations took place on the lower deck. All sample plates were secured to the welding platform on the weather deck. A hydraulically operated crane was used to lift the welding stand from the deck to the working site in the sea and back again.

<u>Power Source</u>. A welding transformer (50 open volts, drooping characteristic, 400 allowable amperes) was used to transform AC current (50 cycle) delivered from a generator (380 volt capacity) to DC current. DC reverse polarity was used in all experiments because of the ease in initiating and maintaining an arc, and the less dense flux-cloud produced during welding, with no apparent loss in weld penetration.

<u>Underwater TV Camera and Monitoring System</u>. A watertight TV camera was operated by a diver from M.I.T. The welding operation underwater was videotaped on Tabasis.

<u>Underwater Electrode Holder</u>. A water-proofed welding electrode holder was used in the entire experiment.

<u>Underwater Welding Stand</u>. The stand was built at GKSS, West Germany. Two platforms for downhand and vertical welding were used to fix the base plates.

<u>Welding Cable</u>. A welding and ground cable with a 50 meter

length was used. To protect working personnel from shock hazards and retard corrosion of the connection due to electrolysis, all connections were fully insulated from the water by several wrappings of plastic tape.

The conditions for the welding experiment are itemized as follows:

1. Environmental conditions

Depth:	12.5 m
Temperature:	6-7 °C on the average
Visibility	generally good
Underwater current:	generally low
Salinity:	low

2. Welding conditions

Power supply:	drooping characteristic
Polarity:	DCRP
Welding speed:	20 cm/min. on the average
Open voltage:	50 volts
Operating current:	200-250 amps (machine setting)
Operating voltage:	20-40 volts
Welding position:	downhand and vertical

3. Diving time

The maximum diving time was limited to 80 mins/day because of the surface diving restriction and depth restriction. It was divided into two sessions, normally morning and afternoon, with 40 minutes for each dive. Three persons, a welder/ diver, an emergency diver, and an underwater TV operator (or photographer) were usually involved in each dive. A research diver occasionally joined the diving team to collect gas-bubble specimens from the arc area.

B. Materials.

Mild steel (ST 37) was the material most often used in the experiments, though medium high strength steel (ST 52) was used for the metallurgical evaluation of flux-shielded and wet manual metal-arc welds.

6 mm-thick plates were used in single-pass butt joints, and the optimum welding conditions determined by examining the weld appearance of these trial welds.

Plates of more than 12.5 mm (1/2") thickness were then recommended because these heaver sizes are used in actual welding in the industry. 15 mm-thick plates were used in welding multi-pass butt joints, the welding conditions determined from the results obtained from the single-pass welding.

Both 6 mm and 15 mm-thick plates were used in welding tee joints (fillet welds).

Single-pass fillet welds were used to investigate weld appearance, penetration depth, shape factor, and weld deposition of the bead. An X-ray inspection of single-pass welds in butt and tee joints, revealed the severity of the defects (cracking, porosity, etc.), in the weld metal. The effect of improper slag-removal before laying subsequent layers did not apply in the single-pass welding.

The mechanical properties (tensile strength, ductility, notch toughness) of the multi-pass welded joints (15 mm-thick plates) were evaluated. The microstructures and the microhardness of the welds were also examined.

Electrodes. Several different types of electrodes were used to investigate how flux coating affects welding characteristics and weld properties. Two types of water proofing materials were also tested in terms of their effect on welding characteristics and weld properties.

Table 5-1 lists the different electrodes and waterproofing materials examined in this study. Electrodes of type S1-d, S1-e, S2-d, S2-e, and N were used in the welding of tee and butt joints. Electrodes of type A and LH were used only in the welding of tee joints.

Ordinary flux designed for submerged arc welding in air was used as the flux in the underwater "flux-shielded" manual metal-arc welding process. Electrodes of type S1-d and N were used in this process.

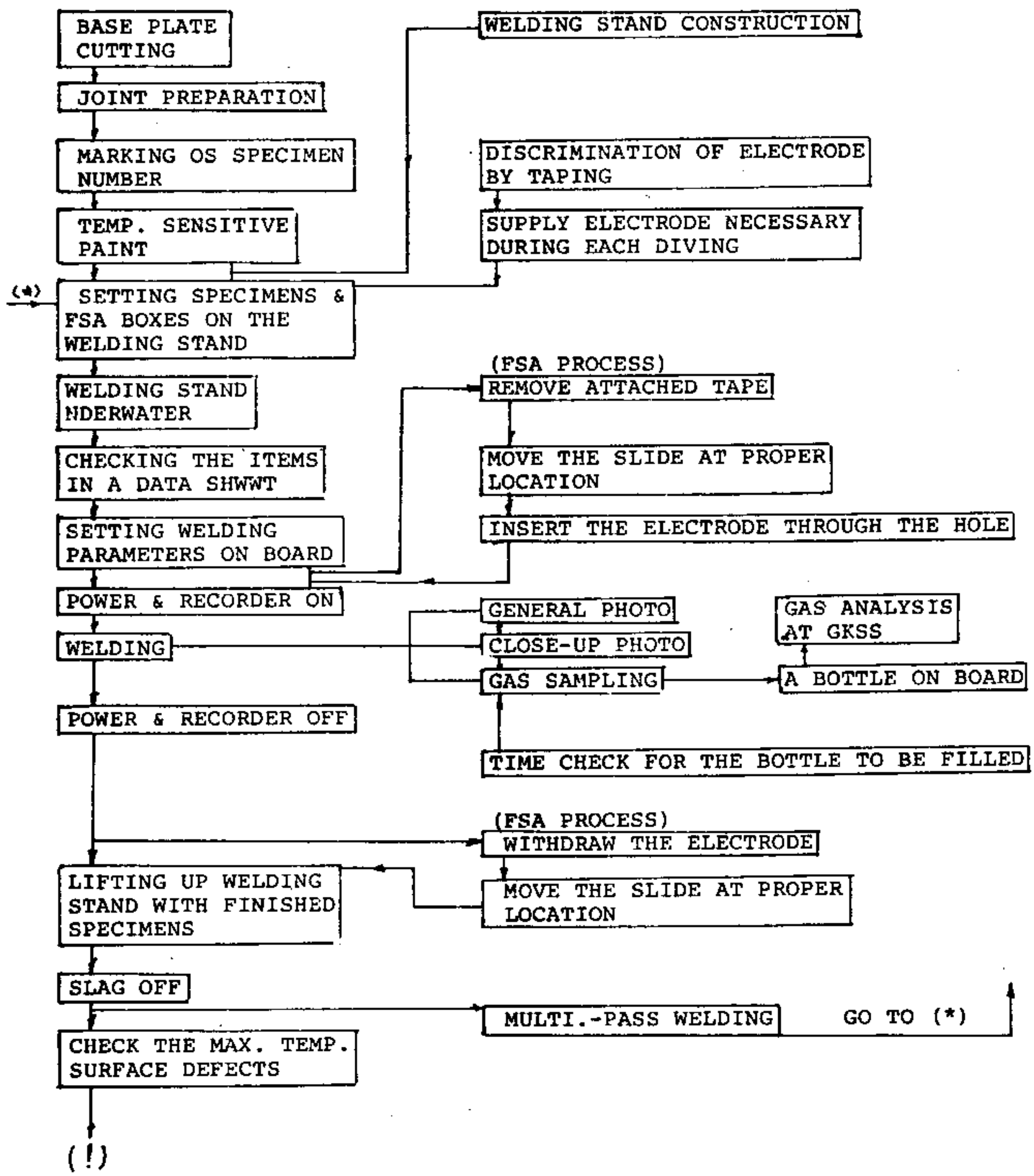
C. Underwater Welding Procedures.

Figure 5-2 is a detailed flow chart of the experimental procedures. It involves three steps:

1. Topside preparations
2. Diving and welding
3. Weld inspections.

Table 5-1 Electrodes used in the experiment

Type of Electrode	Electrode specification	Waterproof material	Size of electrode (dia. x length)	Remarks
Rutile iron powder	S1-d	Duralic	3/16"x14"	E7014
Rutile iron powder	S1-e	Epoxy	3/16"x14"	E7014
Limestone rutile iron powdwe	S2-d	Duralic	3/16"x14"	-----
Limestone rutile iron powder	S2-e	Epoxy	3/16"x14"	-----
Titanium	N	———	1/8"x14"	-----
Low hydrogen	LH	Crayon	3/16"x14"	E7018
Austenitic	A	Crayon	1/8"x14"	E310-16



BASE PLATE CUTTING
JOINT PREPARATION
MARKING OS SPECIMEN NUMBER
TEMP. SENSITIVE PAINT
(*)
SETTING SPECIMENS & FSA BOXES ON THE WELDING STAND
WELDING STAND NDERWATER
CHECKING THE ITEMS IN A DATA SHWWT
SETTING WELDING PARAMETERS ON BOARD
POWER & RECORDER ON
WELDING
POWER & RECORDER OFF
LIFTING UP WELDING STAND WITH FINISHED SPECIMENS
SLAG OFF
CHECK THE MAX. TEMP. SURFACE DEFECTS
(!)
WELDING STAND CONSTRUCTION
DISCRIMINATION OF ELECTRODE BY TAPING
SUPPLY ELECTRODE NECESSARY DURING EACH DIVING
(FSA PROCESS)
REMOVE ATTACHED TAPE
MOVE THE SLIDE AT PROPER LOCATION
INSERT THE ELECTRODE THROUGH THE HOLE
GENERAL PHOTO
CLOSE-UP PHOTO
GAS SAMPLING
GAS ANALYSIS AT GKSS
A BOTTLE ON BOARD
TIME CHECK FOR THE BOTTLE TO BE FILLED
(FSA PROCESS)
WITHDRAW THE ELECTRODE
MOVE THE SLIDE AT PROPER LOCATION
MULTI.-PASS WELDING
GO TO (*)

- continued -

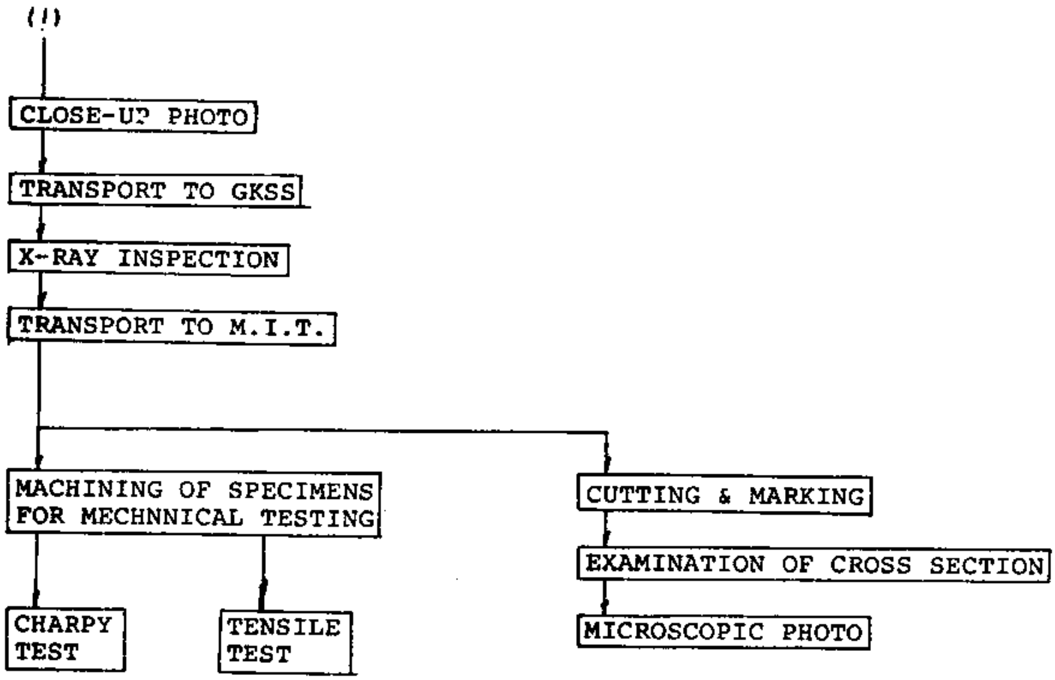


Figure 5-2 Diagram of underwater welding experiment

Topside Preparations. Figure 5-3 shows the shape and size of the plates used. They were 250 mm (length) x 125 mm (width). A 60-degree V-groove was used in all butt joints. A 2=mm root gap was selected for single-pass joints, and a 3-mm root gap for multipass joints.

All plates were stamped and marked as shown in Figure 5-4. Temperature-sensitive paints were used in a number of joints.

In the flux-shielded process, a water-tight box filled with welding flux and polymer was prepared topside.

All the sample plates were fixed on the welding stand using clamps. A welding sequence was attached to the stand before each dive. The stand, along with all the sample plates, the welding cable and the electrode holder, was lowered into place using a hydraulic crane mounted on the shelter deck.

Diving and Welding. The following is a brief outline of a typical diving procedure used in these experimental operations.

