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HUMAN BIOENGINEERING OF DIVING EQUIPMENT

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For many years engineering considerations have taken precedence over human factors considerations in the design of diving equipment in both naval and commercial diving applications. Little systematic human engineering of diving gear has been accomplished, and it has only been in recent years that an analysis of human factors has truly begun. For the most part, the diver has in effect been asked to compensate for inadequacies in the design of diving equipment (Bachrach and Egstrom 1974).

During the past several years, there has been a collaborative program between the Behavioral Sciences Department of the Naval Medical Research Institute in Bethesda, Maryland, and the Performance Physiology Laboratory at the University of California at Los Angeles that has approached the problems of physiological and performance correlates of underwater activity from a systematic standpoint. The program has attempted to define and quantify the tasks involved in diver performance and the impact of equipment on performance, as well as the physiological cost of both work and equipment on the diver.

A project completed during this collaborative research program was the biomechanical analysis and comparison of two diving systems, (1) the Mark V hardhat (Fig. 1), the standard U.S. Navy surface-supplied system; and (2) the prototype Mark XII (Fig. 2), which is a possible replacement for

Figure 1. Mark V diving dress.

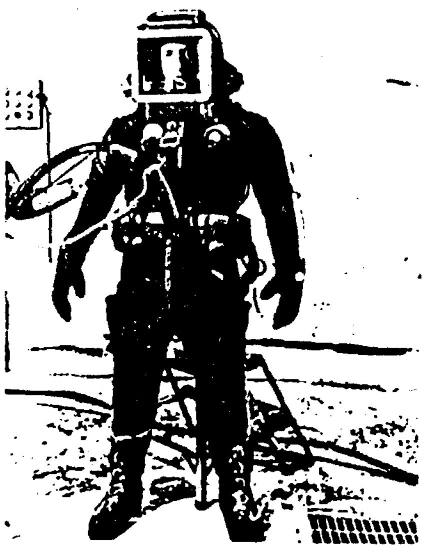

Figure 2. Mark XII diving dress.

the Mark V. One of the presumed advantages of the Mark XII in the original design was its greater flexibility over the Mark V diving dress. Accordingly, the initial approach to the comparison was a biomechanical analysis of the two systems using 14 measures based on dynamic anthropometry and drawn from the movements of divers performing underwater work. (Biomechanical-analysis technique involves functional measurements concerned with the quantitative assessment of joint angle changes and range of motion while an individual performs volitional movements). A swimsuit baseline was taken of a diver's movements, followed by a dry and wet analysis of each system. It was assumed that the diving system itself would impose certain external mechanical limitations on the normal internal mechanical stops that are expected in physical motion. The goal was to assess the effect of the suit on the free movement of the individual.

It was found that the prototype Mark XII allowed more movement for two important arm functions, shoulder joint abduction and shoulder joint flexion. Overall, in most of the 14 measures, the flexibility of the Mark XII was clearly demonstrated. The laboratory studies assessed the systems, dry and wet, in a tank; they were followed by an open-sea evaluation of the two diving suits in Hawaii in 60 feet of water using several performance tasks, including the ENERPAC cutting task (Liffick, Mittleman, and Quirk 1974); a self-contained load-handling lift pontoon (Condo and Armstrong 1973); and the UCLA Pipe Puzzle (Weltman, Egstrom, Willis, and Cuccaro 1971). The UCLA Pipe Puzzle is a standardized assembly task in which a team of divers put together a real-world pipe assembly. It is an effective measure of various types of performance.

To correlate the impact of the suits and the work task with physiological events, a telemetry system developed by Kanwisher, Lawson, and Strauss (1974) measured heart rate while a diver was performing in the water. Here again, the correlation of physiology and performance provides crucial information about what work the diver is doing, the physiological cost of this work, and the system and equipment he is using. These data are crucial for planning dives that maximize diver efficiency and safety. In one diver the Mark V diving system appeared to produce more physiological strain. This diver showed a heart rate peak of 184 beats a minute wearing a Mark V, which suggests marked effort, but his resting heart rate on the deck of the barge was around 80 beats per minute, and he never peaked higher than 152 in the Mark XII. It appears that the Mark V in this particular diver under these conditions required marked physiological effort, which suggests that one can quantify strain in the water, thereby providing more information about diver task and cost of physiology and equipment.

