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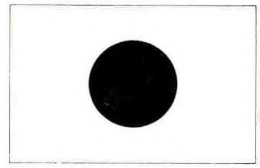
VOL. 4, NO. 1, 1986



Proceedings of the Eighth Meeting of the

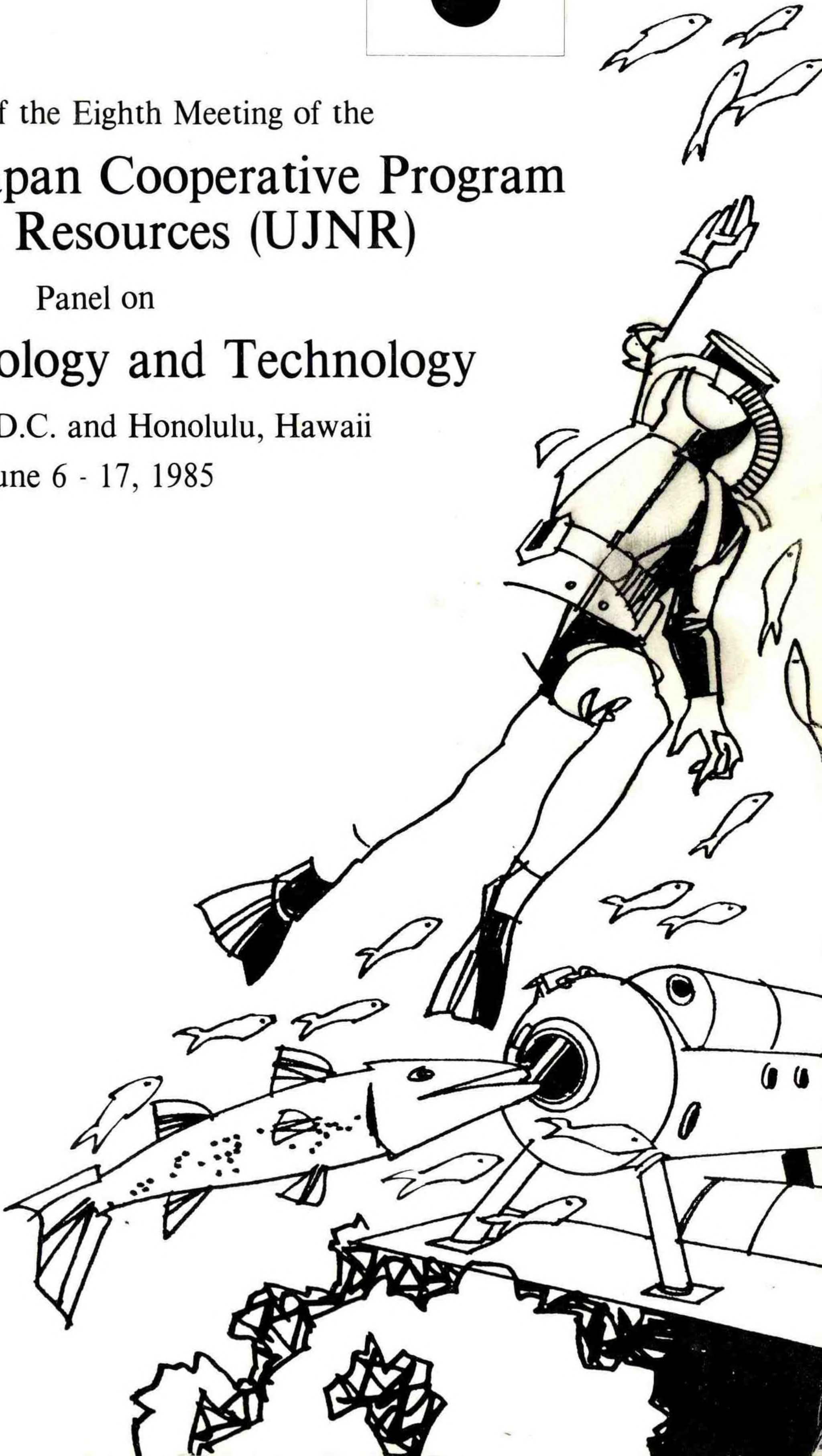
United States - Japan Cooperative Program in Natural Resources (UJNR)

Panel on

Diving Physiology and Technology

Washington, D.C. and Honolulu, Hawaii

June 6 - 17, 1985



U.S. DEPARTMENT
OF COMMERCE
National Oceanic and
Atmospheric Administration

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Malcolm Baldrige, Secretary

National Oceanic and Atmospheric Administration
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Oceanic and Atmospheric Research
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8th Joint Meeting of UJNR Panel on Diving Physiology and Technology
June 6-June 17, 1985

Conference Agenda

Locations:

June 6-8	Beaumont Conference Room Undersea Medical Society 9650 Rockville Pike Bethesda, Maryland 20814 (301) 530-9225
June 15-17	University of Hawaii Bio Med Building Room T 211 (808) 948-8827

Thursday
June 6

9:00-9:40

1) Opening of Conference

a)	William S. Busch	- Chairman of U.S. Panel
b)	Kenji Okamura	- Chairman (acting) of Japanese Delegation
c)	Kaname Ikeda	- Science Counselor, Embassy of Japan
d)	Robert Junghans	- Chief, NOAA International Affairs Oceanic and Atmospheric Research
d)	Walter Telesetsky	- U.S. Chairman, Marine Resources and Engineering Coordination Committee

2) Designation of Session Chairman and Co-chairman

3) Adoption of agenda

Session No. 1

9:40-10:00	C. Shilling	"Overview of Undersea Medical Society"
10:00-10:20	H. Nakayama	"SEADRAGON VI: A 7-Day Dry Saturation Dive at 31 ATA. I. Objectives, Design, and Scope"
10:20-10:40		Coffee Break

10:40-11:00	S. K. Hong	"Characteristics of Diuresis and Nocturia Observed During a 7-Day Exposure to 31 ATA (SEADRAGON VI)"
11:00-11:20	K. Shiraki	"SEADRAGON VI: A 7-Day Dry Saturation Dive at 31 ATA. IV. "Circadian Analysis of Body Temperature and Renal Function"
11:20-11:40	P. Pegnato	"Recent Developments in Equipment and Procedures for Diving in Waters Containing Hazardous Substances"
11:40-12:00	R. Vann	"Saturation Decompression With Nitrogen-Oxygen"

12:00-1:00 Lunch (UMS Dining Room)

1:00-4:00 Field Trip to David Taylor Model Basin

7:00-10:00 U.S. Reception Dinner at home of William S. Busch

Friday,
June 7

Session No. 2

9:00-9:20	J. Beckman	"Measurement and Pharmacological Modification of O_2 Free Radicals in CNS Hyperbaric Injury"
9:20-9:40	A. Aoki	"Future Plans for Diving Work Experiments at JAMSTEC"
9:40-10:00	W. Fife	"The Use of Nonexplosive Mixtures of Hydrogen and Oxygen for Deep Diving"
10:00-10:20	N. Naraki	"Fall in Deep Body Temperature Caused by Cold Gas Inhalation in Hyperbaric Helium-Oxygen Environments (16 and 31 BAR)"

10:20-10:40		Coffee Break
10:40-11:00	C. Lambertsen	"Predictive Studies V - Definition of Organ Oxygen Tolerance in Man"
11:00-11:20	M. Yamada	"TV Under Hyperbaric Conditions"
11:20-11:40	J. Miller	"The Diving Scientist and Undersea Technology From 1985-2000"
11:40-12:00	N. Miyata	"The Largest Semi-Submerged Catamaran Kaiyo"
12:00-1:00	Lunch (UMS Dining Room)	

Session No. 3

1:00-1:20	J. M. Wells	"Diving Operations in Heated/Contaminated Water"
1:20-1:40	JAMSTEC	"Development of a Japanese Deep Research Submersible of the 6000-Meter Class" by Deep Sea Technology Department
1:40-2:00	W. Schane	"Some Practical Lessons Learned From Shallow Water Saturations"
2:00-2:40	G. Butler	"Aspects of Training Commercial Divers and ROV Pilot/Technicians"
2:40-3:00		Coffee Break
3:00-3:20	A. Bachrach	"Biomechanical Assessment of MK12 Dive System: NOAA Modification for Anti-Contaminant Use in Contaminated Waters"
3:20-3:40	M. Hattori	"Small ROVs Developed by JAMSTEC"

3:40-4:00	L. Aaron	"Outfitting an Undersea Habitat"
4:00-4:20	C. Kubokawa	"Possible Future Joint Projects--U.S. and Japan"
4:20-4:40	R.W. Hamilton	"New Repetitive No-Stop Excursion Procedures for Nitrox Saturation Diving"

Saturday,
June 8

9:00-11:00 Field Trip to Naval Medical Research Institute

11:30-12:30 Lunch - Bethesda Officer's Club

6:00-10:00 U.S. Reception Dinner at home of Art Bachrach

Sunday,
June 9

Free Day, Washington, DC

Note: Members of Japanese delegation will fly to Duke University to tour the F. G. Hall Laboratory on June 10

Monday,
June 10

Transit to Long Beach to attend Undersea Medical Society meeting

Friday,
June 14

Transit to Honolulu, Hawaii

Saturday,
June 15

9:00-9:20 Opening of Second Half of Conference

a) Hosts - University of Hawaii
(Yu Chong Lin and Alex Malahoff)

Session No. 4

9:20-9:40	Yu-Chong Lin	"Reduced Orthostatic Tolerance in Hyperbaric Environments: Partial Results From a UJNR Cooperative Dive, SEADRAGON VI"
9:40-10:00	I. Nashimoto	"A Dive Profile Recording System"
10:00-10:20	R.W. Hamilton	"Special Problems of Treating Decompression Sickness in Habitat Diving"
10:20-10:40		Coffee Break
10:40-11:00	M. Kawashima	"Prevention of Dysbaric Osteonecrosis"
11:00-11:20	L. Sealey	"Interuterine Fetal Bends"
11:20-11:40	H. Yamaguchi	"The Newest Diver Tool System"
11:40-12:00	A. Malahoff	"Polymetallic Sulfides--A Renewable Marine Resource"
12:00-1:00	Lunch	
2:00-5:00	Field Trip to Hawaii Undersea Research Laboratory Facility at Makapuu Point	
5:00-7:00	U.S. Reception at Makai Pier	

Sunday, June 16 — Free day

6:00-10:00 U.S. Reception Dinner at home of Y.C. Lin

Monday,
June 17

Session No. 5

9:00-9:20	W. S. Busch	"Overview of NOAA's Undersea Projects"
9:20-9:40	M. Yamada	"Timekeeping Devices in Diving"
9:40-10:00	T. Laughlin	"Opportunities for Cooperation in Pacific Marine Sciences and Services"
10:00-10:20	N. Ito	"Marine Fouling Animals of the Japanese Coasts"
10:20-10:40		Coffee Break

12:30-1:30 Lunch at Hawaii Hyperbaric Treatment Center

1:30-4:00 Tour of Hyperbaric Treatment Center

Presentation: Frank Farm, "Diving and Decompression Sickness Treatment Practices Among Hawaii's Diving Fishermen"

Conference Wrap-up

Japanese Chairman: Kenji Okamura

U. S. Chairman: William S. Busch

End of Conference

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Joseph Beckman
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INTRODUCTORY REMARKS - U.S. CHAIRMAN

During the month of June 1985, the National Oceanic and Atmospheric Administration's Office of Undersea Research had the pleasure of hosting and sponsoring the Eighth Joint Meeting of the United States-Japan Cooperative Program in Natural Resources (UJNR) Panel on Diving Physiology and Technology. The meeting was divided into two sessions; the first was held June 6-8 in Washington, D.C., at the Undersea Medical Society, and the second convened in Hawaii at the University of Hawaii on June 15-17. The Japanese delegation also visited the F. G. Hall Laboratory at Duke University, at the invitation of Dr. Peter Bennett, who hosted the visit. Between the two UJNR sessions, both Japanese and U.S. participants attended the Undersea Medical Society's annual meeting in Long Beach, California.

A diverse and specialized cadre of people--scientists, physicians, engineers, administrators--attended each of the sessions, with 31 U.S. panel members and 13 Japanese panel members participating. The fact that such a large and impressive group came from Japan and that each of the U.S. participants--coming from all parts of the country--provided their own travel funds attests to the keen interest and recognized importance of the Diving Panel's activities and the focus and objectives of the UJNR itself. In total, 35 papers and presentations were given and five study tours were conducted.

Although the Panel's biennial joint meetings are important and productive, their primary function is to serve as a forum for reporting the activities supported by the Panel in the intervening period. In addition, the meetings provide an opportunity to discuss new topics and areas of interest to the participants. Perhaps most importantly, joint activities and programs are initiated and implemented by scientists and engineers from both countries, who work together on research topics of interest to both.

The Diving Physiology and Technology Panel has been very successful in accomplishing these purposes since its inception in 1971. Not only have all of the Panel's joint meetings been productive, but many joint programs have been carried out, such as the SEADRAGON series of hyperbaric experiments, the exchange of scientists and engineers working on numerous projects, the sharing of undersea research facilities, and the exchange of undersea technology, data, and information.

With the support of the impressive and highly enthusiastic members of both the U.S. and Japanese sides of the Panel, I am confident that the activities of the Diving Panel will be expanded to include more scientists working together, both on a one-to-one basis and at higher administrative levels, and more complex joint programs.

I would also like to take this opportunity to thank all of the persons in NOAA's Office of Undersea Research, specifically its Director, Mr. Elliott Finkle, for providing the support for the meeting here in Washington, and Mrs. Marcia Collie for doing the staff work required to implement this meeting, and Dr. Yu-Chong Lin for hosting the second session in Hawaii. I know I speak for everyone on the U.S. side of the Panel when I say we are looking forward to the future and to a very productive and active UJNR Diving Panel.

William S. Busch
U.S. Chairman, UJNR
Diving Physiology and Technology
Panel

THE LARGEST SEMI-SUBMERGED CATAMARAN KAIYO

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INTRODUCTION

In the field of ocean development as well as marine science and technology, there is great demand for stable platforms of relatively small size to support diving work and accurate surveying of the ocean floor.

The Semi-Submerged Catamaran (SSC) KAIYO (fig. 1) is a displacement-type vessel having a unique hull form that departs from that of the conventional mono-hull ships and catamarans. The SSC has two floaters consisting of torpedo-like submerged bodies connected to the above-water platform by streamlined struts. Because of its unique hull form, the SSC has many attractive advantages, such as relatively little movement, sustained speed in the seaway, and ample deck space for a relatively small-sized ship, which can't be achieved with a conventional mono-hull of equivalent displacement.

JAMSTEC has been promoting various kinds of research and development in marine science and technology under Japan's national policies involving the cooperation of public, academic, and private circles for the last 13 years; JAMSTEC decided to build

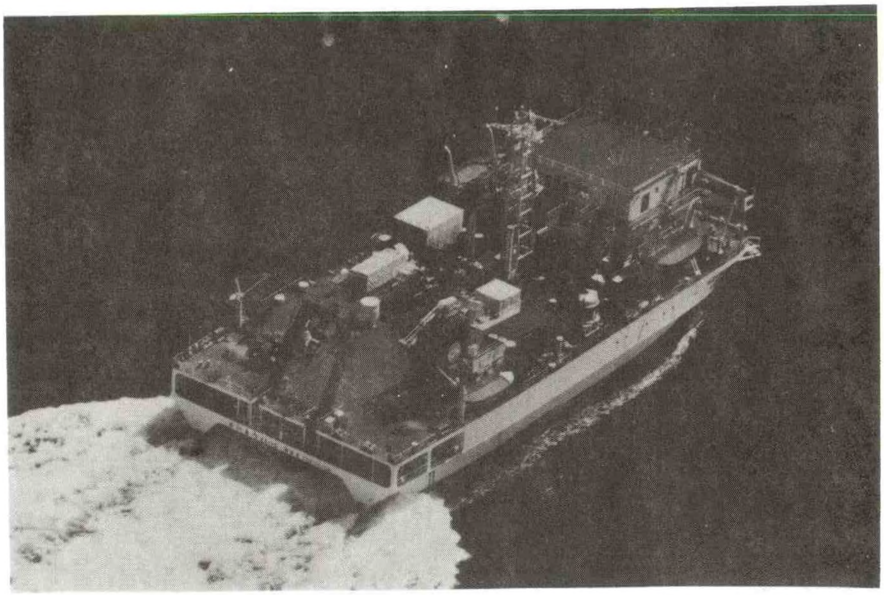


Figure 1.--KAIYO during sea trials

the SSC vessel for the purpose of supporting large-scale field experiments in these areas.

As far as deep diving technology is concerned, JAMSTEC successfully performed the SEATOPIA saturation dive experiments up to depths of 100 m in 1975 and to 31 ATA in a deep saturation dive simulation in 1979.

Construction work on the vessel started in September 1983 at the Mitsui Chiba Works. The vessel was completed in mid-October 1984 and delivered to JAMSTEC on May 31, 1985, after successful sea trials extending over half a year.

TECHNICAL FEATURES

As shown in figure 1, the vessel has various equipment on board to meet the wide range of requirements for a high performance multi-purpose support ship. JAMSTEC plans to use this support ship for various missions as follows:

(1) Field tests of diving work in depths up to 300 m;

(2) Deep ocean floor surveys and very fine-scale investigations of deep water;

(3) Hydrographic surveys of the sea bottom before diving and launching the submersible; and

(4) Training and education on board.

The following features of the SSC are very effective in achieving these goals.

LITTLE MOVEMENT EVEN IN ROUGH SEAS

The SSC is so stable in waves that researchers can make accurate measurements under good working conditions without seasickness. As a result, higher operating efficiency is expected.

WIDE WORKING DECK

In the case of mono-hulls, the width of the deck is restricted both from the resistance and ship motion points of view; the SSC has been designed with a large deck breadth, which provides a large open space for miscellaneous measuring equipment and container houses. In addition, the box-shaped upper structure is free from hydrodynamic effects and flexible deck arrangements will be possible.

GOOD STATION KEEPING

The dynamic positioning system (DPS) with which the vessel is equipped can keep horizontal displacement within a range of 5% of water depth even in rough seas. Where the water depth is less than 100 m, a four-point mooring system will be used.

LOW NOISE

Much consideration was given to factors such as flexible mounting and sound-proof insulation, to reduce noise radiation to the water to an acceptable noise level for underwater communication and acoustic navigation.

OUTLINE OF SSC KAIYO

The basic design concept was presented at the 11th meeting of the UJNR Marine Facilities Panel in 1982, and since then some modifications have been made during the detail design stage.

The following special attention was paid to the final General Arrangement Plan shown in figure 2.

(1) The center well in combination with an A-frame crane is designed so that launching and recovering the SDC, and putting it on the DDC, can be accomplished more easily.

(2) DDC units with a central control panel are provided slightly aft of the center well on the upper deck, where monitoring and communication can be done as well as in the central diving command room.

(3) Two sets of A-frame cranes and surface decompression chambers (SDC) are provided near the well and starboard side of the work deck. Umbilical cable winches with shock absorbers are also arranged to keep the cable in safe condition.

(4) A sea lift crane used to transfer the SDC and for miscellaneous jobs is arranged on the starboard side of the work deck.

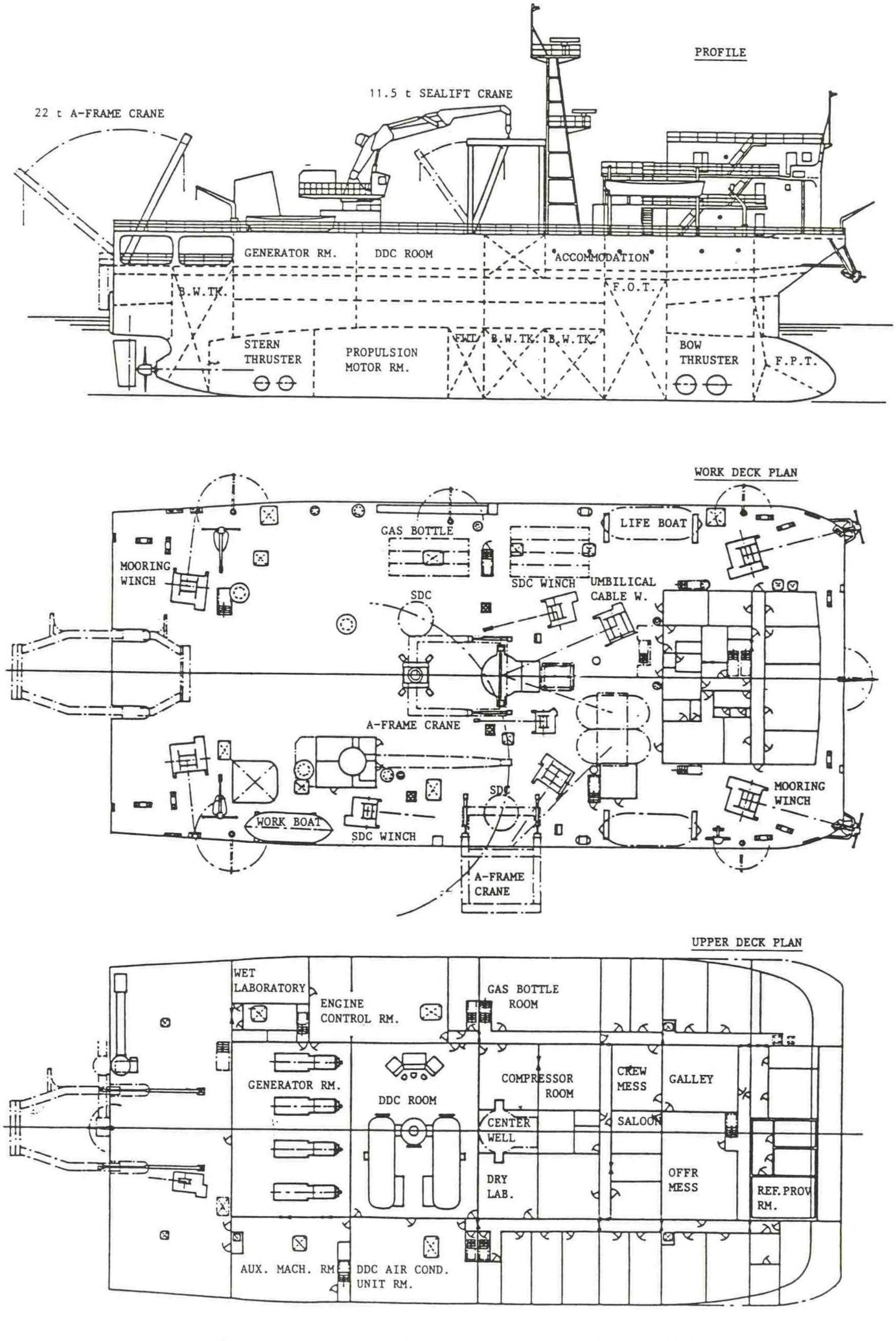


Figure 2.--General Arrangement Plan

(5) Four mooring winches are arranged at each corner on the work deck. This 4-point mooring system is used for station keeping at water depths less than 100 m.

(6) Accommodation space is arranged on the fore part of the upper and work deck so as to provide a spacious open working deck. The central diving command room and dynamic positioning control room are arranged on the aft part of the navigation room.

(7) Four diesel generator engines with a soft mounting device are so arranged on the aft part of the upper deck as to reduce the transmission of vibration and radiation noises into the water.

(8) Eight side thrusters of the controllable pitch propeller are provided on both port and starboard sides of the lower hull.

(9) Electronic equipment such as the microwave, hybrid navigation system (NNSS, DECCA, LORAN-C), meteorological observation system and so on are centralized on the starboard side of the navigation bridge deck.

The principal details can be seen below.

Length overall	61.55 m	Gross tonnage	2,849 t
Length (p.p.)	53.00 m	Service speed	13.25 kt
Breadth (mld)	28.00 m	Complement	69 persons
Depth (upper deck)	10.60 m	Main generator	1,350 kw x 4 sets
Depth (working deck)	13.30 m	Main propeller	CPP x 2 sets
Draft	6.30 m	Thruster	CPP x 8 sets

UNIQUE EQUIPMENT

SATURATED DEEP DIVING SYSTEM

The diving equipment consists of two SDC's, two DDC's, the transfer lock, environmental control units, and mointoring and control panels. The environmental conditions of the chamber can be automatically or manually controlled up to a water depth of 300 m at the central monitoring and control panels.

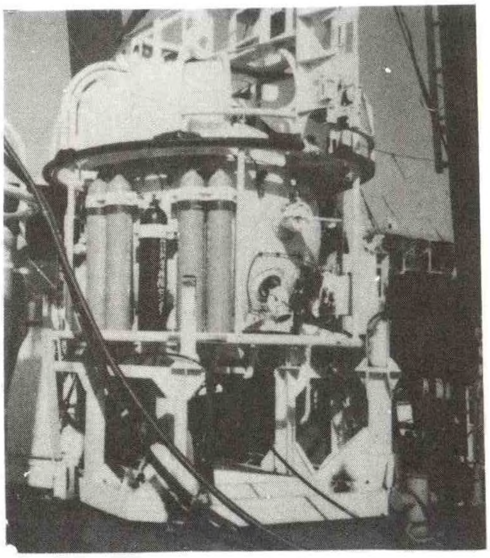
Figure 3 shows the SDC-DDC units and table 1 gives design details of these units, respectively. The chamber arrangement is designed so that a wide variety of research programs can be conducted with complete safety.

MULTI-NARROW BEAM ECHO SOUNDER

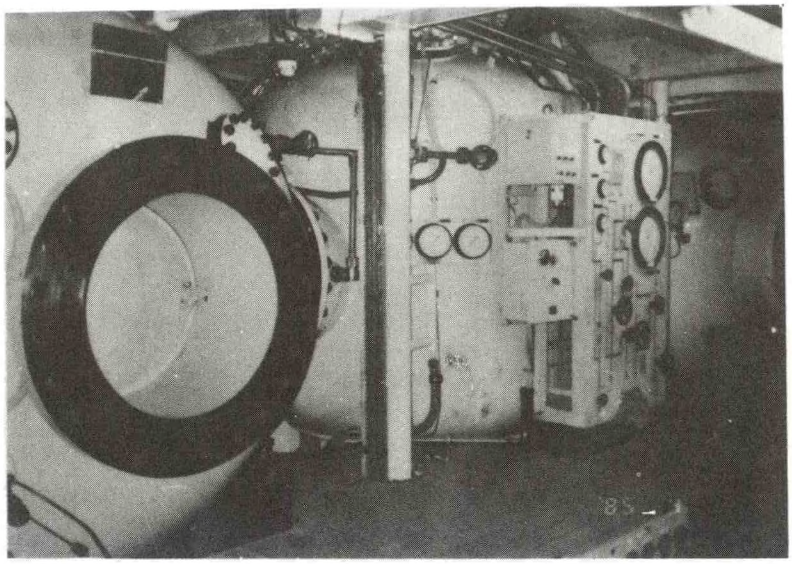
The narrow beam echo sounder is provided for underwater activities, and is used for the purpose of ocean floor surveys such as bathymetric surveys. This equipment can take an accurate measurement of depth distribution in the athwartship direction, ranging to approximately 70 percent of the vertical depth, by forming sixteen (16) echo beams from the projector array and hydrophone array mounted on the bottom of the lower hull. In addition, this device has excellent capability that processes sonar signals in almost real time and provides contour charts.

DYNAMIC POSITIONING SYSTEM (DPS)

Where the water depth is more than 100 m, the DPS is used to keep the ship's position and heading within a horizontal range of about 5 percent of the operating water depth. The system installed



Submersible decompression chamber



Deck decompression chamber

Figure 3.--SDC-DDC on board

Table 1.--Design details of the SDC and DDC

SDC	Type, Number	Spherical (1 set)	Cylindrical (1 set)
	Max. water depth	500 m (external press.) 300 m (internal press.)	300 m (external and internal press.)
	Capacity	3 persons	3 persons
	Dimension	abt. 2.2 m (inner dia.)	abt. 1.9 m (inner dia.) x 2.3 m (inner height)
DDC	Type, Number	Main, sub chamber (2 sets) Transfer lock (1 set)	
	Max. water depth	300 m (inner press.)	
	Capacity	6 persons per each	
	Dimension	Main, sub chamber: abt. 2.1 m x 7.5 m (inner length) Transfer lock: abt. 2.1 m x 2.4 m (inner height)	

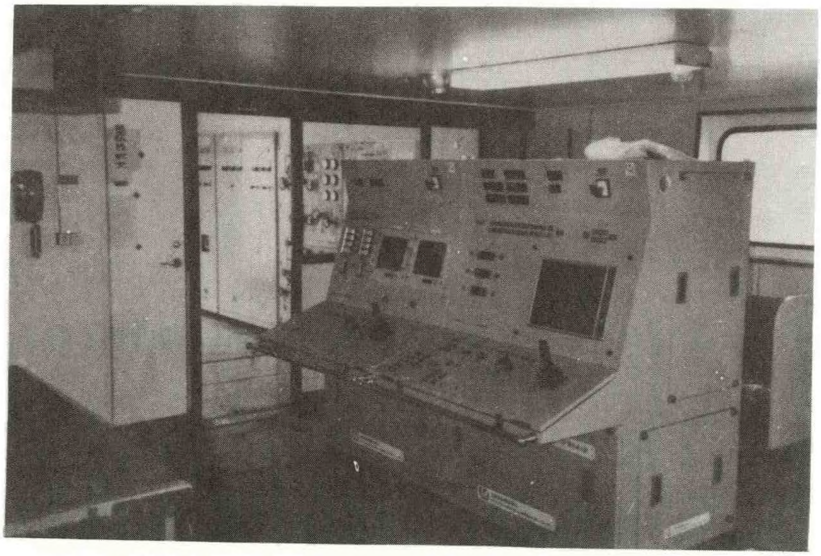


Figure 4.--DPS control console

on the vessel is the first Japanese-made DPS (fig. 4) developed by Mitsui.

This DPS, consisting of eight thruster units, two main propellers, computer control units, acoustic sensors, and navigation positioning equipment, provides precise long-term automatic and manual control of the position and heading of the vessel.

SEA TRIALS

Many kinds of tests (as shown in table 2) were carried out to confirm the performance of the ship itself and the diving units and so on since its completion in mid-October 1984.

SDC-DDC SYSTEM

Working tests on a dive to 300 m proved that all equipment operated in good order. Helium gas was used as the compression gas. SDC launching tests (figs. 5 and 6) were successfully

Table 2.--Test schedule

Speed test, etc.
SDC-DDC system
Working test
Compression test
SDC launching test
Radiating noise measurements
Acoustic navigation test
Microwave, hybrid navigation test
Multi-narrow beam test
Four-point mooring test
Dynamic positioning test

carried out at a depth of 100 m during the mooring test and at 300 and 500 m with the DPS running.

DYNAMIC POSITIONING

Before the DPS sea trials, acoustic reference equipment and surface reference equipment (microwave, Loran C, DECCA, NNSS) were confirmed to be in working order. DPS sea trials were carried out in the open sea at 300 m and 2,000 m water depths. The DPS's excellent holding capabilities were confirmed.

SHIP MOTION MEASUREMENT

Roll and pitch motion were measured in rough seas measuring more than 7 on the Beaufort scale. Figure 7 shows the measured significant pitch and roll amplitude while drifting. In this case, the maximum wind speed was 24 m/sec and significant wave height (H1/3) was 3 m.

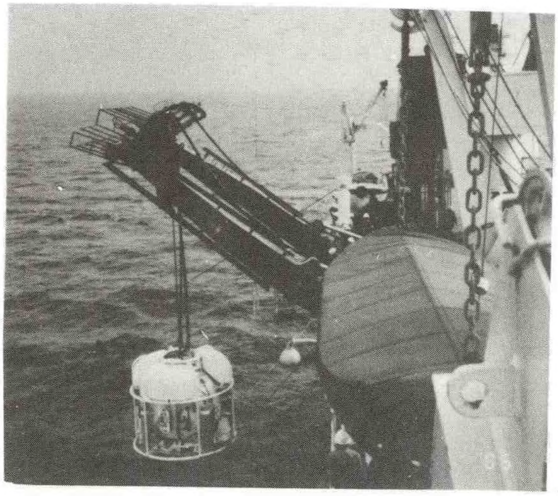


Figure 5.--Launching the SDC from the side of the ship

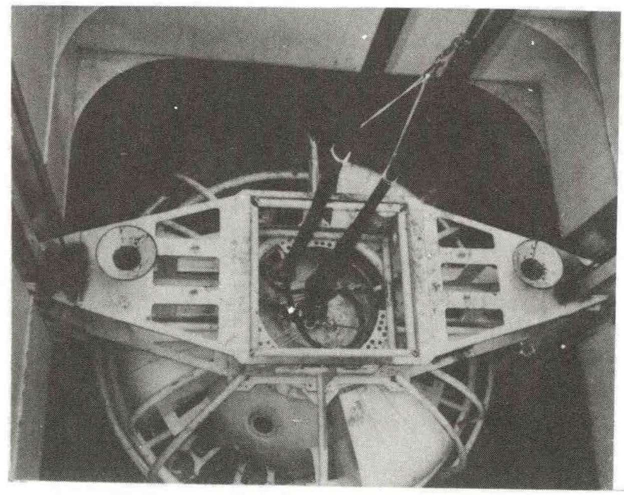


Figure 6.--Launching the SDC through centerwell

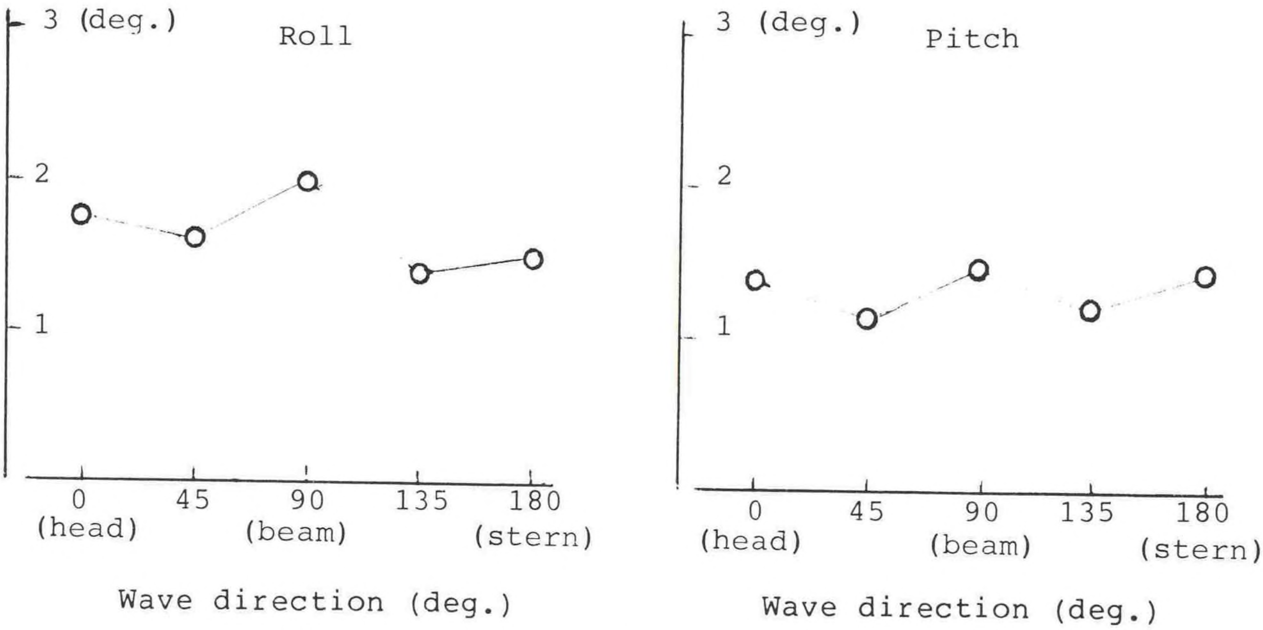


Figure 7.--Measured pitch and roll

CONCLUSIONS

The high performance of the KAIYO proved by these sea trials will contribute to the increased operational efficiency in SDC launching and in achieving accurate data acquisition on board. High mission effectiveness is expected to be achieved through the comfortable accommodation of the crew and the low levels of ship motion, noise, and vibration for crew and researchers during long-term research projects.