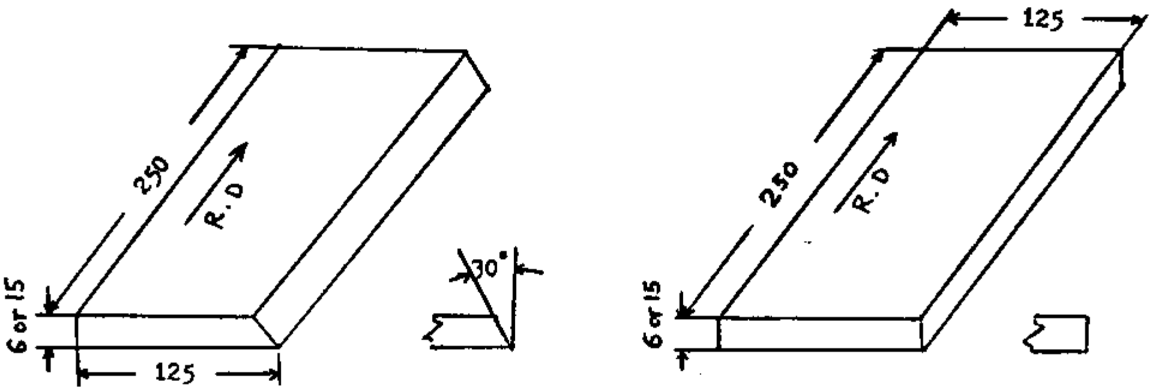
A. Topside preparations
   1. Dry suit with full thermal and electrical insulation for welder
   2. Wet suits for assistant and TV operator
   3. SCUBA tanks filled and readied (200 bar)
   4. Direct wire communications readied

B. Divers descend to bottom

C. Locate and ready stage

D. Determine welding sequence

E. Welding
   1. Attach ground lead
   2. Insert electrode into holder



SPECIMEN FOR BUTT JOINT

SPECIMEN FOR TEE-JOINT

Figure 5-3 Dimension of Specimens, unit in mm

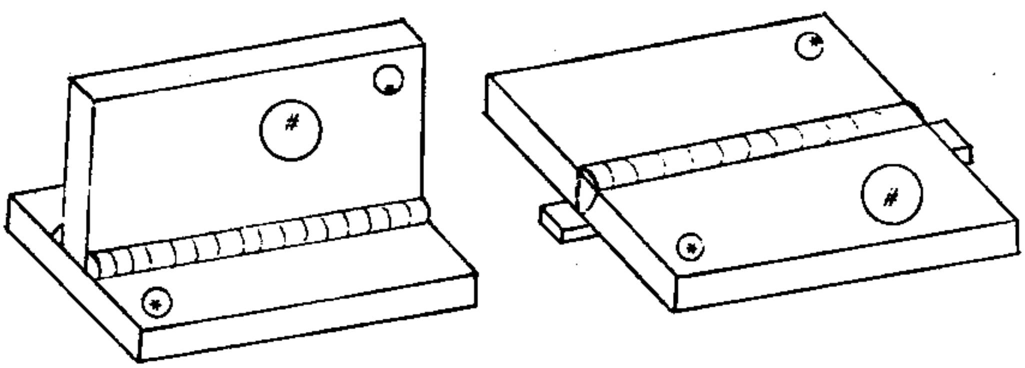


Figure 5-4 Symbolization of Specimens (base plate)

(*) -- PERMANENT MARKS, SAMPLE: M01 - M99 M: MILD STEEL
H: HIGH STRENGTH STEEL

(#) -- TEMPORARY NUMBERS BY PAINT, (USED IN THE DATA SHEETS)

3. Call to surface for current on
4. Wait for reaponse from surface
5. Initiate arc and weld sample
6. Call for current off
7. Wait for response from surface
8. Remove electrode from holder
9. Remove ground electrode
10. Clean weld if sample is multipass
11. Repeat sequence until all samples welded, or air supply low, or welder fatigues

F. Secure samples to stage

G. Attach stage to ship's winch cables

H. Divers surface to ship
   1. Remove diving gear
   2. Clean and store diving gear

I. Stage brought on deck using winch

In welding operations, the preferred "self-consuming" technique for underwater welding was used in this experiment. The current settings for welding with different types of electrodes were determined in advance by examining trial welds made under actual conditions.

On the average, four passes were completed in a ten-minute dive.

The welding current and voltage drop were chart-recorded during every welding session. Gas bubbles were collected and the underwater welding operations videotaped and photographed during certain selected sessions. These all provided information about the total operational features of actual undersea welding.

Weld Inspections. All the sample plates were inspected at M.I.T. Both macro- and microscopic examinations were conducted and the results are discussed in the next section.

5.3 Experimental Results.

The tee- and Butt-joint welds were studied to determine how the flux coating and the water proofing material affects the welding characteristics and the weld properties. Bead-on-plate trials were used to metallurgically evaluate two underwater welding processes.

In this section, the experimental results obtained from tee- and butt-joint welds were summarized. The results obtained from bead-on-plate welds will be discussed in the next section.

The experimental results fall into two categories:

1. Welding operation
2. Weld quality

Welding Operation.

Concerns related to welding operation are primarily related to the production of satisfactory welds using a specific type of welding electrode. The following items are considered important:

1. Operational characteristics
2. Arc stability
3. Gas-bubble compositions

Operational Characteristics. Table 5-2 shows how electrode type affects the general nature of the welding process. The

Table 5-2 Operational characteristics of underwater welding process with different type of electrode

Process	Type of electrode	Current I, amps	Voltage V, volts	Operational characteristics
Shielded metal arc process	S1 - d	170	30	1. easy to start and maintain the arc 2. the max. electrode bottom time=40 mins
	S1 - e	170	30	1. easy to start and maintain the arc 2. longer electrode bottom time 3. waterproof coating provided a good arc protective cup at the electrode tip
	S2 - d	120	35	1. easy to start the arc 2. stability of arc depended on the electrode bottom time 3. the max. electrode bottom time < 10 mins
	S2 - e	140	35	1. easy to start the arc 2. unstable arc and difficult to maintain the arc 3. waterproof coating didn't melt 4. high downward pressure was required to maintain a constant and proper arc length 5. fast fatigue rate of welder/diver
	N	140	30	1. taping and scraping to start the arc 2. very stable arc 3. very easy to maintain the arc
	LH	——	——	1. very difficult to start the arc 2. could not maintain the arc
	A	140	30	1. easy to start and maintain the arc
Flux-shielded metal arc process	S1 - e S2 - d N	150	35	1. very long preparation time for each pass of weld before welding 2. difficult to maintain a smooth arc 3. difficult to keep the electrode along the joint groove 4. welding arc was submerged 5. the operational feature of this welding process has not been well developed for practical applications 6. bead-on-plate trial was conducted for metallurgical evaluation

Depth at welding site: 12.5 m,;Water temperature: 6 - 7°C description of each welding process is based on the observations and feelings expressed by the diver/welder during welding. The type of flux coating and waterproofing materials are the important factors controlling the operational characteristics in the underwater "wet" manual metal-arc welding process.

Arc Stability. Figures 5-5 through 5-7 show the current-voltage recordings for experiments conducted using two different welding processes and several different flux coated (waterproofed) electrodes. The current-voltage records show that for a given electrode the arc running and metal transfer characteristics are voltage-dependent.

Table 5-3 summarizes the experimental observations of arc stability. Several indices of arc stability are tabulated and measured over a typical ten seconds of arc time. The indices are:

1.	Mean No. of arc extenction/sec.	N_e'	#/sec.
2.	Mean No. of short circuits/sec.	N_s'	#/sec.
3.	Mean current	I_m'	amps
4.	Mean voltage	V_m'	volts
5.	Amplitude of fluctuation		
	current	A,	amps
	voltage	E,	volts
6.	Stability factor	S,	I_{max}/I_{min}

The stability factor has been defined by Madatov as the maximum current divided by the minimum current. When the value is near one, the arc is considered stable.

The mean voltage drop during welding varied from 25 to 40

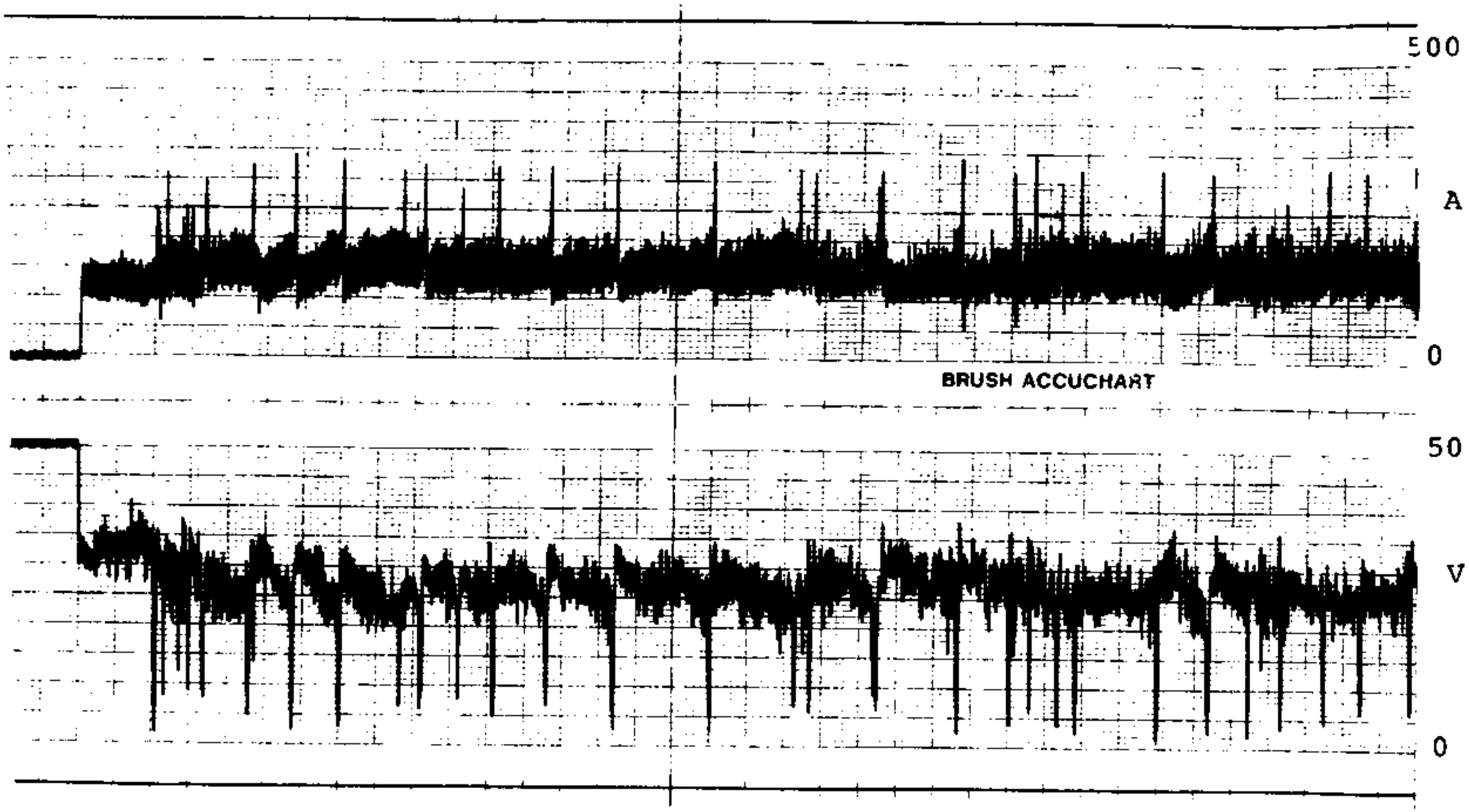


Figure 5-5 Current - Voltage Traces Right After the Arc Started During Flux-shielded Welding Process

Type of electrode: Sl-e
Joint type: Butt
Process: Flux-shielded

Chart speed: 25mm/sec.
Welding position: Downhand

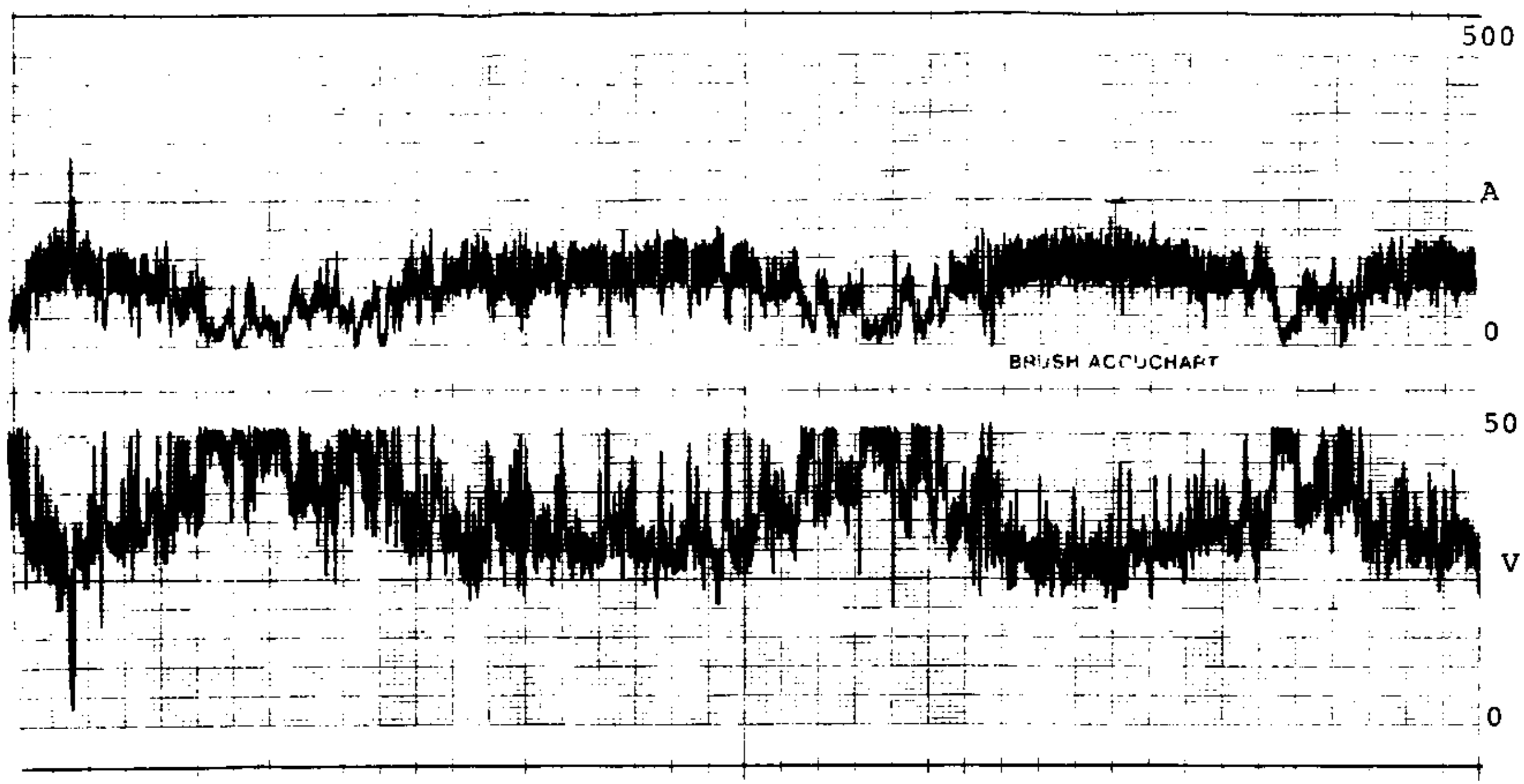


Figure 5-6 Current - Voltage Traces Some Time After the Arc Started During Flux-shielded Welding Process