In 1973 the Undersea Medical Society sponsored a workshop on the Development of Standardized Assessment for Underwater Performance (Bachrach 1975b). From this discussion a working group emerged who sought to develop a task that could be used in open sea and wet pot and which would provide a diver-credible evaluative task allowing for a range of studies from fine coordination and manual dexterity to strength and endurance. The task developed to meet these criteria, known as SP^2, is a conceptual derivation of the UCLA pipe puzzle (mentioned earlier), a task which has proven to be an effective underwater-assessment technique. The SP^2 (Fig. 3) is smaller than the earlier pipe puzzle. It is made up of several assembly procedures that can be modified to fit a given situation. Each procedure can be performed in three work positions (i.e. standing, kneeling, and lying

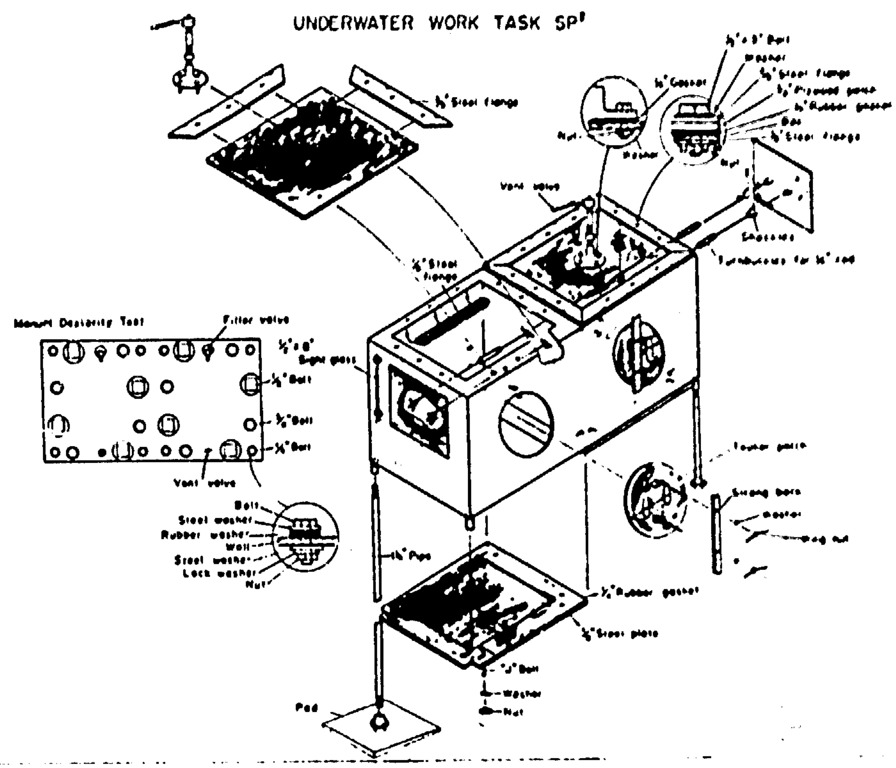

Figure 3. Diagram of SP^2, Underwater Performance Task.

down) and may be completed within 10 minutes. It allows for performance measures ranging from fine coordination to dynamic strength; thus, the human-engineering components in diving equipment can be assessed and correlated with physiological cost of work and impact of equipment under varying water and hyperbaric conditions.

Correlating such a standardized underwater-performance assessment task with human-engineering considerations and physiological correlates of diving work provides important considerations for improving diving performance in the future (Bachrach 1975a). An example of such application of bioengineering would be a system such as the one-atmosphere diving suit known as "JIM". We have proposed a human-engineering evaluation of JIM that would include the following possible techniques of evaluation. Using photogrammetric techniques, still photographs, and projectile motion, an analysis of actual movements of JIM in the water could be accomplished. In addition, there are three important human-factors considerations that might be developed. Through physiological monitoring, it would be possible to assess the general physiological status and the degree of physical exertion required of the operator during the various phases of training and performance evaluation. An examination of critical safety considerations would provide advanced input on possible hazardous conditions that might already exist or could conceivably occur. And last, an analysis of the biomechanical aspects of JIM could furnish information concerning the static and dynamic nature of the basic suit configuration.

Included in the physiological monitoring would be such parameters as heart rate, respiration rate, carbon dioxide production, oxygen consumption, and temperature differentials for various parameters including suit, skin, and ambient water. Among the safety considerations would be visual limitations (external and internal), kinesthetic feedback, and a review of emergency procedures. As for the biomechanical aspects (which would be a major study), we would include the following measures: strength, force application, manipulator dexterity, internal and external reach envelopes and operator anthropometry, dynamic anthropometry, and mobility on inclines, all of which are crucial to effective performance.

A final aspect of a proposed study of a one-atmosphere system such as JIM would be to assess its manipulative limitations with respect to the use of standard tools characteristic of inspection, construction, and salvage. The ability to use standard tools such as hydraulic and hand tools, the analysis of fine and gross motor task performance, and a study of endurance and fatigue, including load-carrying or handling capabilities and distance capabilities, would be important. Another consideration would be performance characteristics in zero visibility, which would be important in an assessment of a system such as JIM because of its visibility dependence. A related series of studies would be visual field evaluations.