Through building and performing sea trials of the world's largest ocean-going SSC, the KAIYO, we obtained much valuable experience and data.

ACKNOWLEDGMENT

The authors wish to express their sincere thanks to members of the committee and persons concerned with this project.

ORGANIZATION OF THE UJNR IN THE UNITED STATES

Walter Telesetsky
National Oceanic and Atmospheric Administration

It is a great pleasure for me to meet with you this morning for the start of the 8th Joint Meeting of the UJNR Panel on Diving Physiology and Technology. I would like to extend a special welcome to Dr. Okamura and to the other distinguished Japanese members of the panel, as well as to all United States participants.

This morning, I will discuss with you how the U.S./Japan Cooperative Program in Natural Resources (UJNR) is organized in the United States. The emphasis of my talk will deal with the panels of the Marine Resources and Engineering Coordination Committee (MRECC), but I will include some historic information about the UJNR as well as mentioning briefly all of the UJNR panels.

Background Information

The UJNR was established in 1964 as a result of a recommendation by the bilateral Committee on Trade and Economic Affairs which was headed by Secretary of State Rusk and Foreign Minister Ohira. It was agreed that exchanges of scientific information, technical data, specialists and research equipment in the field of natural resources would be mutually beneficial to both countries. The objectives of the UJNR, reaffirmed in successive conferences, are to promote the development and conservation of natural resources through the cooperative activities of the two countries, and to share information and results so that a better environment can be developed for the benefit of present and future generations. The UJNR provides a continuing forum primarily for cooperation in the fields of applied science and technology. One of its principal aims is to increase and enhance the bonds of friendship between Japan and the United States through a wide variety of scientific and technological relationships.

Organization in the United States

The UJNR includes 17 panels. In the United States, the work of the technical panels is coordinated by two agencies: the National Oceanic and Atmospheric Administration (NOAA) coordinates the work of the marine panels through the Marine Resources and Engineering Coordination Committee (MRECC), and the Department of Agriculture coordinates the activities of all other panels. Both NOAA and the Department of Agriculture work within the general foreign policy guidance of the Department of State.

The UJNR Panels

The 17 UJNR panels have achieved a long list of successes through the conduct of joint projects and exchanges of scientific information, technical data, research equipment, and scientists. The 17 panels and a statement about what each deals with is as follows:

Marine Panels

Aquaculture Panel is concerned with the cultivation of both marine and freshwater aquatic products.

Diving Physiology and Technology Panel is involved in the fields of diving technology and medicine, and the application of this technology to underwater work and marine science. Emphasis in the near future is expected to involve joint scientific programs using submersibles.

Marine Electronics and Communications Panel is concerned with such areas as ocean circulation, currents, tides, measurement of water depths, fisheries assessment, ocean climatology, and water pollution.

Marine Facilities Panel discusses and reviews ocean and coastal engineering, offshore platforms, undersea systems, marine transportation, ocean energy systems, marine pollution, and ocean disposal.

Marine Geology Panel is active in such fields as seabottom geology and environmental geology of continental shelves.

Marine Mining Panel studies the mining of deep ocean manganese nodules and continental shelf sand and gravel, and the environmental aspects of recovering offshore oil and gas.

Seabottom Surveys Panel promotes the exchange of marine geophysical and bathymetric research data and analyses relating to seabottom surveys.

Non-Marine Panels

Conservation, Recreation, and Parks Panel studies the planning, management, and public use of parks, refuges, and recreation and historic sites as well as the preservation of wildlife.

Earthquake Prediction Technology Panel is leading the exchange of data on earthquake activity and information on instrument development and research techniques.

Fire Research Panel is encouraging cooperation in such areas as fire prevention, toxicity of combustion products, building design and smoke control, research on human behavior in fires, properties and detection of smoke, and fire and arson investigation techniques.

Forage Germplasm Exchange and Evaluation is involved in the introduction, evaluation, and growing of forage seeds in the United States and Japan.

Forestry Panel is concerned with the development and preservation of forest resources, the effects of forests on the environment, and wood utilization and industries.

Mycoplasmosis Panel promotes the exchange of information on mycoplasmosis and other important diseases of poultry and livestock.

Protein Resources Panel is concerned with the distribution and marketing of meat and meat products, the supply of cattle feeds, and research on the utilization of fish and vegetable proteins.

Toxic Micro-Organisms Panel studies micro-organisms that contaminate foods and feed.

Water Research and Technology Panel is concerned with desalination, water systems, waste water reuse, and conservation of water resources.

Wind and Seismic Effects Panel seeks to decrease the damage resulting from extreme winds and earthquakes.

Participating Agencies

Both nations have had extensive participation in the UJNR throughout their government agencies. The following is a list of some of the agencies that participate in the program.

Japan

Environmental Agency
Ministry of Agriculture, Forestry, and Fisheries
Ministry of Construction
Ministry of Foreign Affairs
Ministry of Health and Welfare
Ministry of International Trade and Industry
Ministry of Labor
Ministry of Posts and Telecommunications
Ministry of Transport
Science and Technology Agency

United States

Department of Agriculture

- Agriculture Research Service
- Animal and Plant Health Inspection Service
- Fish and Wildlife Service
- Forest Service
- Office of International Cooperation and Development
- Science and Education Administration

Department of Commerce

- National Bureau of Standards
- National Oceanic and Atmospheric Administration

Department of Energy

Department of the Interior

Bureau of Mines
Minerals Management Service
National Park Service
Office of Water Research and Technology
U. S. Geological Survey

Department of the Navy

Department of State

Department of Transportation

Environmental Protection Agency

National Aeronautics and Space Administration

National Institutes of Health

National Science Foundation

UJNR Meetings

The UJNR meets in plenary session about once every 4 years. When the meetings occur in the United States they are hosted by the Department of State. The purposes of these meetings are to evaluate the overall activities of the UJNR and to determine if changes in direction are needed, such as adding or eliminating panels. Between sessions of the UJNR plenary sessions an Administrative meeting usually occurs to keep both sides aware of progress and potential problem areas. The Marine Resources and Engineering Coordination Committee meets about every 2 years and the panels meet about every 1 or 2 years.

Marine Resources and Engineering Coordination Committee (MRECC)

The fifth UJNR Conference in May 1970 established the MRECC to coordinate all marine activities of the UJNR. The scope and responsibilities of the Committee are as follows:

Coordinate all UJNR activities among the marine panels
Provide for the exchange of information among the panels
Coordinate problems requiring cooperation among the panels
Consider new activities including establishing new panels
Review of panel programs
Communicate with other UJNR activities

I am the U.S. Chairman of the MRECC. The seven MRECC panels and their U.S. Chairmen are:

Aquaculture Panel, Conrad Mahnken, NOAA
Diving Physiology and Technology Panel, William Busch, NOAA
Marine Electronics and Communications Panel, Charles Kearse, NOAA
Marine Facilities Panel, Joseph Vadus, NOAA
Marine Geology Panel, Parke D. Snavely, U. S. Geological Survey
Marine Mining Panel, John Paden, NOAA
Sea-Bottom Surveys Panel, Christopher Andreason, NOAA

There used to be a panel on Marine Environmental Observations and Forecasting, but that was abolished in 1976 due to lack of activity.

Dr. Kilho Park, NOAA, supports me by serving as Executive Secretary for the MRECC and related UJNR activities.

Concluding Remarks

The United States has been pleased with the work of the MRECC panels. Some panels are more active than others. The Diving Physiology and Technology panel has been one of the very active panels. In the past, this panel has concentrated heavily on hyperbaric medicine. Recently, however, emphasis is being given by both sides to the conduct of joint projects involving deep sea submersibles. The enthusiasm of this panel is encouraging and I am confident that the panel will continue to foster future scientific discoveries of interest to both nations.

UJNR
US/JAPAN COOPERATIVE PROGRAM IN NATURAL RESOURCES

o Created 1964 - Cabinet-Level Action

o General Objectives

- Promote Development and Conservation of Natural Resources through Cooperative Activities

- Share Information and Results so a Better Environment can be Developed for the Benefit of Present and Future Generations

o A Principal Aim

- To Increase and Enhance the Bonds of Friendship between Japan and the U.S. through Scientific and Technological Relationships

FORMS OF ORGANIZATION AND COOPERATION

- 17 Panels formed under UJNR
- Department of Agriculture and NOAA provide Co-coordinators of UJNR
  - DOA Responsible for Coordination of Non-Marine Panels
  - NOAA Responsible for Coordination of 7 Marine Panels
- Marine Resources and Engineering Coordination Committee (MRECC) Established in 1970 - U.S. Chairman from NOAA
- Forms of Cooperation
  - Conduct Joint Projects
  - Exchange

    Scientific Information
    Technical Data
    Specialists
    Research Equipment

UJNR PANELS

- NON-MARINE
  - CONSERVATION, RECREATION, AND PARKS
  - EARTHQUAKE PREDICTION TECHNOLOGY
  - FIRE RESEARCH
  - FORAGE GERMPLASM EXCHANGE AND EVALUATION
  - FORESTRY
  - MYCOPLASMOSIS
  - PROTEIN RESOURCES
  - TOXIC MICRO-ORGANISMS
  - WATER RESEARCH AND TECHNOLOGY
  - WIND AND SEISMIC EFFECTS

- MARINE
  - AQUACULTURE
  - DIVING PHYSIOLOGY AND TECHNOLOGY
  - MARINE ELECTRONICS AND COMMUNICATIONS
  - MARINE FACILITIES
  - MARINE GEOLOGY
  - MARINE MINING
  - SEA-BOTTOM SURVEYS

SOME PARTICIPATING AGENCIES IN UJNR

- JAPAN
  - Science and Technology Agency
  - Ministry of Foreign Affairs
  - Environmental Agency
  - Ministry of Health and Welfare
  - Ministry of Agriculture, Forestry and Fisheries
  - Ministry of International Trade and Industry
  - Ministry of Transport
  - Ministry of Posts and Telecommunications
  - Ministry of Labor
  - Ministry of Construction

- UNITED STATES
  - Department of Commerce
    - National Oceanic and Atmospheric Administration
    - National Bureau of Standards
  - Department of the Interior
    - National Park Service
    - U.S. Geological Survey
    - Office of Water Research and Technology
    - Minerals Management Service
    - Bureau of Mines
  - Department of The Navy
  - Department of Energy
  - Department of Agriculture
    - Animal and Plant Health Inspection Service
    - Science and Education Administration
    - Forest Service
    - Office of International Cooperation and Development
    - Agriculture Research Service
    - Fish and Wildlife Service
  - Department of State
  - Department of Transportation
  - Environmental Protection Agency
  - National Science Foundation
  - National Aeronautics and Space Administration
  - National Institutes of Health

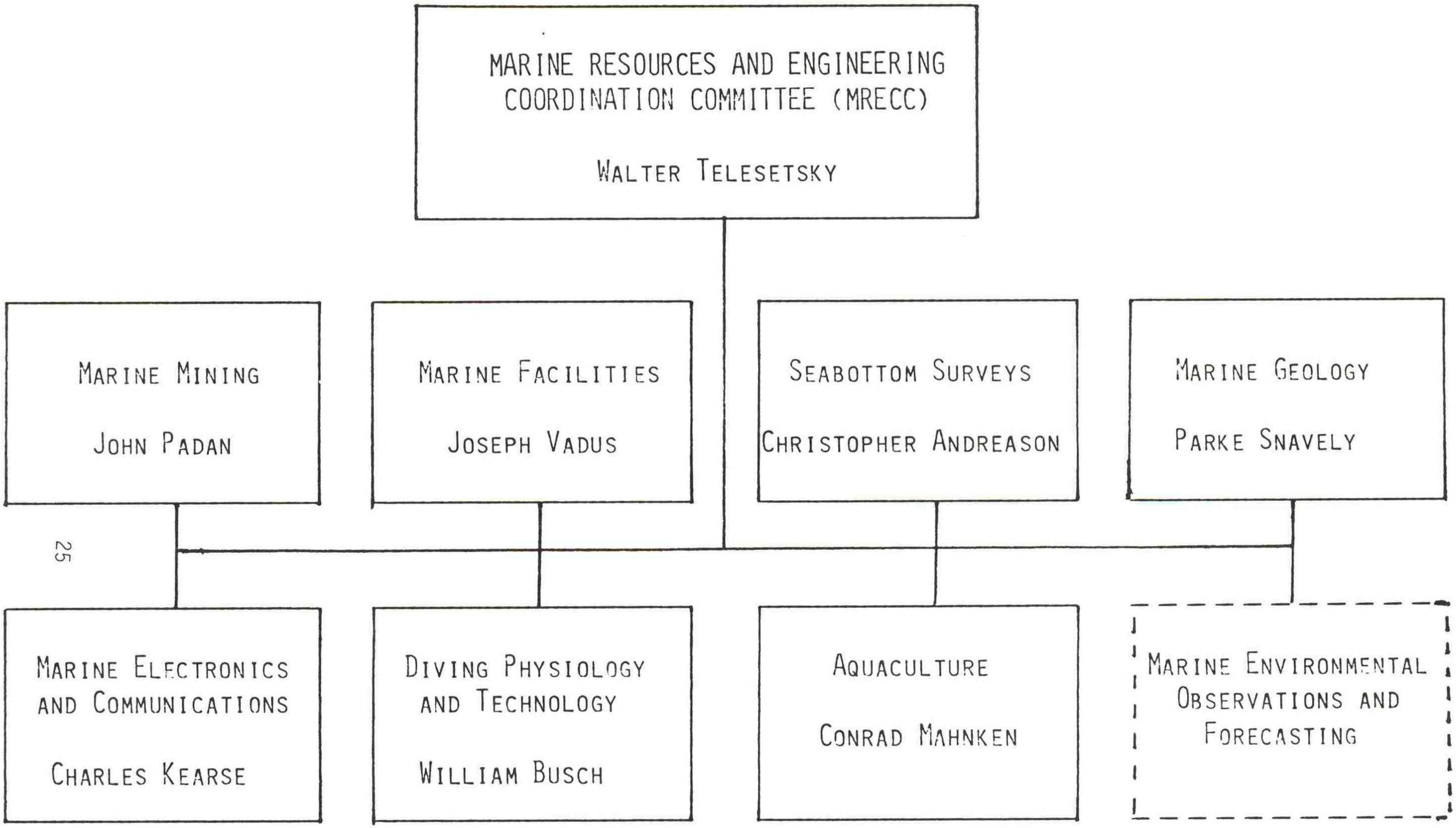
FORMAL MEETINGS

- UJNR General Conferences
  - Every 3-4 Years (DOS hosted when in U.S.)

- Administrative Meetings
  - Meet between General Conferences (DOS hosted when in U.S.)

- MRECC Meetings
  - Meet about every 2 years

- Panel Meetings
  - Meet about every 1-2 years


MARINE RESOURCES AND ENGINEERING COORDINATION COMMITTEE (MRECC)
WALTER TELESETSKY
MARINE MINING
JOHN PADAN
MARINE FACILITIES
JOSEPH VADUS
SEABOTTOM SURVEYS
CHRISTOPHER ANDREASON
MARINE GEOLOGY
PARKE SNAVELY
MARINE ELECTRONICS AND COMMUNICATIONS
CHARLES KEARSE
DIVING PHYSIOLOGY AND TECHNOLOGY
WILLIAM BUSCH
AQUACULTURE
CONRAD MAHNKEN
MARINE ENVIRONMENTAL OBSERVATIONS AND FORECASTING

MRECC RESPONSIBILITIES

- COORDINATION OF PANEL ACTIVITIES
- PROVISION AND EXHANGE OF INFORMATION
- COORDINATION OF PROBLEMS REQUIRING COOPERATION OF PANELS
- CONSIDERATION OF NEW ACTIVITIES INCLUDING ESTABLISHMENT OF NEW PANELS
- REVIEW OF PANEL PROGRAMS
- COMMUNICATION WITH OTHER UJNR ACTIVITIES

SEADRAGON-VI : A 7-DAY DRY SATURATION DIVE AT 31 ATA.
I. OBJECTIVES, DESIGN, AND SCOPE.

H. Nakayama, T. Murai and S. K. Hong

University of Occupational and Environmental Health, Kitakyushu, Japan; Japan Marine Science and Technology Center, Yokosuka, Japan; and State University of New York at Buffalo, Buffalo, New York.

Abstract:

Nakayama H, Murai T, Hong SK. SEADRAGON Ⅵ: a 7-day dry saturation dive at 31 ATA Ⅰ. Objectives, design, and scope. Undesea Biomed. Res. 1985;12:62.Suppl. The dive (SEADRAGON Ⅵ) described in these papers was designed to determine the effects on humans of a prolonged exposure to a 31 ATA dry helium-oxygen hyperbaric environment. Specific objectives were to study 1) circadian changes in renal-endocrine functions, including a comprehensive characterization of nocturia; 2) cardiovascular-endocrine responses to a 90 ° tilt, including an assessment of the sympathetic nerve activity; 3) erythrocyte functions, including the intracellular organic phosphates, and the Donnan ratio for chloride; and 4) blood enzyme profiles. The experiment was conducted in September-October, 1984 over a period of 30 days at the Japan Marine Science and Technology Center, Yokosuka, Japan. Following the 5 day predive control period at 1 ATA air, 4 male divers spent 7 days at 31 ATA helium-oxygen environment, and then returned to 1 ATA air after 13 days of decompression. They stayed an additional 3 days inside the chamber for postdive control measurements. THe chamber temperature was maintained at 27-28 ℃ during pre- and postdive periods, 31-32℃ at 31 ATA, and 31-28 ℃ during decompression. At 31 ATA, PO2 and PCO2 of the chamber gas were maintained at approximately 225 and 2 mmHg, respectively. In this introductory paper, physical and physiological characteristics of individual subjects, the major daily activity schedule, daily caloric intake, and the scope of investigation are presented.

Key words: saturation dive ; SEADRAGON Ⅵ

The Japan Marine Science and Technology Center (JAMSTEC) has been continuously conducting both simulated and open sea saturation diving experiments since its inception in 1970. The long range goals of these experiments are to provide technical capabilities necessary for various underwater activities as well as to explore physiological and medical problems associated with prolonged hyperbaric exposures. Although the early studies (code-named "SEATOPIA") were carried out at moderate depths (or pressure) ranging from 60 to 100 m (7-11 ATA), more recent dives (code-named "SEADRAGON") were carried out at a depth of 300m. The duration of exposure to a high pressure also varied from 3 days to 14 days (1-8) in order to assess the pattern of physiological adaptations. Through these studies, cardiorespiratory, thermoregulatory, and renal-endocrine responses to high pressure have been systematically examined (1-8).

In dives recently carried out at 31 ATA, it was unexpectedly observed that the noctural urine flow increases markedly(7,8). In fact, the divers complained that they had to get up once or twice at night to void, because of which they could not rest well. However, it was not possible even to chracterize these nocturia at that time and thus no measures were taken to counter this disturbing phenomenon. It was also noted in a recent 31 ATA dive(5) that the maximal aerobic power is significantly affected at both high pressure and postdive 1 ATA, suggesting a continuous deconditioning of cardiovasular (or physical) fitness during the course of approximately one month confinement in a hyperbaric chamber. Therefore, it was felt necessary to specifically study the time course of change in the cardiovascular deconditioning index(CID) as a function of either days under the influence of 31 ATA or days of confinement in the hyperbaric chamber.

Goldinger et al. (9,10) reported recently that various parameters of human erythrocyte function tested <u>in vitro</u> change significantly under moderate pressures to which human divers are often exposed. For instance, the active efflux of Na decreases while both the intracellular concentration of adenosine triphosphate (ATP) and the Donnan ratio for chloride increase even at 30-50 ATA. These findings are not only interesing from physiological point of view but may also have a practical importance in defining the depth limit for human divers. In particular, the increase in the Donnan ratio for chloride suggests a possible shift of the oxygen-hemoglobin equilibrium curve to the left, which would affect the transport and delivery of O2 from the lungs to the tissue.

The present study was thus conducted to investigate at 31 ATA the pattern of circadian changes in renal-endocrine functions, orthostatic tolerance as an index of cardiovascular deconditioning, and in vivo erythrocyte functions.

The present dive, code-named "SEADRAGON VI", was conducted from September 28 through October 27, 1984 at JAMSTEC as an integral part of the U.S.-Japan Cooprative Diving Research Program which was initiated in 1972 under the aegis of the United States-Japan Cooperative Program in Natural Resources(UJNR)-Panel on Diving Physiology and Technology. Four dives(3 in Japan and 1 in U.S.A.) were conducted in the past under this plan, and the present dive represents the 5th cooperative dive. As such, the research plan was prepared and carried out by scientists from both countries.

OBJECTIVES:

This investigation was undertaken to study man's response to a 7-day continuous exposure to a dry helium-oxygen hyperbaric environment at 31 ATA (300msw or 1,000fsw equivalent). The following parameters were measured:

1) Circadian changes in renal-endocrine functions, including a comprehensive characterization of nocturia.
2) Cardiovasular-endocrine responses to a 90° body tilt, including an assessment of the sympathetic nerve activity.
3) Erythrocyte functions, including the intracellular organic phosphates and the Donnan ratio for chloride.
4) Blood enzyme profiles.

SUBJECTS:

Four male divers were selected from the pool of ten divers at JAMSTEC who volunteered to serve as subjects. Subject selection involved a consideration of health, physical fitness, technical contribution, motivation, personal stability, maturity and sociability. The physical characteristics of four subjects are shown in Table 1. All subjects are well trained, professional divers and have previously participated, at least, in one dry saturation dive (7-31 ATA) as subjects. All subjects except D participated in all scientific experiments. Subject D was also an aide nurse who is authorized to withdraw blood and was responsible for all venous blood samplings and, in addition, for continuous measurements of blood pressure during orthostatic tolerance tests. He was, therefore, unable to participate in the latter test as a subject. All candidates were informed of the exact nature of the study, including the hazards associated with participation in this experiment, and gave written, informed consent. Moreover, all experimental procedures were critically examined and approved by the JAMSTEC Safety Committee.

DIVE PROFILE:

The dive was carried out at JAMSTEC, Yokosuka, Japan using the diving simulator (hyperbaric chamber) facilities used in previous dives(4-8).

The overall dive profile is shown in Fig. 1 (top panel). All divers entered the chamber at 1000 h on September 28, 1984 (dive day 1) to become acquainted with the new living environment as well as to systematically check out all equipment. The predive 1 ATA control period started at 0700 h on September 29 (dive day 2) and lasted for 5 full days. Compression started at 0800 h on October 4 (dive day 7) with helium and was carried out at a rate of 0.25 ATA/h, with a 30 min stop at 16 ATA followed by a 60 min stop each at 21 and 26 ATA. The compression to 31 ATA was completed at 2230 h (14.5 h after its start). At 31 ATA, the chamber gas was composed of approximately 0.3 ATA O_2 (0.97%), 0.79 ATA N_2(2.55%), and 29.91 ATA helium(96.48%), with a density of 6.0 gm/l(or 5.1 times higher than that of 1 ATA air). The chamber pressure was maintained at 31 ATA continuously until 0700 h on October 12 (dive day 15) when decompression started. In other words, the subjects spent a total of 7 days, 8 h and 30 min (or 176 h and 30 min) at 31 ATA.

The decompression was carried out according to modified U. S. Navy schedules, and was completed at 1630 h on October 23 (dive day 26). It took a total of 11 days, 19 h and 30 min (or 273.5 h). The completion of decompression was delayed by 3 h because of the occurrence of decompression sickness in one subject(B) at 2.7 ATA. The postdive 3-day 1 ATA control period began at 0700 h on October 24 (dive day 27), and the subjects emerged from the chamber at 1000 h on October 27 (dive day 30).

ENVIRONMENTAL PARAMETERS:

Chamber temperature, relative humidity, and O2 pressures throughout the entire dive are also shown in Fig. 1. All of these environmental parameters were carefully controlled and continuously recorded throughout the dive. Despite some variations, especially during the predive 1 ATA control period, the chamber temperature was successfully controlled and maintained at 28±1 ℃ during predive and postdive 1 ATA periods and at 31.5±0.5 ℃ at 31 ATA. During decompression, it was gradually lowered from 31.5 to 28℃. Although the relative humidity was mostly maintained at 60±10% level as planned, it transiently rose to an uncomfortable level of nearly 90% during the middle of the predive 1 ATA control period (dive day 4) because of the breakdown of the humidity control unit. All subjects felt too warm or hot during the latter period, but occasional active sweatings were observed only in one subject (B).

Oxygen pressure was raised from 0.21 ATA at predive 1 ATA (air) to 0.3 ATA during the hyperbaric period including the decompression phase. On the other hand, CO2 pressure was kept at a level below 0.005 ATA by continuously circulating the chamber gas through a CO2-absorbing unit.

EXPERIMENTAL SCHEDULE:

Because of the mutual interference with each other, the studies dealing with circadian changes in thermal and renal-endocrine functions were conducted on different days from those dealing with orthostatic tolerance, as indicated in Fig. 1(above the dive profile). On those days marked by upward arrows, venous blood samples were obtained from all subjects and used for studies on erythrocyte functions and plasma enzyme profile. No blood samples were taken during decompression. A specific designation of dive days for various experiments is shown in Table 2.

DAILY ACTIVITY SCHEDULE:

All subjects adhered to the general daily activity schedule shown in Table 3 throughout the dive except for 7 days designated for orthostatic tolerance tests(Table 2). A more specific activity schedule related to individual experiments is given in the respective companion papers(13-20). No regular physical exercise regimen was included in the daily activity schedule. However, the subjects were occasionally engaged in mild exercise when they found some free time.

Hot meals, both Japanese and western, was prepared for breakfast, lunch and dinner. The snack consisted of tea, fruit juice, a small bowl of noodles, or a small piece of cake. All food items were weighed before and after each meal, and the net caloric intake as well as the carbohydrate, fat and protein intake were computed from the Standard Table of Food Composition in Japan(12). Although there were small variations, the daily caloric intake was maintained at approximately 2700 Kcal/day (Table 4). The body weight was reduced by approximately 1 Kg during hyperbaric periods, which was partly due to dehydration (13). Moreover, the skinfold thickness (and hence the body fat) was not different between predive and post-dive periods. Table 4 also gives the average daily intake of carbohydrate, fat and protein, all of which remained at comparable levels throughout the dive. It should be noted,however, that the values given in Table 4 for caloric and carbohydrate intake are comparable to, while those for fat and protein intake are approximately 10-20% greater than, the corresponding national average for the contemporary Japanese adult male (21).

SCOPE OF STUDY:

To meet the dive objectives, the following specific studies were conducted:

1) Circadian changes in thermal and renal-endocrine functions:

   a. Diurnal and noctural excretion of water and electrolytes, body fluid balance, Na and K balance, and plasma chemistry(13).

   b. Diurnal and noctural excretion of antidiuretic hormone(ADH) and aldosterone; plasma ADH , renin-aldosterone and parathyroid hormone; circadian rhythms for urinary excretion of ADH and aldosterone(14).

   c. Circadian rhythms for body temperature (rectal and mean skin) and urinary excretion of water and elecrolytes(15).

2) Orthostatic tolerance test(a 90 ° body-tilt):

   a. Heart rate, blood pressure, the stroke volume (by impedance cardiography), intrapulmonary distribution of gas and blood (by impedance pneumography), and cardiovascular index of deconditioning(16).

b. Sympathetic nerve activities(17)

c. Changes in plasma volume and plasma cortisol, renin-aldosterone and ADH(18).

3) Erythrocyte functions: Intracellular concentrations of adenosine triphosphate(ATP) and and diphosphate(ADP), 2,3-diphosphoglycerate(DPG), and inorganic phosphate; Donnan ratio for chloride(19).

4) Plasma enzymes: Glutamic-oxaloacetic transaminase (GOT), glutamic-pyruvic transaminase (GPT), lactic dehydrogenase (LDH), alkaline phosphate (AlK), and creatine phosphokinase (CPK)(20).

Overall, the dive was carried out uneventfully with the exception of a mild decompression sickness observed during the terminal phase of the decompression period (see above) and provided us with sufficient information to meet all of the dive objectives. The eight companion papers cited above will cover each area of the study comprehensively.

Acknowledgments:

The authors are most grateful to the four subjects, all support crews, and all scientists from both Japan and U.S.A. without whose splendid cooperation and dedication this study could not have been accomplished. Special thanks are also extended to Mr. K. Umezawa, Director General of JAMSTEC, Mr. M. Saeki, Director of Research and Development, JAMSTEC, and Mr. W. S. Busch, Program Manager for Undersea Research, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, for their support and encouragement.

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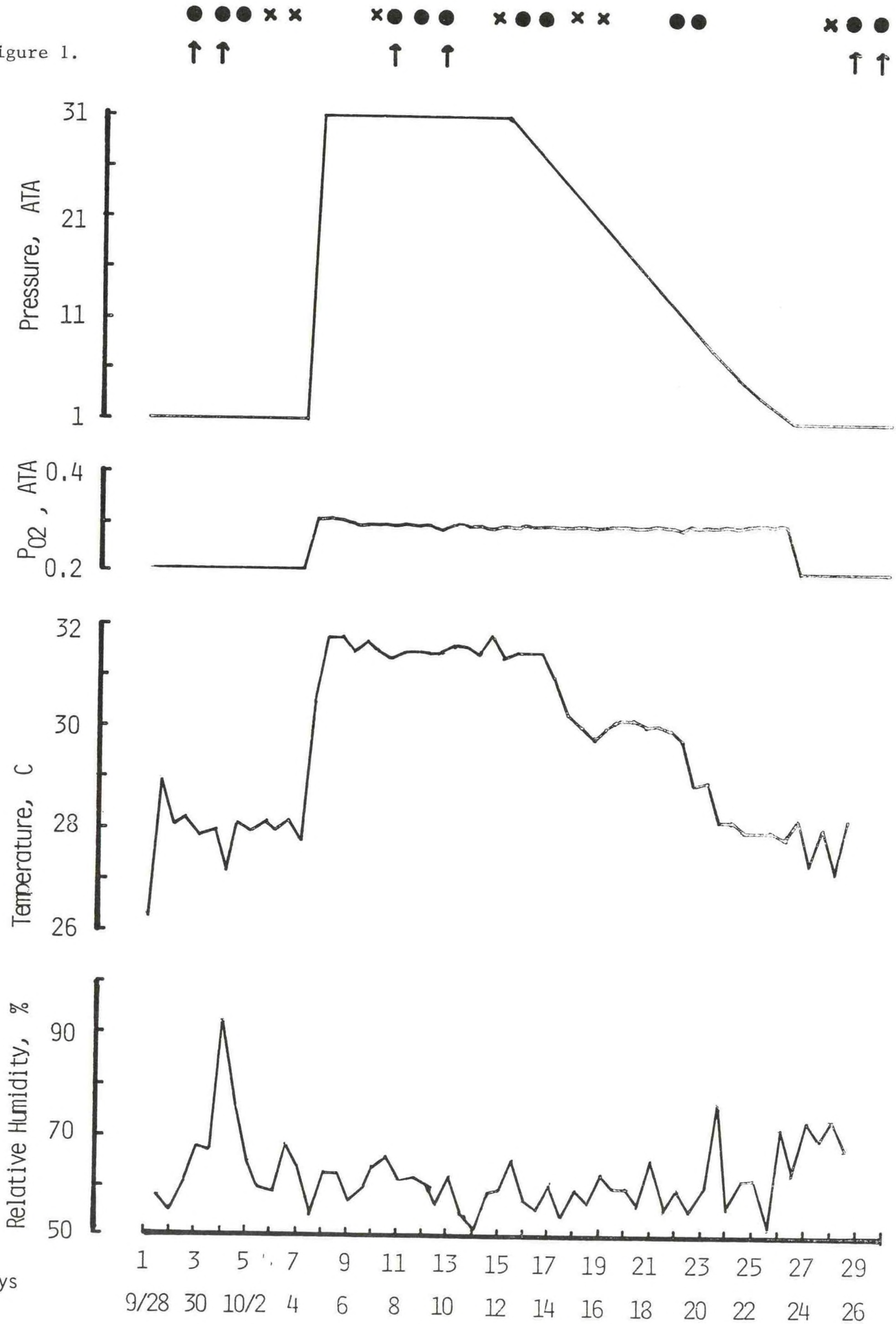
Figure 1.



Pressure, ATA
31
21
11
1
P_{O2}, ATA
0.4
0.2
Temperature, C
32
30
28
26
Relative Humidity, %
90
70
50
Days
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
9/28
30
10/2
4
6
8
10
12
14
16
18
20
22
24
26

Figure 1 Legend:

Environmental parameters and dive profile. Dive days and calendar days are shown in abscessa. Environmental parameters recorded at 0700 and 1900 h are used. Solid circles and "X" marks on top of the figure indicate days when circadian changes for renal-endocrine functions and orthostatic tolerance, respectively, were determined; upward arrows indicate days when venous blood samples wee obtained from all subjects.

Table 1 Physical Characteristics of Subjects before Dive

Subject	Age (yr)	Wt (kg)	Ht (cm)	S. A. (m^2)	SFT* (mm)	Fat** (%)	Years as a diver
A	32	65.4	173	1.80	38	16.4	4
B	28	55.0	164	1.60	55	20.8	4
C	23	60.2	167	1.69	36	15.8	6
D	33	62.2	167	1.72	29	13.3	2
Mean	29.0	60.7	168	1.70	39.5	16.6	4.0
S. E.	2	2.2	2	0.04	5.5	1.6	0.8

* Skinfold thickness which represents the sum of 4 sites (biceps, triceps subscapula, and iliac crest)

** Computed from the SFT by the formula of Durnin and Rahaman (11).

Table 2 Designation of Dive Days for various Experimewnts

Dive Periods	Dive Days	Circadian Changes	Orthostatic Tolerance	Erythrocyte Functions	Blood Enzymes
Predive, 1 ATA	2, 3,	X		X	X
	4	X			
	5, 6,		X		
31 ATA	9, 14		X		
	10, 12	X		X	X
	11	X			
Decompression	15, 16	X			
	17, 18		X		
	21, 22	X			
Postdive,1 ATA	27		X		
	28, 29	X		X	X

Table 3 Major daily activity schedule inside the chamber

Clock hour	Activity
0700	Rise from bed; empty urinary bladder; measurements of body weight, resting heart rate and resting blood pressure; venous blood (on designated days only, see Fig. 1)
0800	Breakfast
0900	Various (physiological and psychological) tests*
1000	Empty urinary bladder; various tests
1200	Lunch
1300	Empty urinary bladder; various tests*
1600	Empty urinary bladder: various tests*
1800	Dinner
1900	Empty urinary bladder; various tests*
2200	Empty urinary bladder; snack
2300	Retire; sleep EEG and body temperatures (on designated days only) all night long

* These tests include electroencephalography, measurements of bubble detection in blood, fatigue and psychomotor performances, and daily communications with the diving medical officer. Measurements of respiratory heat loss were also made several times during each dive period on the basis of non-interference with studies on circadian changes in thermal and renal-endocrine functions.

Table 4 Daily food intake during various dive periods.

Dive Periods	Dive day	Calory (kcal)	Carbohydrate (gm)	Fat (gm)	Protein (gm)
Predive, 1 ATA	3 - 6	2536 ±82	345 ±12	83 ± 5	96 ± 3
31 ATA	7 - 14	2661 ±88	356 ±13	96* ± 4	95 ± 3
Decompression	15 - 26	2859* ±94	383* ±13	102* ± 5	100 ± 3
Postdive, 1 ATA	27 - 29	2924 ±172	392* ±17	103 ± 9	109 ± 4

Each value represents the mean (±S E) of 4 subjects.