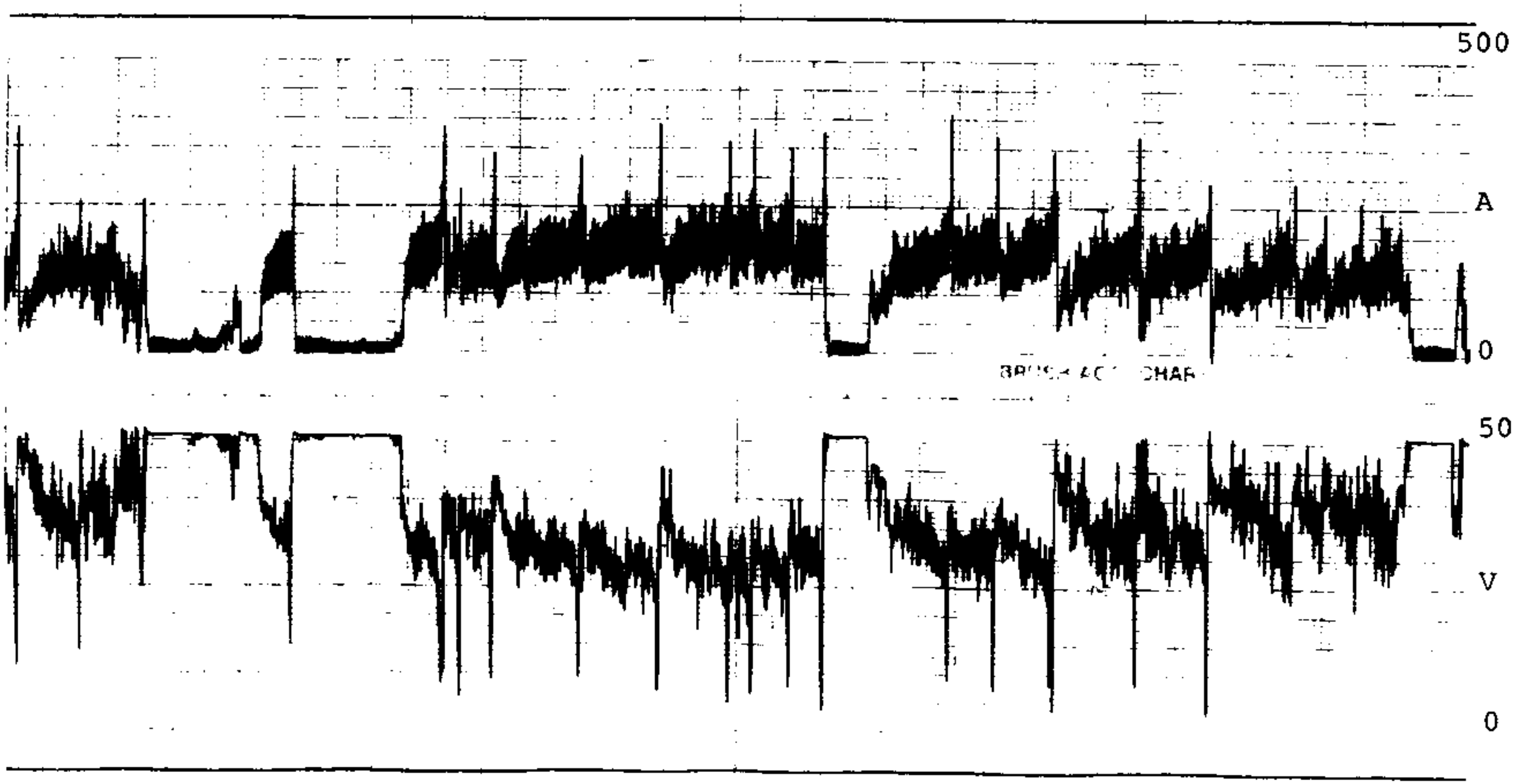


Figure 5-7 Current - Voltage Traces Some Time After the Arc Started During Flux-shielded Welding Process

Table 5-3 Arc characteristics of welding with different processes and type of electrodes

Process	Type of electrode	Type of joint	Welding position	Mean current I_m, amps	Mean voltage E_m, volts	Amplitude of current $\tilde{A}$, amps	Amplitude of voltage $\tilde{V}$, volts	Mean no. of short-circuit per sec. n_s	Mean no. of arc extinction per sec. n_e	Stability factor $S = I_{max.}/I_{min.}$
Shielded metal arc process	S1-d	Tee	Downhand	170	30	100	10	4	——	1.83
	S1-d	Butt	Downhand	180	23	110	10	5	——	1.88
	S1-e	Tee	Downhand	180	27	150	13	4	——	2.43
	S1-e	Butt	Downhand	170	33	150	15	3	——	2.58
	S2-d	Tee	Downhand	120	35	100	15	1	——	2.43
	S2-d	Butt	Downhand	120	32	80	15	1	——	2.00
	S2-e	Tee	Downhand	130	40	80	13	2	——	1.89
	S2-e	Butt	Downhand	150	35	80	8	3	——	1.73
	N	Tee	Downhand	150	25	80	10	1	——	1.75
	N	Butt	Downhand	140	30	80	8	2	——	1.80
	A	Tee	Downhand	130	27	80	10	6	——	1.89
	S1-d	Tee	Vertical	170	32	120	12	3	——	2.09
	S1-d	Butt	Vertical	140	30	100	15	5	——	2.11
	S1-e	Tee	Vertical	170	30	120	10	4	——	2.09
	S1-e	Butt	Vertical	150	30	100	15	4	——	2.00
	S2-d	Tee	Vertical	120	32	100	15	2	0.5	2.43
	S2-d	Butt	Vertical	150	28	100	14	4	——	2.00
	S2-e	Tee	Vertical	130	35	90	12	2	——	2.06
	S2-e	Butt	Vertical	140	32	100	12	3	——	2.11
Flux-shielded process	S1-d*	Butt	Downhand	170	30	90	10	6	——	1.72
	S1-d*	Butt	Downhand	150	27	80	8	4	——	1.75
	S1-d#	Butt	Downhand	120	35	80	7	3	4	2.00
	S1-d#	Butt	Downhand	170	35	70	7	3	2	1.52

* Datas were taken right after the arc started

\# Datas were taken sometime after the arc started volts, the mean welding current, from 120 to 180 amps. At high voltage (long arc length) there is a high incidence of arc extinctions. As voltage (arc length) is reduced the arc extinctions become less frequent and an increasing number of short-circuits occur.

The mean number of short circuits per second indicate the possible modes of metal transfer. Electrodes of type S2-d and N have a volue that approaches one, and the metal tranfer mode may be considered globular.

The mean number of arc extinctions per second indicate the amount of welding arc discontinuity. The flux-shielded manual metal arc process has a value from 2 to 4. Figures 5-5 through 5-7 indicate the variations of welding current and the voltage drop due to varying arc length during flux-shielded welding. Figure 5-5 shows the current-voltage traces present immediately after the flux-shielded welding arc was started. Figures 5-6 and 5-7 show these traces present a short time after the arc was started.

The stability factor varied from 1.52 to 2.58. Electrodes of type Sl-e, S2-e, and N have values from 1.75 to 1.89, and produce an arc that is considered relatively stable. Electrodes of type Sl-e and S2-d have a value over 2, and the arc is unstable. Welding arcs in the vertical position usually appeared unstable. Welding using a type LH electrode did not meet with any success.

In the type Sl electrode, an epoxy waterproof coating reduces the arc stability. But in the type S2 electrode, the epoxy waterproof coating improves the arc stability.

Gas-bubble Composition. The gas-bubbles that formed during the welding with S1-d and N electrodes were collected and analyzed. Table 5-4 shows the gas composition as examined by a mass-spectroscopic analysis.

The gas containers (500 ml) remained virtually gas tight until the analyses were done, as indicated by the lack of oxygen. The gas bubbles that formed during welding with an S1-d electrode were found to be 40% hydrogen. With a N electrode, they were 30%.

Weld Quality.

Since there is no standard classification system for underwater weld quality, air weld quality was used as a basis for comparison. The results of the experiment are summarized as follows:

1. Weld appearance
2. Structural discontinuities in weld
3. Metallurgical investigation
4. Mechanical properties

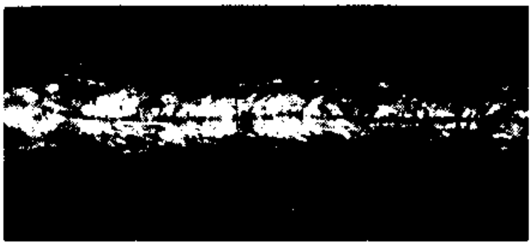
Weld Appearance. Photographs 5-2 through 5-11 show the single-pass butt welds produced by the different electrodes.

Table 5-4 The chemical composition of gas-bubble examined by massspectroscopic analyser

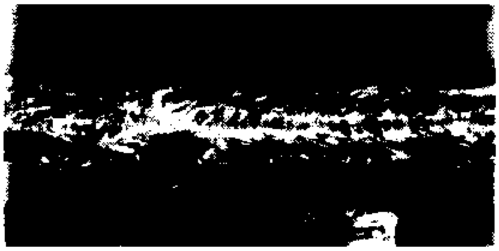
Type of electrode	H_2	CO	CO_2	Others
A-d	45%	43%	8%	4%
C	30%	55%	10%	5%

(a) 

Air weld(Butt)
Type of electrode: S1-d
Welding position: downhand

(b) 

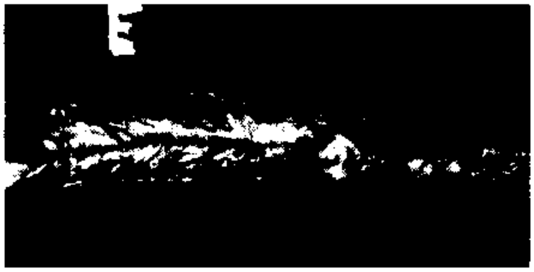
Underwater weld(Butt)
Type of electrode: S1-d
Welding position: downhand

(c) 

Underwater weld(Butt)
Type of electrode: S1-e
Welding position: downhand

(d) 

Underwater weld(Butt)
Type of electrode: S2-d
Welding position: downhand

(e) 

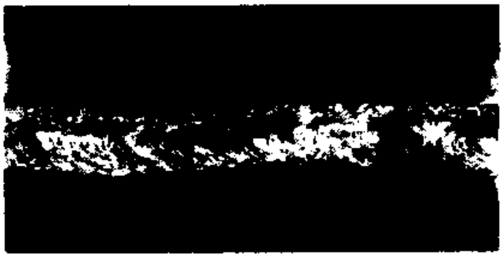
Underwater weld(Butt)
Type of electrode: S2-e
Welding position: downhand

Photo. 2,3,4,5,6
Bead appearances obtained by different types of electrode.

(f)

Underwater weld(Butt)
Type of electrode: S1-d
Welding position: vertical

(g)



Underwater weld(Butt)
Type of electrode: S1-e
Welding position: vertical

(h)

Underwater weld(Butt)
Type of electrode: S2-d
Welding position: vertical

(i)

Underwater weld(Butt)
Type of electrode: N
Welding position:

(j)

Underwater weld(Butt)
Type of electrode" S1-e
Welding position: downhand
Process: flux-shielded

Photo. 7,8,9,10,11
Bead appearances obtained by different types of electrode and flux-shielded process.

The following parameter (shape factors) were used to indicate the weld bead shape for fillet welds:

1. Weld leg length to penetration depth ratio, R
2. Convexity to bead width ratio, S

Figure 5-8 graphically illustrates these terms.

Table 5-5 summarizes undercut, bead smoothness, and bead regularity observations, as well as two shape factors. The shape factor data in the table was obtained from the fillet welds.

For air welds, the weld leg length to penetration depth ratio, R, is less than 2.0. Electrode S1-e has the lowest value and the flux coating with type S1 has the highest. An acceptable penetration is obtained when using electrode N, but not electrode S2. In general, electrodes of type N give the best weld profile (see Table 5-5); the convexity is almost zero.

Structural Discontinuities in Weld. Structural discontinuity is an interruption in the soundness of the weld:

1. porosity
2. slag inclusions
3. lack of fusion
4. lack of penetration
5. undercut
6. cracks

Photographs 5-12 - 5-14 are X-ray radiographs of some sample welds obtained during the program. Structural discontinuities appear on the radiographs as various shapes, white

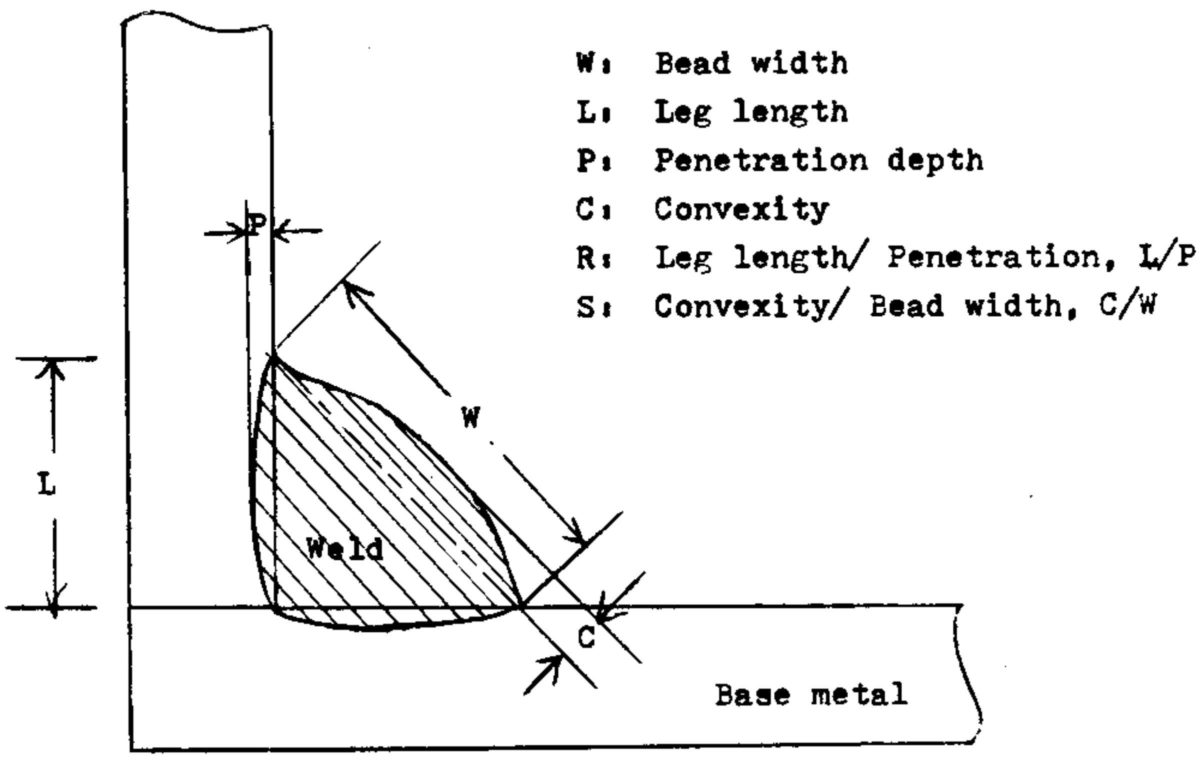


Fig. 5-8 Definitions of symbols for weld shape factors

Table 5-5 Weld appearances and shape factors for the welds made by different types of electrode and process.