We would hope to accomplish such a study on a system such as JIM. Whether it is actually accomplished or not, this proposal provides an example of the kinds of bioengineering considerations that we believe must be a part of any planning for the development and assessment of diving systems of the future. We cannot ignore human factors and physiology if we are to have an effective, safe, performing diver.

Human bioengineering should be applied not only to the diver's equipment, but to the hyperbaric research laboratory as well. As an example, construction of a Hyperbaric Research Facility (HRF) is in progress at the Naval Medical Research Institute at Bethesda, Maryland. This laboratory will be engaged in many aspects of hyperbaric research. The major tool for this research will be a man-rated hyperbaric chamber complex capable of simulating various diving conditions, with a possible maximum depth of 3300 fsw.

Ideally, a human-engineering program for a system the size of the HRF is initiated during the preliminary design stages of the project. A detailed human-engineering analysis should be made available to the system design engineers to guide them in selecting components to meet the specifications. Research has shown that man's performance efficiency is directly influenced by work-space design and layout. Since the control consoles would present the greatest concentration of information for the chamber operators (and the greatest potential for operator error), a human-engineering assessment of the control complex would be of high priority. The chamber complex also is a restricted area where small groups of men will be confined for periods of up to 90 days; in addition, these personnel will be required to perform several functions in a relatively short period of time in an abnormal environment. Thus, chamber-crew work and habitability during normal operation and during emergency conditions should receive thorough human-engineering consideration in the design of the complex.

Several sets of guidelines are offered which provide criteria for planning these all-important work areas. Design of work space has been investigated by McCormick (1970) and by VanCott and Kinkade (1972). Visual, auditory, and tactile presentation of information as it relates to the human-engineering design of man-machine communications has been investigated by Chapanis (1959, 1965) and VanCott and Kinkade (1972).

At the present time a human-engineering design analysis of the HRF complex is underway in the Behavioral Sciences Department. This analysis is being conducted using full-scale mock-ups of all chambers and of selected control consoles. The initial effort will be directed toward determining human-engineering limitations imposed by the present design, thus providing guidelines for use by the final design engineer. A secondary effort will provide options to be considered at a future date if changes are required.

The objective of the initial study will be to compare the present design with current U.S. Navy standards, which outline required minimum human-engineering criteria. The evaluative techniques during this phase of the study will be a combination of subjective comparisons by divers (as well as nondivers) and operational simulation using experienced divers as test subjects.

The need for this type of study of hyperbaric systems has existed for many years and has become readily apparent by the fact that every system constructed to date has required a major retrofit program after initial completion of construction. This study will be the first time that full-scale mock-ups have been used by the U.S. Navy as an evaluative tool for a hyperbaric facility.* They should prove to be invaluable during the final design phase of the present construction contract.

In this summary of possible applications of human-engineering methodologies to the design of diving equipment, we have touched upon three specific areas: (1) the assessment of a new prototype diving system, the Mark XII, compared with the standard U.S. Navy diving dress the Mark V; (2) a proposed assessment of a one-atmosphere diving system (briefly considered); and (3) a brief statement of work in progress on a human-factors assessment of a hyperbaric-chamber facility. These are examples of existing methodologies that have important application to diving systems. The orchestration of human engineering, performance assessment, and physiology appears to us to be crucial for truly effective operations and research.

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*) Such a program has been developed by the Defence and Civil Institute of Environmental Medicine, Toronto, Canada, for its chamber complex.

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For many years it has been the practice of most Navy and commercial diving groups to place less emphasis on human factors in the design of diving equipment than on engineering considerations. The importance of human factors in the design of such equipment is becoming recognized. Recently an assessment of diving equipment under consideration by the U.S. Navy was conducted by laboratories at the Behavioral Sciences Department, Bethesda, Md.; the Kinesiology Department, University of LB

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California at Los Angeles; and the U.S. Navy Experimental Diving Unit, Panama City, Fla. The systematic analysis was based on physiological factors and human-engineering considerations. In particular, comparative analysis of the standard U.S. Navy Mark V and the prototype Mark XII, a surface-supported dive system designed to replace the Mark V, showed that a comparison of the two systems, using biomechanical analysis and physiological assessment, can offer important leads to design and modification. Other possible applications of human-engineering methodologies to the design of diving equipment briefly discussed are: a proposed assessment of a one-atmosphere diving system; and work in progress on a human-factors assessment of a hyperbaric-chamber facility.