* Significantly different from the corresponding predive 1 ATA values ($P<0.05$, unpaired t tests).

REFERENCES

1. Matsuda, M.; Nakayama, H.; Ito, A.; Kirigaya, N.; Kurata, F.K.; Strauss, R.H.; Hong, S.K. Physiology of man during a 10-day dry heliox saturation dive (SEATOPIA) to 7 ATA. I. Cardiovascular and thermoregulatory functions. Undersea Biomed. Res. 1975;2:101-118.

2. Matsuda, M.; Nakayama, H.; Kurata, F.K.; Claybaugh, J.R.; Hong, S.K. Physiology of man during 10-day dry heliox saturation dive (SEATOPIA) to 7 ATA. II. Urinary water, electrolytes, ADH, and aldosterone. Undersea Biomed. Res. 1975;2:119-131.

3. Nakayama, H.; Matsuda, M.; Ito, A.; Kirigaya, N.; Kurata, F.K.; Strauss, R.H.; Claybaugh, J.R.; Hong, S.K. Physiological functions during a 10-day heliox saturation dive to 7 ATA. In: Shilling, C.W.; Beckett, M.W., eds. Underwater Physiology VI. Proceedings of the Sixth Symposium on Underwater Physiology. Bethesda: Federation of American Societies for Experimental Biology, 1978:99-131.

4. Matsuda, M.; Nakayama, H.; Arita, H.; Morlock, J.F.; Claybaugh, J.R.; Smith, R.M.; Hong, S.K. Physiological responses to head-out immersion in water at 11 ATA. Undersea Biomed. Res. 1978;5:37-52.

5. Ohta, Y.; Arita, H.; Nakayama, H.; Tamaya, S.; Lundgren C.E.G.; Lin, Y.C.; Smith, R.M.; Morin, R.; Farhi, L.E.; Matsuda, M. Cardiopulmonary functions and maximal aerobic power during a 14-day dry heliox saturation dive at 31 ATA (SEADRAGON VI). In: Bachrach, A.J.; Matzen, M.M., eds. Underwater Physiology VII. Proceedings of the Seventh Symposium on Underwater Physiology. Bethesda: Undersea Medical Society, Inc. 1981:209-221.

6. Matsuda, M.; Hong, S.K.; Nakayama, H.; Arita, H.; Lin, Y.C.; Claybaugh, J.R.; Smith, R.M.; Lundgren, C.E.G. Physiological responses to immersion at 31 ATA (SEADRAGON IV). In: Bachrach, A.J.; Matzen, M.M., eds. Underwater Physiology. Bethesda: Undersea Medical Society, Inc. 1981:209-221.

7. Nakayama, H.; Hong, S.K.; Claybaugh, J.R.; Matsui, N.; Park, Y.S.; Ohta, Y.; Shiraki, K.; Matsuda, M. Energy and body fluid balance during a 14-day dry saturation dive at 31 ATA (SEADRAGON IV). In: Bachrach, A.J.; Matzen, M.M., eds. Underwater Physiology VII. Proceedings of the Seventh Symposium on Underwater Physiology. Bethesda: Undersea Medical Society, Inc. 1981:209-221.

8. Shiraki, K.; Sagawa, S.; Kinda, N.; Nakayama, H.; Matsuda, M. Hyperbaric diuresis at a thermoneutral 31 ATA He-02 environment. Undersea Biomed. Res. 1984;4:341.

9. Goldinger, J.M.; Kang, B.S.; Choo, Y.E.; Paganelli, C.V.; Hong, S.K. The effect of hydrostatic pressure on ion transport and metabolism in human erythrocytes. J. Appl. Physiol. 1980; 49:224-231.

10. Goldinger, J.M.; Kang, B.S.; Morin, R.A.; Paganelli, C.V.; Hong, S.K. A method for separating cells and suspending medium at high pressure. Undersea Biomed. Res. 1980; 8:59-62.

11. Durnin, J.V.G.A.; Rahaman, M.M. The assessment of fat in human body from skin-fold thickness. Brit. J. Nutr. 1967;21:681-689.

12. Standard Table of Food Composition in Japan. Ed.: The Research Council of Resources, Science and Technology Agency. 1982.

13. Shiraki, K.; Hong, S.K., Park, Y.S.; Konda, N.; Claybaugh, J.R.; Takeuchi, H.; Matsui, N.; Nakayama, H. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. II. Characteristics of diuresis and nocturia. In preparation.

14. Claybaugh, J.R.; Matsui, N.; Takeuchi, H.; Park, Y.S.; Nakayama, H.; Hong, S.K. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. III. Salt- and water-regulating hormones. Undersea Biomed. Res. 1984; 11,1:65.

15. Konda, N.; Naraki, N.; Shiraki, K.; Sagawa, S.; Nakayama, H.; Hong, S.K. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. IV. Circadian analysis of body temperature and renal functions. In preparation.

16. Arita, H.; Lin, Y.C.; Sudoh, HJ.; Kuwahira, I.; Ohta, Y.; Saeki, H.; Ikawa, S.; Tamaya, S.; Nakayama, H. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. V. Cardiovascular responses to a 90° body-tilt. In preparation.

17. Mano, T.; Miwa, T.; Lin, Y.C.; Nakayama, H. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. VI. Sympathetic nerve activities during a 90° body-tilt. In preparation.

18. Matsui, N.; Claybaugh, J.R.; Shiraki, K.; Nakayama, H.; Hong, S.K. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. Plasma volume and hormonal changes during 90° body-tilt. In preparation.

19. Sagawa, S.; Goldinger, J.M.; Shiraki, K.; Nakayama, H.; Hong, S.K. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. VII. Erythrocyte functions. In preparation.

20. Goldinger, J.M.; Nakayama, H.; Takeuchi, H.; Hong, S.K. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. VIII. Plasma enzyme profiles. In preparation.

21. The Nutritional State of the Japanese: The results of 1981 Nutritional Survey. Ed. Section on Nutrition, Bureau of Public Health, Ministry of Health and Welfare. Dai-ichi Publishing Co., Tokyo, Japan. 1983.

CHARACTERISTICS OF DIURESIS AND NOCTURIA OBSERVED DURING A 7-DAY EXPOSURE TO 31 ATA (SEADRAGON VI)

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The maintenance of body fluid homeostasis is one of the most important basic physiological functions, and is achieved by careful control of salt and water intake and output. Any body fluid imbalance could lead to serious disturbances of cardiovascular and cellular functions. During prolonged exposure to a hyperbaric environment, human divers develop a sustained diuresis without increasing their fluid intake. Despite this apparent imbalance of fluid intake and urinary water loss, a mild dehydration seems to develop only during the early phase of the hyperbaric period. Based on these and other observations, it was proposed that hyperbaric diuresis is caused primarily by the suppression of insensible water loss. In a saturation dive conducted at the JAMSTEC in 1979 (SEADRAGON IV), a new phenomenon characterized by a pronounced increase in overnight urine flow (i.e., nocturia) was observed at 31 ATA. However, neither the characteristics nor the mechanism of this hyperbaric nocturia is understood at present. Therefore, in the recent U.S.-Japan cooperative dive at 31 ATA (SEADRAGON VI), held at JAMSTEC last year, we directed our attention to characterizing fully the diurnal and nocturnal diuresis. We hoped that such an analysis would provide a clue to the elucidation of the mechanism and the development of countermeasures.

DAILY URINE FLOW AND SOLUTE EXCRETION

Urine flow increased rapidly from approximately 1,000 ml/day during a 5-day predive period (1 ATA) to 1,500 ml/day on the day of compression and then to 2,000 ml/day during the first 4 days at 31 ATA. Urine flow then decreased somewhat but remained at 1,700-1,800 ml/day until the last decompression period, after which it rapidly returned to the predive level. It should also be noted that the overnight urine flow increased markedly at 31 ATA and during the early decompression period. Such increases in daily urine flow at high pressure were accompanied by decreases in Uosm (urine osmolality) in the absence of any change in either the glomerular filtration rate, as estimated by the endogenous creatinine clearance (Ccr), or in fluid intake. Moreover, the diuresis was accompanied by an increase in osmolal clearance (Cosm) and a decrease in negative free water clearance. These results indicate that the increase in daily urine flow at pressure has both water and osmotic diuresis components. Both plasma level and urinary excretion of antidiuretic hormone (ADH) decreased significantly at pressure, consistent with the previous view that there is a suppression of the ADH system at pressure, most likely because of the suppression of insensible water loss, and accounting for the decrease in negative free water clearance. The increase in Cosm was largely caused by increases in the excretion of K, Pi (inorganic phosphate), and urea. In fact, the fractional excretion of filtered K and Pi increased significantly at 31 ATA, while that of Na and Cl decreased.

DIURNAL AND NOCTURNAL URINE FLOW AND SOLUTE EXCRETION

The 24-hr urine output was partitioned into two components, diurnal (0700-2200 hr) and nocturnal (2200-0700 hr), and various urinary parameters were compared. Although diurnal and nocturnal urine flows increased at pressure, the relative magnitude of the increase was much greater for nocturnal (150%) than for diurnal flow (50%). Although Uosm decreased to a comparable level at pressure in both periods, the amount of osmotic substances excreted (UosmV) increased significantly only during the night. Ccr remained the same for both day and night throughout the dive. Overall, the diurnal increase in urine flow at pressure was entirely due to a reduction in negative free water clearance, while the nocturnal diuresis was largely due to increased Cosm. In other words, the diurnal diuresis is essentially a water diuresis, while the nocturnal diuresis is mostly osmotic. Actually, the negative free water clearance also decreased at pressure during the night, but its magnitude was smaller than that during the day, which may be attributed to the increased Cosm. Urinary ADH excretion also decreased at pressure both during the day and night, again explaining the reduced negative free water clearance in both periods.

As in the case of the daily excretion of solutes at pressure, the diurnal excretion of K, Pi, and urea increased while that of Na and Cl decreased significantly at 31 ATA, resulting in no net changes in the excretion of total osmotic substances. Similarly, the nocturnal excretion of K and urea increased significantly at 31 ATA and at 31-25 ATA. However, in contrast to the diurnal pattern, the nocturnal excretion of both Na and Cl did not decrease but rather tended to increase ($\sim$20%) at these high pressures. On the other hand, the nocturnal excretion of Pi and Ca remained the same at pressure. Overall, increases in the excretion of Na, Cl, K, and urea accounted for approximately 85% of the nocturnal increase in the excretion of osmotic substances at 31 ATA and for 70% at 31-25 ATA. Although the nature of the remaining "other" substances cannot be defined at present, both Ca and Pi can be excluded. In other words, the increase in nocturnal excretion of Na and Cl is a specific effect of pressure, which was induced only at night when the divers were in bed. Conversely, the phosphaturic effect of pressure appears to be present only during the day when the divers are mostly in an upright position. Because of the marked nocturnal diuresis at pressure, the overnight share of the daily excretory load of water and certain solutes (Na, K, Cl, urea) increased from approximately 30% at 1 ATA to 40% or so at pressures above 25 ATA. On the other hand, the overnight share of the daily excretion of Ca, Pi, and creatinine remained the same (30-40%) throughout the entire dive.

PLASMA COMPOSITION

Osmolality as well as Na and Cl levels decreased slightly (but significantly), while the plasma protein level and hematocrit both increased significantly at 31 ATA. Most of these changes were reversed by the postdive 1 ATA period. On the basis of the increase in hematocrit values, the plasma volume was estimated to decrease by $\sim$10% by the fifth day of exposure to 31 ATA and returned to the predive level by the seventh day at 31 ATA. Body weight also decreased continuously at 31 ATA, amounting to nearly 1.0 kg by the end of the 31 ATA period. These results indicate that the diuresis observed at 31 ATA in this dive led to a net loss of body fluid. Evidently, the urinary loss of water exceeded the pressure-induced decrease in insensible water loss. Overall Na balance appeared to be maintained, while the K balance became negative during the 31 ATA period, during which K excretion increased markedly.

SUMMARY

There appear to be at least three factors associated with hyperbaric diuresis. The first factor is the suppression of insensible water loss, which accounts fully for the diurnal diuresis but only partly for nocturnal diuresis. The second factor is a mild inhibition of the tubular reabsorption of certain solutes, which is largely responsible for the nocturnal diuresis. A third factor appears to be operating during the early phase of hyperbaric exposure and to be responsible for the induction of a net dehydration without raising plasma osmolality.

Seadragon VI: A 7-Day Dry Saturation Dive at 31 ATA. IV. Circadian Analysis of Body Temperature and Renal Functions.

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ABSTRACT

Circadian rhythms of body temperature, urine flow, and urinary excretion of electrolytes were investigated in 4 male subjects before, during, and after a 7 day stay in a dry heliox 31 ATA environment. The chamber temperature was maintained at about 28°C during pre- and postdive 1 ATA periods and was raised to 31.5°C at 31 ATA. The circadian rhythm of the rectal temperature analyzed by the cosinor fitting method showed the same mesor (the mean level of fluctuation) and the amplitude at 31 ATA compared with those at 1 ATA. However, a reversible leftward phase shift was noted at 31 ATA, in which the acrophase shifted to 1435 h at 31 ATA from 1540 h (predive) or 1610 h (postdive) at 1 ATA. This shift was attributed to an early rise of the rectal temperature during night at 31 ATA. The mean skin temperature at 31 ATA was the same as that at 1 ATA. The circadian rhythm of urine flow was distorted by a marked nocturia at 31 ATA. Although the diurnal rhythm was still preserved during the early 31 ATA period, it disappeared thereafter until the mid-decompression period. Circadian rhythms of sodium, chloride and potassium excretion rate were also greatly affected at 31 ATA, while those of calcium and phosphate were not. These results indicate that a prolonged exposure to 31 ATA alters the basic pattern of circadian rhythms for thermoregulatory and certain renal functions.

INTRODUCTION

A peculiar alteration of the characteristic circadian rhythm for urine flow was observed in Japanese saturation divers during a multi-day exposure to 31 ATA, as manifested by marked increase in nocturnal urine flow and excretion of osmotic substances (1). Although the data base was rather limited, the results from the above dive also suggested that circadian rhythms for water- and salt-regulating hormones such as antidiuretic hormone (ADH) and aldosterone may be modified under high pressure (2). Indications for the alteration of certain parameters of circadian rhythms at 51 ATA were reported by Rostain et al. (3) for body temperature, heart rate and urinary excretion of Na and K, which they attributed to changes in the central nervous system function under high He-O2 pressure.

The present investigation was undertaken to more rigorously analyze the pattern of circadian rhythms for body temperatures and urinary excretions of water and electrolytes at 31 ATA He-O2 environment. Since the circadian rhythm is one of the most fundamental biological phenomena, a more complete assessment of circadian rhythms of human subjects living in a confined, hyperbaric environment would be important in the evaluation of overall physiology of divers.

METHODS

Thermal and urinary data used for the circadian rhythm analyses were obtained for 3 consecutive days each during predive 1 ATA (dive days 2,3 and 4) and 31 ATA (dive days 10, 11 and 12) periods and for 2 consecutive days during the postdive 1 ATA (dive days 28 and 29) period. For details of the overall dive profile, refer a companion paper of the procedure. Only urinary data were obtained for 2 consecutive days each during early (31-25 ATA; dive days 15 and 16) and late (14-8 ATA; dive days 21-22) decompression periods. All subjects followed the same regular routine activity schedule on these days and avoided any strenuous exercise or other unusual activities that might alter circadian rhythms. All subjects rose from bed at 0700 h and retired at 2300 h. The hyperbaric chamber was kept dark during the bed-time. Breakfast was given at 0800 h, lunch at 1200 h, dinner at 1800 h and a light snack at 2200 h.

A. Body temperature: Skin temperatures were measured with copper-constantan thermocouples over 7 areas (forehead, chest, forearm, hand, thigh, calf and foot) and the mean skin temperature (Tsk) was calculated by the formula of Hardy and DuBois (6). The rectal temperature (Tre) was measured by a copper-constantan thermocouple inserted into the rectum 10-15 cm beyond the anal sphincter.

B. Urine collection and analysis: Each subject freely voided into a separate container during and at the end of each of the six intervals (0700-1000, 1000-1300, 1300-1600, 1600-1900, 1900-2200, and 2200-0700 h of the next day). All samples were analyzed for osmolality, Na, K, Cl, Ca, inorganic phosphate (Pi), urea and creatinine, as described in a companion paper by Shiraki et al. (7).

C. Circadian rhythm analysis: The rhythm parameter is obtained by the least-squares regression of a cosine function of the form (8):

$$f(t) = M + A \cos (wt + \phi)$$

where f(t) is the value at time t, M the mean level of fluctuation (the mesor), A the amplitude (half the range of oscillation) w the angular frequency (assumed to be 1) and ϕ the time of maximum (the acrophase). Cosinor fittings were applied to daily individual data, daily averages of 4 subjects or the average of 3 or 2 consecutive days for different dive periods. Average body temperatures (representing 21 and 11 measurements during daytime and night, respectively) for each 10 min period were used as the value at 50 min of each hour. For the urine flow and urinary excretions of solutes, curve fittings were done such that the integrated value of cosine wave during each 3 h interval during daytime and 9 h during night gave the measured amounts during the given interval. The significance of the fitted cosine wave was assessed by testing the null hypothesis using a variance ratio test.

RESULTS

A. Body temperatures: Circadian changes in Tre are shown in Fig. 1. Tre was high during daytime and low during night. There was no significant difference in the average Tre between predive and 31 ATA periods (37.15 vs 37.18 °C for daytime and 36.58 vs 36.64 °C for night) as shown in Table 1. However, during the postdive period, Tre during daytime (but not night) was significantly higher than that during the predive period. The highest Tre was observed at 1350-1450 h in every subject during both predive and 31 ATA periods and at 1450-1650 h during postdive period. According to the cosinor fitting, significant circadian rhythms were detected at both 1 and 31 ATA. The mean levels of fluctuation (i.e., the mesors) were 36.96, 37.00 and 37.07°C, the amplitudes 0.37, 0.36 and 0.49°C, and the acrophases at 1540, 1435 and 1610 h, during predive, 31 ATA and postdive periods, respectively (Fig. 1). Tre showed a phase shift to the left (phase-advance) at 31 ATA as compared with the rhythms at 1 ATA (pre- and postdive periods). Although the acrophase showed small interindividual differences, it appeared about an hour earlier at 31 ATA than at 1 ATA in every subject. Furthermore, accounting for the phase shift at 31 ATA, a prominent difference in the pattern of changes in Tre was observed during night.

Tsk also showed a circadian rhythm, having a low during daytime and high during night. According to the cosinor fitting, mesors were 34.34 and 34.21°C, amplitudes 0.33 and 0.41°C, and acrophases 0255 and 0315 h, during predive and 31 ATA periods, respectively.

Among the regions where we measured the skin temperatures, forehead was the only region which was always exposed to the ambient and was thought to display a "physiological" circadian rhythm (i.e., not affected by the clothing and blanket). In general, the skin temperature over the forehead was consistently lower at 31 ATA than at predive 1 ATA, although a circadian rhythm was detected at both predive 1 ATA and at 31 ATA.

B. Urinary Excretion of Water and Solutes: Circadian rhythms for average urine flow (V) are shown in Fig. 2. In general, the peak urine flow was observed at 1300-1600 h throughout the predive period, the 3rd (dive day 10) and 4th (dive day 11) days at 31 ATA, and the 3rd day (dive day 29) of postdive period. According to the cosinor fitting using the average value for each period, acrophases were located at 1525 and 1357 h at pre- and postdive 1 ATA, respectively. At 31 ATA, urine flow data did not fit the cosine wave for 24 h period because of a marked nocturia. However, when the level of fluctuation of cosine wave based on the data obtained during the predive period (dashed line) was compared with the data obtained during the 31 ATA period, the diurnal (i.e., daytime) rhythms were comparable to each other although the mean level was raised at 31 ATA. Furthermore, the decrease in urine flow during 1900-2200 h at 31 ATA seems to suggest that there may be a phase-advance as noted for the rhythm of Tre and the forehead skin temperature. Interestingly, the diurnal rhythm completely disappered from the 5th day at 31 ATA (dive day 12) and reappeared on the 8th day of decompression (11-8 ATA; dive day 22) with the acrophase at 1151.

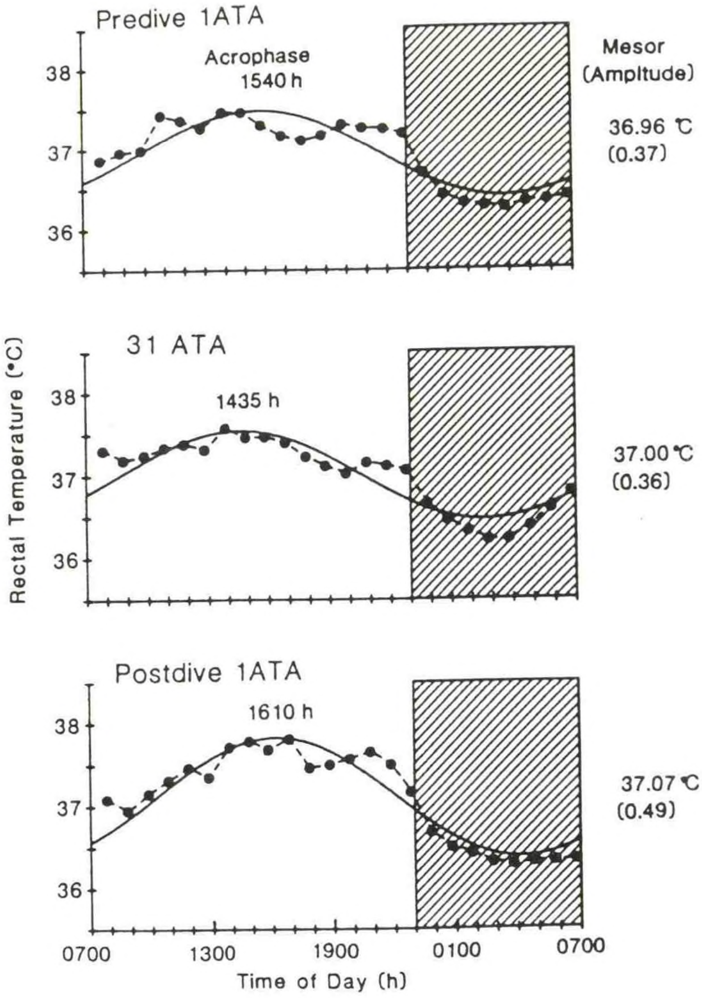

Fig. 1. The best fitting 24-hour cosine wave for the rectal temperature fitted by least squares at each dive period. Average values of 3 (predive 1 ATA and 31 ATA periods) or 2 (postdive 1 ATA period) consecutive days in 4 subjects are used for the analysis. Acrophase, mesor and amplitude values are also indicated. The hatched area represents the dark (sleep) period.

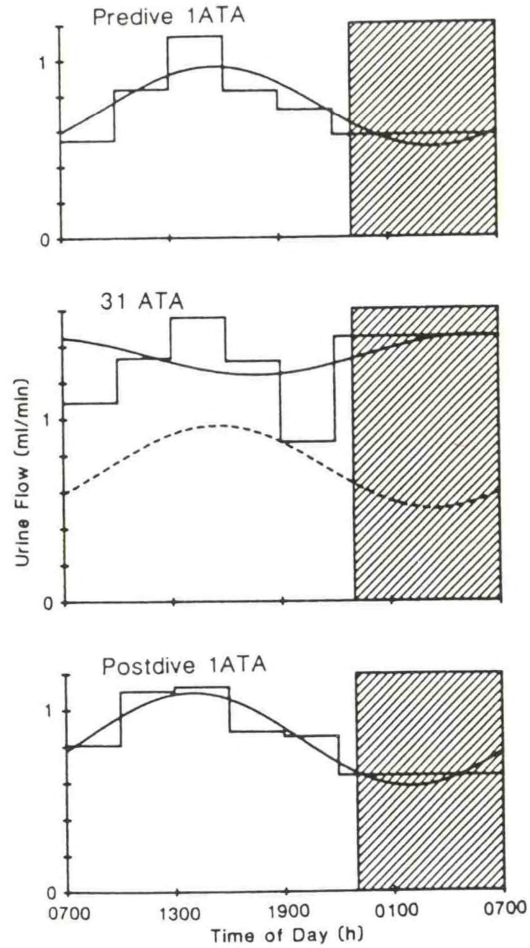

Fig. 2. The best fitting 24-hour cosine wave for urine flow at 1 ATA (pre- and postdive) and 31 ATA. Average values of 3 (predive 1 ATA and 31 ATA) or 2 (postdive 1 ATA) consecutive days in 4 subjects are used for the analysis. The dashed line (31 ATA) representing the best fitted cosine wave obtained at predive 1 ATA period is included for comparison. The hatched area represents the dark (sleep) period.

Table 1. Average ambient (Ta) rectal (Tre) and mean skin (Tsk) temperature (°C) during various phases of dive

		Ta	Tre	Tsk
Predive 1 ATA (3 days)	Daytime (0700-2300 h)	28.12 ±0.06 (48)	37.15 ±0.02 (178)	34.07 ±0.04 (166)
	Night (2300-0700 h)	28.04 ±0.08 (24)	36.58 ±0.03 (89)	34.63 ±0.04 (78)
31 ATA (3 days)	Daytime	31.75 ±0.03 (48)	37.18 ±0.02 (187)	33.96* ±0.03 (152)
	Night	31.74 ±0.04 (24)	36.64 ±0.03 (96)	34.78* ±0.05 (70)
Postdive 1 ATA (2 days)	Daytime	28.91 ±0.04 (32)	37.30** ±0.02 (128)	34.60** ±0.06 (64)
	Night	28.41 ±0.03 (16)	36.60 ±0.03 (63)	34.78 ±0.06 (32)

Each value represents the mean (±SE) of the number of hourly measurements indicated in parenthesis.
See "Methods" for the frequency of temperature measurements and the computation of hourly means.
Tre and Tsk represent the mean of 4 subjects.

*$p<0.05$, **$p<0.01$, as compared to corresponding predive 1 ATA values.

The circadian rhythm for the urinary excretion of osmotic substances (UosmV) and K (UkV) during the predive period was similar to that of urine flow. On the average, the acrophase was 1520 and 1510 h for UosmV and UkV, respectively. The urinary excretion of sodium (UNaV), chloride (UClV), calcium (UCaV), inorganic phosphate (UPiV) also showed significant circadian rhythms at predive 1 ATA. The acrophases of UNaV and UClV appeared consistently at a fixed time of the day, 1406 h for Na and 1401 h for Cl. The circadian rhythms of UCaV and UPiV were also relatively stable at predive 1 ATA, with the acrophase of 1510 h and 2107 h, respectively. The rate of urea excretion (UureaV) showed a similar circadian rhythm as that of UosmV at predive 1 ATA but with some phase delay. The circadian rhythm for creatinine excretion (UcrV) was less marked than that of the other substances throughout the experiment. At 31 ATA, the characteristic circadian rhythm of UosmV was again disrupted by a marked nocturnal increase. However, the basic diurnal rhythm seemed to be still maintained. Furthermore, in contrast to the loss of the diurnal rhythm for urine flow toward the end of the 31 ATA period and during the early decompression period, a relatively stable diurnal rhythm was observed for UosmV even during these periods. During the postdive period, the circadian rhythm of UosmV became parallel to that of urine flow again, with the acrophase at 1408 h. In contrast, the circadian rhythm for UkV at 31 ATA were highly variable and no trend can be found. There appeared to be a reversal of the usual rhythm by the 5th day (dive day 12) at 31 ATA which is sustained throughout the decompression period. The acrophase gradually shifted rightwards during decompression (0737 and 1013 h for early and late decompression periods, respectively) and the postdive period (1227 h), approaching the predive value (1505 h). The mesors were higher at 31 ATA and then gradually decreased during decompression. The pattern of changes in the circadian rhythms for Na (and Cl) excretions and urea during various dive periods, was very similar to that of UosmV except that the mesor for Na excretion decreased slightly at 31 ATA (Table 3). On the other hand, the circadian rhythm for Ca and Pi excretion remained largely intact during the course of dive.

DISCUSSION

Many physiological functions display characteristic circadian rhythms even under constant conditions where the rhythms free run. Usually, however, many activities associated with daily life (e.g., food and fluid intake, environmental temperature, physical exercise, exposure to light, and sleep) would modify the quantitative parameter(s) of the circadian rhythm for certain functions. In the present study, all subjects living in the identical environment also followed the same daily activity schedule. Although the food and fluid intakes were not controlled, they were maintained fairly constant throughout the entire experimental period with the daily average of approximately 2,700 Kcal (5) and 2,800 ml (7) respectively. The daily intake of proteins, Na and K was also maintained fairly constant (7). The only major variable was the environmental pressure (mostly helium pressure) which was raised to 31 ATA for 7 days and was then lowered to the sea level over a period of 12 days (5). The environmental temperature was raised from approximately 28°C at 1 ATA to 31.7°C at 31 ATA to provide a thermoneutrality (9,10). In order to further aid thermal comfort, the subjects were allowed to freely adjust their clothing during daytime and to use blankets as needed during sleep. Under these experimental conditions, fairly consistent circadian rhythms were observed during the predive 1 ATA period for body temperatures (rectal and skin) and urinary excretions of water and various electrolytes and solutes. Although there were some minor daily variations in the parameters of the circadian rhythm, the basic pattern is quite similar to that reported in the literature (11-15). Most likely, these minor variations are due to the inevitable daily variations of such experimental conditions as the environmental temperature and food and water intake. Although the basic circadian rhythm for Tre appears to be preserved throughout the experimental periods, a consistent leftward phase shift was observed at 31 ATA as compared to pre- and postdive 1 ATA periods. This phase shift at 31 ATA was entirely due to the different behavior of Tre during sleep. It was noted that Tre always decreases during sleep at night but it remains low at 1 ATA until the subjects wake up and arise from the bed (0700 h) whereas it already begins to increase at 31 ATA from 0250-0350 h while the subjects are still asleep. As a results, the early morning Tre was consistently higher at 31 ATA than at 1 ATA, advancing the acrophase by 1 h at the former pressure. Webb (16) also observed a consistent elevation of early morning Tre at 37 ATA in four subjects. Similarly, Rostain et al.(3) observed a shift of the acrophase for oral temperatures from 1640 h at 2 ATA to 1500 h at 51 ATA. In the latter study, the observed phase shift in Tre was accompanied by a similar but more marked phase shift in the heart rate in two out of three subjects. Although the mechanism underlying such a phase shift in Tre at high pressure can not be elucidated at present because of the limited data base, it is of interest to note a similar phase shift at 31 ATA for the skin temperature of the forehead, a region of the body always exposed to the environment. These results suggest that the heat production during sleep may be higher at hyperbaric environment. In fact, a significant increase in basal metabolism was observed in a 4 ATA dive (17). However, it is premature at this stage to overspeculate about the mechanism of this interesting phenomenon.

The characteristic circadian rhythms for various renal functions evident at 1 ATA were considerably distorted due to development of nocturia which is basically osmotic in nature (7). When the cosinor fitting method was applied to 31 ATA urine flow data, the usual circadian rhythm disappeared totally (Fig. 2). However, a careful inspection of the data indicates that the diurnal rhythm is still preserved until the 4th day (dive day 11) at 31 ATA. In other words, the nocturia at 31 ATA appears to be a non-circadian component added onto the usual circadian rhythm (9). On the 5th day at 31 ATA (dive day 12), however, the characteristic diurnal rhythm disappeared and did not return to normal until the late decompression period (Fig.1). In the other study dealing with the circadian rhythm for urine flow in the hyperbaric envirnment, Rostain et al (3) found that the basic rhythm is not altered either during 4 days at 51 ATA or during 8 days of decompression. However, these authors also report a slight (10%) reduction in the mesor value at 51 ATA, in a marked contrast to the present (7) and the overwhelming majority of previous dives in which a significant diuresis is observed at pressure (18). It is thus difficult to directly compare the present results with those of Rostain et al. (3). The circadian rhythms for urinary excretion of total osmotic substances, Na (and Cl) and urea were also distorted at 31 ATA due to the nocturnal increase in urinary excretion of those substances. However, in contrast to the apparent disappearance of the diurnal (and circadian) rhythm for urine flow during the later 31 ATA and early decompression periods, the characteristic diurnal rhythms for urinary excretion of Na (and Cl), urea and total osmotic substances were preserved throughout the entire experimental period. These findings indicate that there is a dissociation at high pressure of the mechanism controlling the diurnal excretion of water from that of major osmotic substances. Such differential effects of high pressure on circadian rhythms for various solutes are further illustrated by the fact that the usual circadian rhythm for K excretion disappered totally from the beginning of the 31 ATA period while that for Ca and Pi excretion was more or less preserved throughout the entire experimental periods.

Since the urinary excretion of each substance is specifically controlled by many extra- and intrarenal factors, it is virtually impossible to even speculate the mechanism for the pressure effects on circadian rhythm which itself is governed by a multi-oscillator system. Although the experimental conditions need to be much more strictly controlled in order to study the pressure effects on the circadian rhythm, many practical and technical problems associated with a complicated saturation diving operation make it rather difficult to do so. Nonetheless, it is still significant to note that, even under the usual multi-day saturation diving conditions, apparently pressure-induced alteration in circadian rhythms for certain physiological functions were evident. These alterations in certain circadian rhythms under pressure most likely reflect some subtle effects of high pressure on the CNS function.

REFERENCES

1. Nakayama H, Hong SK, Claybaugh JR, et al. Energy and body fluid balance during a 14-day dry saturation dive at 31 ATA (SEADRAGON VI). In: Bachrach AJ and Matzen MM, eds. Underwater Physiology VII. Proceedings of the seventh symposium on underwater physiology. Bethesda: Undersea Medical Society, Inc., 1981. pp 541-554.
2. Claybaugh JR, Hong SK, Matsui N, Nakayama H, Park YS, Matsuda M. Responses of salt- and water-regulating hormones during a saturation dive at 31 ATA (SEADRAGON IV). Undersea Biomed Res 1984; 11:65-80.
3. Rostain JC, Naquet R, Reinberg A. Effects of a hyperbaric situation (500 meter depth, heliox atmosphere) on circadian rhythms of two healthy young men. Int J Chronobiol 1975; 3:127-139.
4. Claybaugh JR, Matsui N, Takeuchi H, Park YS, Nakayama H, Hong SK. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. III. Salt- and water-regulating hormones. Under. Biom. Res. 1984; 11:65.
5. Nakayama H, Murai T, Hong SK. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. I. Objectives, design, and scope. Undersea Biomed Res. 1985; 12:62 Suppl.
6. Hardy JD, DuBois EF. The technique of measuring radiation and convection. J Nutr 1938; 15:461-475.
7. Shiraki K, Hong SK, Park YS, et al. SEADRAGON VI: A 7-day dry saturation dive at 31 ATA. II. Characteristics of diuresis and nocturia. Undersea Biomed Res. In preparation.

8. Halberg F, Tong YL, Johnson EA. Circadian system phase - an aspect of temporal morphology; procedure and illustrative examples. In: Mayersbach , ed. The cellular aspect of biorhythms. Berlin: Springer, 1966; pp 20-48.
9. Shiraki K, Sagawa S, Konda N, Nakayama H, Matsuda M. Hyperbaric diuresis at thermoneutral 31 ATA He-O2 environment. Undersea Biomed Res 1984; 11:341-354.
10. Webb P, Troutman SJ, Frattali V. et al. Hana Kai II: A dry saturation dive at 18.6 ATA. II. Energy balance. Undersea Biomed Res 1977; 4:221-246.
11. Mills JN. Human circadian rhythms. Physiol Rev 1966; 46:128-171.
12. Minors DS, Mills JN, Waterhouse JM. The circadian variations of the rates of excretion of urinary electrolytes and of deep body temperature. Int J Chronobiol 1976; 4:1-28.
13. Wesson LG. Electrolyte excretion in relation to diurnal cycles of renal function. Medicine 1964; 43:547-592.
14. Minors DS, Waterhouse JM. Circadian rhythms and the human. Bristol; Wright PSG, 1981; pp 311-319.
15. Loutit JF. Diurnal variation in urinary excretion of calcium and strontium. Proc Roy Soc B 1965; 162:458-472.
16. Webb P. Thermal stress in undersea activity. In: Lambertsen CJ, ed. Underwater Physiology V. Proceedings of the fifth symposium on underwater physiology. Baltimore; Williams and Wilkins, 1976; pp 705-724.
17. Shiraki K, Konda N, Sagawa S, Nakayama H, Matsuda M. Body heat balance and urine excretion during a 4-day saturation dive at 4 ATA. Undersea Biomed Res 1982; 9:321-333.
18. Hong SK, Claybaugh JR, Shiraki K. Body fluid balance in the high pressure environment. In: Shiraki K, Matsuda S. eds. Hyperbaric Medicine and Underwater Physiology, Kitakyushu; Program Committee of IV UOEH Symposium, 1983; pp 223-234.