Process	Type of electrode	Type of joint	Welding position	Weld appearance			Weld shape					
				Under-cut	Smooth-ness	Regu-larity	Bead width (W,mm)	Leg length (L,mm)	Convex-ity (C,mm)	Pene-tra-tion (P,mm)	L/P (R)	C/W (S)
Shielded metal-arc process	S1-d	Tee	Downhand	no	good	good	7.0	5.0	1.0	1.5	3.3	0.14
	S1-d	Butt	Downhand	no	good	good	—	—	—	—	—	—
	S1-e	Tee	Downhand	no	good	good	7.0	5.0	1.0	2.0	2.5	0.14
	S1-e	Butt	Downhand	no	fair	fair	—	—	—	—	—	—
	S2-d	Tee	Downhand	no	good	good	8.0	6.0	2.0	0.5	12.	0.25
	S2-d	Butt	Downhand	slight	poor	severe	—	—	—	—	—	—
	S2-e	Tee	Downhand	slight	severe	severe	9.0	7.0	0.2	0.5	14.	0.02
	S2-e	Butt	Downhand	slight	severe	severe	—	—	—	—	—	—
	N	Tee	Downhand	no	good	good	6.0	5.0	0.0	1.0	5.0	0.00
	N	Butt	Downhand	no	good	fair	—	—	—	—	—	—
	A	Tee	Downhand	severe	fair	fair	8.0	6.0	1.5	1.2	5.0	0.19
	S1-d	Butt	Downhand (air weld)	no	good	good	—	—	—	—	—	—
	S1-d	Tee	Vertical	no	good	good	—	—	—	—	—	—
	S1-d	Butt	Vertical	slight	fair	fair	—	—	—	—	—	—
	S1-e	Tee	Vertical	severe	severe	severe	—	—	—	—	—	—
	S1-e	Butt	Vertical	severe	severe	severe	—	—	—	—	—	—
	S2-d	Tee	Vertical	slight	fair	fair	8.0	6.0	0.0	1.5	4.0	0.0
	S2-d	Butt	Vertical	slight	fair	fair	—	—	—	—	—	—
	S2-e	Tee	Vertical	severe	severe	severe	10.	7.0	0.2	2.0* 0.2#	3.5 35.	0.02
	S2-e	Butt	Vertical	severe	severe	severe	—	—	—	—	—	—
Flux-shielded process	S1-d	Butt	Downhand	no	severe	severe	—	—	—	—	—	—

* Leg length on the vertical side.
# Leg length on the horizontal side.

AIR WELD

(a)

(b)

AIR WELD

Photo 22 X-ray radiographs of air welds made by electrode S1-d
(a) Tee joint, (b) Butt joint

3 A

(a)

(b)

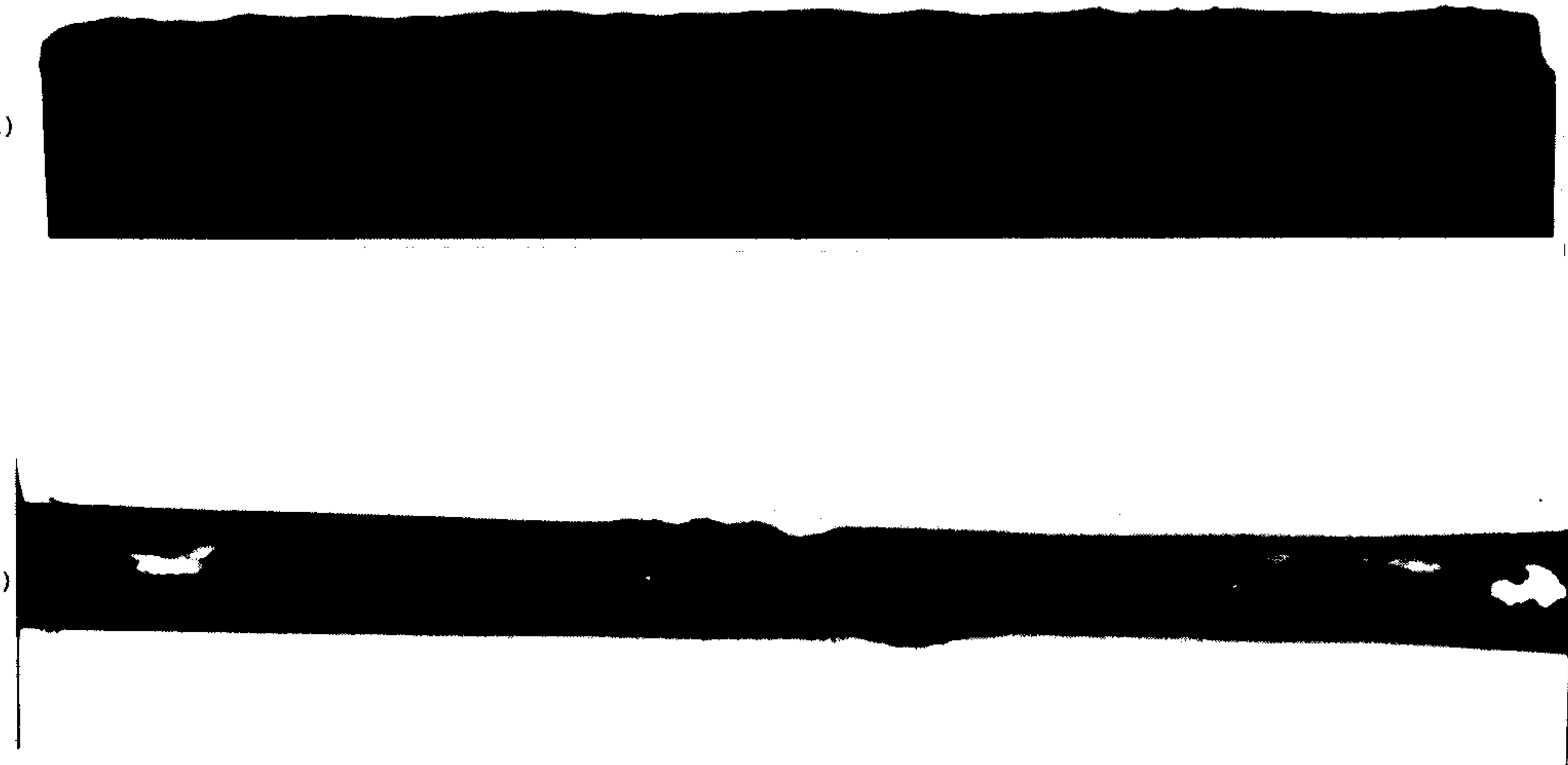


Photo 13 X-ray radiographs of underwater welds made by electrode S1-d
(a) Tee joint, (b) Butt joint

(a)

(b)

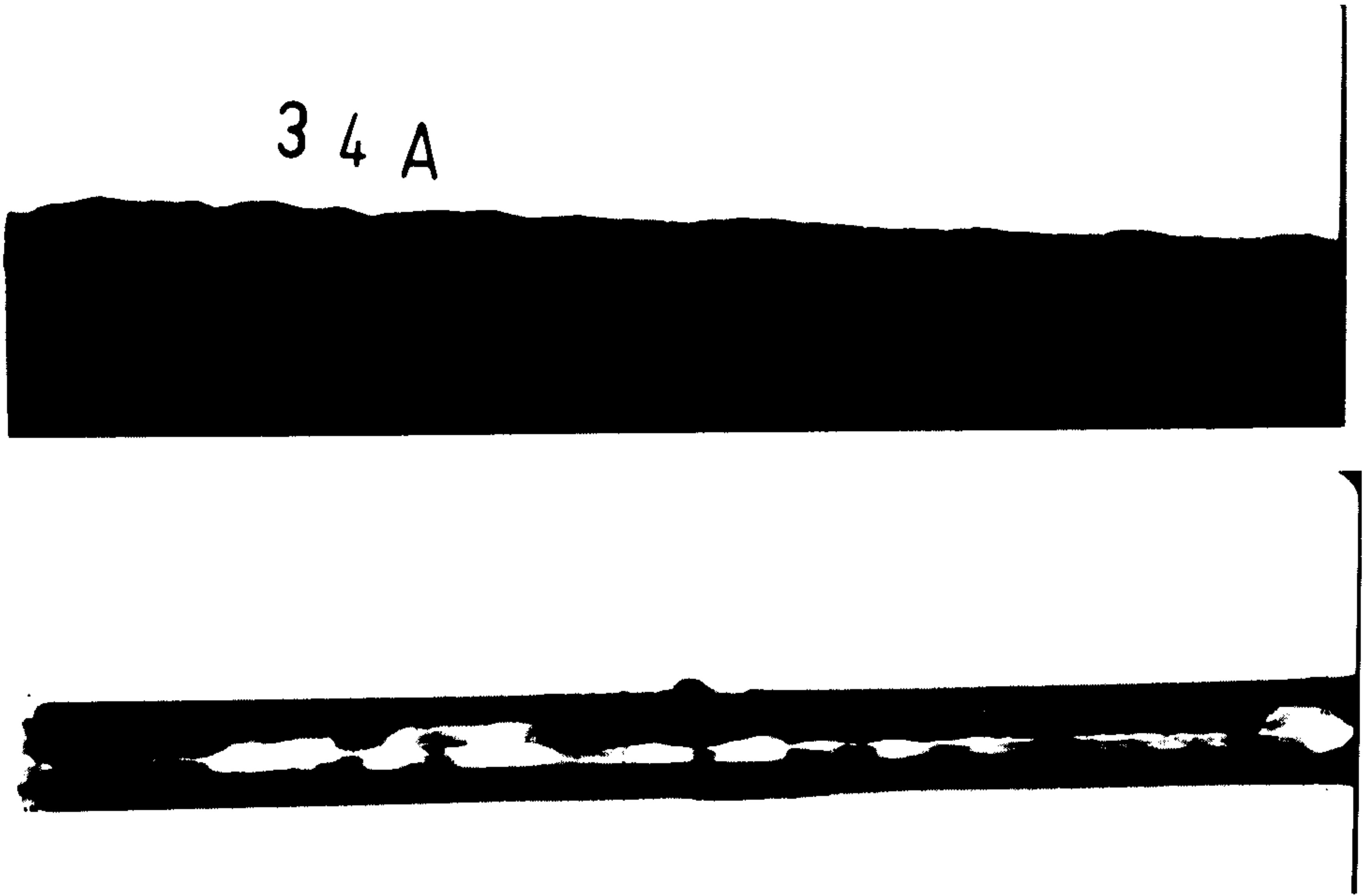


Photo 14 X-ray radiographs of underwater welds made by electrode Sl-e
(a) Tee joint, (b) Butt joint

and grey lines, round spots, and irregular areas.

Table 5-6 summarizes the weld defect data collected from the X-ray radiographs.

The joint penetration is inadequate in the butt welds made using electrodes S1-e, S2-d,and S2-e (photograph 13). Butt welds made using electrodes S1-d and N (photograph 14) give better results. Linear porosity continues to be a problem. Inadequate joint penetration is also present in the beginning and at the end of all of the welds.

Fillet welds made by electrodes S1-d and S1-e appear to be sound in photographs 13 and 14. Porosity and discontinuities are present in the rest of the fillet welds. Very porous weld beads were found in the welds made by austenitic electrode. A longitudinal surface crack along the center line was also found.

The effect of welding position on weld soundness was studied. The same electrodes (S1-d) were used for both of these welds; all the vertical welds have serious defects.

Welds made using the flux-shielded process are sound. The deposited metal laid on the side of the groove is due to misaligned electrode manipulation during welding.

It is very difficult to draw any conclusions about the multipass butt welds produced in this experiment. Porosity, slag inclusions, lack of fusion, lack of penetration and undercut were so severe that none of the welds can be classified as

Table 5-6 Summary of the severity of weld defects shown in the x-ray radiographs

Process	Type of electrode	Type of joint	Welding position	Single- or multi-pass	Porosity	Slag inclusions	under cut	Lack of fusion	Lack of penetration	Cracks
Shielded metal-arc process	S1-d	Tee	Downhand	single (air weld)	good	good	good	good	good	no
	S1-d	Butt	Downhand	single (air weld)	good	good	good	good	slight	no
	S1-d	Tee	Downhand	single	good	good	good	good	good	no
	S1-d	Butt	Downhand	single	poor	poor	poor	poor	poor	no
	S1-e	Tee	Downhand	single	good	good	good	good	good	no
	S1-e	Butt	Downhand	single	—	—	—	severe	severe	no
	S2-e	Tee	Downhand	single	poor	—	—	slight	—	yes
	S2-d	Butt	Downhand	single	severe	severe	severe	severe	severe	no
	N	Tee	Downhand	single	severe	good	good	good	good	no
	N	Butt	Downhand	single	fair	—	—	fair	fair	no
	A	Tee	Downhand	single	severe	—	—	good	good	severe
	S1-d	Butt	Vertical	single	severe	severe	severe	severe	severe	no
	S1-e	Tee	Vertical	single	severe	—	—	good	good	no
	S1-e	Butt	Vertical	single	severe	severe	severe	severe	severe	no
	S2-d	Tee	Vertical	single	severe	—	—	—	—	no
	S2-d	Butt	Vertical	single	severe	severe	severe	severe	severe	no
	S2-e	Tee	Vertical	single	severe	—	—	severe	—	yes
	S2-e	Butt	Vertical	single	fair	severe	severe	severe	severe	no
	S1-d	Butt	Downhand	multi	poor	fair	fair	severe	fair	no
	S2-d	Butt	Downhand	multi	severe	poor	poor	severe	poor	no
	S2-e	Butt	Downhand	multi	severe	severe	severe	severe	severe	no
	N	Butt	Downhand	multi	fair	fair	fair	fair	fair	no
Flux-shield process	S1-d	Butt	Downhand	single	good	good	good	good	good	no

acceptable. This may be cuased by not removing the slags deposited in previous passes, or by improprer preparations before laying subsequent beads. Electrodes S1-d and N did make relatively sound welds, however.

Photographs 15 through 18 are corss-sections of the multi-pass butt welds. The number of non-metallic inclusions entrapped during welding varied. Welds made by electrode N and by the flux-shileded process are relatively sound. Uneven bead contours are shown in the welds made by electrode S2-d and flux-shielded process. Cracks were initiated on the surface when using the flux-shielded process because of the excessive bead convexity.

Metallurgical Investigation. The photographs of micro-structures of two base plates used were also studied: Mild steel (ST-37) and medium high strength steel (ST-52). Mild steel was used to investigate how different flux coatings and waterproof materials affect the underwater operational (welding) characteristics and the weld quality.

HT-52 steel was used for the metallurgical investigation of different underwater (bead-on-plate) welding processes: Shielded metal-arc and flux-shielded metal-arc. This is discussed in the next section.

The microstructure and microhardness of the multipass butt welds were studied in these metallurgical investigations.

Photo 15

Photo 16

Photo 15 Macrostructure of underwater multi-pass butt weld made by electrode S1-d

Photo 16 Macrostructure of underwater multi-pass butt weld made by electrode S2-d

Photo 17

Photo 18

Photo 17 Macrostructure of underwater mutli-pass butt weld made by electrode N.

Photo 18 Macrostructure of underwater mutli-pass butt weld made by electrode S1-d, Flux-shielded process

(Microstructure.) Before examining the metallurgical structure at X 128 magnification, the specimens were cut from the multipass butt-welded samples and the polished surfaces etched with a 1% nital solution.

The directional dendrite (columnar structure) is the primary structure found in weld metals. Slag inclusions and porosity were severe.

Photographic study was done to find the degree of slag inclusion and porosity in the multipass welds made using four different electrodes and the flux-shielded process. No clear difference was found among these four welds.

(Microhardness.) A Turkon hardness tester was used to measure the microhadness of the multipass butt welds. The test was performed by applying a 500-gram load. It was measured as indicated in Figure 5-9. The data has been converted to Vickars hardness values (Diamond Pyramid, 10 kg).

Figure 5-10 shows the average Vickers hardness value measured in the base metal, the weld metal, and the heat affected zone.

Since medium high strength steel (ST-52) was used in the

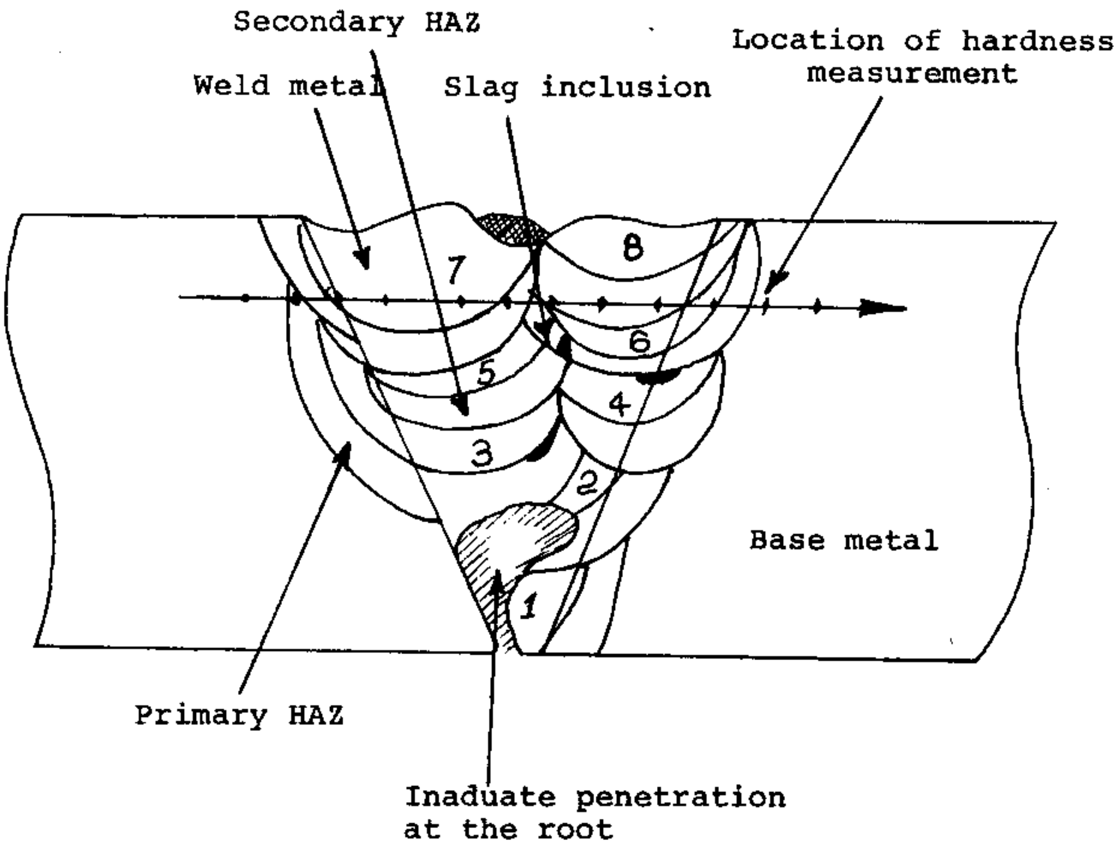


Figure 5-9 The Location of Microhardness Measurement for Underwater Multi-pass Butt Welds.

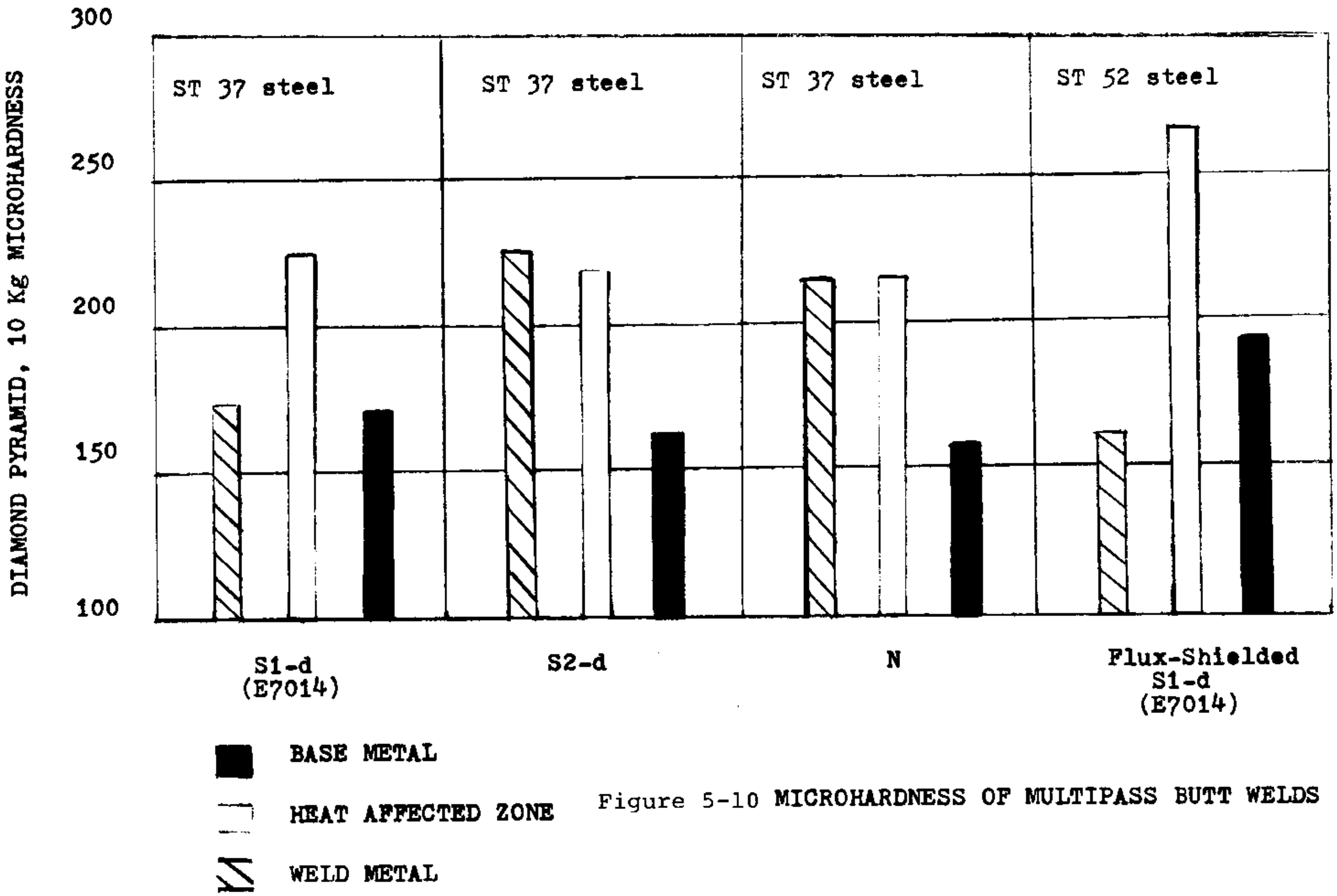


Figure 5-10 MICROHARDNESS OF MULTIPASS BUTT WELDS

flux-shielded welding process, the hardness was comparatively higher in the primary HAZ than in the other three welds. However, the weld metal was much less hard than in the other three, because the cooling rate was somewhat reduced.

The flux coatings do not have much effect on the hardness values of the welds. The hardness varies widely in the secondary HAZ in all three welds except in those welded using a flux-shielded process.

Mechanical Properties. The following mechanical properties of multipass welded joints were considered:

1. Tensile strength
2. Yield strength
3. Ductility (% elongation and % reduction of area)
4. Charpy V-notch toughness at 0° C

Table 5-7 summarizes the data obtained from multipass butt welds produced using different types of electrode.

In a butt joint, the weld metal should develop the same tensile properties as the base metal. In underwater welds, the tensile strength of the weld metal can be only 80% of the base metal, not including the weakening effects of severe slag inclusion and incomplete fusion. In our experimental data, even lower percentages were found due to the improper slag-removal procedures and inadequate preparation of the groove for the subsequent weld passes.

The charpy impact strength is low in all the welds. Welds

Table 5-7 The mechanical properties of multi-pass butt welds

Process & Electrode type	Tensile Strength (KSI)	Elongation (% in 2")	Reduction of Area (%)	Charpy Impact Strength (ft-lbs at $0^{o}C$)
SMA & S1-d (ST 37 steel)	42	15	30	WM 17(13 - 18) HAZ 20(16 - 24)
SMA & S2-d (ST 37 steel)	37	12	29	WM 21(20 - 22) HAZ 8(6 - 10)
SMA & N (ST 37 steel)	46	20	41	WM 16(12 - 20) HAZ 4
FSMA & S1-d (ST 52 steel)	20*	—	—	WM 9(4 - 14) HAZ 8(6 - 10)

SMA : Shielded Metal-Arc Process

FSMA: Flux-Shielded Metal-Arc Process

* The true strength(applied force devided by the area of welded metal) is 60 KSI

made using electrode S1-d had the highest value in the HAZ (20 ft-lbs at 0° C). Welds made using electrode N had a relatively higher tensile strength (46 KSI) but a poor charpy rating. Welds made using electrode N were relatively sound, had a higher tensile strength, but a low impact strength. This is a problem inherent in the use of titanium electrodes.

5.4 Metallurgical Evaluation of Underwater Welds.

In underwater welding, hydrogen induced cracking both in the weld metal and the HAZ is a serious problem. An underwater weld is rapidly quenched to a temperature where cold cracking takes place and hydrogen diffusion from the joint virtually ceases. The rapid cooling rate also produces microstructures susceptible to cracking even when mild steel is involved.

The M.I.T. flux-shielded process was designed to reduce the cooling rate and the hydrogen pick-up by a direct flux covering of the joint.

The objective of this study is to determine how much this process reduces the peak hardness and the diffusible hydrogen content evolved from the weld as compared to that with the underwater "wet" process.

Bead-on-plate welding was used in the evaluation. An air weld was also made for sake of comparison.

5.4.1 Experimental Procedure.

Bead-on-plate welds were made under the same conditions described in Section 5-2 using both the "wet" manual metal arc

process and the flux-shielded process, both in the flat position and both with type N electrodes.
The type N electrode was developed in Germany and the chemical composition of the coating flux has not been published.

In both cases, a nominal welding current setting of 200 amps and a nominal arc voltage of 25 volts were employed. An air weld was also made using the same welding conditions. The beads were laid on a 10 mm-thick ST-52 steel plate, the chemical composition and mechanical properties of which are shown in Table 5-8.

Direct current reverse polarity was employed. Specimens for metallurgical and hardness examinations were taken from the bead-on-plate welds. The distribution of inclusions in welds were also examined using an optical microscope.

5.4.2 Experimental Results.

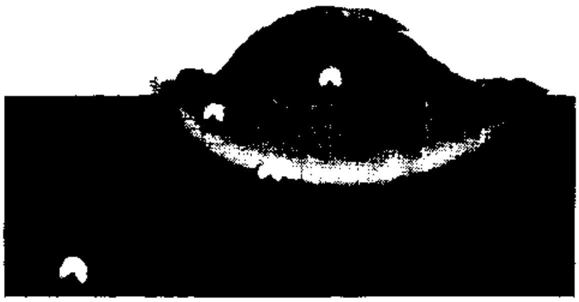
Bead Shapes of Welds. The bead shapes of three welds are shown in photograph 19. The bead shape of the flux shielded weld is similar to that of the "wet" weld and tends to be round.

The bead shape of the aire weld, on the other hand, is lense-like. The round marks in the welds are traces of the hardness measurements.

Table 5-9 shows the bead width, the penetration depth and the bead shape factor (bead width/penetration depth). In table 5-9, though the shape factor of flux-shielded weld is 8.8, slightly bigger than those of "wet" and air welds, there is no

Table 5-8 Chemical composition and mechanical properties of ST52 steel

C (%)	Si (%)	Mn (%)	P (%)	Yield Point kg/mm^2	UTS kg/mm^2	Elongation (%)
0.16-0.20	0.45-0.55	1.00-1.25	<0.06	>36	52-64	>22



UNDERWATER"wet"

FLUX-SHIELD

AIR

Photo 19 Bead shapes of underwater "wet," flux-shield and air welds, X 3.5

Table 5-9 Bead shapes of underwater "wet", FLUX-SHIELD and air welds (unit: mm)

WELDING PROCESS	BEAD WIDTH	PENETRATION DEPTH	SHAPE FACTOR
"WET"	11.4	1.42	8
FLUX-SHIELD	10	1.14	8.8
AIR	16.6	2.29	7.3

$$\text{Bead Shape Factor} = \frac{\text{Bead Width}}{\text{Penetration Depth}}$$

Table 5-10 Widths of columnar structures and dendrite arm spacings in weld metals of underwater "wet", FLUX-SHIELD and air welds (unit: μ)

WELDING PROCESS	WIDTH OF COLUMNAR STRUCTURE	DENDRITE ARM SPACING
"wet"	40-60	15-25
FLUX-SHIELD	60-95	15-25
Air	80-155	30-40

significant difference among them. The air weld has a wider bead and a deeper penetration than the underwater welds.