RECENT DEVELOPMENTS IN EQUIPMENT AND PROCEDURES FOR DIVING IN WATERS CONTAINING HAZARDOUS SUBSTANCES

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INTRODUCTION

The NOAA Diving Program (NDP) first became involved with diving in polluted waters during the mid-1970's. NOAA's scientists were heavily involved with studies concerning the ecology of the New York Bight, an area that is approximately 10 miles south of New York City and is a dumping ground for a multitude of raw sewage and industrial wastes. Many of the studies being conducted in the New York Bight involved project support utilizing divers. Because the pollutants in the water were causing a growing concern for the health and safety of the divers, an effort was undertaken by the NDP to provide equipment and procedures that would increase the level of protection that was afforded to the divers by currently available diving equipment. The original effort concentrated primarily on pathogenic microorganisms, but was expanded to include hazardous chemicals, nuclear reactor effluents, and diving in nuclear reactor containment pools. As the effort progressed, Federal, state, academic, and industrial organizations began to express an interest in the studies being done by NOAA. The interest resulted in the formation of an informal working group whose purpose was to pool expertise to further the studies. Through the informal working group an interagency agreement was formed between NOAA and the Environmental Protection Agency (EPA). The agreement provided the funding for a four-year project dedicated to the development, modification, and demonstration of equipment and procedures for use in polluted water diving. The project has resulted in a number of new ideas and procedures. Some of the ideas and procedures have already been applied to operations in the field, while others more conceptual in nature will be developed further and may be utilized in future diving operations.

EQUIPMENT MODIFICATION AND EVALUATION

Relative to equipment, there are three areas of primary concern. They are the suit, the mask or helmet, and the configuration of the breathing system. All the equipment considered was off-the-shelf and commercially available. Modifications were made to various systems to improve the system's performance in a polluted environment.

SUITS

When choosing a suit three factors should be taken into consideration. The basic material from which a suit is constructed will have a considerable effect on the amount of pollutant that can be absorbed or passed through the suit to come in contact with the diver. Obviously the choice of a suit will be dependent upon the pollutant that is contaminating the water. NDP evaluated a number of suits during a one-week exercise at the Naval Surface Weapons Center in White Oak, Maryland.

Suits that were made of standard neoprene were not given serious consideration, because neoprene material acts as a sponge and absorbs a large amount of water. In the past, neoprene suits worn to respond to oil spills were discarded after minimal use for this reason. Eventually any contaminants will degrade and pass through a neoprene material; this is likely to be especially true during decontamination procedures when a high pressure sprayer, used to clean a diver, might force the contaminant through the suit material. To prevent this from occurring, a suit with a smooth outer surface should be selected. It is also important that the seams of the suit be sealed by a vulcanizing process or similar procedure. This type of material and construction will also aid in the decontamination of the diver. The number of openings and the type of openings in the suit must also be considered when selecting the suit. Minimizing the number of openings in a suit will obviously minimize the number of possible failure points. In all cases, boots should be attached to the suit; this will leave a maximum of 3 or 4 openings in the suit, depending on whether or not the suit is of the neck entry or shoulder entry type (type 0). The neck-entry suit presents the minimum number of openings but is not compatible with many of the helmets that are currently available on the market. There will, therefore, usually be four possible failure points: the neck openings, the shoulder zipper, and the two wrist openings. A positive locking mechanism should be used to attach the gloves and helmet to the suit, and a heavy-duty (HD) zipper should always be used for shoulder entry suits. There have been discussions concerning the possibility of constructing a double zipper or zipper within a zipper. Further discussions with manufacturers have confirmed that this could be done easily, but it has not yet been tried. It should be noted that the HD zippers used in the suits considered have a very low failure rate. During three years of testing and use, NOAA has not experienced any leaks or failures that could be attributed to the zipper. Zipper failures can usually be traced to improper maintenance, abuse, or human error.

GLOVES

Despite the work that has been done, divers' gloves still remain the weakest point in the polluted water diving systems developed and observed by the NDP. The gloves actually present two separate problems. The first problem concerns the material of which the gloves are manufactured. Gloves, because of the way they are used, must take a great deal of stress, and yet they must be highly flexible so as not to inhibit the operational effectiveness of the diver. Gloves may also be exposed to high concentrations of contaminants. Using gloves in a chemical environment could limit the choice of gloves. Degradation of the glove material could further weaken the glove and increase the possibility of a tear or puncture occurring.

The method or mechanism for attaching the glove to the suit creates the second problem. The ideal situation would be a positive locking mechanism that would not stress the glove at the point of attachment and could not accidentally unlock during the dive. This type of glove would have to be compatible with the suits that are currently used for diving in contaminated waters. This type of glove does not exist in the diving industry at this time but has been developed and is being used on the suits worn by NASA's astronauts. The potential for an exchange of technology in this area is very high and future work to develop gloves for diving should include a cooperative effort with NASA. Currently the NOAA polluted water system uses a two-glove, two-ring system. An inner ring is placed inside the suit before the diver dons the suit. After the suit has been donned, the inner glove, a thick latex glove, is put on over the suit cuff and inner ring. The inner glove is sealed in place using an outer ring that is designed to lock with the inner ring. Although the rings lock, they can and have accidentally opened during test dives. The tenders must be extremely careful as they dress the diver to ensure that the rings are properly positioned. The second glove, a 40-mil-thick natural rubber glove, is put on over the first glove and both rings. It self-seals on the outer ring and an additional rubber band can be positioned over the outer ring to further seal the outer glove. The outer glove provides the primary protection and abrasion resistance. The inner glove will not provide any abrasion or tear resistance but will keep the hand dry and prevent further leakage into the suit if a small leak develops, which should allow the diver enough time to end the dive and return to the surface. During initial efforts, the NOAA diving team tried to use a third outer glove to provide more puncture and tear resistance; it was a heavy cotton or light canvas work glove. Unfortunately, the third glove was too cumbersome and the diver lost too much dexterity. The two-glove, two-ring system was finally decided upon as the optimum system at present. Future work will have to be done to eliminate the weaknesses that exist in the glove system.

BOOTS

Various types of boots need to be considered in choosing or designing the suit. For a system that is not free swimming, a heavy-duty boot with a steel toe and steel shank offers the best protection. With a free-swimming system, a boot that will accommodate fins will have to be used. Such a boot should be made of a thick, smooth material that will resist abrasions and punctures, provide a non-slip sole, and lend itself to decontamination.

As part of the suit system, NOAA has developed a lead sole similar to a shoe insert. Each sole weighs 5 pounds and fits into the boots of a nonswimming system. This places the weight low on the diver's center of gravity and helps prevent the possibility of an inversion or blow-up. This also means there is less weight that has to be put on a belt or in pockets on the diver and in turn there is less equipment to decontaminate at the end of the dive. On some systems the lead soles replace the weighted boots that are part of the standard dress. The U.S. Navy Mark XII system is an example of a system of which this is true. Overall, the lead soles provide a measurable increase in the diver's comfort, mobility, and safety, and would be a positive addition to any deep sea system.

MASKS AND HELMETS

The second area of primary concern in equipment selection for polluted water diving is the selection and mating of a mask or helmet. During the initial investigations, a large effort centered on the U.S. Navy Mark I Mod 0 band mask and the AGA Divator full face mask. Further work included the Draeger hood, the Superlight 17B, the Desco helmet, the U.S. Navy Mark XII, and the Helmax SSS. Of the seven systems that were evaluated, five are considered viable options, under specific conditions, for polluted water diving. The band mask was modified a number of times but was finally dropped as a feasible system due to the wetness that occurred around the head and face area. The wetness was a direct result of the neoprene hood and the zipper used to close the hood. Several attempts were made to modify the hood and exclude the wetness, but none of the results was satisfactory. The Draeger hood was not given further consideration because it is rarely used in the United States and it is not readily available as an off-the-shelf stock item. The breathing system on the Draeger hood was modified during this early evaluation and the concepts behind the modifications were taken into consideration in subsequent evaluations of helmets. The AGA Divator mask was one of the original masks evaluated. It is the only mask that is presently being considered for polluted water use and is actually being used by NOAA divers for increased protection against microbial hazards. The mask is a positive-pressure demand system that can be used with SCUBA or surface-supplied air. If the mask is used for surface-supplied diving, a special one-way valve should be installed at the air inlet to prevent a squeeze in the event of an air loss. The mask provides a measurable increase in protection through the full face coverage, separate air intake and exhaust ports, and a positive interior pressure that will seat and seal the mask skirt against the diver's hood. The mask is lightweight, inexpensive, and easily maintained. NOAA currently trains its divers in the use of the mask during its Operational Diving Course, and the mask is routinely used to support operational divers.

Four helmets were evaluated: two demand systems and two free-flow systems. Both demand systems were modified to enhance the ability of the breathing configuration to totally exclude any intrusion by contaminated water. The standard exhaust valve was first modified to incorporate a "series exhaust valve" (S.E.V.). With a standard exhaust valve, there is the potential for minute droplets to catch on the edge of the flapper valve; during a subsequent inhalation, a vacuum is momentarily created and the droplet forms a fine mist or vapor that is inhaled into the lungs. This sequence could be extremely detrimental to the health of a diver working in contaminated waters. With the S.E.V., a second inner valve serves two purposes: it lessens the vacuum effect on the first or outer valve where the droplets form and inhibits any mists from passing through and into the diver's lungs. The valve has been used successfully on the Superlite 17B, the Helmax SSS, and the Draeger hood. The valve does not appear to increase the exhalation resistance by any appreciable amount.

The valve has not been tested on a breathing machine but has been tested by many divers under a variety of working conditions. Currently it is commercially available on the Superlite 17B and the Helmax SSS.

A second modification was made to the second-stage diaphragm cover. In the normal set-up, the diaphragm references the ambient water pressure through the cover and is therefore in direct contact with the water. If noncompatible materials are present in the water, the diaphragm could be damaged or could fail totally, allowing the contaminated water to flood into the helmet. To prevent this, the NDP developed a "diaphragm protector" cap. The cap encompasses the diaphragm, isolating it from the water. The cap is piped back into the helmet. The interior pressure of the hat is the same as the ambient water pressure, since the suit acts essentially as a diaphragm does. If there is a neck dam, the pressure transfers across it. The helmet diaphragm then senses or references the ambient water pressure through the pipe. Use of the "diaphragm protector" has been only partially successful. It has been installed on both demand systems, and on both helmets it noticeably increased inhalation resistance. Further work showed that a near-perfect seal between the diver and the oral nasal was needed to reduce the resistance. If there was no seal, the diver, when inhaling, would actually be drawing on both sides of the helmet diaphragm. The net result would be no air flow. The diaphragm protector was used during a polluted water exercise/demonstration and the concept does hold a lot of promise. There are still a number of problems that will require additional work to reduce the inhalational resistance and to make the system operationally ready.

By the nature of their design, free-flow systems provide an increased level of protection over a demand system in a contaminated environment. Unfortunately, the high air flow requirements may set prohibitive operational constraints. The only modifications made to the free-flow helmets were to install a series exhaust valve on the Desco helmet. The valve worked well in the free-flow helmet, as it had in the demand systems. The U.S. Navy Mark XII SSDS helmet was not modified but was used as a stock item off the shelf. The NDP did make a minor procedural modification to the U.S. Navy Daily Predive Procedures. Table 2.Z; Step 3.2, P, Flow and Leak Test; of the Operation and Maintenance Instructions for the Mark XII SSDS state that the helmet exhaust valve spring tension screw should be set at 0.3 ± 0.05 psig. At this setting, with the exhausted valve open full and the inlet valve set between four and six ACFM, the system appeared to be slightly buoyant; among the members of the NDP dive team, there was general consensus on this point. The dive team tried a number of lower settings and found that a setting of 0.25 ± 0.05 psig was an optimum setting that provided an adequate air flow, which lets the divers feel more stable on the bottom and in control of their buoyancy. The setting of 0.25 ±

0.05 psig is considered to be the standard for the Mark XII polluted water diving system in the NOAA Diving Program. Informal inquiries were made as to why the technical manual called for a higher setting but no definite replies were presented. All NOAA tests and evaluations indicated that the lower setting is safe and operationally more effective.

DIVER UMBILICALS

Equipment and procedural modifications were evaluated to increase the operational capability of the diving systems and to lessen the problems associated with decontamination procedures. These evaluations focused largely on diver umbilicals; three independent concerns pertaining to umbilicals arose. The original fluorescence dye test, which will be further discussed in this paper, revealed that the duct tape used to marry most diver umbilicals was also a "hot spot" for contaminants. The glue material on the tape collected the dye like flies on fly paper, indicating that it would also collect and hold any contaminant the umbilical came in contact with. To alleviate the problem, new umbilicals were made up using electrical tie wraps. They provide the strength to maintain the umbilical and did not collect any dye during the tests. The tie wraps do have to be cut and filed where the tail comes through the lock to avoid chafing and cutting the tender's hands, but the solution has otherwise been perfect and it does not interfere with normal diving operations.

In the time since the NDP's tests and evaluations have been run, a new option has been presented as a method to do away with the need for anything to marry with the umbilical. The new design is a three-element umbilical manufactured with a helical twist in it. The helical twist causes the umbilical to act in the same way a three-strand line does. Initial inquiries and tests indicate that the helical umbilical will also provide a solution for the next problem that is described.

The elements that comprise a diver's umbilical were reviewed with a view toward reducing the number of elements. A standard diver's umbilical has historically been composed of four service elements: an air supply hose, a communications line, a lifeline, and a pneumo hose to measure the diver's depth. This presents a decontamination problem and can be an operational frustration. There is a movement within the diving community to combine the communications line and the lifeline, thereby reducing the number of required service elements. The standard deep sea umbilical as used on the Mark XII is designed in this manner. The communications line, which has 18 leads and is covered by a Kevlan braid, also acts as the lifeline. With a lightweight umbilical, the idea was to use an inexpensive "spiral four" communications cable as the communications and lifeline, thereby reducing a lightweight umbilical to the three elements. This umbilical was used on a number of test dives and for an equipment demonstration. It appeared to work well. More detailed destructive testing of the "spiral four" cable revealed that the breaking strength of this type of wire made it inadequate to serve as a lifeline. The breaking strength of this cable is supposed to be in excess of 1500 pounds, but no documentation can be found to substantiate this.

The cable is a military surplus item that was designed for use as a land communications line. It is commonly sold as diver's communications cable and does serve that specific purpose quite well. In actual tests, the wire broke over a range between 350 lbs and 550 lbs, which is below strength requirements for a diver's lifeline. The tests were run on an increasing lineal pull until the cable failed. Various methods of attaching the snap shackle did not increase the breaking strength but did affect where the wire broke. In view of these data, NOAA opted not to use the spiral four cable as a commications/lifeline in operational diving. However, it appears that the helical umbilical will also solve the strength problem. The communications/lifeline from a section of helical umbilical was separated from the umbilical and tested in the same manner as the spiral four communications cable. Under tension in excess of 1500 psi, the communications/lifeline from the helical umbilical was still intact.

It appears that an ideal lightweight umbilical for polluted water diving would be a three-element helical umbilical with a singular covering. Different covers could be purchased for use in a variety of chemicals, depending on the properties of the chemicals. This type of umbilical may be available in the near future.

Flow tests were performed on a lightweight umbilical to evaluate its use on a Mark XII helmet in place of a deep sea umbilical. An air fitting was commercially available to adapt the helmet air inlet to a lightweight fitting, and the communication bulkhead was replaced to adapt the helmet to a marsh-marine fitting. Individuals in the commercial industry were using the helmet with lightweight umbilicals, but no formal testing had been done to evaluate if the minimum air flow requirements were met. Tests were conducted in a recompression chamber using in-line flow meters. Based on the results of the flow tests, NOAA began to use the lightweight umbilical to support the Mark XII helmet on dives up to 150 feet. The ability to use a lightweight umbilical with the Mark XII helmet makes it a more feasible choice for use in scientific support diving. This was one of the deciding factors in NOAA's decision to designate the Mark XII helmet as Level A Polluted Water Dress (Level A: highest level of personal protection in hazardous materials operations).

THE SUIT-UNDER-SUIT SYSTEM

During the equipment modification and evaluation stages of the project, a new concept in suits was developed. It is a positive pressure diving system called the "suit under suit" (SUS).

The SUS is an innovative solution to two problems associated with contaminated water diving - thermoregulation and leakage. The SUS consists of an inner, thin, foam neoprene neck-entry dry suit with attached booties. A conventional dry suit with ankle exhaust valves and an adjustable arm-mounted exhaust valve are worn over the inner suit. A "neck dam" installed in the outer suit is clamped to the entrance yoke of the inner suit, thereby creating a closed cavity between the two suits and separating the diver's head from the suits. An outer chafing/restraining garment is worn over the outer suit.

Clean water of the desired temperature (hot or cold) is pumped into the area between the two suits to warm or cool the diver. Since the entire volume of the suit is filled with water under a pressure slightly greater than that of the outside water, a puncture or leak in the suit results in clean water leaking out, rather than outside water coming in, as is the case with air-filled suits. In the latter, the air pressure below the chest level of a standing diver is lower than the outside water pressure. The insulating quality of the inner suit prevents burning of the diver in the event very hot water is accidentally sent down the umbilical; this type of accident has happened several times with commercial hot water suits.

INWATER TESTING AND PROCEDURE DEVELOPMENT

Throughout the entire project, a constant effort was required to align the dive team members' thought processes with the fact that the equipment and procedures being developed and tested were for use in waters that would contain hazardous substances. This constrained the NDP team and forced them to minimize the number of areas on the equipment that would hold contaminants. On-site diving procedures had to be reviewed and revised to minimize the number of personnel who would be exposed to contaminants during a project and to integrate the divers into an overall response team.

Equipment was first evaluated on a piece-by-piece basis under strictly controlled conditions. Standard diving procedures were used. As individual pieces of equipment successfully passed evaluations, they were combined with other pieces of equipment and these pieces were then evaluated as a system. When the systems had been successfully evaluated, they were reevaluated with modified diving procedures for diving at hazardous dive sites.

The initial tests were conducted at the Naval Surface Weapons Center in White Oak, Maryland. The diving was conducted in a tower that is 100 feet deep and 60 feet in diameter. The tank holds approximately 1-1/2 million gallons of water and has a platform in the tank that can be lowered or raised to control the bottom depth. Portholes along the side of the tank allow direct viewing at various depths.

The first dives were conducted at shallow depths, sometimes as shallow as 10 feet. A safety diver was in the water with the test diver and the platform was lowered to the test depth. Using the platform, the descent could be stopped instantly at any point and, if necessary, raised to the surface. During the initial dives, the divers swam with the suits and helmets, practiced various joint movements, and evaluated the equipment for flexibility, usability, and comfort. More dives were made at increasing depths and the equipment was put through more strenuous tests. Throughout all the dives, still and video documentation were used to record the performance of the equipment. The documentation was later reviewed to further improve the equipment and to analyze weaknesses. It was also used for presentations and can be used in the future as a training aid.

Evaluations of a Mark XII suit that was designed to negate the need to use an outer garment with the Mark XII system were conducted in a series of dives that permitted direct comparisons of the different suit styles. The standard Mark XII has a smooth outer surface and requires a second suit, called an outer garment, to hold the system's weights and to restrict the inner suit from over-inflation and blow-up. In the effort to reduce the amount of equipment and its associated decontamination problems, an inner suit was designed using a thicker, more stretch-resistant material. The suit was manufactured with pockets to hold the weights that were a part of the inner suit. Restraint straps were located on the legs in the same manner as on the standard outer garment. Test dives using this suit showed that the weights stretched the suit excessively and that over-inflation in the chest and arm area caused flexibility problems and made the system too buoyant. The suit was redesigned. In the new design the pockets are detachable. Tests are being made on the suit by the U.S. Navy and the U.S. Coast Guard.

During the initial test dives, a different approach to protecting the diver was also considered and tried at the test tank. The approach was to put the diver, using standard SCUBA gear, in a surface personnel protection suit, specifically in a Level A total encapsulation suit. This one-piece suit is "gas tight" and is usually used with surface self-contained breathing apparatus. Valves in the suit vent the air exhaled by the user. The first dive showed immediately that the encapsulating suit was extremely buoyant and could not be used in its standard configuration. Even when holding an additional 50 pound weight on a down line, the diver could not remain on the bottom. As the suit alternately filled with air and then vented the air, the diver would uncontrollably ascend and descend. This was caused by the fact that the suits are designed to be loose fitting and that the exhaust valves will only vent when the interior pressure of the suit causes them to open. The possibility does exist that the suit could be redesigned, but this was not pursued and the entire approach was dropped.

One of the main criteria for a successful evaluation of a suit, helmet, or system was water-tight integrity. As the systems were increasingly improved until they approached absolute integrity, it became harder to evaluate them because of the moisture that was present from condensation of the diver's breath.

The next series of tests was designed to provide quantitative data on the watertight integrity of each suit and helmet that was still under consideration. A special 5000 gallon test tank was prepared at the Environmental Protection Agency's Oil and Hazardous Material Simulated Environmental Test Tank (OHMSETT) facility in Leonardo, New Jersey. The water in the tank contained a deep pink fluorescent dye and ammonia solution. Both the dye and the ammonia were used as tracers to measure any leakage in the diving systems.

Under the dive suit a special white body suit was worn. The material of the body suit, which has an affinity for the fluorescent dye, was chosen so that it would show any leakage under inspection in a dark room with an ultraviolet light. The body suits were inspected pre- and post-dive to rule out any erroneous indications. The interior of all the equipment was also inspected. Specific attention was given to the inside of the helmets, gloves, and the zipper area of the suits. It should be noted that extreme care has to be used to avoid inadvertent spreading of the tracers. The tests showed how careful and precise a team has to be to avoid inadvertent spreading of contaminated substances.

METHODS OF LEAK DETECTION

Three methods were used to measure or detect possible leakage of the ammonia tracer. One method was to place cotton balls in the areas of the helmet where leaks were most likely to occur. This included the interior of the mating surface and the exhaust valves. After the dive, the cotton balls were removed, sent to a lab, and processed for indications of the ammonia tracer. The second method utilized a polymeter to measure gas concentrations. The direct reading instrument pumps air through a detector tube that indicates the presence of a specific substance. For the test dive, a tube that indicates ammonia was used. The tubes provide an actual measurement and more importantly provide an immediate visual sign of the presence of the substance being measured. Using rubber hoses designed for use with the polymeter, the sampling inlet can be placed at the location where any leakage is most likely to occur. A harness, which can hold two polymeters, was worn by the test diver under the suit. Using a hose, one tube was placed in the diver's helmet and a second tube sampled the chest area of the suit. If used with the Mark XII helmet, the tube could be placed on the inside of the upper part of the faceplate, allowing the diver or outside personnel to read the tube. The third method used in the tests to sense any leakage of ammonia was smell. Since ammonia has a strong biting smell, any minute amount of leakage would be noticed immediately by the diver. The test dives run at the OHMSETT facility were completely successful and no leaks were found in any of the systems tested.

DECONTAMINATION PROCEDURES

During the dives run at OHMSETT, the first steps were taken toward establishing a decontamination procedure for the diver. After each dive, the diver was sprayed down with a high-pressure sprayer that mixed various solutions with water. For the OHMSETT dives, a three-step spray was used. The first spray was a vinegar-water mix to neutralize the ammonia, followed by a betadine washdown, and a final fresh water rinse. Between the second and third wash, heavy-duty brushes were used on critical areas where the dyes had been found to accumulate. The zippers, the helmet locking mechanisms, seams formed by the helmet mating surfaces, boots, and the soles of the boots are examples of areas that need special attention during decontamination.

The most important point noted during the initial work on decontaminating a diver was the amount of time needed for the procedure. The first 10 minutes after a diver surfaces are critical to assessing the diver for signs or symptoms of barotraumas, most notably an air embolism. Therefore, the decontamination procedure must be short but effective. This raises one of the more important questions associated with polluted water diving: if a diver exhibits signs of an air embolism, which concern is more critical--the barotrauma and the immediate need to treat it with oxygen and recompression, or the need to decontaminate the diver prior to removing his gear? A secondary question is, what are the potential consequences of putting a diver into a recompression chamber, a hyperbaric environment, if he hasn't been decontaminated, and what are the associated risks to chamber and medical personnel treating the diver? This issue was raised in a number of discussions but it was decided that it can only be resolved on a case-by-case basis, depending on the hazardous substance(s) involved. It is definitely a problem that must be considered as part of pre-dive planning. The basic question is: in the event of an accident, what has priority, decontamination or immediate medical treatment?

A second question raised by the OHMSETT test dives concerned the location of the diving supervisor during the dive operation. Traditionally, the location of the diving supervisor is in the immediate proximity of the diver, and the supervisor is in direct contact with the diver. The diving supervisor usually has the last word on any issue related to the dive. Diving at a contaminated site raises a conflict because one of the primary objectives of a response team is to minimize the number of people exposed to contaminants. Supervisors often do their work 100 or more yards away from the actual site; in addition, there is a site supervisor who directs the entire operation and coordinates the individual team supervisors. As with the "decontamination versus recompression" question, the question of the location and responsibility of the diving supervisor was discussed in detail on several occasions. This issue was not resolved until the dive team developed and began working with the concepts of "hot zones" and "clean zones." At this point in the process, it was decided that the diving supervisor should be located at a location independent of the dive site and in the designated clean zone. Direct responsibility for the diver then lies with the tenders and the decontamination team. Given this procedure, it is important that key members of the decontamination team be trained tenders who have received training to familiarize them with divers; diving; diving medical maladies; and how to respond in the event of an accident. It was also decided that when working with a full response team, the diving supervisor would be responsible to the site supervisor, also referred to as the "on scene coordinator," in all matters except those directly related to the diver.

To further their knowledge and increase the dive team members' ability to work as a part of a response team, two divers were sent to an EPA course on Hazardous Material Incidents Response Operations. The course was very basic and was designed to provide newcomers with information on the concepts, principles, and equipment that would be used at a waste site and when responding to incidents involving hazardous substances. The knowledge that was gained through attending the course was then used in the development of the diving equipment and procedures and to further integrate the members of the dive team into a unit that could work as an integral part of a full response team.

To gain more experience and to evaluate the polluted water system further, open water dives were also conducted. These dives were done at various locations. In addition to contributing to the development of the system and further refinement of the equipment, each series of dives added to the diving team's experience in setting up and conducting a dive and using the new equipment and procedures.

After OHMSETT, the next series of test and evaluation dives was run at the NOAA Diving Hyperbaric/Training Center in Miami, Florida. The NOAA test tank at the center was used and the tests run at the OHMSETT were repeated using the Superlite 17B and the Mark XII, the two helmets that were considered to be the most promising for application to polluted water diving.

In Miami, a glove tester designed and built by the Diving Program was evaluated. The glove tester was used to check gloves for leaks prior to their use. All gloves, both inner and outer, were checked prior to every dive. The tester is a simple device and can be built by any dive team working in polluted water or by a hazard response team working at a spill dump site. As mentioned previously, gloves are one of the areas of high stress and abrasion. The tester assures that the diver's gloves are, at the very least, intact at the beginning of the dive.

In Miami, the dive team began to apply its knowledge of hazardous response operations. Boundaries were set up to designate hot zones, decontamination areas, and clean zones. The decontamination procedures started at OHMSETT were used and refined. Patterns and guidelines were set for the use of the high-pressure sprayer. Top-to-bottom downward actions of the sprayer were optimal; it is extremely important not to bring the nozzle tip too close to the equipment being cleaned. Trials showed that pressure from the spray could push contaminants through any seams, zippers, or sealing surfaces that are hit with the full force of the sprayer. An optimum distance is approximately 1 1/2 feet at the closest point; this distance also reduces the splashback and decreases the amount of contaminants that may be splashed onto personnel working in the decontamination area. Obviously, decontamination personnel should be aware of the splashback and work accordingly. Work also continued on efforts to reduce the amount of time needed to do a complete, thorough decontamination.

On one dive there were indications that leakage had occurred. The leak was traced to a pinhole near an underarm seam. A review of the pre-dive procedures revealed that the suit had not been leak-tested prior to the dive. Again, this indicates the importance of adhering to a strict set of pre- and post-dive procedures.

The third series of system integrity tests was also run at the Miami facility. The first half of this series was devoted to further integrity tests. Personnel from the NOAA Hazardous Materials Response Branch and the United States Coast Guard's East Coast Strike Team provided training and information to finalize the decontamination procedures. To make the decontamination process more realistic, molasses and honey were poured over the diver just prior to starting through the decontamination line to simulate a hazardous substance.

During this period, a large effort went into coordinating the air supplies of the decontamination team and the tenders, in order to provide proper support to the diver. Communication was also a problem that had to be overcome. This was especially true for communications between the dive supervisor and the tenders, who were working in Level A personal protective gear.

The second half of this test period was used to run dives testing the thermal limits of the SUS system. A mixed gas port of the Mark XII helmet was modified to accept the cable for a medical harness. The harness, worn by the diver, measured the interior helmet temperature and the diver's rectal temperature, and provided an EKG reading to measure the diver's heart rate. Dives were conducted in water with temperatures up to 44.4°C (112°F). They were conducted with and without cooling water being pumped into the SUS system. Dramatic differences were seen in the degree of heat stress experienced by the divers during the test. The thermal evaluations were done to support working dives being made in nuclear thermal effluents and containment pools, which are considered a type of polluted water.

The last series of dives at the Miami test tank completed the primary work on equipment testing and procedure development. The next step was to run a full-scale scenario demonstrating the equipment and procedures. Initial plans were made to conduct the exercise at the NOAA Sand Point facility in Seattle, Washington. In the interim between Miami and Seattle, minor upgrades were made to the equipment to incorporate new changes that had occurred, but these changes did not require additional testing. At the time of the presentation of this paper, more changes and upgrading have occurred. The field of polluted water diving is relatively new. Equipment changes and new ideas will require more testing and evaluation in the immediate future to continue to advance the state-of-the-art in polluted water diving.

FIELD EVALUATION AND DEMONSTRATION

NOAA's final step in the development of polluted water diving equipment and procedures was to stage a four-day demonstration. The NOAA Sand Point facility was chosen for the demonstration because it offered an accessible dive site with adjacent piers and good shore support. Personnel from NOAA, the U.S. Coast Guard, and the EPA participated in the exercise. There were also observers from many other agencies and organizations with interest in the areas of polluted water diving and hazardous materials response.

Various tasks were performed during the exercise to demonstrate that the polluted water equipment and procedures could be used to complete standard projects in a nonstandard environment. Examples of the tasks included the installation of tide gauge float wells; underwater cutting; and current meter removal and replacement. Tasks that could be utilized only during a hazardous material response were also simulated.

Three diving systems were demonstrated. They were the Mark XII helmet, the Superlite 17B with NOAA modifications, and the NOAA Suit Under Suit. The SUS was used with the Mark XII helmet. The primary exercise was the simulation of a drum search and recovery. Fifty-five gallon drums filled with 50 lbs. of sand were scattered and buried on the bottom by SCUBA divers on the days previous to the exercise. The exercise started when the complete team arrived on site in their vehicles as if they had just been called to an actual response. All the equipment had been previously packed so that it could be transported and set up for immediate use. Once on scene, lines were set up to designate the hot zone, the decontamination area (also called the warm zone), and the clean or cold zones. According to the demonstration scenario, the different zones were all considered clean until the first diver entered the water. In the hot zone, a modified lean-to was set up to protect the tenders from the heat of the sun while the divers were working. Similar shelters were set up in the clean zone and the decontamination zone to protect the surface personnel. The diver also needs to be shaded from the sun during the pre-dive dressing procedures, because heat stress is a critical factor when people are entirely encapsulated in a suit that retains heat and prevents cooling. Physical collapse with severe medical repercussions can occur rapidly under a hot sun. Large amounts of liquids must be on the site for consumption, and supervisors must be aware of the signs and symptoms of heat stress. Any liquids or food should be consumed only by personnel who are in the clean zone or have been properly decontaminated and cleared by the site supervisor.

To set up for the dive, the majority of the umbilicals were laid out in the hot zone. A short section on the air supply end, and enough to permit the diver to be dressed, remained in the clean zone. After the dive, enough umbilical from the diver's end is cleaned as the diver passes through decontamination; this allows the diver to return through the clean zone, where the undressing of the diver is completed.

All the equipment and personnel in the decontamination zone need to be ready before the dive can start. If an emergency situation arises just after the dive commences, the decontamination team must be ready to react to it immediately. Once they begin to work, their air must be constantly monitored and coordinated with the diver's activity. Personnel with a low air supply should have their tanks rotated just prior to the diver's exit from the water, so that they can give their full attention to the diver and not run low on air during the actual decontamination procedure.

A method to ensure that the diver is properly supported by tenders and decontamination personnel is to use a rotation system. When a tender or a decontamination team member runs low on air, a standby is rotated into the team. The individual who rotates out goes through a partial decontamination, receives a new air supply, and then becomes the standby ready to rotate in when the next individual needs to rotate. Separate back-ups can be used for tending and for members of the decontamination team. The rotation can also be used to provide a break for individuals who are overheated or need a short rest.

When the dive site and the decontamination team and support personnel were ready, the final steps to dress the diver were taken. Leak tests were performed in a large tank of clean water located behind the dressing area. This last test, taken just prior to the dive, is designed to help prevent any catastrophic failures or oversights from occurring in contaminated water. The tank was a fiberglass container with dimensions of approximately 6' X 12' X 3'. It was brought on-site in the equipment vans and filled from a local fire line. The dip test is also used to find any minor leaks prior to the diver being dressed.

After the final leak test, the equipment that does not contribute to the air-tight integrity of the diving system is put on, and the diver passes from the clean zone through the warm zone into the hot zone. At each zone interface, the responsibility for the diver is passed to the support personnel for that zone.

The site supervisor and the diving supervisor were located in a truck set up as a command post. When the zones were set up on the initial arrival of the response teams, personnel two-way speakers were set at strategic locations. Through the speakers, the command post could communicate with personnel in each zone. The wire and speakers are inexpensive and therefore disposable. Surface personnel were able to communicate with their breathing apparatus in place and could hear through their protective gear; this overcame the large problem that exists in the field of hazardous materials response teams when individuals attempt to communicate but must also wear personal protective equipment.

During the demonstration dives, the 55-gallon drums were located and individually marked with a float. Each drum was then placed in an overpacking drum which had been lowered to the diver. The packing drums were then floated to the surface with lift bags, towed to a holding area by surface personnel using a tag line, and then lifted out of water with a small truck-mounted crane. The overpacking drums were stored in an area away from the operation. In an actual response, they would then be removed or destroyed in a manner outlined by Environmental Protection Agency procedures.

The drum search and recovery exercise was run for approximately six hours without any major problems. Divers and surface personnel were rotated through the teams. The air supplies were maintained by an air-pumping station located independent of the dive site to simulate actual response conditions that might require air to be pumped a long distance from the dive site. It may often not be possible to bring a large air source supply on-site, and this would require that small amounts of air be shuttled in to the site. This method was chosen over the option of running an air line from the main source to the dive site; the method chosen has the advantage of reducing the number of possible failure points or ruptures. A small bank of bottles was pumped full and transported to the dive site where it was cascaded into the diver's main bank. This procedure worked well and did not interfere or inhibit diving operations.

Air bottles for surface personnel were filled at the remote site and transported back to the dive site. For a large operation, many air bottles, perhaps as many as three or four times the number of personnel on air, are needed; there may have to be individuals on the surface support team who are solely dedicated to maintaining the air supplies.

When the drum recoveries were complete, the entire site was broken down, repacked, and transported back to the starting point. The drum recovery and the entire field evaluation demonstration were considered an unqualified success.

SUMMARY

The exercise conducted in Seattle demonstrated that the equipment developed by NOAA could be used operationally and that divers could be supported by surface personnel using Level A personal protective equipment. The equipment and procedures developed were the result of an intensive three-year effort that essentially brought the state-of-the-art in polluted diving to the point where it is today. This was done by integrating existing diving knowledge and new designs, modifications, and changes in procedures. At each step, existing equipment and procedures were considered and incorporated, whenever possible. Every effort was made to use existing equipment that could be purchased off-the-shelf.

Through the work that has been done by NOAA and other interested parties, polluted water diving has evolved into a distinct form of specialized diving. This evolution is just beginning, and we can expect to see more developments in the near future. Increased demands will be put on divers and diving systems as we attempt to clean up the waters that have been receptacles for toxic wastes. Above all, safety must continue to be the primary concern. Divers should be made aware that a standard diving dress offers less than minimal protection in many situations. In some circumstances, it may not be possible to dive at all, and this must be accepted. Future developments will decrease the number of situations where this is true, and in time divers may be able to respond to any given situation. Until then, the requirement of every dive planned in waters containing hazardous materials must be carefully evaluated and weighed against the short-term and long-term hazards of each particular toxic substance involved. This paper has only reviewed a few of the many questions that must be answered before a polluted water-diving operation can begin.

REFERENCES

1. Blackwell, J. W. and Wells, J. M., Diving in Water Containing Hazardous Materials. Paper presented at United States - Japan Cooperative Program in Natural Resuorces (UJNR) Panel on Diving Physiology and Technology, Nov. 1983.

2. Environmental Protection Agency, "Hazardous Materials Incident Response Operations." Hazardous Response Support Division, Oct. 1982.

3. National Institute for Occupational Safety and Health, "Personal Protective Equipment For Hazardous Materials Incidents: A Selection Guide." Department of Health and Human Services; DHHS (NIOSH) Pub. No. 84-114, Oct. 1984.

4. National Oceanic and Atmospheric Administration, "NOAA Diving Manual." 2nd edition, Government Printing Office Pub. No. 003-017-00468-6, Dec. 1979.

5. Stringer, Jack, "Surviving Underwater Deathtraps." National Oceanic and Atmospheric Administration; NOAA Reprint, Vol. 15, No. 1, Winter 1985.

6. Tejada, Susan, "Safe Diving in Polluted Waters." Environmental Protection Agency; EPA Journal, Vol. 11, No. 2, March 1985.

7. Traver, R. P. and Wells, J. M., Summary of On-Scene Coordinator Protocol For Contaminated Underwater Operations. Paper presented at the International Diving Symposium, Feb. 1984.

8. U. S. Navy Department, Operation and Maintenance Instructions, Mark 12 Surface Supported Diving System; NAVSEA 0994-LP-018-5010, June 1979.

9. U. S. Navy Department, U. S. Navy Diving Manual, NAVSEA 0994-LP-001-9010, 1979.

10. Wells, J. M., Equipment Innovations Cut Risks For Divers in Polluted Waters. Sea Technology Magazine, Vol. 25, No. 12, Dec. 1984.

SATURATION DECOMPRESSION WITH NITROGEN-OXYGEN[1]

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Suppose we have divers saturated at some arbitrary depth, and we wish to decompress them to the surface (fig. 1). Let us decompress at a constant rate of ascent. Upon surfacing, we find that the incidence of decompression sickness is 10%. On the next dive to the same depth, we choose a slower ascent rate for greater safety, and this results in a 5% incidence. If we use progressively slower ascent rates in future dives, we may presumably reduce the incidence of decompression sickness to any desired level. In this manner, saturation decompression schedules could be developed empirically with no recourse to theory. While not guaranteeing the most efficient schedules, the method would be easy to use, with the ascent rate being the only undetermined parameter.

THE EFFECT OF OXYGEN

How should the ascent rate be chosen? The literature indicates that several factors besides ascent rate affect the

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[1] This manuscript is part of a paper which was presented during the UMS/NOAA Workshop, Decompression from NITROX Saturation Diving, on January 8-9, 1985, at the Institute for Environmental Medicine, University of Pennsylvania.

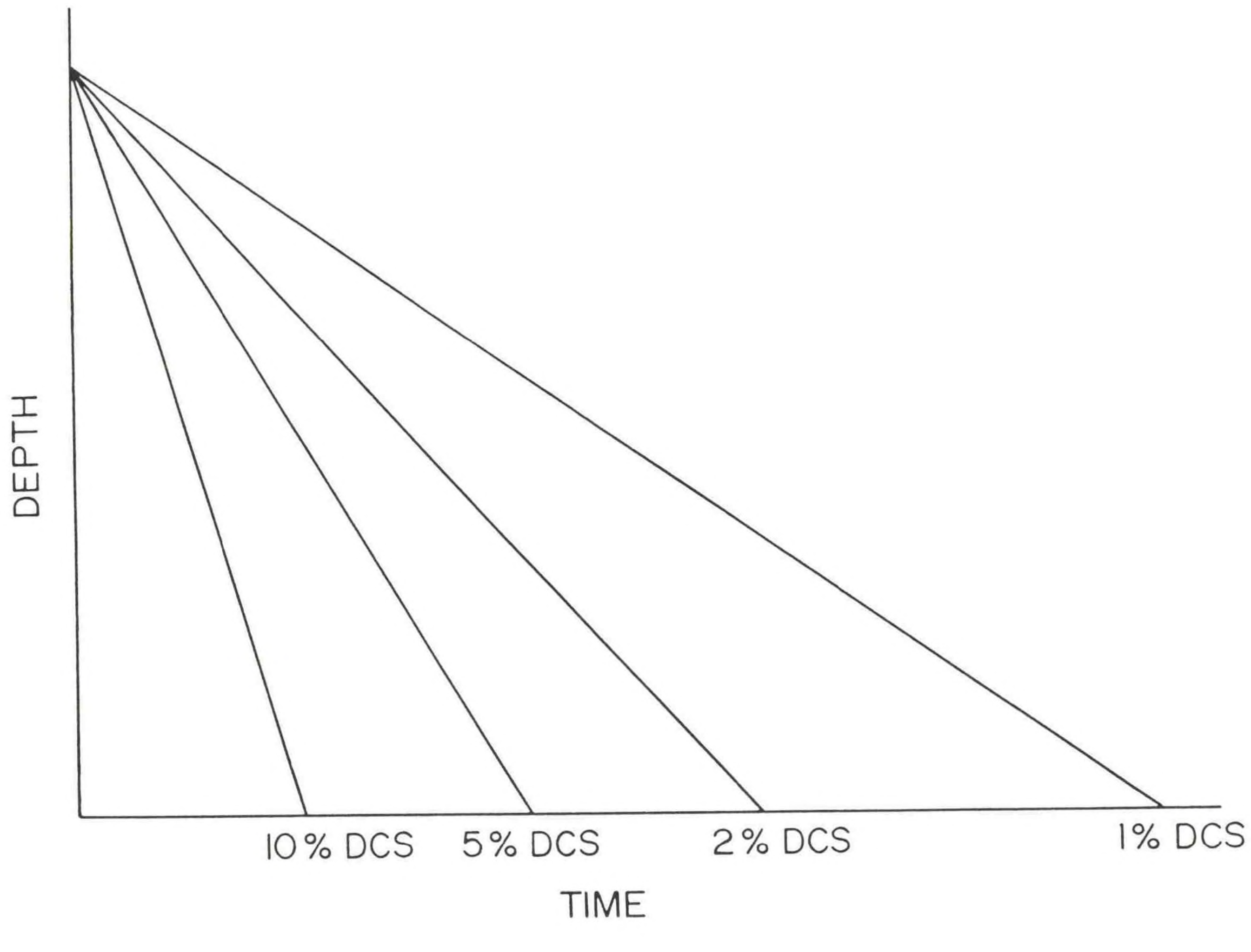


Figure 1.--An empirical method for developing saturation decompression schedules

Table 1.--PIO2 and DCS risk

PIO2 (ATM)	% DCS	Number of Dives	Mean Depth (fsw)	Mean Rate (fph)
0.22	52	27	646	3.5
0.4	0	42	794	3.8

incidence of decompression sickness. One such factor is the inspired oxygen partial pressure which was studied by Vorosmarti, Hanson, and Barnard (1978) in a series of helium-oxygen saturation dives (table 1). These dives used PIO2's of either 0.22 atm or 0.4 atm. With 0.22 atm, there was a 52% incidence of decompression sickness. With 0.4 atm, no decompression sickness occurred despite deeper dives and faster ascent rates.

The influence of oxygen partial pressure on the risk of decompression sickness has been recognized for many years. Among numerous studies of the subject, two from the 1960's are useful here. One of these is Van Liew's demonstration that the rate of inert gas elimination from subcutaneous gas pockets in rats is proportional to the PIO2 (Van Liew et al. 1965, Van Liew et al. 1968). The other is the theoretical prediction by Workman (1969) and by Schreiner and Kelley (1967) that the ascent rate from a saturation dive is proportional to the PIO2 or

$$R = K * PIO2 \qquad (1)$$

where R is the ascent rate and K is the proportionality constant.

Let us adopt this latter hypothesis and call equation (1) the rate equation. By using progressively smaller values of K in

Table 2.--Depth and DCS risk

Mean Depth (fsw)	% DCS	Number of Dives	Mean Rate (fph)
62	13	107	3.2
151	31	45	2.5

succeeding dives, the incidence of decompression sickness could be reduced to any desired level as described earlier. The rate equation, therefore, should qualify as an empirical basis for developing saturation decompression schedules.

The rate equation can be integrated to find the form a decompression schedule assumes for either a constant oxygen partial pressure or a constant oxygen fraction (fig. 2). When the PIO2 is constant, depth is a linear function of time

$$D(t) = Dsat - K * PIO2 * t/33 \qquad (2)$$

where Dsat is the saturation depth in fsw, t is time in hours, and K is measured in fph/atm. When the FIO2 is constant, however, the ascent rate decreases in proportion to the falling oxygen partial pressure, and depth is an exponential function of time

$$D(t) = (Dsat + 33\ FSW) * e^{(-K*FIO2*t/33)} - 33\ FSW \qquad (3)$$

THE EFFECT OF SATURATION DEPTH

A second factor affecting the risk of decompression sickness is the saturation depth itself. This is shown in table 2 where 152 air or nitrogen-oxygen decompressions are divided into groups having saturation depths of less than 100 fsw or greater than 100 fsw (Barry et al. 1984). The shallower group, with a mean depth

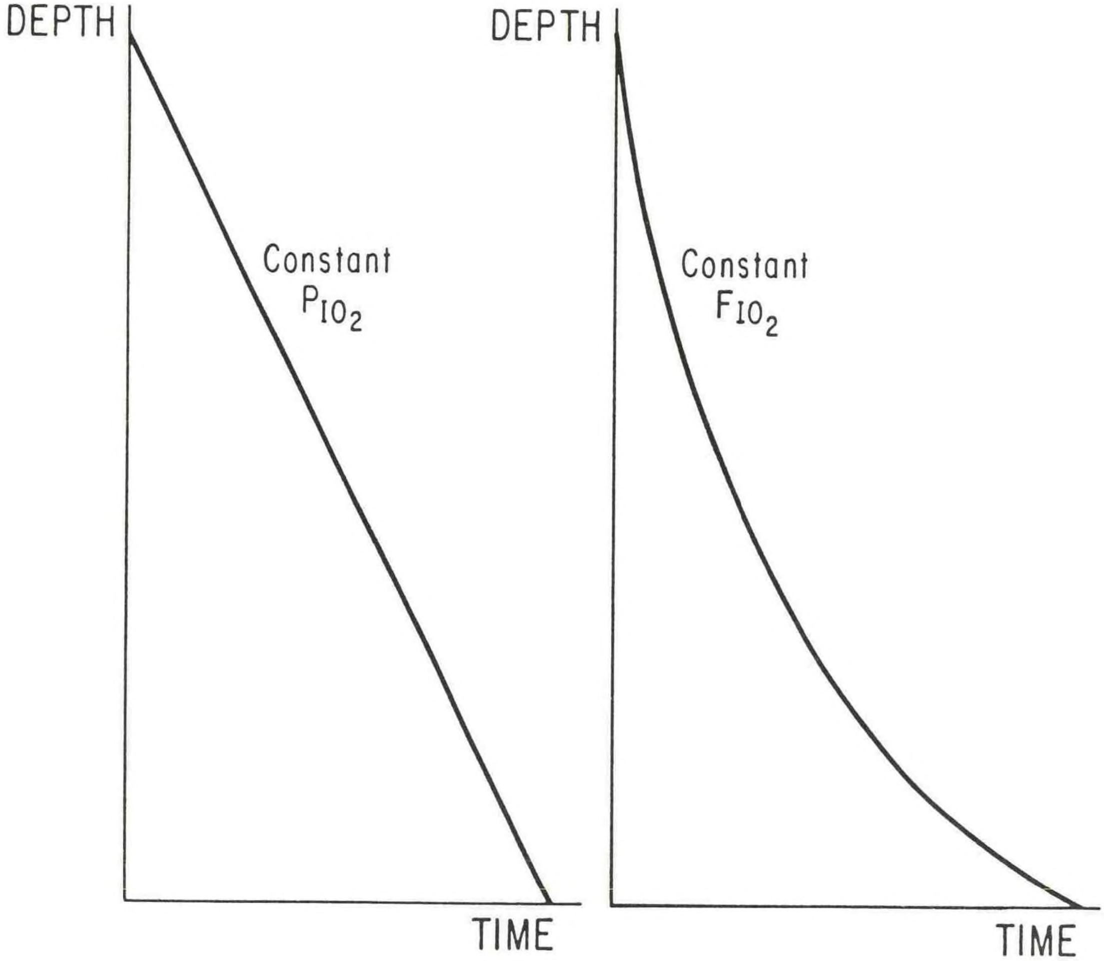


Figure 2.--Saturation decompression schedules based upon the rate equation for constant PIO2 and constant FIO2

of 62 fsw, had a 13% incidence of decompression sickness. The deeper group, with a mean depth of 151 fsw, had a 31% incidence even with slower ascent rates.

Why should the saturation depth affect the risk of decompression sickness? Let us suppose, as most evidence indicates, that decompression sickness is caused by undissolved gas and that the risk of decompression sickness rises with increasing gas volume. If we assume that gas evolves continuously during a linear ascent, we can conclude that the decompression risk increases with time as the gas volume expands.

This situation is illustrated in figure 3 where undissolved gas is represented by spherical bubbles. The bubble present after ascent from the deeper dive is larger than the bubble present after the shallower dive because more time is available for growth. Thus, for the same rate of ascent, the risk of decompression sickness is greater for the deeper dive.

If the ascent rate is reduced, gas evolves more slowly, and a smaller bubble develops. Schedule 1 in figure 4 has a slower ascent rate and a lower gas volume than schedule 2. Schedule 1 will have a lesser decompression risk than schedule 2.

Schedule 3 in figure 4 represents the effect of increasing the PIO2. A higher PIO2 permits a faster ascent rate with no additional bubble growth since, as Van Liew et al. (1965, 1968) demonstrated, increasing the PIO2 increases the rate of inert gas elimination.

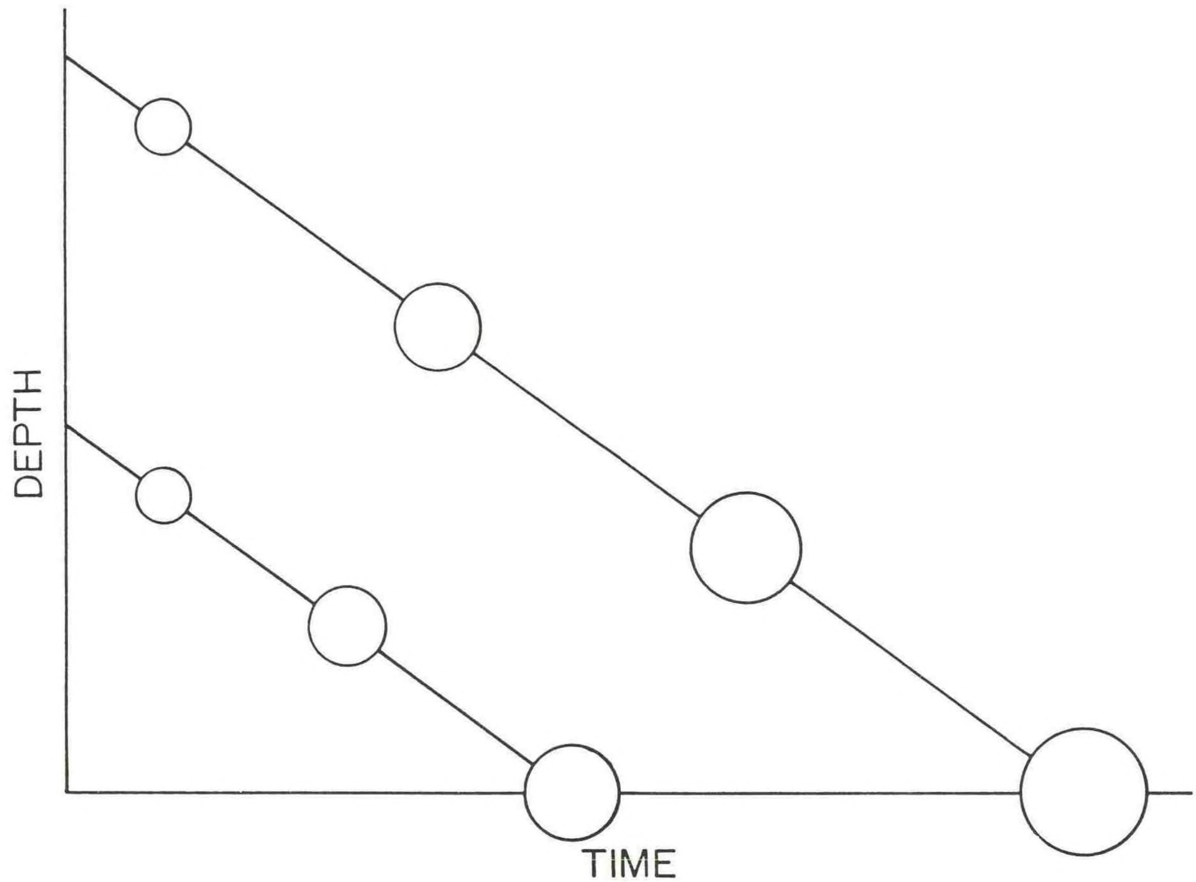


Figure 3.--The effect of saturation depth upon the bubble volume at sea level.

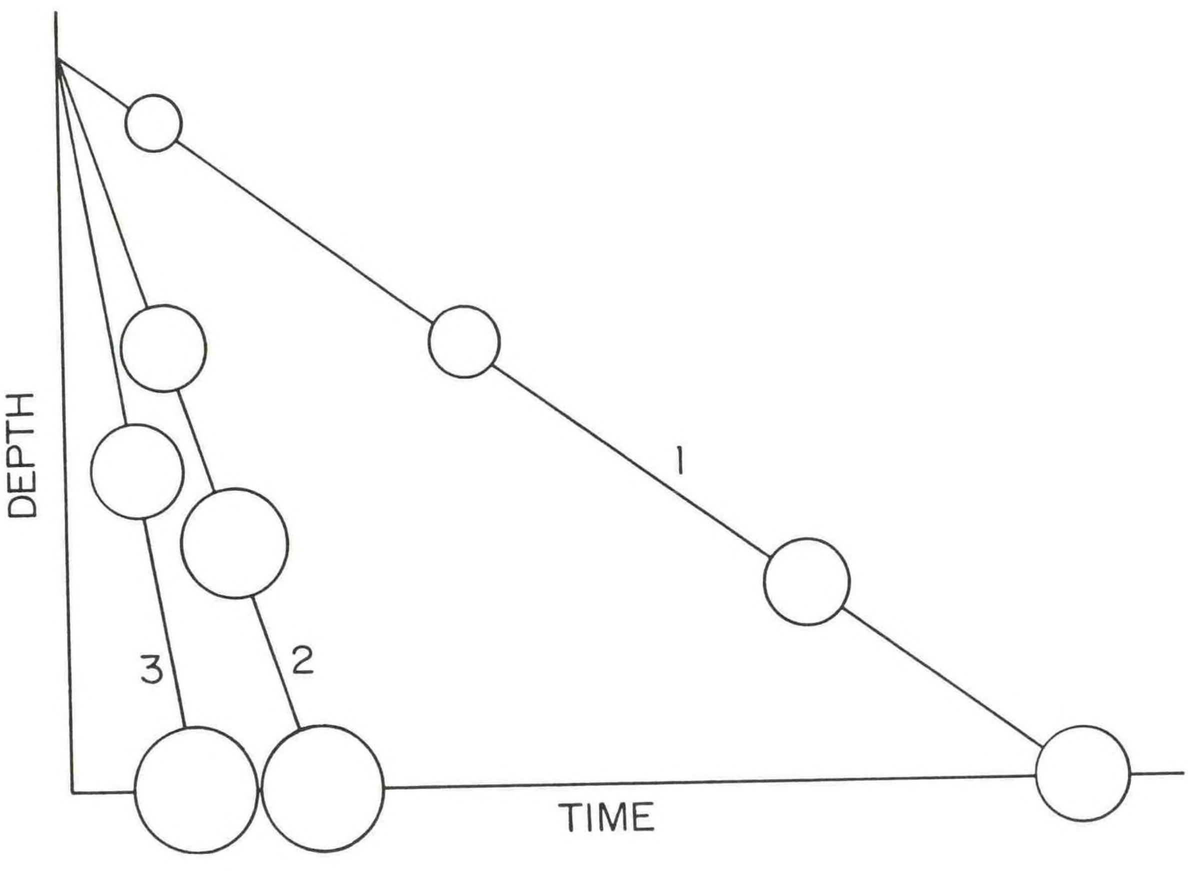


Figure 4.--The effects of ascent rate and PIO2 upon bubble volume at sea level. Schedule 1 has a slower ascent rate than schedule 2. Schedule 3 has a higher PIO2 and a faster ascent rate than schedule 2.

What effect does saturation depth have upon the rate equation? Its form remains unchanged, but the magnitude of K decreases with increasing depth. This ensures that deeper dives will have the slower ascent rates they require to avoid unduly large bubbles.

A QUANTITATIVE MODEL OF BUBBLE GROWTH AND RESOLUTION

The effects on ascent rate of saturation depth and oxygen partial pressure can be put into quantitative form with the aid of a simple model. The resulting theory can then be fit to experimental data using the likelihood method that was recently introduced to diving by Weathersby et al. (1984).

Let us suppose, as shown in figure 5, that the volume V of a bubble increases in proportion to the ascent rate and decreases in proportion to the PIO2. The rate of change of the bubble volume is thus equal to the difference between the rates of increase and decrease

$$dV/dt = C1*R - C2*PIO2 \tag{4}$$

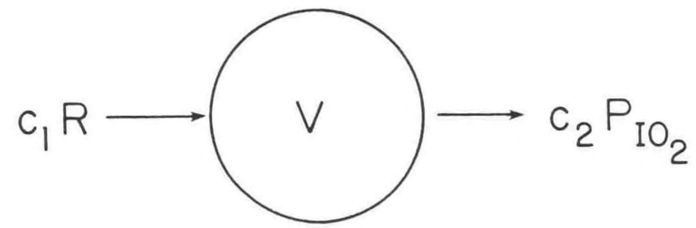
where C1 and C2 are proportionality constants. This relationship is readily integrated to find bubble volume as a function of time for constant PIO2

$$V = V0 + (C1*R - C2*PIO2)*t \tag{5}$$

where V0 is the initial bubble volume, and for constant FIO2

$$V = V0 + (C1*R - C2*FIO2*P0)*t + 0.5*C2*FIO2*R*t^2 \tag{6}$$

where P0 is the initial barometric pressure. Equations 5 and 6 apply where R is zero during decompression stops.



$$\dot{V} = c_1 R - c_2 P_{IO_2}$$

Figure 5.--A decompression model which assumes that bubble growth is proportional to the ascent rate and bubble resolution is proportional to the PIO2.

With these functions, it is possible to predict how the bubble volume will change during any decompression. Figure 6 shows the SCORE decompression schedule which resulted in 7 decompression incidents in 48 trials. The rate of bubble growth is rapid when the ascent rate is high. As the ascent rate is decreased, the bubble growth rate also decreases.

LIKELIHOOD AND DCS RISK

In their discussion of likelihood, Weathersby et al. (1984) pointed out that as in pharmacology where the response to a drug can be related to the dose that is given, so the risk of decompression sickness can be related to the environmental parameters. This is illustrated in figure 7 by a dose-response curve which associates decompression risk with bubble volume. Since bubble volume is a function of depth, gas mix, and ascent rate, the dose-response curve can predict the fractional risk for any decompression schedule.

The actual outcome of a decompression, however, does not have a fractional risk but rather a risk of either zero or one.

Theory	Experiment
$0 \leq P(DCS) \leq 1$	$X = 1$ if DCS
$P(\text{no-DCS}) = 1 - P(DCS)$	$X = 0$ if no DCS

Theory predicts that the probability of decompression sickness, P(DCS), will be between zero and one and that the probability of no decompression sickness will be 1 minus P(DCS). The experimental outcome which shall be defined as X, on the other hand, is 1 if decompression sickness does not occur.

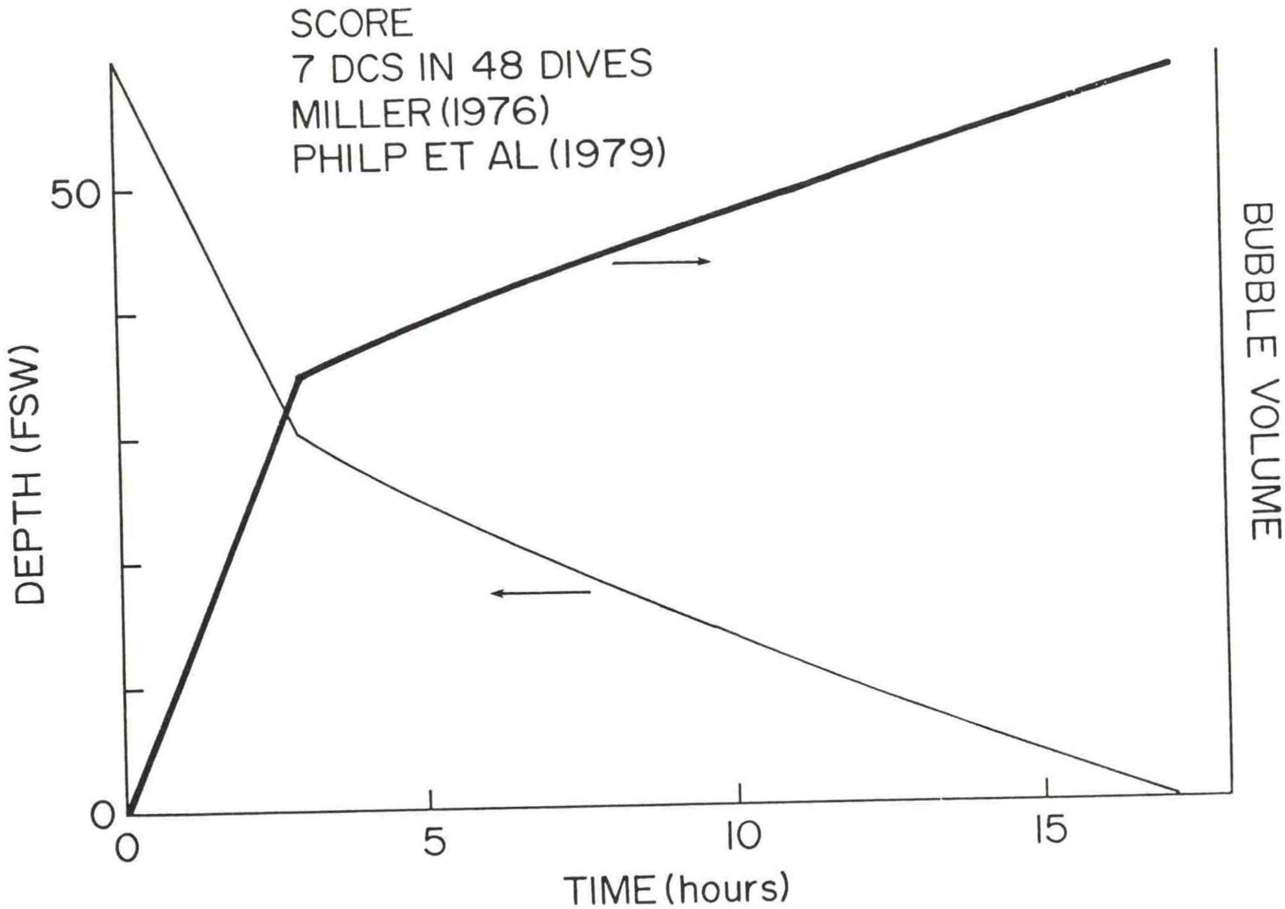


Figure 6.--Bubble growth during the SCORE decompression schedule

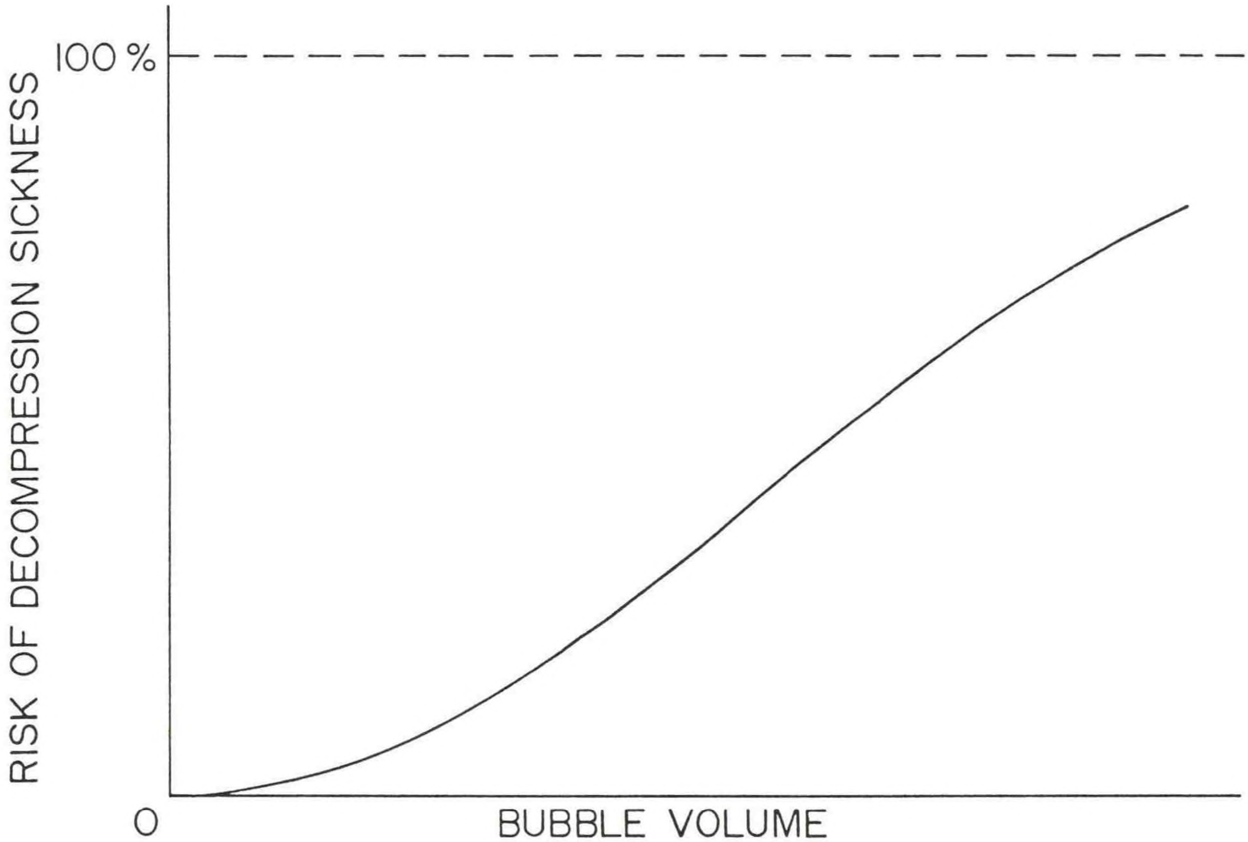


Figure 7.--A dose-response curve relating the risk of decompression sickness to the bubble volume

This dichotomy is resolved by likelihood. Likelihood is the probability of an outcome. Thus, when decompression sickness occurs with an outcome X of 1, the likelihood is equal to P(DCS), the probability of decompression sickness.

If X = 1, likelihood = P(DCS).

When decompression sickness does not occur and the outcome X is zero, the likelihood is equal to P(no-DCS), the probability that decompression sickness does not occur.

If X = 0, likelihood = P(no-DCS).

Expressed quantitatively,

$$\text{Likelihood} = P(\text{DCS})^{X} * P(\text{no-DCS})^{1-X} \qquad (7)$$

This formulation combines information from both theory and experiment. Indeed, likelihood is a measure of the error (or agreement) between theory and experiment as the following examples illustrate.

Consider a theory which is always correct. When decompression sickness occurs, this theory predicts that P(DCS) is one. Calculation shows that the likelihood also is one.

$$X = 1 \qquad P(\text{DCS}) = 1$$

$$P(\text{DCS})^{X} * P(\text{no-DCS})^{1-X} = 1^{1} * 0^{0} = 1$$

When decompression sickness does not occur, the correct theory predicts that P(no-DCS) is one. Again, the likelihood is found to be one.

$$X = 0 \qquad P(\text{DCS}) = 0$$

$$P(\text{DCS})^{X} * P(\text{no-DCS})^{1-X} = 0^{0} * 1^{1} = 1$$

Now consider a theory which is always incorrect. When decompression sickness occurs, this theory predicts that P(DCS) is zero. When decompression sickness does not occur, the incorrect theory predicts that P(no-DCS) is one. In both cases, the likelihood is zero.

$$X = 1 \qquad P(DCS) = 0$$

$$P(DCS)^X * P(\text{no-DCS})^{1-X} = 0^1 * 1^0 = 0$$

$$X = 0 \qquad P(DCS) = 1$$

$$P(DCS)^X * P(\text{no-DCS})^{1-X} = 1^0 * 0^1 = 0$$

The magnitude of the likelihood, between zero and one, is a measure of the error or agreement between theory and experiment. Likelihood allows the quantitative comparison of theories. These theories may be empirical or physiological.

ANALYSIS OF EXPERIMENTAL DATA

The concept of likelihood may be extended to a series of observations by multiplying the likelihoods of individual observations. (This is analogous to finding the probability of a series of coin tosses by multiplying the probabilities of the individual tosses.) As the individual observations need not be made on the same decompression schedule, observations on all well-documented schedules may be used. The results of 21 air or nitrogen-oxygen saturation decompression schedules were found in the literature and are summarized in table 3. These include a total of 233 man-decompressions in which there were 39 cases of decompression sickness for an incidence of 16.7%. Appendix A lists complete information on all schedules.