It can therefore be said that the flux-shielded weld was cooled in a manner similar to the "wet" weld.

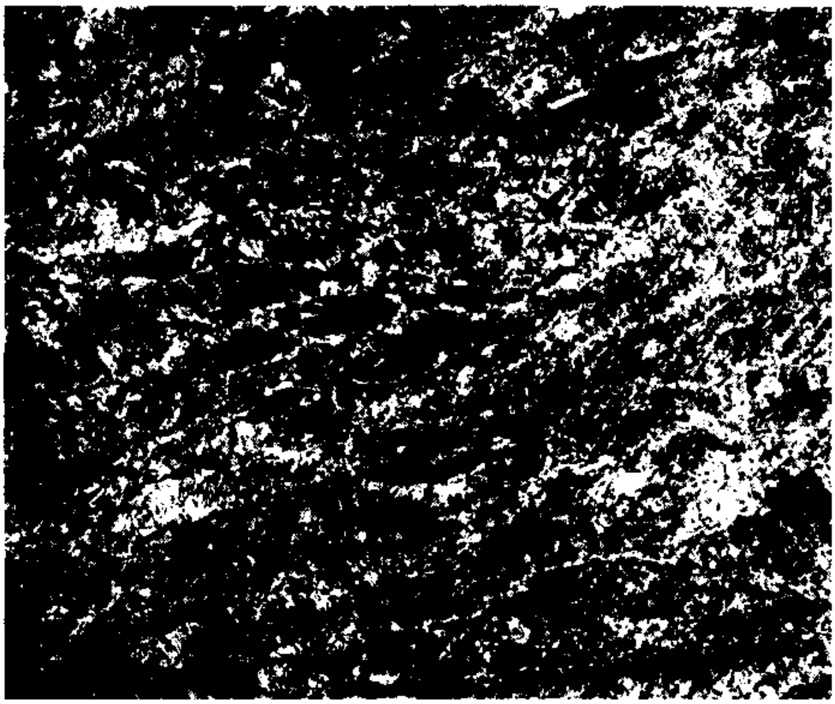
5.4.3 Microstructures of Welds

Through the photographic analysis of the welds (photograph 20), it was found that the microstructures of the weld metal in the "wet" weld shows narrower columnar widths and needle-like ferrites. In the HAZ, a martensite structure and small cracks under the bead can be seen. The cracks propagating along austenitic grain boundaries.

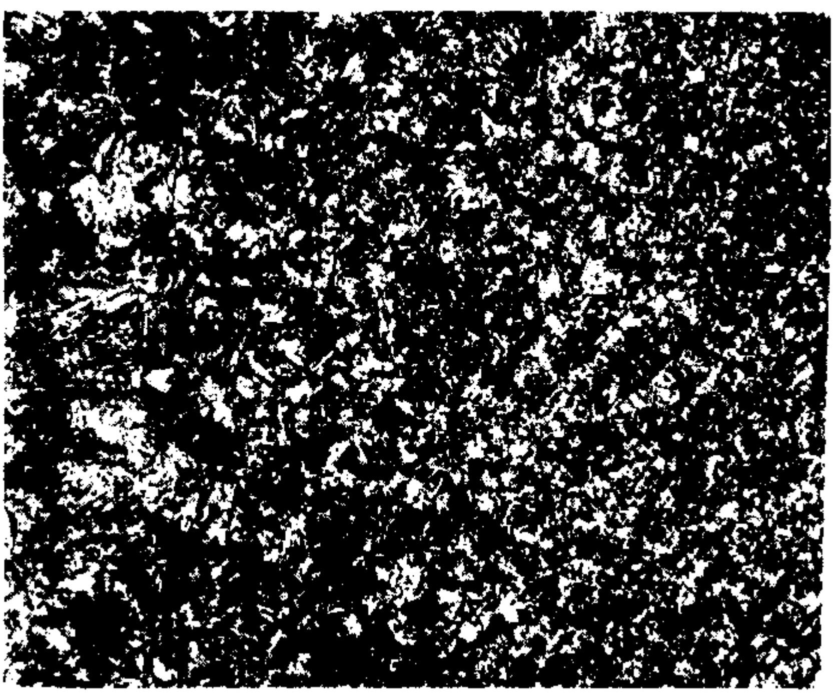
The microstructure of the weld metal of the flux-shielded weld shows irregular ferrites and the width of the columnar structures is slightly larger than the width of those in the "wet" weld. The HAZ has a martensitic structure and no observable cracks.

The air weld has wider columnar structures than the underwater weld and a bainitic structure can be seen in the coarse grain zone of the HAZ.

The widths of the columnar structures of "wet," flux-shielded and air welds are tabulated in Table 5-10 and increase in that order.



WELD METAL



HAZ

Photo 20 Microstructures of weld metal and HAZ in underwater "wet" weld, X 128

5.4.4 Solidification Structures.

Solidification structures of "wet" flux-shielded and air welds are shown in photograph 21. Columnar dendrite structures can be seen in every weld. The primary dendrite arm spacing in the air weld is apparently wider than that in the underwater welds. The primary dendrite arm spacing in the flux-shielded weld is almost as wide as that in the "wet" weld. This indicates that the solidification rate of the flux-shielded weld is approximately the same as that of the "wet" weld and higher than that of the air weld.

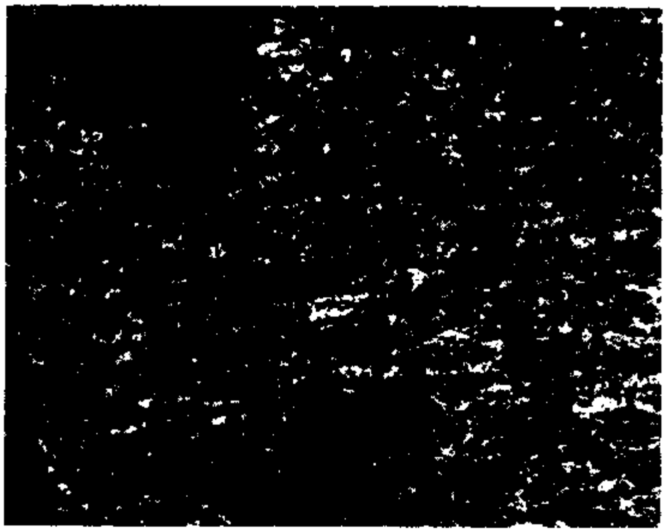
Table 5-10 compare the dendrite arm spacing of the welds. The dendrite arm spacing of the "wet" and flux-shielded welds is 15-25 μ, about one half of that of the air weld (30-40 μ).

From the above, it can be concluded that the flux-shielded weld and the "wet" weld have similar microstructures.

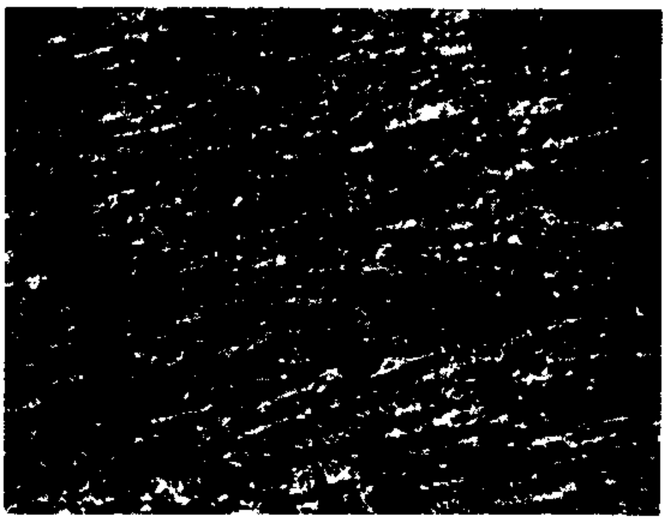
5.4.5 Hardness Distributions in Welds.

Hardness distributions in the "wet", flux-shielded and air welds are illustrated in Figure 5-11. The peak values of hardness in the HAZs of the "wet" and flux-shielded welds are about 430 and 375, respectively, exceeding 350, the critical value for weld integrity. On the other hand, the peak value in the air weld is about 250, significantly low.

But the peak hardness value of the flux-shielded weld is



UNDERWATER"wet"



FLUX-SHIELD

AIR

Photo 21 Solidification structures of underwater "wet," flux-shield and air welds, X 128

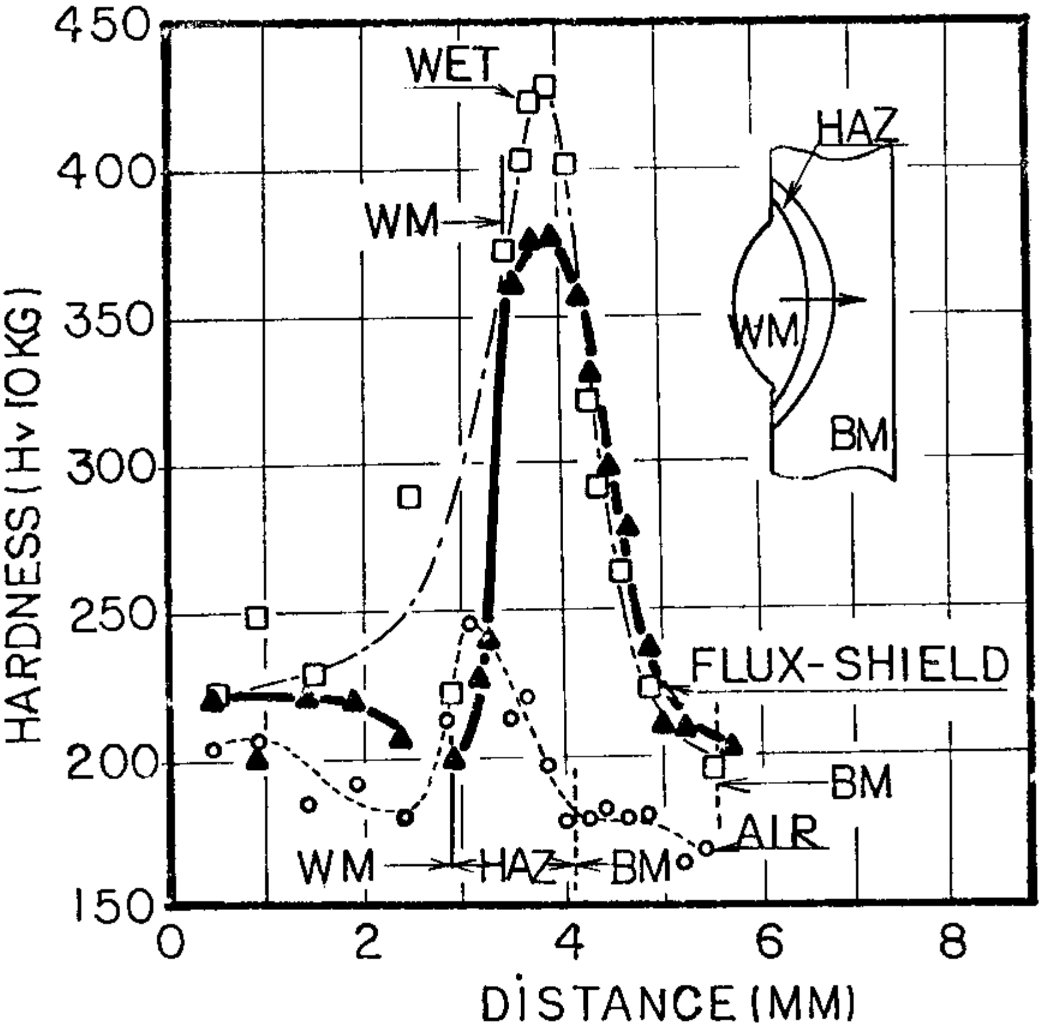


Figure 5-11 Hardness distributions in underwater "wet," flux-shield and air welds

50 less than that of the "wet" weld. This could be one of the reasons why the flux-shielded weld contains no crack.

5.4.6 Inclusion-Distributions in Welds.

The photographic study of the inclusion-distributions of the welds shows that the underwater welds contain many more large inclusions than the air weld. This is because the solidification rate of the underwater welds is so high that inclusions, mainly oxidation products, cannot float completely out of the weld pool.

5.4.7 Determination of Hydrogen Content Evolved from Welds.

In order to metallurgically evaluate flux-shielded underwater welds, it is important to measure the diffusible hydrogen content evolved from the weld.

CHAPTER 6: CONCLUSIONS

6.1 Experimental Conclusions on Underwater Stud Welding and Flux-Shielded Welding Processes.

This investigation was focused on underwater welding phenomena and most of the conclusions drawn in it concern that subject. It is hoped that our work will help further research and development efforts in underwater welding and this report and these conclusions are offered with that in mind.

Other researchers in other projects have come to many of the same experimental conclusions as we express in this report. Our own restatement of them adds to their credibility and helps to build basic knowledge about underwater welding phenomena. This body of knowledge and its systematic development and expansion is and will continue to be our primary concern.

The stud welding process, quick and simple in operation no matter what the welding environment, we felt to be readily adaptable to underwater joining. The new underwater flux-shielded technique, which (after proper refinement) will significantly improve underwater weld strength through a slowing of the quenching rate, we also felt to be an appropriate subject for investigation.

6.1.1 Experimental Conclusions About Stud Welding.

1. The capacitor discharge stud welding system is easily adaptable to an underwater welding process, when a small moveable chamber is utilized to exclude the water from the weld area.

2. A "dry" chamber underwater welding process produces better weld reliability and better quality welds than a "wet" underwater process under similar welding conditions.

3. Welding voltage has little effect on stud weld quality, but the greater heat input achieved with higher voltages produces stud welds with larger weld areas. Corresponding stud and base metal heat-affected zones are also larger for higher voltages.

4. Base plate preparation does not affect stud weld quality. This is difficult to explain since the stud penetration into the base plate is shallow. Stud welds made using the vertical welding position are not as reliable as those made using the more common flat welding position. This is probably due to gravity affecting the molten weld metal.

5. Wet underwater welding carried out in salt water appears to yield better quality stud welds, than when studs are welded in plain tap water. This is due to the higher electrical conductivity of the highly ionic salt solution.