Table 3.--Air and N2-O2 saturation decompression schedules

Depth	DCS	Dives	Name	Reference
50	2	2	Pre-SHAD	Hamilton et al. (1982)
	0	2	SHAD I	
	1	3	SHAD III	
60	1	2	SHAD II	
	7	48	SCORE	Miller (1976), Philp et al. (1979)
	4	10	Dive 1	Thalmann (1984)
	3	10	Dive 2	
	1	10	Dive 3	
	1	10	Dive 4	
	1	11	Dive 5	
	1	20	Dives 6 & 7	
	0	10	Dive 8	
	2	23	AIRSAT 1 & 2	Eckenhoff and Vann (1985)
65	1	18	SUREX 65	
75	0	6	SUREX 75	
90	0	3	NOAA OPS I	Miller et al. (1976)
132	3	12	AIRSAT 3	Eckenhoff and Vann (1985)
	1	15	AIRSAT 4	
165	5	10	OI/NOAA	Barry et al. (1984)
197	5	6	NISAHEX	Muren et al. (1984)
198	0	3	NISAT I	Hamilton et al. (1982)

The bubble volumes occurring at the surface, or at the depth of decompression sickness, were found for each of these schedules as shown earlier for the SCORE decompression. From these volumes, the probabilities of decompression sickness were predicted using the risk function as a dose-response curve

$$P(DCS) = 1 - e^{(-C3 * V^{C4})} \qquad (8)$$

where V is the bubble volume and C3 and C4 are undetermined parameters. Having found the probabilities and knowing the experimental outcomes, the likelihood could be calculated for the whole series of schedules.

The magnitude of the likelihood is controlled by the values of the parameters C1 and C2 in the bubble model and C3 and C4 in the risk function. A steepest descent method was used to find the parameter values which gave the maximum likelihood and defined the best agreement between theory and experiment. The natural logarithm of this likelihood is -100.16, and the corresponding parameter values are

$$C1 = 0.6$$
$$C2 = 0.0533$$
$$C3 = 0.3457$$
$$C4 = 2.0868$$

The relationship between K in the rate equation and the saturation depth can now be determined for any decompression risk. The total decompression time for ascent from a saturation pressure Ps to a final pressure Pf (the surface or the pressure at which decompression sickness occurred) at a constant PIO2 is

$$t = \frac{Psat - Pf}{R} \tag{9}$$

Substituting this and R = K * PIO2 into equation 5 and solving for K with V0 equal zero gives

$$K = \frac{C2}{C1 - \dfrac{V}{Psat - Pf}} \tag{10}$$

The value of V in equation 10 corresponding to any decompression risk can be found from equation 7. Equation 10 also may be used to find the value of K for each decompression schedule.

This information is shown in figure 8. The curves indicate how K decreases with increasing saturation depth for decompression risks of 2, 5, 10, 20, 30, 40, 50, and 60%. The value of K for each decompression schedule is shown by a square, a diamond, or a circle. The enclosed number is the percentage of decompression sickness observed for that schedule. The square indicates that there were 2 to 6 trials on a schedule, the diamond indicates 10 to 15 trials, and the circle indicates 18 to 48 trials. The mean error between observed and predicted decompression sickness for the 21 schedules was 11%. As might be expected, the errors were greatest for schedules with the fewest trials. Table 4 lists the values of K as a function of saturation depth and decompression risks of 1, 2, 5, and 10%.

ESTIMATION OF SATURATION DECOMPRESSION SCHEDULES

The dashed line in figure 8 is from earlier estimates of how K varies with saturation depth for both nitrogen-oxygen and helium-oxygen (Vann 1984). Maximum likelihood gives a more objective estimate of K, but it is necessary to choose a suitable decompression risk. A 2% risk was arbitrarily selected, and schedules were calculated for air decompression using the appropriate value of K for the saturation depth. These schedules are shown in figure 9 and are listed in appendix B.1 (fsw) and appendix B.2 (msw). To avoid pulmonary oxygen exposures of greater than 600 cptd, the maximum depth was limited to 80 fsw.

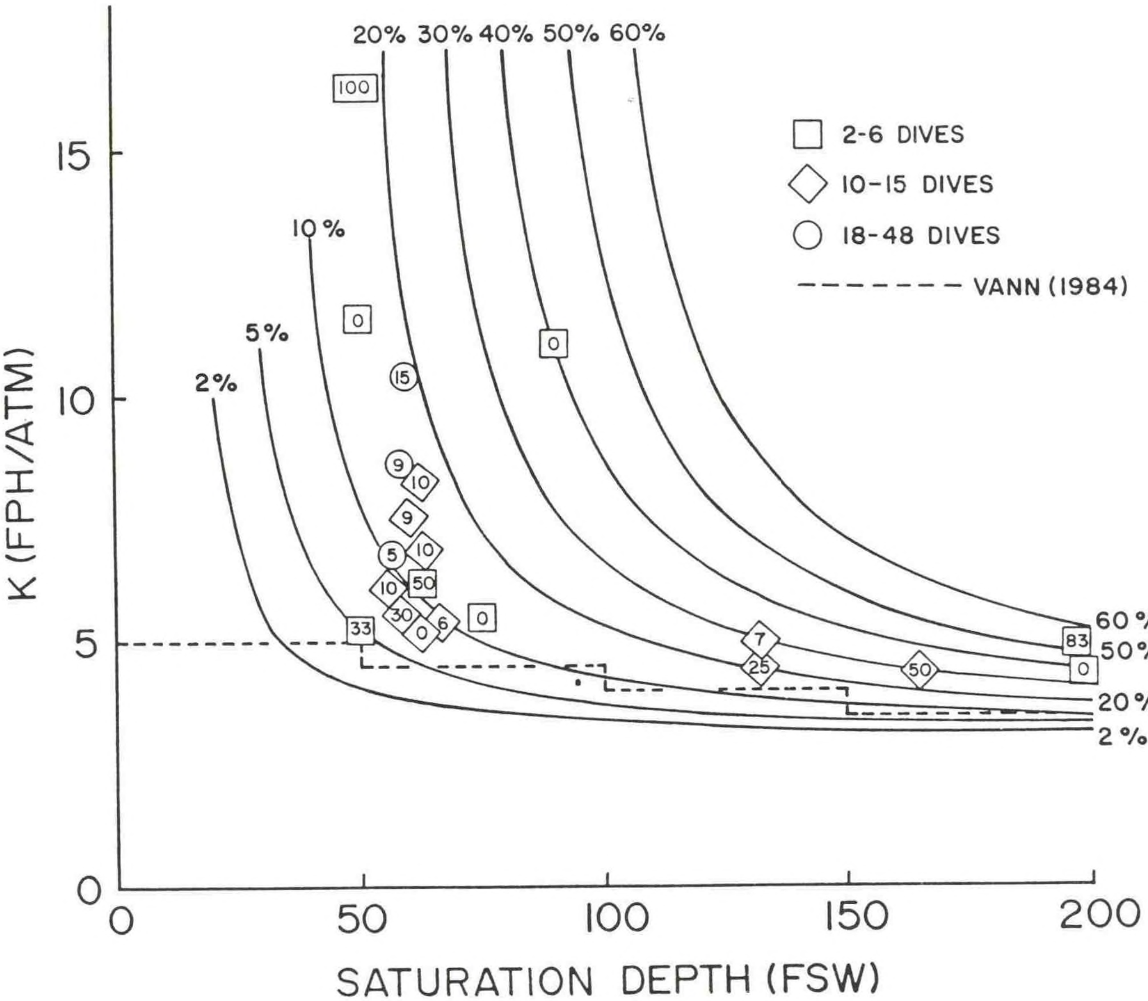


Figure 8.--The relationship between the value of K in the rate equation and the saturation depth for several decompression risks. The values of K for the individual schedules are shown.

Table 4.--K as a function of saturation depth and DCS risk

	K (fph/atm)			
DCS Risk	1%	2%	5%	10%
Depth (fsw)				
30	4.42	5.53	11.05	-
40	3.92	4.53	6.53	13.21
50	3.67	4.08	5.24	7.77
60	3.52	3.83	4.63	6.09
70	3.43	3.67	4.28	5.28
80	3.35	3.56	4.05	4.80
90	3.30	3.48	3.88	4.48
100	3.26	3.41	3.76	4.26
110	3.23	3.36	3.67	4.09
120	3.20	3.32	3.59	3.96
130	3.18	3.29	3.53	3.85
140	3.16	3.26	3.48	3.77
150	3.14	3.24	3.44	3.70
160	3.13	3.21	3.40	3.64
170	3.12	3.20	3.37	3.59
180	3.11	3.18	3.34	3.54
190	3.10	3.17	3.32	3.51
200	3.09	3.15	3.29	3.47

The ascent rate was reduced at 10 fsw intervals to compensate for the falling oxygen partial pressure as required by the rate equation. The ascent rate was calculated for the PIO2 at the end of the depth interval. For dives to 50 fsw and deeper, a PIO2 of 0.5 atm was assumed at saturation depth, and K was reduced so that decompression could begin immediately upon switching to air without an equilibration period.

A second set of schedules (see fig. 10, appendix B.3 (fsw), and appendix B.4 (msw)) was calculated for a PIO2 of 0.5 atm on the bottom and to 45 fsw during decompression. Air is used from

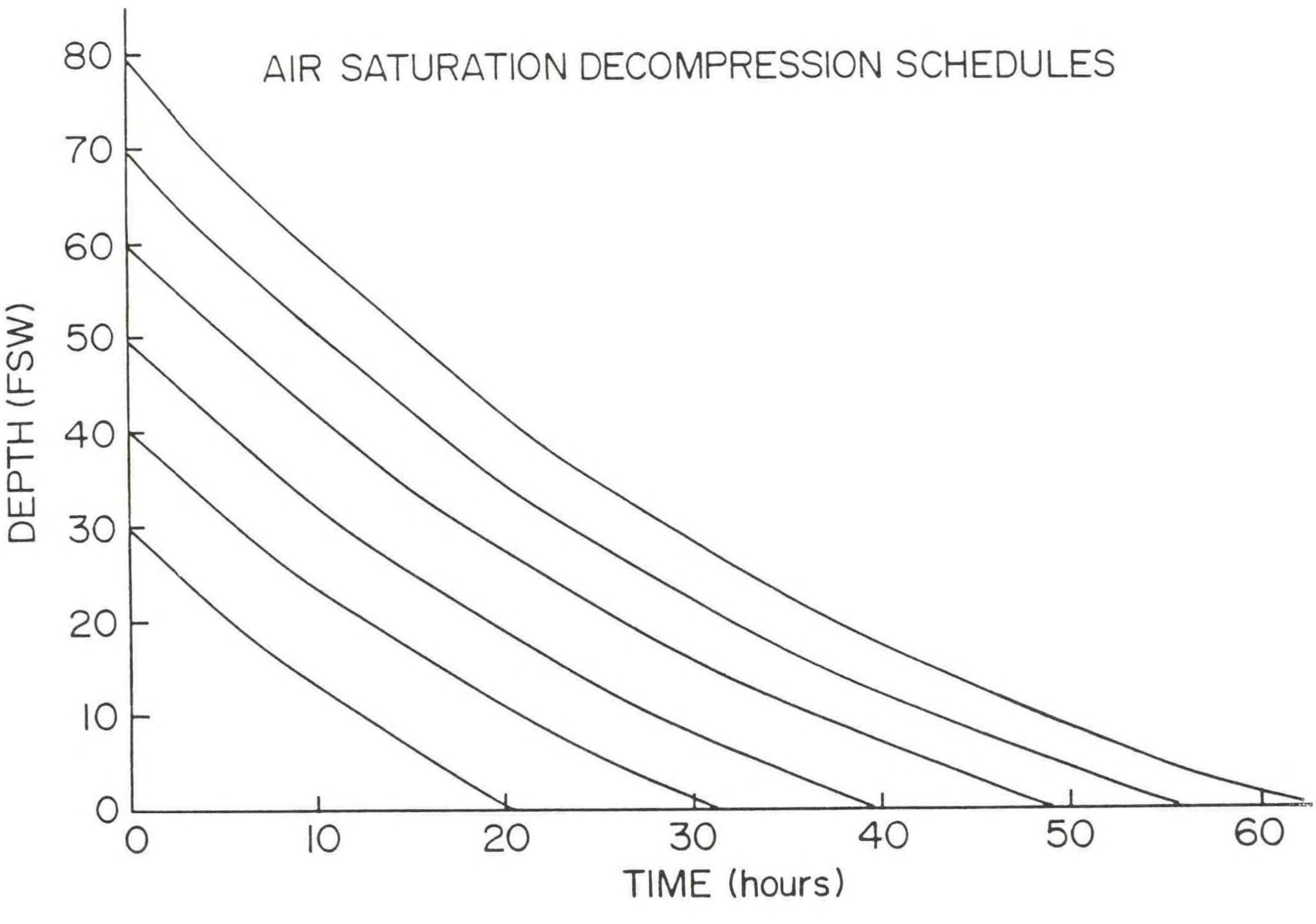


Figure 9.--Saturation decompression schedules for a PIO2 of 0.5 atm (see appendixes B.3 and B.4)

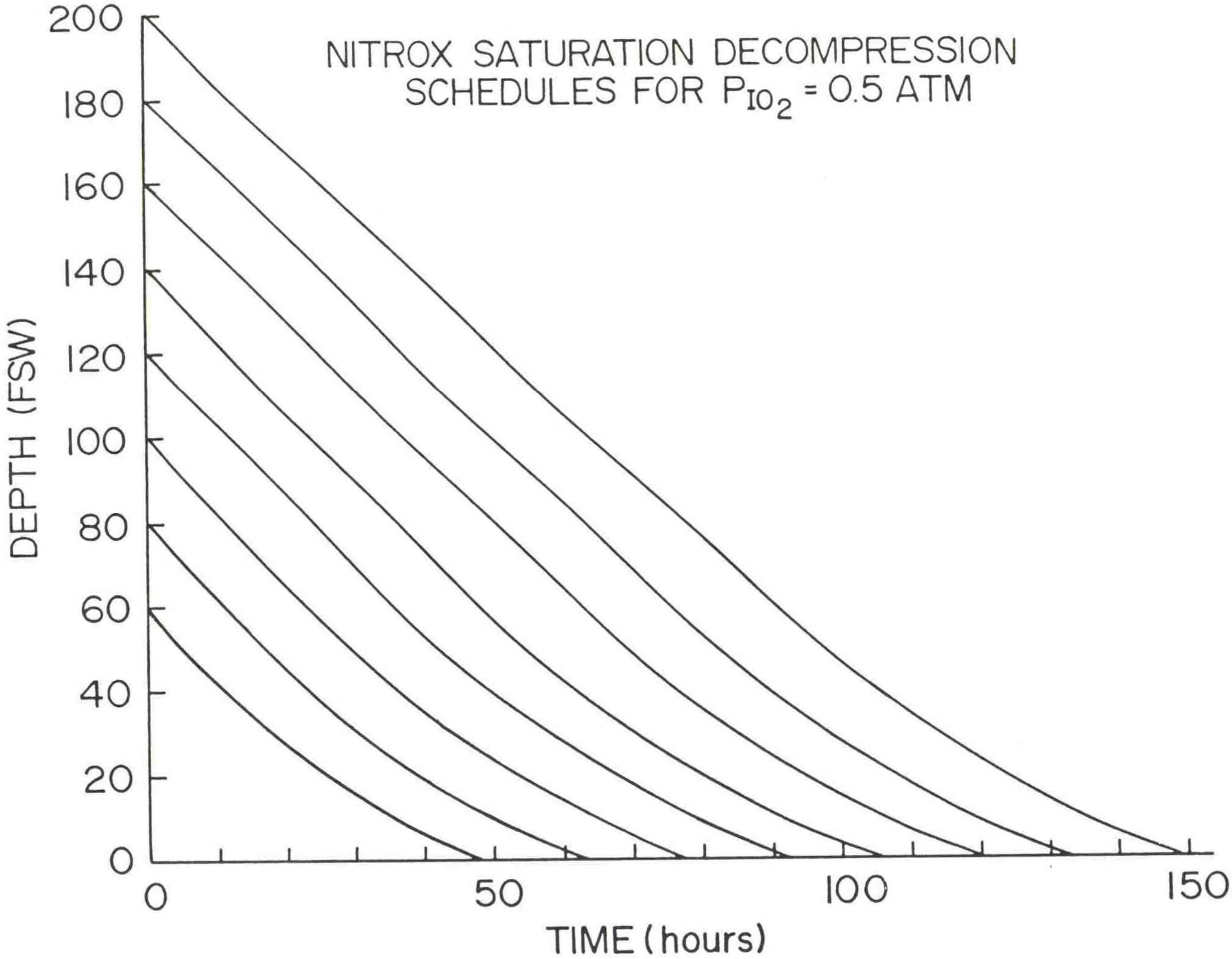


Figure 10.--Saturation decompression schedules for PIO2 of 0.5 atm (see appendixes B.3 and B.4)

45 fsw to the surface. These schedules are not limited by pulmonary oxygen toxicity and have saturation depths ranging from 200 to 30 fsw in 10 fsw increments. The ascent rate is constant until 45 fsw after which it is reduced at 10 or 15 fsw intervals as required by the falling oxygen partial pressure.

Schedules also were calculated for a PIO2 of 0.6 atm (see fig. 11, appendix B.5 (fsw), and appendix B.6 (msw)) which allowed a savings in decompression time of up to 10%. These schedules use a PIO2 of 0.5 atm on the bottom and do not exceed a pulmonary oxygen exposure of 600 cptd for decompression from the maximum depth of 170 fsw. Air is used from 60 fsw to the surface. The value of K was chosen so that decompression could begin immediately upon raising the PIO2 to 0.6 atm. In terms of depth traveled per uptd, oxygen is most efficiently used during decompression at partial pressures of just over 0.5 atm.

CONCLUSIONS

This paper began by discussing an empirical method for finding the ascent rates from saturation dives. These rates were estimated in a subsequent analysis. The estimates are easily modified and can be refined with additional data and other decompression models. Perhaps more important, however, is the likelihood principle described by Weathersby et al. (1984). This principle has at last bridged the gap between theory and experiment and may be the most significant theoretical tool in diving since Haldane's decompression model.

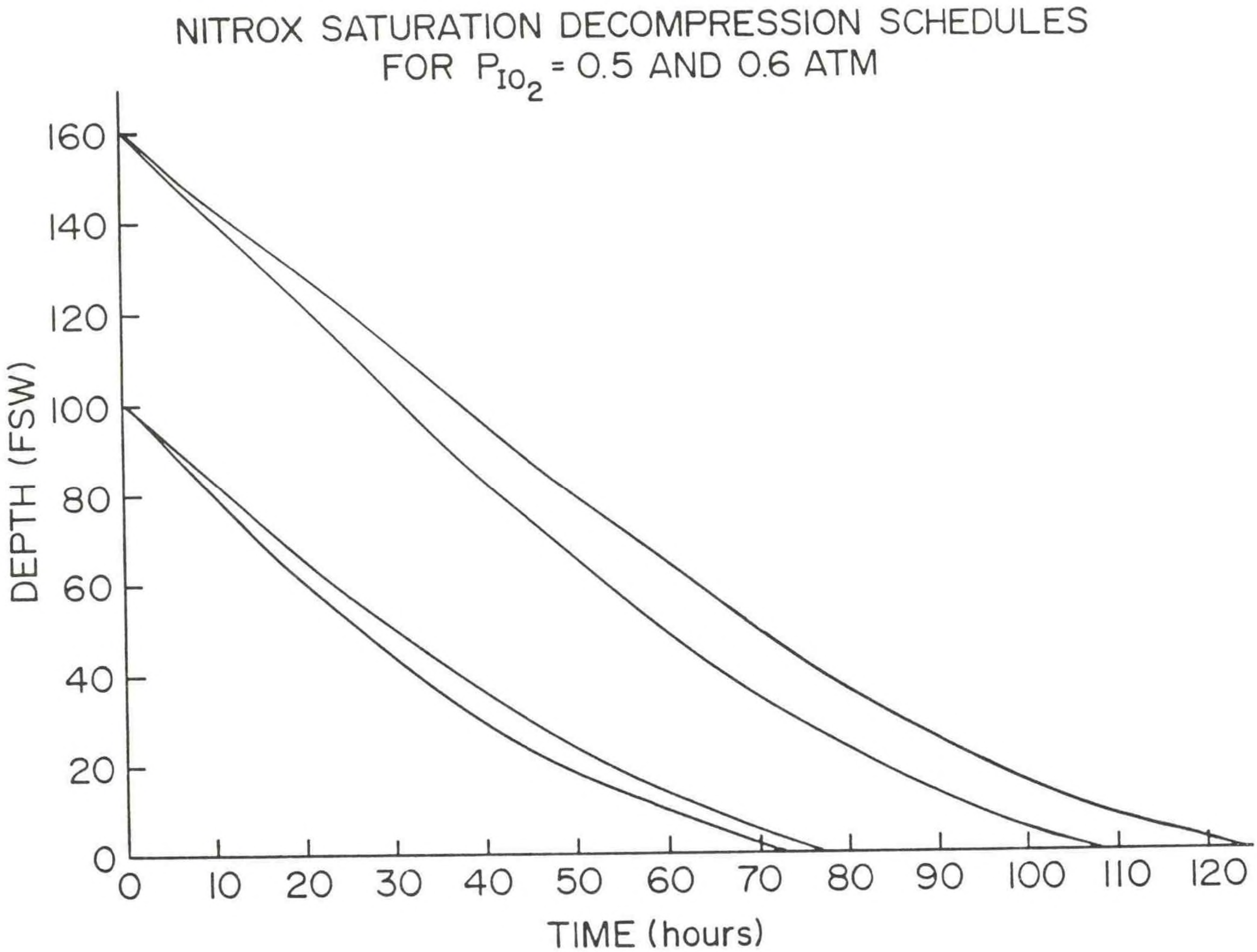


Figure 11.--Saturation decompression schedules for a PIO2 of 0.6 atm (see appendixes B.5 and B.6)

REFERENCES

Barry, P. D., R. D. Vann, D. A. Youngblood, R. E. Peterson, and P. B. Bennett. 1984. "Decompression From a Deep Nitrogen/Oxygen Saturation Dive: A Case Report," Undersea Biomed. Res. 11(4):387-393.

Eckenoff, R. G., and R. D. Vann. 1985. "Air and Nitrogen/Oxygen Saturation Decompression: A Report of 4 Schedules and 77 Subjects," Undersea Biomed. Res. 12(1):41-52.

Hamilton, R. W., Adams, G. M., Harvey, C. A., and Knight, D. R. (eds.), 1982. "SHAD-NISAT: A Composite Study of Simulated Shallow Saturation Diving," Naval Submarine Medical Research Laboratory Report Number 985, August.

Miller, J. W. (ed.). 1976. Vertical Excursions Breathing Air From Nitrogen-Oxygen or Air Saturation Exposures. U.S. Department of Commerce, Rockville, Md., May.

Muren, A., J. Adolfson, H. Ornhagen, M. Gennser, and R. W. Hamilton. 1984. "NISAHEX: Deep Nitrox Saturation With Nitrox and Trimix Excursions," pp. 713-730. In: Underwater Physiology VIII, A. J. Bachrach and M. M. Matzen (eds.).

Philp, R. B., P. B. Bennett, J. C. Andersen, G. N. Fields, B. A. McIntyre, I. Francey, and W. Briner. 1979. "Effects of Aspirin and Dipyridamole on Platelet Function, Hematology, and Blood Chemistry of Saturation Divers," Undersea Biomed. Res. 6(2):127-145.

Schreiner, H. R., and P. L. Kelley. 1967. "Computation Methods for Decompression From Deep Dives," pp. 277-299. In: Proceedings of the 3rd Symposium on Underwater Physiology, C. J. Lambertsen (ed.), Williams and Wilkins, Baltimore.

Thalmann, E. D. 1984. "Development of a 60 FSW Air Saturation Decompression Schedule." Undersea Biomed. Res. 11(1, Suppl.): Abstract, 18.

Van Liew, H. D., B. Bishop, D. Walder, and H. Rahn. 1965. "Effects of Compression on Composition and Absorption of Tissue Gas Pockets." J. of Appl. Physiol. 20:927-933.

Van Liew, H. D., W. H. Schoenfisch, and A. J. Olszowka. 1968. "Exchanges of N2 Between a Gas Pocket and Tissue in a Hyperbaric Environment." Resp. Physiol. 6:23-28.

Vann, R. D. 1984. "Decompression After Saturation Diving," pp. 175-188. In: Proceedings of the 3rd Annual Canadian Ocean Technology Congress, Toronto, March.

Vorosmarti, J., R. de G. Hanson, and E. E. P. Barnard. 1978. "Decompression From Steady-State Exposures to 250 Meters," pp. 435-442. In: Underwater Physiology VI, C. W. Shilling and M. W. Beckett (eds.), FASEB, Bethesda, Md.

Weathersby, P. K., L. D. Homer, and E. T. Flynn. 1984. "On the Likelihood of Decompression Sickness," J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 57(3):815-825.

Workman, R. D. 1969. "American Decompression Theory and Practice," pp. 252-290. In: The Physiology and Medicine of Diving and Compressed Air Work, P. B. Bennett and D. H. Elliott (eds.), 1st edition, Bailliere, Tindall, and Cassell, London, England.

FUTURE PLANS FOR DIVING WORK EXPERIMENTS AT JAMSTEC

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The objectives of research in diving technology and development at JAMSTEC are to establish safer and more efficient diving technology to be used in the underwater activities of divers. Major thrusts of the program are:

- o Development of safe and efficient diving procedures and operational procedures for saturation diving;
- o Development of a deep diving system and an underwater working system; and
- o Research in diving physiology and psychology.

From 1985 to 1989, an open-sea experimental diving program named "New-Seatopia" will be conducted at 60 m, 100 m, 200 m, and 300 m depths to develop diving technology to be used in saturation diving at depths up to 300 m. The program of this open-sea diving experiment is shown below.

OBJECTIVES

This program is administered by the Manned Underwater Technology and Engineering Department of JAMSTEC with a budget from the Science and Technology Agency. The objectives of this program are:

- o to establish safe and efficient decompression procedures for saturation diving;

- to establish diving methods and techniques for use with the diving system;
- to establish operational diving procedures for use with the diving support vessel and deep diving system;
- to investigate the functioning of the deep diving system, diving equipment, and diving support system; and
- to investigate diver working performance and to establish methods of monitoring the physical condition of the divers during the operational period.

TASK DESCRIPTION

This program is designed to assess the effectiveness of diving technology at depths up to 300 m and to apply this technology to the development of underwater working technology. Three types of underwater technology are being assessed:

- Underwater maintenance technology;
- Underwater construction technology (underwater welding and cutting, underwater connecting, etc.); and
- Underwater survey technology (underwater search techniques, underwater photography, etc.).

Currently, this program is divided into the following major task areas:

- Decompression procedure tasks are designed to investigate safe and efficient standards and allowable decompression speeds and stops and to investigate temperature, humidity, and diving gas requirements.

- Investigations of diving methods and techniques, using the deep diving system, to determine the most suitable control procedures for the system when it is used in diving operations and to establish permissible limits for underwater work time, repetitive dives.
- Investigations of diving methods and techniques to establish procedures for living patterns, food, and clothing while in the DDC, to assess equipment performance during dives to 300 m, and to evaluate methods of diver monitoring and fitness measurement.
- Investigations of diving operational procedures, using the Diver Support Vessel and the DDS to assess required levels of organization and training and of reserve supplies needed for dive operations.
- Investigations of the underwater performances of the DDS, diver equipment, and dive support equipment to evaluate the SDC's handling equipment, gas supply and recovery system, winches, tensioners, and guide wire system.
- Diver working performance tasks investigate permissible safe and efficient underwater work loads for divers.

DIVING SUPPORT VESSEL AND DEEP DIVING SYSTEM

DIVING SUPPORT VESSEL

The semi-submersible catamaran-type underwater research support ship KAIYO was completed and delivered to JAMSTEC on 31 May 1985. The vessel can carry a crew of 29 and as many as 40 researchers. The KAIYO's specifications are:

Length overall	61.55 m
Breadth	28.00 m
Depth (working deck)	13.30 m
Draft	6.30 m
Gross tonnage	2,849 t
Service speed	13.25 kt
Complement	69 persons
Main generator	1,250 kw x 4 sets
Main propeller	CPP x 2 sets
Thruster	CPP x 8 sets

DEEP DIVING SYSTEM

The KAIYO's deep diving system is an SDC-DDC system used for diving experiments. It was manufactured in cooperation with JAMSTEC and several Japanese makers. This system has the capability to control 6 divers and to descend to 500 m.

Experimental Diving Program

This program called the "New-Seatopia" was started this year, and four open-sea diving experiments using the dive simulator will be conducted this year. These open-sea diving experiments will include:

- o Unmanned test

  SDC-DDC System and diving support equipment will be tested at depths up to 100 m to confirm operational procedures to get operational data for this depth.

- o 60 m saturation diving experiment

  6 divers will be saturated at depths up to 60 m and will stay on the bottom a maximum of 9 days. These experiments will be conducted twice this year.

- 100 m saturation diving experiment

  6 divers will be saturated at up to 100 m depths and will stay on the bottom 7 days; this experiment will be conducted once this year.

- 31 ATA research dive

  4 divers will be saturated for a period of 1 week in the JAMSTEC Diving Simulator.

From 1986 to 1989, open-sea diving experiments at depths up to 300 m will be conducted. Through this program, we hope to establish safe and efficient deep diving technology for use at depths up to 300 m.

THE USE OF NONEXPLOSIVE MIXTURES OF HYDROGEN AND OXYGEN FOR DEEP DIVING

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INTRODUCTION

The effects of hydrogen-oxygen (hydrox) breathing mixtures on animals initially was examined in 1789 by Lavoisier, who placed guinea pigs in bell jars containing a mixture of hydrogen and oxygen. The animals apparently survived 8 to 10 hours. Lavoisier thought their deaths occurred because the oxygen was used up. We now know that his assumptions were wrong because their deaths were due to the buildup of carbon dioxide. He did not blame hydrogen for the deaths. For the next 148 years, there appeared to be no interest in hydrox. However, in the early 1900's Case and Haldane used themselves as guinea pigs and spent 6 minutes breathing this mixture at a depth of 10 atmospheres. They did not report any adverse reactions.

In 1943, Arne Zetterstrom of the Swedish Navy suggested the use of hydrogen as an alternate to helium. Zetterstrom made four dives in the ocean using a mixture of hydrogen and oxygen, which he made by cracking ammonia gas. These dives ranged from 40 meters to 160 meters. On the last dive he lost his life due to a malfunction of a winch on the ship, which pulled him directly to the surface. His death was not due to breathing hydrogen.

After this failure in Sweden, interest in hydrox lay dormant until 1966, when Brauer began to study the possible effects of hydrogen on various mammals. His work led him to conclude that molecular hydrogen was not toxic to the body. As a result of this work, Brauer and the French company COMEX at Marseilles attempted to carry out a 300-meter chamber dive, at which depth they planned to breathe hydrox. This was not successful due to the appearance of the high pressure nervous syndrome while still breathing helium.

In 1968, Edel, who was working with hydrox at J&J Marine Diving Company, and Fife, from Texas A&M University, joined in the study of both humans and animals exposed to hydrox. This series ended in 1969 with human exposures of up to 2 hours' duration at a depth of 70 meters. No ill effects were noted from the hydrogen even though one of us (WPF) breathed hydrox for 1 1/2 hours on one dive, and less than 1 week later repeated the dive, remaining on hydrox for 2 hours. Some of the shorter dives produced decompression sickness in some of the divers, but the two just-mentioned dives were uneventful.

Also in 1969, French workers carried out a series of dives on rabbits and baboons. Some concern was created when their rabbits died after 7 1/2 hours. It was later found that the problem was caused by contaminated breathing gas.

In 1976, Fife began a series of studies to develop human decompression tables for hydrox under the support of the Texas A&M Sea Grant Program, and to continue the study of possible adverse effects of molecular hydrogen on the body. Hydrox decompression tables were developed and tested to a depth of 91 meters. Further, an extensive study was begun with dogs on the effects of hydrox on blood and body tissues resulting from extended exposures to a depth of 333 meters. Dives of up to 108 hours of continuous hydrox exposure were studied.

Recently, COMEX in France has again renewed its interest in the use of hydrox. They have just completed several deep chamber dives and now contemplate open ocean diving on this gas mixture, while Fife has again begun work to develop techniques by which the diver can shift from air to hydrox without the use of helium.

TECHNIQUES OF HYDROX DIVING

SAFETY

Hydrogen Combustibility

Hydrogen-oxygen mixtures are not combustible if the oxygen content is less than 4%, with the balance being hydrogen. In fact, hydrox cannot be ignited even with an open flame or spark. Thus, the secret to using hydrox is in assuring that hydrogen at no time comes in contact with oxygen if the oxygen is greater than 4% by volume. For added safety, most workers in the field limit the oxygen to no more than 3% by volume.

The main problem with hydrox diving is that any leaks may cause hydrogen to come into contact with air. This can result in an explosive gas mixture near such leaks. For this reason, great care must be exercised to assure that no leaks occur. The state of the art makes such caution feasible but requires constant attention. After over 6,000 hours of actual hydrox exposure on lower animals and man, we are convinced that this problem can be solved for commercial application. Since less than 4% hydrogen in air or oxygen also is not combustible, we are able to detect the presence of a leak well before it becomes dangerous.

Hydrogen Embrittlement

It has been shown by Kesterson that embrittlement should not be a serious problem when alloy steels are used. Previous reports have shown that cast iron hatches are subject to such embrittlement, but we are confident that it is not a serious problem under the conditions in which we are using hydrox.

OPERATING TECHNIQUES

Basic Principle

The use of hydrox for diving has certain basic limitations that can be overcome but which must be recognized and understood. The first is that to be nonexplosive, the oxygen percentage in the mixture must never be greater than 4%, with the remaining 97% being hydrogen. On the other hand, it is essential that the diver inspire enough molecules of oxygen to sustain life. At ground level this is accomplished by having 21% of the air be oxygen. These oxygen molecules exert a barometric pressure of about 160 mm Hg. It is this pressure that provides the really critical number of oxygen molecules to sustain life. And, no matter how deep we go in the ocean or how high we go in the air, we must have at least this partial pressure of oxygen in our breathing mixture.

A second factor which most people are already familiar with is that when air is compressed to a pressure equal to 2 atmospheres, the volume is reduced to half that found before compression, and the gas molecules are twice as close together as before. This means that at 2 ATA, the percentage of oxygen could be reduced by 1/2 (10.5 %), and still have enough oxygen molecules to sustain life because it would have the same number of molecules of oxygen in each given volume of inspired gas as air breathed at ground level. With this in mind, it is clear that if we wanted to be able to breathe a mixture containing only 3% oxygen, we could do so if we went to a pressure of 7 atmospheres absolute (ATA). We arrive at this number by dividing 21 by 3. Thus, if we wish to start using a 3% oxygen breathing mixture, we only need to descend to a pressure equal to 7 ATA, which is a depth of 60 meters under the ocean.

Shifting From Air to Hydrox

The shift from air containing 21% oxygen to a hydrox mixture containing only 3% oxygen, even when this is done at 7 ATA pressure, presents its own problem. If the shift is accomplished by going directly from air to hydrox, it will violate one of the cardinal rules of safety because it will result in 21% oxygen being in contact with hydrogen. That would result in an explosive mixture at that moment and create a danger of fire. To avoid this, upon arriving at a depth of 7 ATA the diver must shift to a nonexplosive breathing mixture containing only 3% oxygen. At first one might think that this could be done by using a mixture of oxygen and nitrogen. This is not feasible because at that depth the nitrogen will create nitrogen narcosis and the diver will feel and act as though he were badly drunk. This would be extremely dangerous and is not permitted. However, this may be overcome by using an intermediate breathing mixture of helium containing only 3% oxygen: only a few breaths of this mixture will wash out all of the air from the breathing system and make it safe to shift to hydrox. After the dive, it is possible to return to air at a depth of 7 ATA by reversing the process.

Living in Hydrox

If a diver must live in a chamber containing hydrox it is necessary to flood the chamber with hydrox. This requires two steps. First, the chamber hatch is closed while containing air, which, of course, contains the proper amount of oxygen. As will be remembered, at ground pressure the 21% oxygen contains 160 mmHg oxygen pressure and is adequate for sustaining life. The chamber then can be pressurized directly with <u>helium</u> to reach a pressure of 7 ATA. At that time the chamber automatically still contains the same amount of oxygen as at the start (less some which has been metabolized), but since much helium has been added, the <u>percentage</u> of oxygen has been reduced to only 3%. It now is no longer combustible. The chamber then may be flushed directly with hydrox. If the diver is to be further compressed to a greater depth, this is done by simply increasing the total pressure by injecting pure hydrogen. The percentage of oxygen automatically is reduced as more inert gas is added so that the oxygen partial pressure remains normal.

Temperature Problems

It is well known that molecular hydrogen has a much higher specific heat than does nitrogen. This results in each hydrogen molecule carrying away more heat from the body than does a molecule of nitrogen. This problem is aggravated by the fact that under hyperbaric conditions the hydrogen molecules are much closer together and, thus, will carry away heat even faster than if they were at one atmosphere pressure. In fact, at a depth of 310 meters, the loss of body heat may be so rapid that body metabolism cannot produce heat fast enough to replace it, even with heavy work. As a result, unless the body is heated externally, the core temperature will gradually drop and the diver may die of hypothermia.

The diver living in a chamber flooded with hydrox also will suffer from heat loss. We found that the diver is not comfortable unless the chamber temperature is raised to at least 34° C. Further, even if clothed, at 310 meters, if the diver does not breathe warm air he will still lose heat through respiration faster than he can produce it. This can be fatal.

In the case of animals--where the animal communicates only through behavior--it is not possible to accurately meet the animal's temperature needs by controlling the chamber temperature. At great depths a change of only 1/2° can cause the animal to become either too hot or too cold. This can be solved, however, by externally heating only one wall of the chamber. The animal then can move toward or away from the wall to seek its comfort zone.

Decompression

There are a number of problems related to decompression, not the least of which is avoiding decompression sickness. However, one problem which often may be overlooked is that during decompression, as the pressure is reduced, the percentage of oxygen does not automatically increase. Thus, the diver will begin to become hypoxic unless additional oxygen is added during ascent. It is easy to calculate what percentage of oxygen must be present by again dividing 21% by the pressure in the chamber (in ATA) at that moment. That amount of oxygen must be added to avoid hypoxia.

RESULTS

Our studies were carried out primarily on our in-house diving dogs as well as on ourselves. Twenty dogs and five humans took part in these studies. The dogs were born and raised in our laboratory and were permanent residents. We considered this to be essential because during the studies of behavior it was important to know each dog's personality so that we could better assess possible effects of the hydrox exposure.

Most of the human subjects were students who were scuba divers working in our laboratory. Of course, all of the humans were volunteers. They were in good physical condition and dived regularly either in the chamber or ocean. The types of experimental subjects and the duration of their hydrox exposures may be seen in table 1.

Table 1.--Hydrox Dives: Subjects and Exposures

Subject	Duration of Hydrox Exposure (hours:min)	Total Duration of Dives (hours:min)
Dog	1,140:10	1,382:42
Rat/Mouse	5,313:00	5,378:15
Man	4:37	41:24
Total	6,457:47	6,802:21

STUDIES OF POSSIBLE PHYSIOLOGICAL DAMAGE

These studies were designed to determine if molecular hydrogen under high pressure would cause cellular damage. This was of concern since it had been shown that molecular hydrogen will scavenge high-energy free hydroxy radicals and, thus, is not completely inert to the body. Our studies involved three different methods of assessing possible damage due to the hydrox. The first was by a study of various blood enzymes. A second way of detecting cell damage was by way of electroencephalography (EEG). To accomplish this we developed an EEG transmitter which we implanted in the muscle layer of the thorax. EEG brain leads were passed surgically from the brain to the transmitter. In this way, we were able to detect any abnormal electrical brain waves while the animals were living at a simulated depth of 310 meters while breathing hydrox. Such recordings would reflect abnormal function of brain cells. In the hands of a neurophysiologist or neurologist it often is possible not only to detect the presence of brain abnormality but to find out where such abnormality is located. The third study involved lung biopsies both before and after the deep hydrox dives. This is a standard procedure which involves tranquilization and local anesthetic and is used daily in hospitals. We were able to obtain lung tissue for study with the electron microscope to search for lung damage resulting from the hydrox.

The results of these studies showed that there is no physiological damage caused by breathing hydrox, at least for as long as 5 days, at a depth of 310 meters. We saw no indication that the diver could not dwell at this depth on this gas mixture for an indefinite period of time. In passing, it is interesting to note that at this depth, oxygen becomes almost a trace contaminant in the breathing mixture because it is necessary to lower the oxygen percentage to about 1% to avoid oxygen toxicity. The reason for this is obvious from the discussion above.

The electroencephalograms did show some abnormality if the animal was compressed rapidly to depth, or if the oxygen partial pressure was allowed to drop slightly. In fact, at 310 meters in depth, it is necessary to elevate the oxygen percentage from 0.67% up to around 1%. This is because of the increased breathing density of the gas and probably some carbon dioxide retention also. Even though the EEG's reflected some abnormalities while at depth, these all returned to normal by the time the animal had been decompressed. Even while at depth, the EEG abnormalities were interpreted as not being alarming.

DECOMPRESSION PROFILE

It was found that decompression from a hydrox dive must be about one-third slower than a dive to the same depth and duration breathing heliox. The reason for this may be that hydrogen is more soluble in the body tissues than is helium. Thus, it requires more time for these extra gas molecules to be eliminated from the body.

CONCLUSIONS

It is concluded that there is no physiological or medical reason why hydrox may not be used for deep ocean diving. Indeed, there are some advantages to its use. They are:

1. Hydrogen is a renewable resource, available to all nations.
2. Hydrogen is a less dense gas than helium, and thus has less breathing resistance than does helium.
3. In many locations, hydrogen is cheaper than is helium.

The main disadvantages to the use of hydrox are:

1. Hydrogen is explosive in air and thus leaks may be dangerous.
2. Hydrox decompression requires a longer time than does helium.
3. There is a natural fear of hydrogen and a resistance to its use.

FALL IN DEEP BODY TEMPERATURE CAUSED BY COLD GAS INHALATION IN HYPERBARIC HELIUM-OXYGEN ENVIRONMENTS (16 AND 31 BAR)

(Respiratory Heat Loss, Seadragon-VI, 1984)

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The hyperbaric helium-oxygen environment (deep saturation diving) presents major problems in terms of the thermal regulatory and respiratory functions of divers. These problems are consequences of the high thermal conductivity, high specific heat, and high density of the environmental and respiratory gas used in these situations (table 1).

To obtain data on the thermal physiological problems of deep sea divers, cutaneous temperature was measured as an index of peripheral temperature, and rectal temperature for core temperature. Although the measurement of rectal temperature was simple in comparison with the measurement of other core temperatures and was utilized as an index of deep body thermal conditions, correspondence between rectal temperature and the temperature of the hypothalamus, which is an important thermal regulatory center, was poor.

The present experiment was designed to elucidate the influence of cold gas inhalation on deep cephalic temperature, reflected by tympanic membrane temperature, in hyperbaric helium-oxygen environments at a depth of 31 bar, corresponding to 300 meters of seawater. Difficulties associated with the inspired gas heaters used with diving equipment can cause a cold gas inhalation problem. For deep sea diving, the fall in deep body temperature is a very

Table 1.--Thermodynamic characteristics of the environmental gas at 30°C

Pressure (bar)	Pressure (m)	Partial Pressure (bar) O_2	Partial Pressure (bar) N_2	Partial Pressure (bar) He	Concentrative Fraction O_2	Concentrative Fraction N_2	Concentrative Fraction He	Density (g/L)	Specific Heat (J/g°C)	Heat Capacity (J/L°C)
1	0	0.21	0.79	-	0.21	0.79	-	1.14	1.01	1.15
16	150	0.30	0.7[illegible]	14.91	0.0188	0.0494	0.9319	3.59	4.94	17.74
31	300	0.30	0.79	[illegible]1	0.0097	0.0255	0.9648	5.91	5.08	30.02

important factor in terms of the safety and physiological functioning of deep sea divers.

METHODS

Four male volunteers inhalated the cold gas for 20 minutes after a 5-minute rest period. Then they rested for 20 minutes during the recovery period, in the sitting position, in warm atmospheric air and hyperbaric helium-oxygen environments (16 and 31 bar).

The experimental protocol is presented in figure 1. The hyperbaric chamber was successively compressed with oxygen to 1.09 bar (0.9 meters in equivalent depth) and with pure helium to the maximal ambient pressure. Ambient gas conditions within the hyperbaric chamber were maintained as follows: oxygen partial pressure was 0.21 $\pm$ 0.01 bar, nitrogen partial pressure was 0.79 $\pm$ 0.01 bar, relative humidity was 50-60%, and temperature was maintained in the comfort zone.

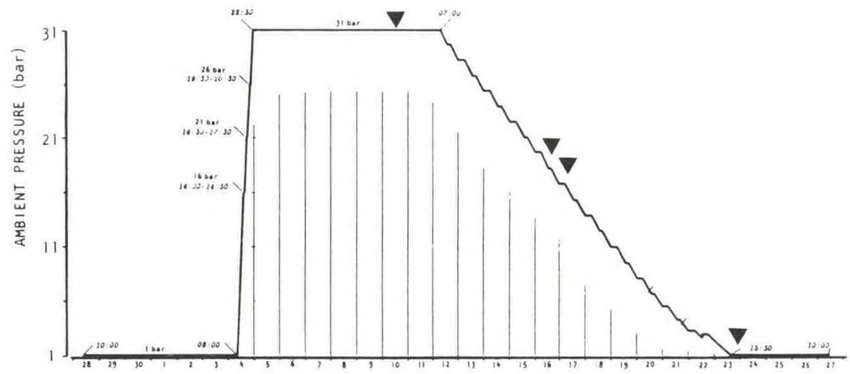

Figure 1.--Experimental protocol of ambient pressure (see text for details).
▲ : Cold gas inhalation test

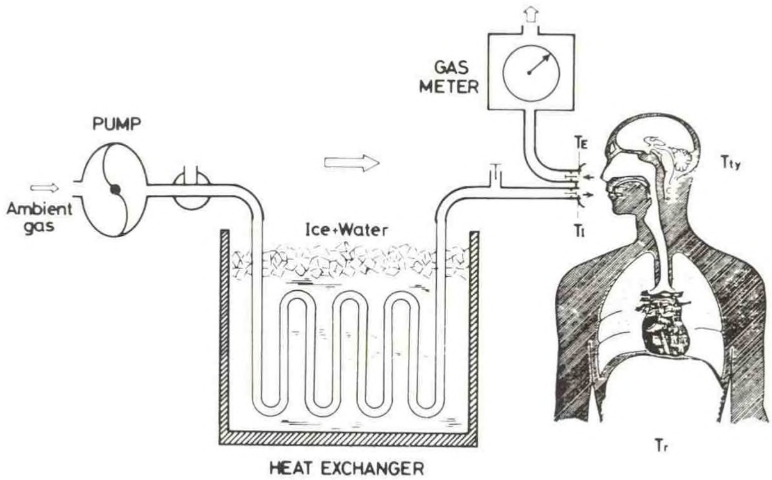

Figure 2.--Diagrammatic representation of cold gas inhalation apparatus (see text for abbreviations).

The subjects inhaled cold gas, cooled via a heat exchanger pipe in ice water (fig. 2), by mouth with the nose clipped shut. The tympanic membrane, rectal, and ventilatory gas temperatures were continuously recorded, and expiratory minute volume and cardiac frequency were also measured every minute during the experiment.

The physical characteristics of the subjects are presented in table 2; no dysfunction of the tympanic membrane was observed during the pre- and post-experimental medical examinations.

RESULTS

Inhalant gas temperatures were maintained at about 6°C at 31 bar, 7°C at 16 bar of hyperbaric helium-oxygen, and 15°C at atmospheric air environments with the cooling apparatus used in the present experiment. The subjects complained of the rapid cooling of the thorax from inside and of dyspnea; particularly in

Table 2.--Physical characteristics of subjects

Subject	Age (yr)	Height (cm)	Weight (kg)
Y.T.	32	173	65
M.N.	28	164	55
T.H.	23	167	60
T.S.	33	167	62

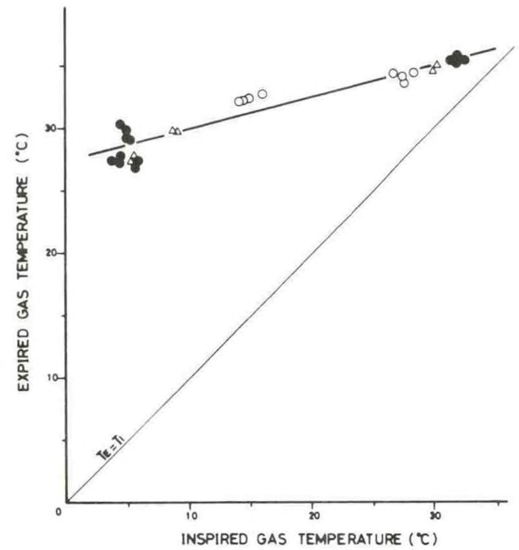

Figure 3.--Expired gas temperature as function of inspired gas temperature in atmospheric air and hyperbaric helium-oxygen environments (16 and 31 bar, 4 subjects).
- Equations of regression line between expired (Te) and inspired (Ti) gas temperature in three environments were as follows:

○ 1 bar: $Te = 30.5 + 0.134 \cdot Ti$ ($n = 8$, $r = 0.955$)
△ 16 bar: $Te = 26.9 + 0.260 \cdot Ti$ ($n = 6$, $r = 0.982$)
● 31 bar: $Te = 27.1 + 0.262 \cdot Ti$ ($n = 13$; $r = 0.950$)

There was no significant difference between these three regression lines with analysis of covariance, and we present only one regression line in the figure:

$$Te = 27.4 + 0.256 \cdot Ti \quad (n = 27;\ r = 0.954)$$

the 31 bar helium-oxygen environment, they reported feeling that the cold inhalant gas was like eating an ice cream cone.

Figure 3 shows the linear relationship between the inspired and the expired gas temperature in each experimental environment.

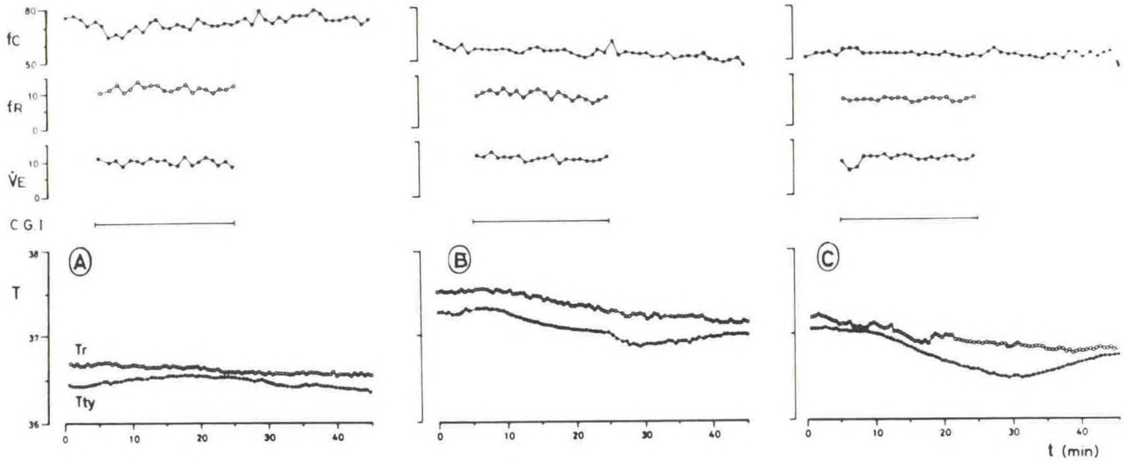

Figure 4.--Changes in cardiac frequency (f_C), respiratory frequency (f_R), expiratory minute volume ($\dot{V}e$), tympanic membrane temperature (Tty), and rectal temperature (Tr) during successive 5 minutes of rest, 20 minutes of cold gas inhalation (CGI), and 20 minutes of recovery (subj. T.S.).

Environmental pressure:

A:1 bar air, B:16 bar HE-O2, C:31 bar He-O2

(f_C in beats/min, f_R in breaths/min, $\dot{V}e$ in LATPS/min, T in °C)

No significant difference between three regression lines was found using an analysis of covariance. The high points in the high inspired gas temperature range were obtained using warm ambient gas respiration within the chamber.

Cardiac frequency, respiratory frequency, expiratory minute volume, and tympanic and rectal temperatures during preparatory rest (5 min), cold gas inhalation (20 min), and recovery-rest after the cold gas inhalation (20 min) are presented in figure 4 for the 31 and 16 bar hyperbaric helium-oxygen and atmospheric air environments. Figure 5 shows the mean values of two deep body temperature changes (tympanic membrane and rectal) from the

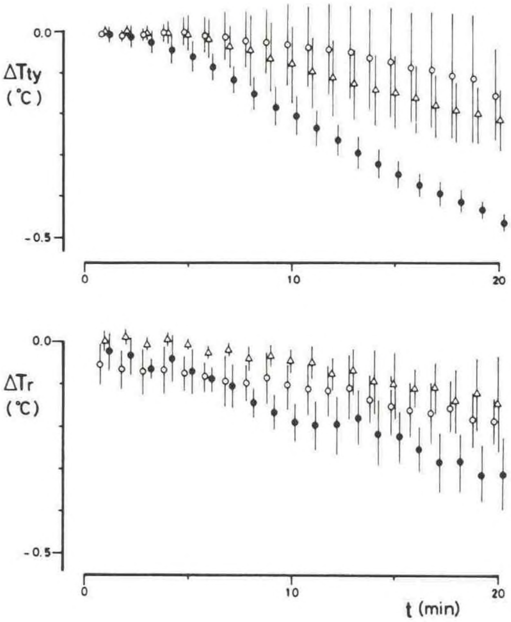

Figure 5.--Changes in tympanic membrane temperature and rectal temperature, from warm resting base line, during cold gas inhalation at atmospheric air and hyperbaric helium-oxygen environments.

-Mean values ± s.d.; ratings for 3 subjects are given.

-Environmental conditions:

○:1 bar air, △:16 bar He-02, ●:31 bar He-02

start of cold gas inhalation. There was no notable influence of cold gas inhalation on cardiac frequency, respiration frequency, or expiratory minute volume. The response of the tympanic membrane temperature to cold gas inhalation and to recovery warm ambient gas respiration was more rapid and definite compared with that of rectal temperature in the hyperbaric-oxygen environments. These tendencies of deep body temperature were particularly noticeable at higher environmental pressures.

The relationship between the tympanic membrane and rectal temperatures of the four subjects is plotted in figure 6. The

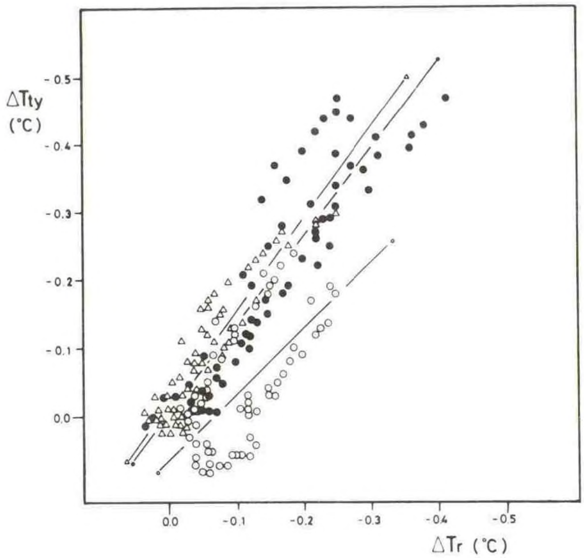

Figure 6.--Comparison between change in tympanic membrane temperature and change in rectal temperature measured in four subjects during cold gas inhalation in atmospheric air and hyperbaric helium-oxygen environments.

-Equations for regression lines between change in tympanic membrane temperature (ΔTty) and change in rectal temperature (ΔTr) in three environments were as follows:

1 bar:	$\Delta Tty = 0.062 + 0.961 \cdot \Delta Tr$	n= 60	r= 0.661
16 bar:	$\Delta Tty = -0.014 + 1.366 \cdot \Delta Tr$	n= 60	r= 0.918
31 bar:	$\Delta Tty = -0.002 + 1.312 \cdot \Delta Tr$	n= 60	r= 0.904

-There was a significant difference only between results in atmospheric air and in two hyperbaric helium-oxygen environments (16 and 31 bar), according to the analysis of covariance.

correlations were excellent for all experimental environments. The regression coefficient increased as ambient pressure increased, and this increase was statistically significant ($p < 0.02$).

DISCUSSION

The relationship between expired and inspired gas temperatures observed in the present experiment (fig. 3) agrees well with the results reported by Boutelier and colleagues (1971), Jacquemin and coworkers (1971), Varene and his group (1976), and Piantadosi (1983) in humans and by Naraki and coworkers (1984) in cats in hyperbaric helium-oxygen environments.

Dyspnea during cold gas inhalation in hyperbaric helium-oxygen environments was also observed by Rawlins and Tauber (1971) and by Hoke and colleagues (1972). It is induced by the constriction of the respiratory tract caused by the penetration of the cold gas into deep intrathoracic airways. The mechanism of this phenomenon is probably explained by the results of McCaffery (1983), who determined that the temperature of the right lower pulmonary lobe decreased by 10°C during cold air inhalation (-17°C) in an atmospheric environment.

The importance of brain temperature in the thermoregulatory system has been observed in many animal experiments. However, direct measurement of brain temperature in humans is very difficult, and hence the tympanic membrane temperature has been used as a good index of brain temperature, particularly of hypothalamic temperature (Benzinger 1983, 1969; Wurster et al. 1966; Nadel et al. 1970; Hayward et al. 1977; Cabanac et al. 1979; McCaffrey et al. 1979; Caputa and Cabanac 1980).

In the present experiment, the response of the tympanic membrane temperature (representing brain temperature) was more rapid and definite than that of rectal temperature (figs. 4 and 5). The rapid response of the rectal temperature compared with that of the tympanic membrane temperature was observed in atmospheric air conditions in exposures to cold water (Hayward et al. 1979), and in the perfusion of blood from the right femoral artery by Shiraki and his colleagues (1984). McCaffrey and researchers (1975a,b) ascribed the high thermal response of rectal temperature to the heating of feet and legs and the high response of tympanic membrane temperature to the heating and cooling of the face, neck, and head. The results of the present experiment showing a rapid response in tympanic membrane temperature in comparison with that of rectal temperature can probably be explained by McCaffrey's hypothesis: Environmental thermal stress on the head and/or neck segments behaves very similarly to direct heat loss or heat gain from the respiratory tract, and it induces important temperature changes in the tympanic membrane and brain without changing aortic blood temperature.

The amplitude of the two deep body temperature changes during cold gas inhalation was the same as in atmospheric air environments (the slope of the regression line in fig. 6 was about 1), but in hyperbaric helium-oxygen environments the tympanic membrane temperature change was about 1.3 times that of rectal temperature.

The considerable fall in deep body temperature, especially in brain temperature, such as occurs in deep sea divers having trouble with their respiratory apparatus causes important problems in terms of performing diving work, physiological functioning, and diver safety. Figure 7 shows the decrease in mean body temperature caused only by respiratory heat loss due to the inhalation of cold gas in hyperbaric helium-oxygen conditions. It was estimated under the following conditions: mean specific body heat: 3.47J/g°C; body weight: 60 kg; ventilatory minute

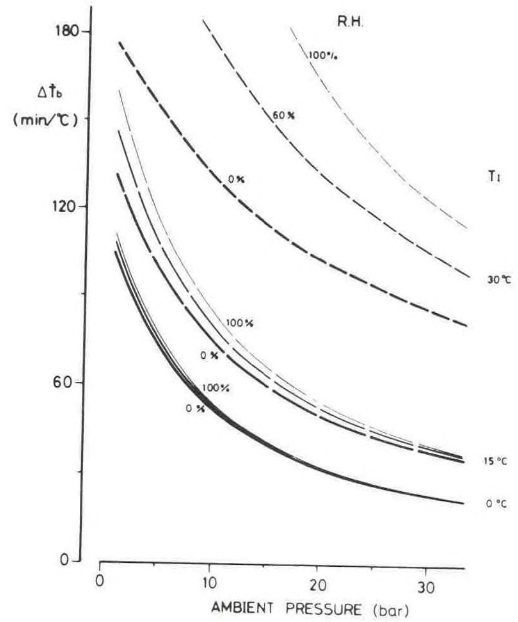

Figure 7.--Estimation of the fall in mean body temperature caused only by respiratory heat loss due to cold gas inhalation in hyperbaric helium-oxygen environments (see text for details).

volume: 10 LBTPS/min; respiratory equivalent: 0.63 LBTPS/mmol; expired gas saturated with water vapor at the expired gas temperature; three levels of inspired gas temperature (0°C, 15°C, and 30°C); and three levels of inspired gas humidity (0%, 60%, and 100%).

If inspired gas heater trouble occurs in deep waters in the temperate region, the water and the inspired gas temperature are about 15°C at 100 m of depth. Within 70 minutes, the mean body temperature decreases by 1°C, according to the results shown in figure 7. At 300 m of depth, the water and inspired gas temperature are about 10°C, and within 30 minutes the mean body temperature decreases by 1°C. In addition to the above estimated values, the fall in deep body temperatures, especially in brain and lung temperatures, is probably more important than the mean body temperature during cold gas inhalation, because respiratory heat loss occurs in the form of direct heat loss from the body core near these important organs.

When considering the capacity and precision of deep sea diving respiratory apparatus, the regulation of the inspired gas temperature is at least as important for the diver's security as the composition of the respiratory gas.

REFERENCES

Benzinger, T. H., C. Kitzinger, and A. W. Pratt. 1963. "The Human Thermostat," pp. 637-665. In: Temperature--Its Measurement and Control in Science and Industry. New York, Reinhold, vol. 3, part 3.

Benzinger, T. H. 1969. "Heat Regulation: Homeostasis of Central Temperature in Man." Physiol. Rev. 49:671-759.

Boutelier, C., J. Colin, and J. Timbal. 1971. "Determination du coefficient d'echange thermiques l'eau en ecoulement turbulent." J. Physiol. (Paris) 63:207-209.

Cabanac, M., and M. Caputa. 1979. "Natural Selective Cooling of the Human Brain: Evidence of Its Occurrence and Magnitude." J. Physiol. (London) 286:255-284.

Caputa, M., and M. Cabanac. 1980. "Muscular Work as Thermal Behavior in Humans." J. Appl. Physiol. 48:1020-1023.

Hayward, J. S., J. D. Eckerson, and M. L. Collis. 1977. "Thermoregulatory Heat Production in Man: Prediction Equation Based on Skin and Core Temperatures." J. Appl. Physiol. 42:377-384.

Hoke, B., D. L. Jackson, J. M. Alexander, and E. T. Flynn. 1976. "Respiratory Heat Loss and Pulmonary Function During Cold-Gas Breathing at High Pressures," pp. 723-740. In: C. J. Lambertsen (ed.), Underwater Physiology V: Proceedings of the Fifth Symposium on Underwater Physiology. FASEB, Bethesda, Md.

Jacquemin, C., P. Varene, and J. L'Huillier. 1971. "Aspects respiratoires de l'environment thermique hyperbare." J. Physiol. (Paris) 63:293-295.

McCaffrey, T. V., R. D. McCook, and R. D. Wurster. 1975a. "Effect of Head Skin Temperature on Tympanic and Oral Temperature in Man." J. Appl. Physiol. 39:114-118.

McCaffrey, T. V., G. S. Geis, J. M. Chung, and R. D. Wurster. 1975b. "Effect of Isolated Head Heating and Cooling on Sweating in Man." Aviat. Space Environ. Med. 46:1353-1357.

McCaffrey, T. V., R. D. Wurster, H. K. Jacobs, D. E. Euler, and G. S. Geis. 1979. "Role of Skin Temperature in the Control of Sweating." J. Appl. Physiol. 47: 591-597.

McFadden, E. R. 1983. "Respiratory Heat and Water Exchange: Physiological and Clinical Implications." J. Appl. Physiol. 54:331-336.

Nadel, E. R., S. M. Horvath, C. A. Dawson, and A. Tucker. 1970. "Sensitivity to Central and Peripheral Thermal Stimulation in Man." J. Appl. Physiol. 29:603-609.

Naraki, N., H. Burnet, G. Imbert, and M. Hugon. 1984. "Respiratory Heat Loss Under Hyperbaric Helium-Oxygen Atmospheres." Jpn. Annal. Physiol. Anthrop. 3:227-236.

Piantadosi, C. A. 1982. "Respiratory Heat Loss Limits in Helium-Oxygen Saturation Diving." U.S. Navy Experimental Diving Unit Report No. 10-80. 23 pp.

Rawlins, J. S. P., and J. F. Tauber. 1971. "Thermal Balance at Depth," pp. 435-442. In: C. J. Lambertsen (ed.), Underwater Physiology. Proceedings of the Fourth Symposium on Underwater Physiology. Academic Press, New York.

Shiraki, K., N. Konda, and S. Sagawa. 1983. "A Comparison of Temperature Measured in Esophagus, Tympanic Membrane, Aorta and Right Atrium During Hyperthermia in Man." Jpn. J. Biometeor. 20:74-80.

Varene, P., J. Timbal, H. Vieillefond, H. Guenard, and J. L'Huillier. 1976. "Energy Balance of Man in Simulated Dive From 1.5 to 31 ATA," pp. 755-763. In: C. J. Lambertsen (ed.), Underwater Physiology. Proceedings of the Fifth Symposium on Underwater Physiology. FASEB, Bethesda, Md.

Wurster, R. D., R. D. McCook, and W. C. Radwall. 1966. "Cutaneous Vascular and Heating Responses to Tympanic and Skin Temperature." J. Appl. Physiol. 21:617-622.

PREDICTIVE STUDY V
"DEFINITION OF ORGAN OXYGEN TOLERANCE IN MAN"

Relation to Adaptations for Human
Performance in the Space Environment

Relation to Rational Extension
of Hyperoxygenation Therapy

Relation to Human Performance
in the Undersea Environment

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PREDICTIVE STUDIES V

Definition of Oxygen Tolerance in Man

SUMMARY

This Program recognizes that the essential life element, oxygen, combines useful effects critical to relief of hypoxia, with serious toxic effects which limit oxygen use in therapy of many disease states. It also recognizes that opportunity now exists to extend the tolerance to oxygen at normal and higher ambient pressures, with potentially large application to clinical therapy in many conditions of local or systemic hypoxia.

The planned scope of the Program is based upon more than thirty years of leadership in oxygen tolerance investigation by this laboratory, along with results of extensive research world-wide. Emphasis upon selected organ functions derives from the requirement to now search beyond the pulmonary toxicity and central nervous system convulsions long recognized as prominent consequences of oxygen poisoning.

Goals of the proposed research are to define inherent oxygen tolerance in normal man under conditions that are relevant to therapeutic use of increased inspired oxygen pressures and uses of oxygen in undersea operations. Specific aims of this project include investigation of the rate of development of oxygen poisoning of specific organ functions at O_2 pressures of 1.0, 1.5, 2.0, 2.5, and 3.0 ATA (the full range of oxygen pressures encountered in medicine including hyperoxic therapy, and in undersea operations).

Concurrent measurements of oxygen effects on organ systems and functions are performed. For measurement of changes in sensory and brain function, monitoring of electroencephalographic activity and intermittent evoked cortical electrical responses are accompanied by repeated measurements of perceptual, cognitive, and psychomotor function. Visual functions are monitored by repeated measurements of visual acuity, visual fields, color vision, dark adaptation, and 2-flash discrimination thresholds, with electroretinography in selected conditions. Auditory function is measured by pure tone air conduction audiometric determinations of hearing thresholds. Vestibular reactivity is intermittently tested by thermal stimulation. Changes in blood electrolyte, hormonal and cellular composition are measured along with influences of oxygen exposure upon excretory functions. Observations of neurologic oxygen tolerance will be correlated with development of pulmonary toxicity through measurements of the vital capacity and maximal flow rates during

inspiration and expiration and other selected indices of pulmonary function.

The range of inspired oxygen pressures of 1.0, 1.5, 2.0, 2.5, and 3.0 ATA was selected because pulmonary oxygen intoxication occurs at 1.0, 1.5, and 2.0 ATA in the absence of obvious neurologic effects of oxygen toxicity, while definite neurologic symptoms precede the development of prominent pulmonary effects at 3.0 ATA, and because the actual rate of occurrence of mental or sensory decrement is still unknown at any of these pressures. In addition, these measurements will provide necessary guidelines for the design of a future Predictive Study aimed at (a) optimizing the effectiveness of programmed intermittency of hyperoxic exposure over a wide range of useful oxygen pressures, and (b) combined use of synthetic blood substitutes and hyperoxygenation to improve oxygen delivery without limitations of oxygen toxicity.

TOLERANCE OF HUMAN ORGAN SYSTEMS TO CONTINUOUS OXYGEN EXPOSURE

(Predictive Studies V)

BACKGROUND

Uniqueness of Oxygen in Therapy

Oxygen is unique in that its broad importance in occupational activity, and its basic importance to the preservation of life in disease, coexist with universally toxic properties. These, at sufficient pressure and duration of oxygen exposure, will ultimately disrupt or destroy the vital processes of essentially any cell. The balance between life-sustaining and destructive properties of oxygen is maintained in part by intrinsic cellular antioxidant defense mechanisms that have evolved in eons of adaptation to atmospheric oxygen tensions (1,2). Because of this balance, pure oxygen or high partial pressure of oxygen in nitrogen or helium diving mixtures can be breathed for usefully long periods at one and more atmospheres ambient pressure. The extent and safety of further improvement of this ability to use oxygen at high pressures, depends upon clear demonstration of rate of development of adverse effects of oxygen on critical body functions (2b).

SPECIFIC AIMS

Aims

The Predictive Study V overall work plan represents a major coordinated investigative Program, planned and prepared for by over six years of preliminary research. It encompasses multiple correlated projects and multiple conditions of oxygen exposure. The overall goal is determination of safe limits of oxygen tolerance (to oxygen poisoning) for specific vital organs and critical functions in normal man, during continuous exposure to each of several levels of increased inspired oxygen pressure. This aim is directed to the use of the measurements to construct oxygen tolerance tables and diagrams as guides for rational medical therapeutic and occupational use of continuous periods of hyperbaric oxygen exposure.

A major second aim is to provide the necessary baseline information required for optimal extension of human organ oxygen tolerance through study of programmed interruption of oxygen exposures over the full range of useful oxygen pressures.

Together these aims are fundamental to advancement of oxygen use in medicine and occupational states.

Scope of Proposed Further Work

The First Phase of the Predictive Study V, determination of oxygen tolerance at 3.0 ATA, has been largely accomplished as a first step in the overall Program.

Overall Conditions for continuous respiratory exposure to oxygen at rest cover a range of oxygen pressures relevant to many conditions in medicine, including 1.0, 1.5, 2.0, 2.5 and 3.0 ATA, with normoxic control for equivalent circumstances. The resting state is intentionally employed to provide for determination of maximum tolerance, as the necessary baseline for related later examination of modifying factors.

Scope of Measurements at all pressures includes central nervous system electrical, cognitive, psychomotor and sensory functions, for direct comparison with changes in pulmonary/respiratory/cardiac and other vital functions within the same individual (see Table 1 - "Scope of Measurements"). Where preliminary experiments are found to indicate prominent effects of oxygen, repetitive measurements will seek to determine rates of onset and rates of recovery. Where magnitude of measurable effect is too small to allow quantitation of rate of development, determination will include overall effect of exposure. Where practical, subjects will be employed for more than one oxygen pressure exposure.