6. Cooling rates obtained with a dry chamber underwater welding process are intermediate between the rapid quenching found in wet underwater welding and the slow cooling found with air welding. Even with studs welded in air the speed of the stud welding process produces a microstructure that is highly non-equilibrium in nature. The hardness values obtained in the hardness profiles can be related to the cooling rates experienced by the stud welded joints. A detailed study of such hardness

profiles will lead to a better prediction of resulting weld microstructure, and from there a prediction of the mechanical properties of the welded joint is possible.

7. As a diver's tool, the capacitor discharge stud welding tool appears to be better suited for precision placement and quick watertight application than the velocity power gun, which is already used in underwater joining. The perfect underwater tool is one that is simply constructed and easy to maintain, while being suited for quick manipulation in the harsh ocean environment when completing the joining process required of it.

8. Underwater welding, whether wet or dry, requires greater heat input into the weld to obtain a weld size similar to that found in air welding. Intuitively it is thought that dry chamber underwater welding demands less voltage than a wet underwater welding process to achieve the same weldment area and this has been proven with experimental evidence with the stud welding process.

6.1.2 Experimental Conclusions on Underwater Flux-Shielded Welding Process.

1. The cooling rate can be effectively reduced by insulating the face of the plate and using flux-shielding in the arc zone.

2. No shielding gas is needed. This may prove to be an advantage when using the flux-shielded process in deep-sea operations.

3. Although the hardness is reduced in the weld metal, certain samples indicate a hardness-increase in the HAZ. The

reason for this has not been determined.

4. The mechanical strength is increased when flux-shielding is used in the arc area. It has not been determined how the finely distributed inclusions found in the weld metal will affect the weld properties.

5. The operational features must be improved before the process can be used in practical applications.

6.1.2.1 Conclusions Drawn from the Baltic Sea Field Experiment.

The operational characteristics of the flux-shielded process have not been refined to the point where it is ready for practical application. In this manual process, the welding arc is buried in the flux so that the welder cannot see the arc, and this is its inherent problem. Occasionally the welder even finds he has put the bead in the wrong place. It is also difficult for the welder to maintain a constant arc length.

We were interested in the flux-shielded process because of its potential effect in reducing the hardness and improving the metallurgical structures of the weld metal and the HAZ. We deduced from our examinations of the microstructure, the micro-hardness, and the inclusion distribution that the flux covering was effective in reducing the quenching rate. But we also found little difference between flux-shielded welds and "wet" welds as far as bead shapes and solidification rates were concerned, indicating that the two were formed in a similar manner. This may have been because the flux became wet during the operation or because having a flux covering only near the weld was not sufficient to substantially reduce the cooling rate.

Hasui et al have reported that the use of water-glass shielding effectively reduces the peak hardness achieved in the HAZ of plasma welds (reduces it about 50--Hv 200g). This agrees with our observations.

Observable hydrogen cracks were not found in the flux-shielded weld, but were in the "wet" weld. It is not clear whether this was because the cooling rate was reduced or because the hydrogen content was reduced. In this regard, the following questions should be studied sometime in the near future:

1. How much softening can obtained when flux covering is used?

2. How much of a diffusible hydrogen content results when flux-covering is used?

6.1.2.2 The Effect of Coating Flux on Underwater Welding Performance and Weld Quality.

In air welding, weld metal deposited with a basic coating generally has less oxygen and thus better mechanical properties than that deposited with an acidic coating. With the basic electrode, however, it is difficult to make a smooth, nice-looking weld bead, and it is difficult to remove slag. On the other hand, the more fluid acidic flux covers the weld metal better. But the weld metal made by the acidic electrode tends to have poor notch toughness.

Almost all the electrodes used in underwater welding have acidic coatings in order to maintain a smooth welding arc. Electrode LH used in this experiment had a low-hydrogen coating, and it was extremely difficult to maintain a smooth arc. Electrodes S1 and N were acidic, resulting in a better weld appearance and extremely low impact values, which agrees with previous findings.

S2, a newly-developed electrode with a neutralized flux coating, readily absorbed moisture. With this electrode, both the kind of waterproofing used and the amount of time spent in the water were extremely important. Because of these two factors, the welding performance of this electrode was not consistant in the experiment. But we found that the impact strength of the weld obtained from an S2 electrode was double that of the weld from an N electrode.

A, an austenitic electrode, gave a smooth welding performance, but the bead was too porous and longitudinal cracks were observed on the bead surface.

6.1.3 Further Development of Underwater Stud Welding and Flux-Shielded Welding Processes.

1. Further investigation of the portable stud welding tool as a viable underwater welding technique is needed. The testing of larger studs is recommended, since the small 10-24 threaded studs are not of much commercial importance. The larger stud diameter is sure to require greater voltage when welded underwater and the implications of this need to be thoroughly examined.

2. The effects of pressure on the welding arc are still a subject for debate. Although some arc welding processes have been used in 400 to 500 feet of water, prediction of pressure-induced effects on the resulting underwater weldment is still a hit-or-miss proposition.

3. The development of accurate computer models of underwater welding and the weldment cooling rates will aid in the prediction of microstructural changes in the weld metal. Since the weld microstructure greatly affects the mechanical properties of a welded joint, the ability to predict what it will be is important in determining weld quality and reliability.

4. The development of a total, integrated deep-ocean weld-joining system is needed and the testing of feasible welding processes for such a system is strongly urged.

5. Better underwater welding methods and equipment need to be developed. These new systems are essential if the welding industry is to keep pace with the increase in repair and construction being done in the ocean, and to catch up with the ever-increasing depth-capabilities of divers.

6.2 The Formulation and Evaluation of a Conceptual Design for an Underwater Deep-Sea Welding System.

The following is a list of desirable attributes for an overall system. This list constitutes the conceptual design of a deep ocean stud welding system and serves as a model for evaluating the entire concept. The conceptual design also becomes the guideline for detailed equipment design if the project is deemed feasible.

1. The work vehicle employed in this system must be capable of a wide range of missions in addition to stud welding.

2. The total system should eventually be able to operate in depths of at least 5000 feet.

3. Safety and cost considerations favor an unmanned, remotely operated system.

4. A surface-connected cable must be used for the power source.

5. The capacity to rough-clean the weld area prior to welding must be provided.

6. Stable welding head placement for a period of 5 to 10 seconds must be assured.

7. The arc-welding process can be carried out in a wet environment without the complication of welding head enclosure or gas supply system, although a dry arc-area environment would improve the weld quality somewhat.

8. The stud welding gun must be capable of automatic reloading or must employ multiple welding heads.

The same conceptual design can be applied to the flux-shielded underwater welding process. In addition, the process should be automated and operable by remote control when used in deep-water applications. One necessary part of this system would be an automatic-reloading capability for the flux cartridges.

In the evaluation of this conceptual design, two major limitations are of prime importance:

1. It is not known if an electric arc can be used at depths as great as 5000 feet. Studies of the effects of pressure on a welding arc have been confined to relatively modest pressures, equivalent to several hundred feet at most. High pressure studies must be undertaken before stud welding or flux-shielded welding can be considered condidates for deep ocean application. Since most of the salvage work anticipated in the near future will involve ferrous metals, development of flux tips for studs and flux coverage for arc shielding used in a high pressure environment is another area requiring research.

2. The requirement for a surface supplied power source places the underwater welding processes at a disadvantage when they are compared with the self-contained devices. This means the processes can be used in surface-tethered diving systems only, and that they cannot be used with most manned submersibles. Whether or not this restriction is significant depends upon the demands the overall salvage operation places on the work vehicle.

On the positive side, most of the diving requirements imposed in the conceptual design can be met by existing remotely-operated recovery vehicles (such as the U.S. Navy's CURV III) with only relatively minor modification.

In summary, both the stud welding and the flux-shielded welding processes require an extensive developmental effort before they can become operational. Even then, the stud welding will be somewhat limited by the large pulse of electrical power it demends. The advantages that stud welding offers over the existing velocity power tool are, at present, not sufficient to justify the costs involved in developing the stud welding process for deep underwater us. The development of flux for underwater use is another area requiring research. This becomes even more important in flux-shielded welding processes.

6.3 Comparison of Field Practice and Laboratory Experiments.

Welding performed in a laboratory-simulated underwater environment differs from welding in an actual underwater environment. A comparison between the experimental simulation (see Figure 6-1) and the actual undersea process (see Chapter 5 for procedure) shows immediately that the laboratory welding procedure is simpler.

The sea environment imposes several problems not dealt with in the laboratory.

1. Electrode bottom time (electrode waterproofing and flux coating).

2. Diver stability.

3. Electrical safety.

4. Water temperature and pressure.

The two welding processes (shielded metal arc and flux-shielded metal arc) tested in the Baltic Sea as well as in the

WELDING ARRANGEMENT

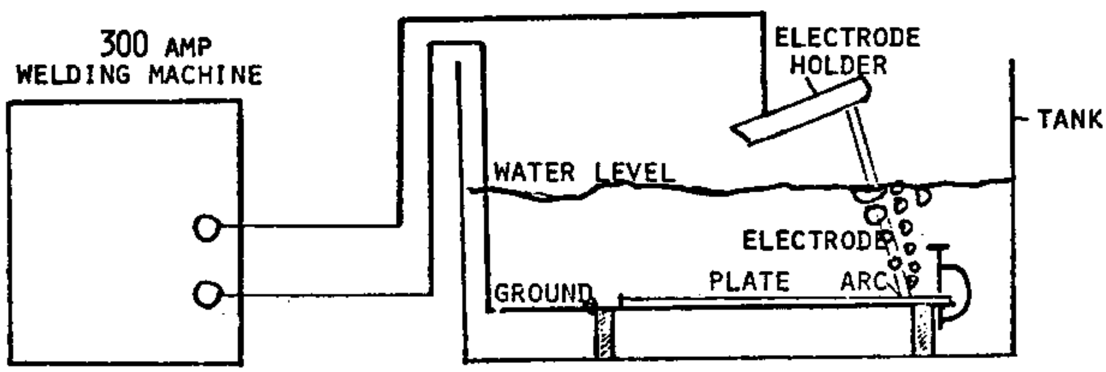


Figure 6-1 Experimental simulation of underwater welding arrangement.

laboratory allow us to compare laboratory experiments with field practice. The results obtained in this study have been summarized in the last few chapters, and the following conclusions have been reached:

6.3.1 The Effect of Waterproofing Materials on the Welding Performance in Actual Diving Conditions.

The effect of waterproofing materials on the weld quality is not clear. No substantial difference was observed when a stronger waterproofing coating (such as epoxy) was used with an E7014 electrode. The results were debatable when an epoxy coating was used with a neutral electrode.

According to the results, a neutral electrode with duralic waterproofing could do a satisfactory job if the electrode bottom time were less than ten minutes. After ten minutes of immersion in water, the flux coating would begin to peel off and leave a bare tip on the end of the electrode against the base plate during welding. Epoxy coating improves the strength of the flux coating, but may disturb the arc stability if it is too thick.

The waterproof coatings have the following effects on the arc stability:

1. If the waterproof coating does not melt fast enough during welding, a long, unstable arc results.

2. If the unmelted thick coating collapses during welding, the welding arc will be disturbed.

3. Bubble frequency is increased and the welding becomes less stable if the coating collapses.

4. If the shielding is not efficient, water will rush into the arc area and heat will be lost.

In order to develop a proper waterproof coating for underwater "wet" shielded metal-arc welding, the following must be taken into consideration.

1. The melting speed of the waterproofing coating that will provide a suitable arc protective cup at the electrode tip.

2. The amount of strength needed in the waterproof coating to increase the electrode bottom time and resist higher static water pressure.

3. The thickness of the waterproof coating may be critical.

Two other factors may improve the moisture-resisting capability of an underwater electrode. One is finer mesh size ingredients for the flux coating and the other is a stronger binder to hold the ingredients together.

6.3.2 Diver's Stability and Electrical Safety.

Manipulating the electrode in actual undersea diving conditions is different from doing it in a small laboratory tank. The welder/diver is afloat in the undersea environment and cannot resist reaction forces caused either by the arc force or by the forces needed to maintain a constant arc length. A downward force is required to push the electrode toward the base plate and to keep a constant arc length during welding.

Using an electrode with an epoxy waterproof coating resulted in strong reaction forces during welding in the Baltic Sea. The arc length increased (arc voltage) with the time (see Figure 5-12). This phenomenon was never encountered in laboratory welding since the welder was not afloat.

It may be worthwhile to measure the minimum forces acting on the electrode required to keep a constant arc length during underwater welding.

According to the U.S. underwater welding and diving regulations, many precautions must be taken to protect personnel from electrical shock. The use of a positive-operating disconnecting safety switch in the welding circuit is mandatory. Knife switches are the only disconnecting switches approved for use. We did not take these precautions in our experiments, resulting in some degree of danger for our welder/diver when he was in a "wet" condition.

6.3.3. The Effect of Water Temperature and Pressure on Welding.

The working temperature at the site averaged 6 to 7°C. This was another striking difference between the laboratory study and the field project. The effect of that temperature on the welding process has not yet been determined. Yet another subject on our agenda will have to be how low temperature affects arc mode and heat distribution in underwater welding. The working depth was 12.5 meters, and pressure effects were considered minor.

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APPENDIX A

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APPENDIX B

UNITED STATES PATENT ON UNDERWATER STUD WELDING GUN INVENTED BY PROF. K. MASUBUCHI AND DR. M. KUTSUNA

United States Patent [19]

Masubuchi et al.

[11] **3,989,920**

[45] **Nov. 2, 1976**

[54] **UNDERWATER STUD WELDING GUN**

[75] Inventors: **Koichi Masubuchi**, Arlington, Mass.; **Muneharu Kutsuna**, Takarazuka, Japan

[73] Assignee: **Massachusetts Institute of Technology**, Cambridge, Mass.

[22] Filed: **May 15, 1975**

[21] Appl. No.: **577,582**

[52] **U.S. Cl.** .... **219/98; 61/69 A;** 219/72; 219/99

[51] **Int. Cl.[2]** **B23K 9/20; B23K 11/04**

[58] **Field of Search** .... 61/69 R, 69 A; 219/74, 219/72, 98, 99

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Primary Examiner—J. V. Truhe

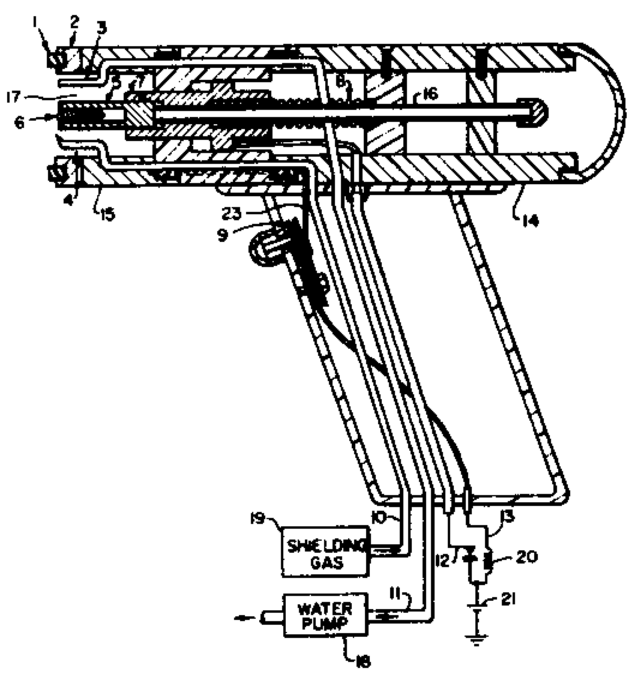
Assistant Examiner—N. D. Herkamp

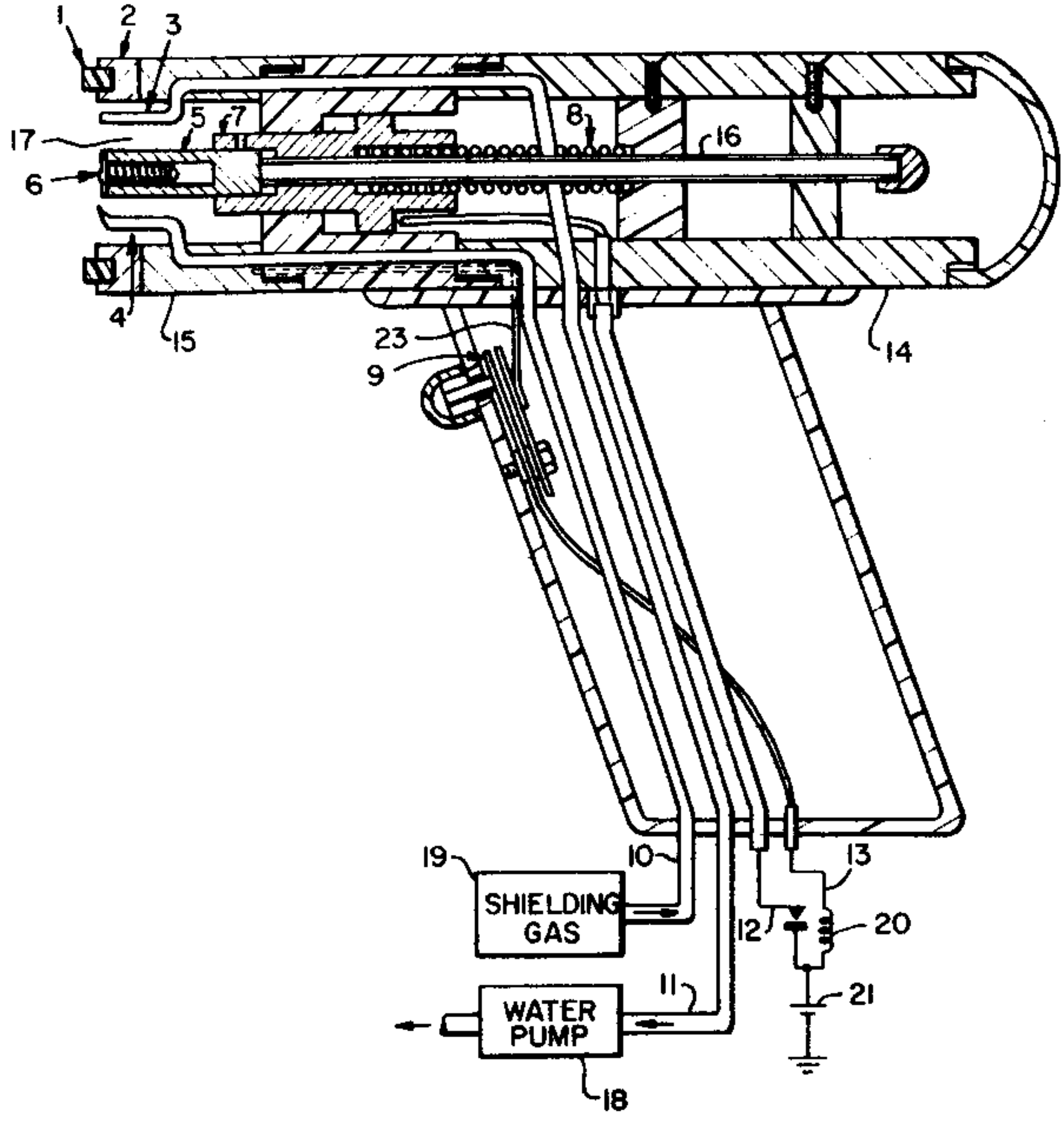
Attorney, Agent, or Firm—Arthur A. Smith, Jr.; Martin M. Santa; Robert Shaw

[57] **ABSTRACT**

A conventional stud-welding gun has been modified to allow it to be used for welding under water. The stud is contained within a water-tight enclosure formed at the end of the gun by pressing the seal at the end against the object to which the stud is to be welded. A water pump evacuates the enclosure and a stream of inert gas is provided to expel water and dry the region where the weld is to occur.

3 Claims, 1 Drawing Figure

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UNDERWATER STUD WELDING GUN

The Government has rights in this invention pursuant to Sea Grant No. 04-4-158 awarded by the National Oceanic and Atmospheric Administration in the U.S. Department of Commerce.

The general purpose of this invention is to provide a stud-welding device which can be used quickly and safely under water to join metals by means of a local pumping system with appropriate sealing materials and a clamping magnet.

The former underwater joining processes are classified as dry chamber underwater arc welding processes and wet underwater arc welding processes. These methods, however, cannot be used to join metals in the deep sea. Furthermore, the properties of welds obtained in shallow sea are not always sound. For instance, in wet underwater welding processes used at the depth that a diver can go down, the moisture surrounding the arc goes into the weld to stay and a brittleness of weldments occur.

On the other hand, in the prior-art dry chamber underwater welding processes, a large chamber is sunk; and high pressure argon or helium gas is used to obtain a dry space under the water. In this way a good weldment is obtained because the water near the point to be welded is removed. However, this facility is not feasible for use in the deep sea, because a man must dive into the dry chamber to weld. Moreover, there is no satisfactory sealing system.

It is therefore an object of the present invention to provide a new, small underwater stud-welding gun as shown in the FIGURE. By means of this gun, the inventors have made it possible to pump out the water near the welded point and to dry up the welded surface by fitting a gas nozzle near the welding chip.

With the invention of the new underwater stud-welding gun, a new technique for welding a bolt within one minute has been developed for use at deep sea levels (up to a depth of approximately 5,000 feet). This new underwater stud-welding gun can be affixed to the manipulator of very deep marine vehicles thus making possible the welding of metals at deep sea level.

The FIGURE shows a cross-sectional view of the welding gun of this invention.

DETAILED DESCRIPTION OF THE INVENTION

The preferred embodiment of the invention utilizes a modified form of a conventional stud-welding gun, as for example, a "Nelson" stud-welder. The conventional stud-welder comprises a housing **14** of plastic or similar electrically-insulating, impact-resistant material having at one end a hollow, metallic cylinder **15**. The stud **6** to be welded to a plate (not shown) is slidably contained within metallic tip **5**. The tip **5** is mounted in metallic tip holder **7** which is attached to guide rod **16**. Spring **8** mounted along rod **16** provides a compression force on stud **6** when the stud **6** is pressed against the surface to which it is to be welded.

The cylindrical end **15** has been modified to include a cylindrical magnet **2** attached to it in order to provide a magnetic attraction force to the metal to which the stud **6** is to be welded. A resilient sealing material, such as rubber, synthetic rubber or deformable plastic, is inserted in a cylindrical groove in the magnet **2**. The stud **6** extends out of the enclosure or cavity **17** formed by magnet **2** and end **15** before spring **8** is compressed. The FIGURE shows stud **6** in the position that it will be in when welding takes place. The mechanical contact of magnet **2** with the sheet to be welded provides a stop which determines the maximum movement of the stud **6** and thereby the maximum compression of spring **8**. The seal **1** is compressed to provide a watertight chamber **17** when the stud **6** is pressed against the sheet.

A nozzle **3** contained in chamber **17** drains water from the sealed enclosure **17** through the action of water pump **18** to which it is connected by tube **11**. A nozzle **4** has its open end located in proximity to the end of stud **6**, when stud **6** is in the position shown in the FIGURE. A shielding gas, of argon or similar inert gas, provided by source **19**, flows through tube **10** and nozzle **4** to expel any water from the space between the welding surface of stud **6** and the sheet to which it is to be welded and to dry this space.

Welding is accomplished as in the conventional stud-welding gun by closing switch **9** of wire **13**. This switch **9** activates a control circuit, shown as relay **20**, by energizing the coil of the relay **20** through an electrical power source **21**. The high-current-capacity contacts of relay **20** provide the welding current from source **21** through wire **12** to stud **6**. The sheet to which the stud is to be welded is connected to the ground terminal of power source **21**. Switch **9**, as shown, is connected to the metallic cylindrical end **15** and magnet **4** by wire **23**. Therefore, the magnet **2** must be in electrical contact with the sheet to be welded before the relay **20** can be activated and thus provides a safety feature.

Although the preferred embodiment of the invention has employed a magnet **2** to assist the operator in holding the end of the gun in contact with the sheet to be welded, it is apparent that the magnet **2** is not absolutely necessary. If magnet **2** is not used, the cylinder **15** would be longitudinally extended so that it occupied the region of the magnet **2**. Other variations of this invention will be apparent to those skilled in the art without departing from the scope of this invention.

What is claimed is:

1. An underwater stud-welding gun comprising
   - a stud-welding gun having a cylindrical end enclosure containing a stud-holding tip,
   - a resilient sealing member attached to the end of said cylindrical enclosure and extending along the circumference of said cylindrical enclosure,
   - means for removing water from said cylindrical enclosure when said sealing member is pressed against a welding surface thereby forming a watertight sealed cylindrical enclosure,
   - means for providing a flow of inert gas in the space between the end of the stud-holding tip and said surface to remove any remaining water from said space.

2. The stud-welding gun of claim 1, comprising, in addition,
   - a magnetic member attached to the end of said cylindrical enclosure to provide an attraction force between said cylindrical enclosure and said welding surface, said force acting to compress said sealing member and thereby assist in providing the sealing of said cylindrical enclosure.

3. The apparatus of claim 1 wherein said inert gas is argon.

* * * * *

APPENDIX C

CALCULATION OF COST VS. DEPTH RELATIONS FOR DIVING SYSTEMS

Welding Costs for Conventional Surface Diving [44]

depth	bottom hrs. / man day	Daily Costs: salary [a]	depth bonus [b]	support [c]	DDC [d]	HeO_2 [e]	cost / bottom hr.
33 ft.	7 hr.	$ 2000	---	$1500	---	---	$ 125
50	4	2000	---	1500	$ 75	---	223
70	3.5	2000	$ 20	1500	75	---	261
100	2.43	2000	50	1500	75	---	388
140	1.9	2000	130	1500	150	---	549
170	1.2	2000	210	1500	150	---	935
210	0.33	2000	340	1500	150	$2090	5,340

All costs apply to a team of 4 welder/divers and include contractor overhead where applicable.

Charges based on Gulf of Mexico rates.

(a) 500 $/day/welder

(b) Variable with depth

(c) Includes diving and welding support equipment (Diving barge additional if required)

(d) Decompression Chamber (DDC) required below 50 ft. depth

(e) HeO_2 breathing mixture required below 200 ft.

Welding Costs for Saturation Diving[44]

Total Job Costs

job duration	depth	time under[a] pressure	salary[b]	sat syst[c] and support	mixed[d] gas	mobilization	cost[e] / bottom hr.
1 day	200 ft.	3 days	$ 14,400	$ 45,000	$ 12,000	$ 16,000	$ 3,642
1	500	6	28,800	90,000	18,000	16,000	6,367
2	200	4	19,200	60,000	20,000	16,000	2,400
2	500	7	33,600	105,000	26,000	16,000	3,763
5	200	7	33,600	105,000	44,000	16,000	1,655
5	500	10	48,000	150,000	50,000	16,000	2,200
5	800	13	62,400	195,000	56,000	16,000	2,745
10	200	12	57,600	180,000	84,000	16,000	1,407
10	500	15	72,000	225,000	90,000	16,000	1,679
10	800	18	86,400	270,000	96,000	16,000	1,964

See footnotes next page

Welding Costs for Saturation Diving (footnotes)

All costs apply to a team of 4 welder/divers and include contractor overhead where applicable. Charges based on Gulf of Mexico rates.

(a) One day decompression required for each 100 feet of depth regardless of job duration

(b) 1200 $/day under pressure/diver

(c) 15,000 $/day includes saturation diving system and diving and welding support equipment (Diving barge additional if required)

(d) Mixed gas cost assumed 8,000 $/day for work, 2,000 $/day in chamber (Gas cost actually increases with depth but cost data unavailable)

(e) 6 working hours/bottom day/diver

Manned Submersible Deployment Costs[62]

Depth	Bottom hrs. / Day	Cost / Bottom hr.
1 ft.	10 hr.	$1,280
500	10	1.299
1,000	10	1,318
5,000	8	1,765
10,000	6	2,450
15,000	4	3,635
20,000	2	6,821

All costs apply to a manned, untethered submersible with an operating endurance of 12 hours.

Coat data:
1. Surface support 12,000 $/day
2. Salary and consumables 80 $/hour
3. Capital recovery factor is 37.05×10^{-3} $/hour/ft. (Reference 24 adjusted for 8% anuual inflation)

Remotely Operated Work Vehicle Deployment Costs[62]

Depth	Botton hr. / Day	Cost / Bottom hr.
1 ft.	24 hr.	$ 535
500	24	554
1,000	24	573
5,000	24	728
10,000	24	921
15,000	24	1,114
20,000	24	1,307

All costs apply to an unmanned, tethered remotely operated work vehicle with an operating endurance of several days.

Cost data:
1. Surface support 12,000 $/day
2. Salary and consumables 35 $/hr.
3. Capital recovery factor is 38.61×10^{-3} $/hour/ft. (Reference 24 adjusted for 8% annual inflation)