It is expected that detailed follow-up projects will be required for some observations made in this Program.

SIGNIFICANCE TO THERAPEUTICS

The goals of the proposed program have been recognized for many years as having fundamental significance to advancement of therapy with oxygen in states of hypoxia. This significance derives from the multiple roles and effects of oxygen itself in biological processes, in general medical therapy, and in prevention of occupational diseases in undersea and aerospace activity. Postponement in execution of the Program has been related to need to obtain extensive basic information concerning mechanisms and chemical sites of action of oxygen poisoning, and to the difficulties in initiating a comprehensive investigative effort in man. The Program is designed as the Fifth in the Series of Predictive Studies, involving collaboration of a multidisciplinary staff.

Limitations of Oxygen Use

Degree and duration of oxygen exposure. The toxic chemical effects of high oxygen pressures, exerted upon and inactivating multiple cellular and membrane enzyme systems, increase progressively in degree as duration of exposure to high oxygen pressure

TABLE 1.--SCOPE OF PROGRAM PLAN FOR ORGAN AND FUNCTION MEASUREMENTS DURING CONTINUOUS OXYGEN EXPOSURE IN MAN*

Electroencephalography
- Clinical Interpretation
- On-line Spectral Analysis
- Response to Photic Stimulation

Visual Function
- Visual Evoked Cortical Potential Response
- Electroretinography (Dark and Light Adapted)
- Fields (Goldman Perimetry)
- Pupillary Reaction
- Acuity
- Accommodation
- Color Vision

Auditory/Vestibular Function
- Audiometry (Air Conduction)
- Brainstem Auditory Evoked Response
- Cortical Auditory Evoked Response
- High Frequency Audiography
- Eye Tracking, Nystagmography
- Caloric Stimulation, Postural Balance

Somatosensory Cortical Evoked Potential Balance

Muscle Power (Skeletal, Respiratory)

Performance (Perceptual, Cognitive, and Psychomotor)

Pulmonary Function
- Flow-Volume Loops (Forced Vital Capacity)
- Density Dependent Flow Rates (Inspiratory, Expiratory)
- Closing Volumes
- Peak Inspiratory and Expiratory Pressures
- Airway Resistance
- Carbon Monoxide Diffusing Capacity of Lung
- Arterial Blood Gases and Acidity (PCO_2, PO_2, pH)

Respiration/Respiratory Gas Exchange/Metabolism

Temperature Regulation

Cardiovascular Function
- Electrocardiography
- Cardiac Output, Rate, Stroke Volume
- Mean Thoracic Impedance
- Blood Pressure, Systemic Vascular Resistance
- Orthostatic Reflex Responses

Endocrine Activity, via Plasma Hormone Levels

Insulin	Vasopressin	Adrenocorticotropic Hormone
Cortisol	Growth Hormone	Thyroid Stimulating Hormone
Aldosterone		

NOTE* Programmed sequence of sampling and measurements during an exposure of each subject is carried out in accordance with a fixed modular procedure, repeating the specific measures throughout the period of continuous hyperoxia. Frequency of modular measurements, and duration of overall exposure is determined by oxygen pressure level being studied.

lengthens. The rate of enzyme inactivation, with consequent failure of cell and organ function, is speeded progressively as the oxygen partial pressure of an exposure is increased. If all cells and all different enzymes were both a) equally sensitive to oxygen toxicity, and b) exposed in the body to the same partial pressures of oxygen, prediction of oxygen tolerance would be relatively simple. In actual fact, each enzyme has its own susceptibility to oxygen poisoning. Moreover, the same enzyme in different cell forms (brain, lung, liver) has a different cellular environment and different level of exposure to oxygen (2b). Finally, the enzymatic composition of cells in different vital organs is not uniform. For all these reasons, the detectable consequence of cellular poisoning is necessarily grossly different, organ-by-organ (brain, skin, bone, lung, eye, muscle) (2b).

Because of the expected gross difference in effect of oxygen at low and high levels of hyperoxia, it is necessary to determine the rate of development of oxygen toxicity at several oxygen pressures on organ systems critical to therapy and survival.

Functions of Program

Against the background of expanding basic information concerning oxygen toxicity in animals there remains essentially complete unawareness of the rates of development of specific dysfunctions during human hyperoxic exposure. The Program to develop oxygen tolerance limits in man is intended to obtain quantitative, dose-effect information in normal men, concerning pre-convulsive influences of oxygen on functions not previously investigated in detail, over a range of oxygen pressures in which quantitative measurements of oxygen effect on human organ function are lacking. Selection of indices of effect for study in man is based upon information and concept derived in the Institute's ongoing research concerning patho-physiologic mechanisms of oxygen poisoning in tissues, organs and animals.

Relation to Existing Information on Neurological and Pulmonary Oxygen Tolerance

In prior oxygen/undersea/aerospace related research, this Institute performed detailed measurements of rate of development of human pulmonary oxygen poisoning at 2.0 ATA, and analyzed existing other studies to [a] construct clinically useful "Pulmonary Oxygen Tolerance Curves" (3, 2b), (Figure 1); and [b] provide the important concept of a "Unit Pulmonary Toxic Oxygen Dose" (UPTD) (4).

In fact, except as obtained in this Program, no quantitative information relating to rate of development of Pulmonary oxygen poisoning in man exists for oxygen pressures greater than two atmospheres, or between 2 and 1 atmospheres, Figures 2a and 2b.

Fig. 1

OXYGEN TOLERANCE IN MAN

PROGRESSION OF PULMONARY OXYGEN TOXICITY DURING CONTINUOUS EXPOSURE TO VARYING PARTIAL PRESSURES OF OXYGEN

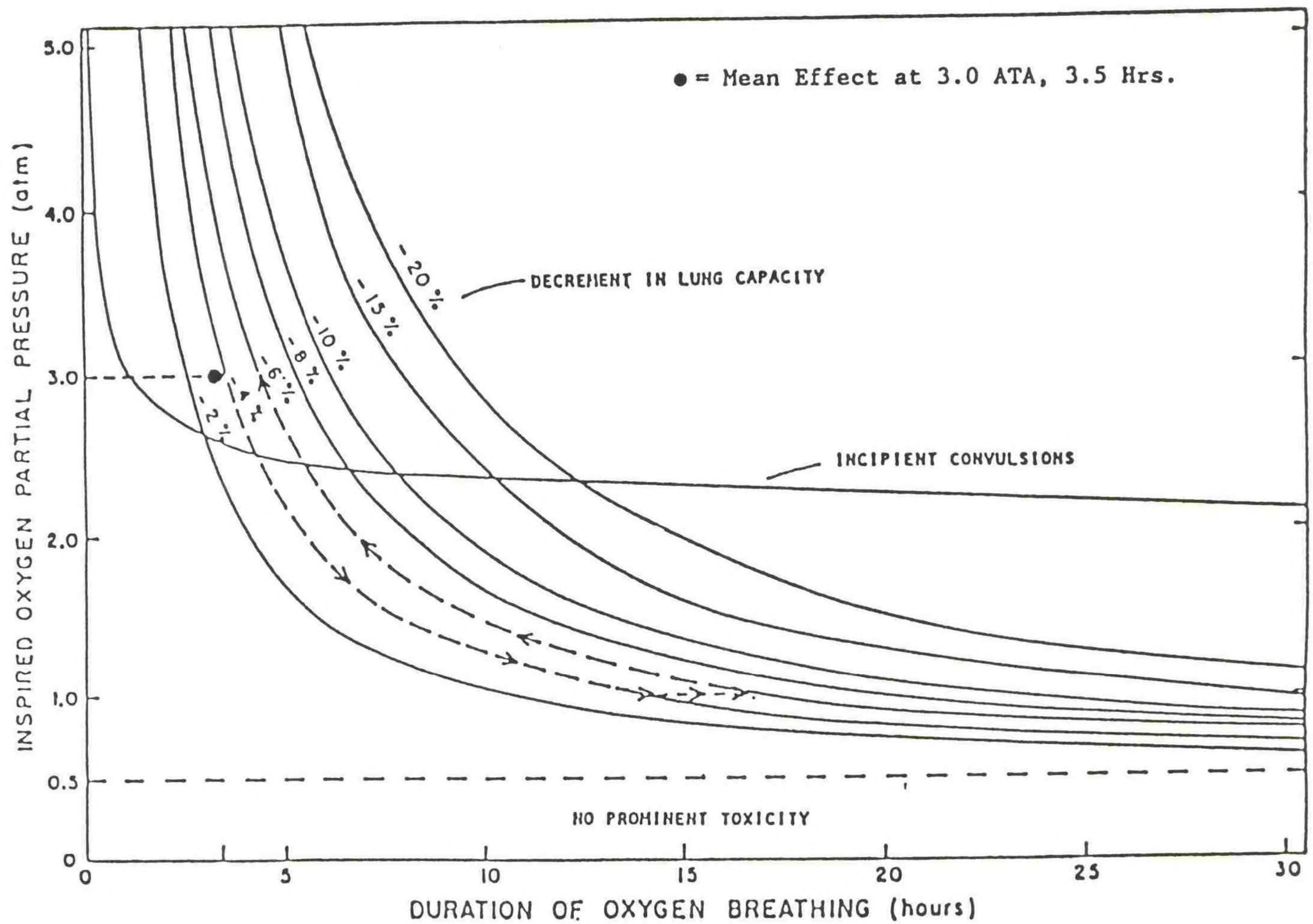


Fig. 2a PULMONARY OXYGEN TOLERANCE IN MAN

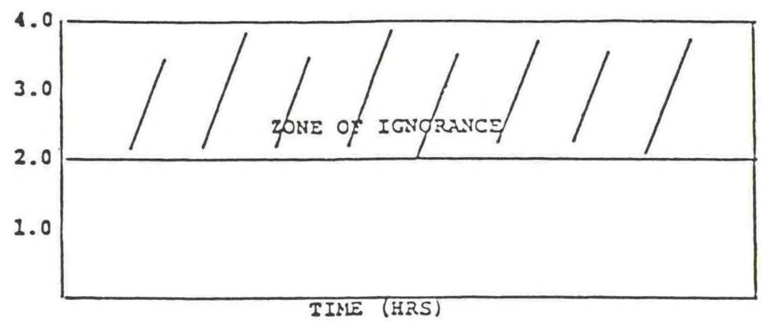
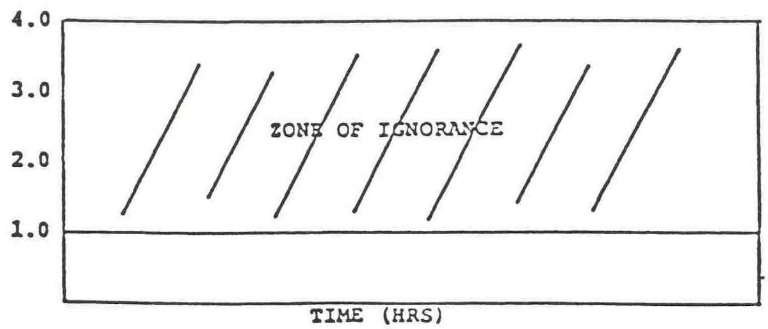


Fig. 2b CENTRAL NERVOUS SYSTEM OXYGEN TOLERANCE IN MAN



Oxygen tolerance limits for Central Nervous System, Blood and other tissue functions are at present essentially unknown above one atmosphere. Following the general descriptive information obtained in many human exposures by Donald (5) and Yarbrough et al (6) during World War II, no systematic study of the characteristics of central nervous system oxygen poisoning in man has been performed. This Institute has determined influences of hyperoxia upon human brain metabolism (7), and the interacting effects of carbon dioxide and oxygen upon brain oxygen tension (8). The important observation by Behnke (9) that human visual function is grossly reduced during prolonged exposure to oxygen at 3.0 atmospheres has not been adequately followed-up in man except at 1.0 atmosphere, in spite of a clear indication of a prominent effect upon this critical central nervous system function. One difficulty, persistent over several decades, has been a preoccupation with oxygen-induced convulsions in animals, rather than with measurements aimed at subtle central nervous system changes which may be detectable in man prior to the onset of convulsions. In this laboratory oxygen convulsions are considered a signal of spreading electrical disruption resulting from cumulative effects of oxygen toxicity, rather than representing the onset of oxygen toxicity (2b). The present Program concerns the pre-convulsive effects of oxygen at high oxygen pressures, and effects upon tissues beyond lung and brain. It does not involve intentional generation or study of convulsions.

Philosophy of Institute Oxygen Program for "Definition and Extension of Oxygen Tolerance." (The Concept of Optimal Intermittency).

A key concept generated early in this Institute's oxygen research Program is that, following a toxic exposure to hyperoxia, a sufficient interval of normoxia will allow for recovery and permit useful hyperoxic exposure again (2b). The duration of the recovery interval required will depend upon the rate of onset, nature and degree of induced poisoning (and hence upon the rate of recovery). By systematic investigation of rates of poisoning of different functions or systems, at different oxygen exposure pressures (ATA PO_2), with tracking as practical of the rates of recovery, it should be possible to define a) tolerance of critical functions to oxygen, b) optimal programs of intermittent oxygen exposure, and c)maximum effective use of oxygen at various pressures from one to several atmospheres. All are important to therapy and undersea and aerospace operations. These concepts, summarized in part by Table 2, form the bases for the animal and human investigations underlying the correlated Programs of Predictive Study V and VI.

TABLE 2 PROGRAM CONCEPTS OF OXYGEN TOLERANCE AND ITS EXTENSION

- OXYGEN IS A UNIVERSAL POISON. ITS EFFECTS MUST BE EXPRESSED IN ALL VITAL FUNCTIONS.
- THE RATE AND DEGREE OF OXYGEN POISONING DEVELOPMENT ARE PROPORTIONAL TO OXYGEN DOSE.
- THE RATE AND DEGREE OF OXYGEN POISONING DEVELOPMENT CAN BE PREDICTABLY DIMINISHED BY SYSTEMATIC INTERRUPTION OF OXYGEN EXPOSURE.
- THE RATE OF RECOVERY FROM OXYGEN POISONING IS ESSENTIALLY UNKNOWN IN ANY TISSUE.
- THE RATE OF RECOVERY FROM SYSTEMIC OXYGEN TOXICITY IS A COMPLEX OF INDIVIDUAL RECOVERY RATES FROM DISCRETE ENZYMATIC AND OTHER CHEMICAL TARGETS.
- THE RATE OF RECOVERY FROM OXYGEN POISONING IS SLOWER FROM SEVERE POISONING THAN FROM MILD TOXICITY.

METHODS

General

The general plan involves systematic exploration of oxygen effects as indicated in Table 1, in sufficient subjects to allow statistical judgment of risk and construction of practical therapy tables for each elevated oxygen pressure. The initial phase of measurement involved the inspired oxygen pressure of 3.0 atmospheres absolute to increase the likelihood of detecting subtle central nervous system or sensory effects.

The Institute's system of using repetitive "modules" of multiple specific measurements by multiple collaborating investigators is used to determine rates of development of detectable effects (Fig. 3). Modular measurements are supplemented by "before-and-after" measurements when necessary.

Subjects and Exposures

Because of the extended period required for the overall Program, and the inadvisability of shifting from one oxygen pressure to another until adequate information is obtained concerning the nature of oxygen effects, it is not yet practical to study each subject fully at each planned exposure pressure. When understanding of effects has been improved, specific patterns of exposure and measurement will be used to improve precision at each oxygen pressure.

Scope of Measurements

Table 1 cites the specific projects and measurements planned to encompass the entire scope of the Continuous Oxygen Tolerance Predictive Study V, as conceived by this Institute. Optimal scope has necessarily been planned in detail as part of the overall Program Plan. At this stage in the Predictive Study the extensive existing program is not optimally supported, and depends heavily upon recruitment of unpaid scientific and technical experts for continued performance. As additional funds become available it will become possible to assure continuity of the required investigative skills.

Specific Measures in Primary Program

Each measurement is performed by an investigator with scientific and technical expertness for the specific organ function.

Electroencephalogram. Recording on Grass polygraph and magnetic tape, from 12 scalp electrodes placed by measurement according to the International 10-20 System, with on-line visualization and energy spectrum analysis. Intermittent periods of "EEG Quiet" for Photic Stimulation and eyes-closed recording.

Somatosensory Evoked Potential. Stimulation of median nerve at wrist. Measurement of potential at Erbs' Point and at cortex.

Hearing and Vestibular Function. Air conduction audiogram over frequencies of 250 to 8000 Hz, using Telephonics TDH-39 Earphones with MX-41/AR Cushions. Continuous electronystagmogram. Caloric stimulation test before and after O_2 exposure. Brain Stem Evoked Potential with stimulation by 20.3, 100-μsec rarefaction clicks per second.

Visual Function. Visual Evoked Potential by checkerboard pattern reversal at a rate of 2 reversals per second. Electroretinogram by strobe flash in a Ganzfeld Full-Field Stimulator and corneal electrodes (Burian-Allen), with one eye dark-adapted and one not. Visual fields by Rodenstock Projection Perimeter.

Cardiac Function. Electrocardiography, with on-line display and magnetic tape recording. Impedance measurement of cardiac output (Minnesota Impedance Cardiograph). Circulatory reflex responses on change from supine to quiet standing position.

Pulmonary Functions. Methods equivalent to those described for prior IFEM Pulmonary O_2 Toxicity Studies (3,11,12). For relatively short period of 3.0 ATA exposure, all measurements made before and after O_2 breathing, to allow exposure time for determination of neurological and cardiovascular effects.

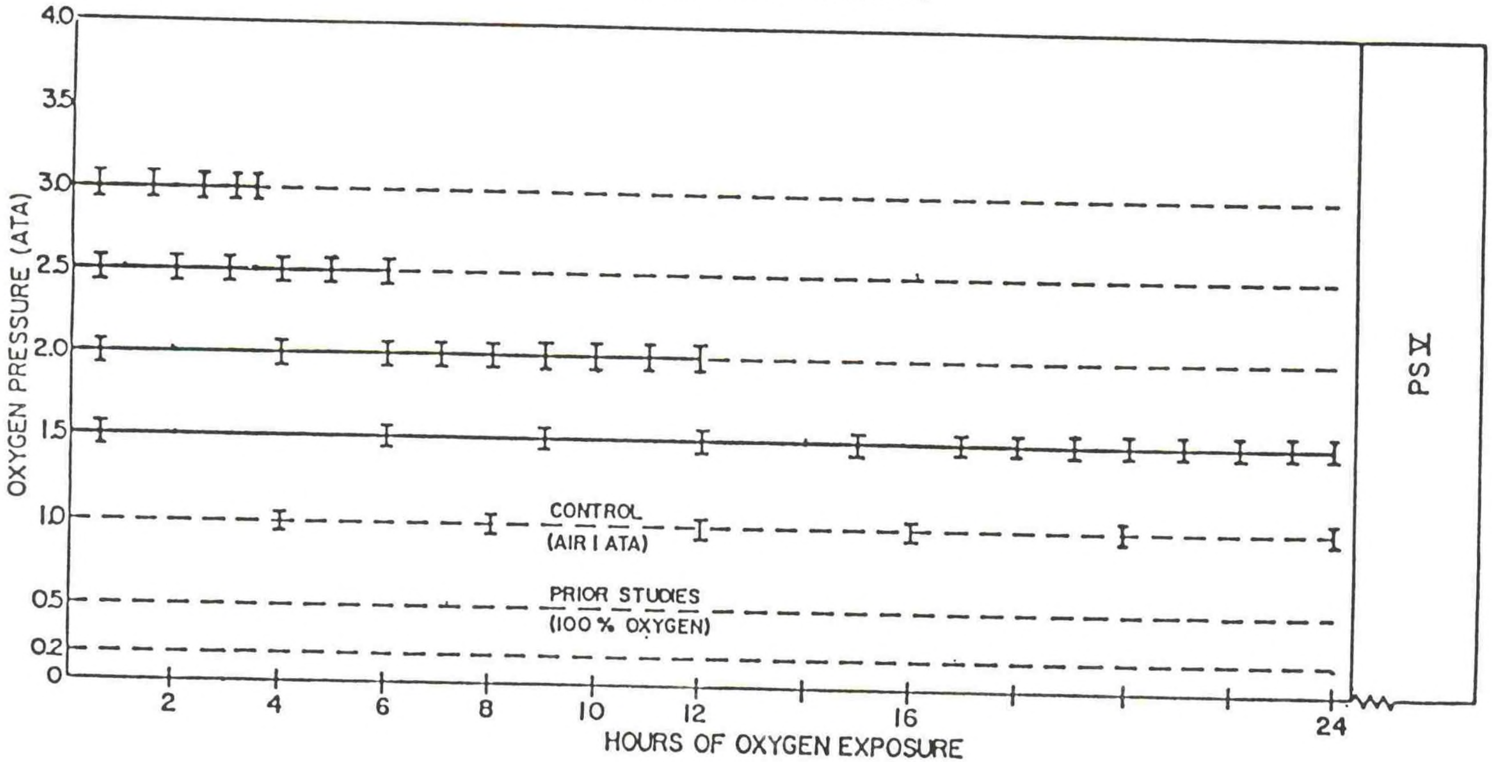
Cognitive/Psychomotor Measurements. Tests are administered, scored and analyzed by the computer-controlled Performance Measurement System developed at IFEM. Subjects are trained to stability. Test sequences are incorporated into the measurement modules, for repetitive use before, during and after oxygen exposure. Test battery before and after oxygen exposure is more extensive than, but includes the short sequences useful within the measurement module. For the module used during oxygen breathing periods Short Term Memory, Visual Reaction Time, Finger Dexterity and General Reasoning are used. As information develops, more specific studies of performance will be conducted.

Particular Problems of Method

The long experiment durations for the lower O_2 pressures create requirements for control which must be considered part of the oxygen study, but which should have relevance to many prolonged studies already performed for other purposes. Feeding, fluid balance and waste elimination are resolved, as is provision for sleep.

Fig. 3

HUMAN CONTINUOUS 100% OXYGEN EXPOSURE CONDITIONS*
(PREDICTIVE STUDIES V)



*Each vertical bar represents a complete measurement module.

Data Analysis

The principle of study within a subject is to obtain repetitive measurements during a control phase as a baseline for changes induced by oxygen, and for determinations of rates of recovery. Each subject therefore serves as his own control for each particular oxygen pressure to which he is exposed.

Where subjects are in fact exposed to more than one oxygen pressure, analysis takes this into account. Where necessary, comparisons are made of populations of subjects exposed at different pressures, as was done for the Institute analysis of human pulmonary oxygen tolerance (4), using regression analysis to derive the desired tolerance curves.

RELATION TO OTHER IFEM OXYGEN STUDIES

Two other key areas of research are fundamental to Predictive Study V (Human Tolerance to Continuous O_2 Exposure) and its planned Predictive Study VI sequel (Extension of Human Oxygen Tolerance).

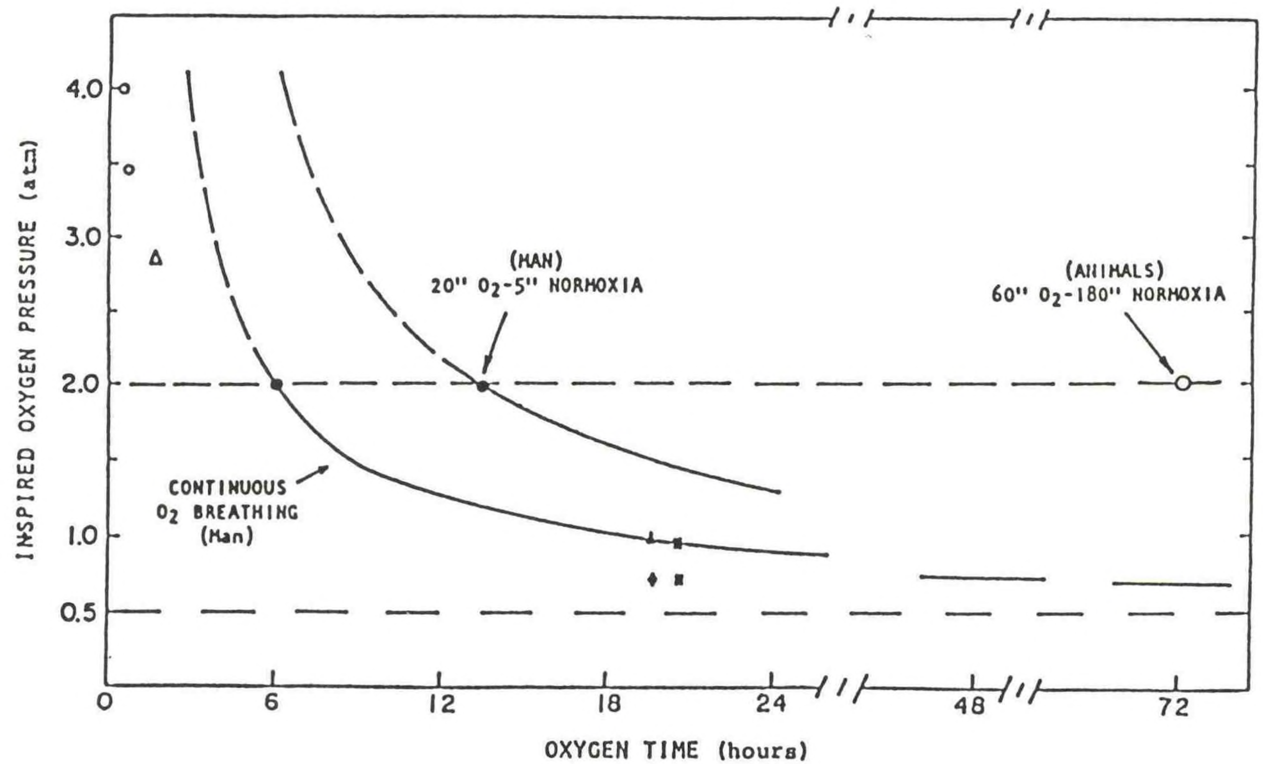
These are (a) the basic program concerning mechanisms and rates of development of oxygen toxicity in animal organs, and (b) the continuation of IFEM applied research in optimal extension of oxygen tolerance in animal organs by systematic interruption of hyperoxic exposure at various pressures.

These interrelated investigations provide the clear promise of gross and useful extension of oxygen tolerance such as is indicated by Figure 4. The figure shows that brief interruption of oxygen exposure at 2 ATA doubles human oxygen tolerance (2b). It also shows that more prolonged interruption in animals allows the equivalent of three days of oxygen exposure at 2.0 ATA with no evidence of pulmonary or CNS oxygen poisoning. Without the interruption such an exposure would be lethal.

Together these complementary basic and applied projects, and the methods they involve, represent the major component of U.S. oxygen tolerance research and applications.

Fig. 4

EFFECT OF INTERMITTENT OXYGEN BREATHING
ON PULMONARY OXYGEN TOLERANCE LIMITS IN MAN AND ANIMALS



Note: Curves represent 4% decrease in Vital Capacity.
Open points represent oxygen exposures without reported pulmonary effect.

REFERENCES

1. Gilbert, D.L. Atmosphere and evolution. In: Oxygen in the Animal Organism. Edited by F. Dickens and E. Neil. Oxford: Pergamon Press, 1974. pp. 641-654.

2. Fridovich, I. The biology of oxygen radicals. Science. 201: 875-880, 1978.

2b. Lambertsen, C.J. Effects of hyperoxia on organs and their tissues. In: Extrapulmonary Manifestations of Respiratory Disease. Edited by E.D. Robin. Vol. 8 of Lung Biology in Health and Disease. Lenfant, C. (ed.). New York: Marcel Dekker, 1978. pp. 239-303.

3. Clark, J.M., and C.J. Lambertsen. Rate of development of pulmonary O_2 toxicity in man during O_2 breathing at 2.0 atm abs. J. Appl. Physiol. 30: 739-752, 1971.

4. Wright, W. B. Use of the University of Pennsylvania Institute for Environmental Medicine procedure for calculation of cumulative pulmonary oxygen toxicity. Experimental Diving Unit Report 2-72, Washington, D.C., 1972.

5. Donald, K.W. Oxygen poisoning in man. I and II. Br. Med. J. 1: 667-672, 712-717, 1947.

6. Yarbrough, I.D., W. Welham, E.S. Brinton and A.R. Behnke. Symptoms of oxygen poisoning and limits of tolerance at rest and at work. U.S. Naval Experimental Diving Unit, (Project X-337, Sub. No. 62, Rept. No. 1), 1947.

7. Lambertsen, C.J., R.H. Kough, D.Y. Cooper, G.L. Enmel, H.H. Loeschcke and C.F. Schmidt. Oxygen toxicity. Effects in man of oxygen inhalation at 1 and 3.5 atmospheres upon blood gas transport, cerebral circulation and cerebral metabolism. J. Appl. Physiol. 5: 471-486, 1953.

8. Lambertsen, C.J., J.H. Ewing, R.H. Kough, R.A. Gould and M.W. Stroud 3rd. Oxygen toxicity. Arterial and internal jugular blood gas composition in man during inhalation of air, 100% O_2 and 2% CO_2 in O_2 at 3.5 atmospheres pressure. Amer. J. Physiol. 8: 255-263, 1955.

9. Behnke, A.R., H.S. Forbes and E.P. Motley. Circulatory and visual effects of oxygen at 3 atmospheres pressure. Amer J. Physiol. 114: 436-442, 1936.

10. Caldwell, P.R.B., Lee, W.L., Jr., Schildkraut, H.S. and Archibald, E.R. Changes in lung volume, diffusing capacity, and blood gases in men breathing oxygen. J. Appl. Physiol. 21: 1477-1483, 1966.

11. Fisher, Aron B., Richard W. Hyde, Ricardo J.M. Puy, James M. Clark, and C.J. Lambertsen. Effect of oxygen at 2 atmospheres on the pulmonary mechanics of normal man. J. Appl. Physiol. 24: 529-536, 1968.

12. Puy, Ricardo J.M., Richard W. Hyde, Aron B. Fisher, James M. Clark, J. Dickson, and C.J. Lambertsen. Alterations in the pulmonary capillary bed during early O_2 toxicity in man. J. Appl. Physiol. 24: 537-543, 1968.

13. Burger, E.J., Jr., and Mead, J. Static properties of lungs after oxygen exposure. J. Appl. Physiol. 27: 191-197, 1969.

14. Dolezal, V. The effect of long lasting oxygen inhalation upon respiratory parameters in man. Physiol. Bohemoslov 11: 149-158, 1962.

15. Gosovic, S.M., and Radovic, A.I. Some cardiorespiratory effects of oxygen toxicity. In: Underwater Physiology VI, ed. by Shilling, C.W. and Beckett, M.W., FASEB, Bethesda, Maryland, 1978, pp. 205-214.

16. Clark, J.M. and C.J. Lambertsen. Alveolar-arterial O_2 differences in man at 0.2, 1.0, 2.0, and 3.5 ata inspired PO_2. J. Appl. Physiol. 30: 753-763, 1971.

17. Butler, F.K., Jr. and E.D. Thalmann. CNS oxygen toxicity in closed circuit scuba divers. Proceedings of the Eighth Symposium on Underwater Physiology, In Press.

18. Hendricks, P.L., D.A. Hall, W.H. Hunter, Jr. and P.J. Haley, Extension of pulmonary O_2 tolerance in man at 2 ata by intermittent O_2 exposure, J. Appl. Physiol.: Respirat. Environ. Exercise Physiol., 42: 593-599 (1977).

PREDICTIVE STUDIES V
Definition of Oxygen Tolerance

PROGRAM RESPONSIBILITIES
STAFFING AND PROJECT RELATIONSHIPS

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Experiments Planning, Medical	R. Jackson, M.D.
	J. Pisarello, M.D.
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	C. Lambertsen, M.D.
<u>MAJOR PROGRAM COMPONENTS</u>	<u>Principal Co-Investigators</u>
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Neurologic/Sensory	
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Spectral Analysis	
Somatosensory Evoked Potential	
Clinical Analysis	
Clinical Neurology	W. Cobbs, M.D.

Vision	W. Cobbs, M.D.; D. Montabana, M.S.
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Hearing/Vestibular Function	D. Schwartz, Ph.D.; R. Marsh, Ph.D.
Audiometry Auditory Evoked Potentials (Brain Stem, Cortical) Nystagmometry	
Taste/Smell	
Muscle	R. Gelfand, M.E.E.
Strength (Hand, Respiratory) Electromyography	
Cardiovascular	J. Pisarello, M.D.
Electrocardiography Circulatory Reflex Cardiac Output	
Pulmonary/Respiratory Functions	J. Clark, M.D.,Ph.D.; R. Jackson, M.D.; R. Gelfand, M.E.E.; M. Rossman, M.D., J. Elias, M.D.
Flow/Volume Relations Volumes Compliance Diffusion Lung-Blood Gas Exchange Respiratory Patterns Metabolic	

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Renal Function	C. Leach, Ph.D.
Plasma Composition	C. Leach, Ph.D.; P. Johnson, M.D.; O.P. Mishra, Ph.D.
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Catecholamines	
Corticosteroids	
Serum Lipid	
Anti-oxidants	
Blood and Microcirculation	C. Dice, M.D.; P. Johnson, M.D.
Capillary Fragility	
Cell, Platelet Concentrations	
Hemoglobin	
Red Cell Membrane	

INITIAL RESULTS OBTAINED

Background - General Experiment Procedure

Training for precision of procedure, timing and method for the modular measurements requires participation of subject during at least three separate days. Preparation begins with a full medical screening prior to an oxygen experiment.

Exposures at 3.0 atmospheres absolute oxygen pressure have been accomplished.

Performance of each experiment at 3.0 ATA required, in addition to training, essentially one week: a day of preparation and control, subject residence overnight prior to hyperoxic exposure, the actual exposure, tracking by specific measurement as necessary following the oxygen exposure day, and data handling prior to a subsequent experiment.

Preliminary Summary of Results

Results obtained are considered in terms of time after beginning of oxygen exposure.

This preliminary summary precedes completion of the full comparative analysis of experiments at 3.0 ATA, for 3.5 hours. Average findings in most instances include:

(a) 18 total subjects studied at 3.0 ATA, from 2.0 to 3.5 hrs., with "Pre-Exposure Control".

(b) 14 total subjects studied at 3.0 ATA PO_2 for full 3.5 hrs., each with his own "Pre-Exposure Control" at 0.2 ATA PO_2.

INCIDENCE OF GROSS NEUROLOGICAL REACTION

Generalized Convulsions occurred in only one subject in the large series of 18 subjects exposed to 3.0 ATA PO_2. This occurred at 180 minutes of the hyperoxic exposure, with ordinary course and recovery, and without sequelae. One other subject failed to complete the full, intended period of 2.0 or 3.5 hrs., due to a previously cited cardiovascular reaction. Information concerning neurological and performance status was obtained up to the abrupt onset of convulsions.

It should be kept in mind that the present program was designed to determine maximal exposure tolerance at various oxygen pressures. For this reason, special care was given to preventing contribution by ancillary factors (added dead space, carbon-dioxide rebreathing, exercise) which can greatly shorten the useful, pre-convulsive period.

BRAIN CORTICAL ELECTRICAL ACTIVITY (ELECTROENCEPHALOGRAPHIC) MEASUREMENT (EEG)

EEG recording was performed throughout the entire duration of each hyperoxic exposure, with EEG-Neurologist present for periodic direct interpretations in rest state.

In the overall series, with a single exception, no significant EEG abnormalities occurred. EEG indications of intermittent drowsiness were observed in most subjects.

In the one subject who developed a generalized convulsion no progressive development of EEG abnormality occurred prior to convulsion, even up to the moment of the seizure onset. Seconds prior to generalized EEG indication of seizure activity, there occurred abrupt "electromyographic activity," which may have been seizure-related. During the generalized seizure the EEG record was obscured with gross electromyographic artifact. Subsequently there could be seen a generalized gross attenuation of activity, followed by gradual return to alert arousal and normal background activity similar to the immediate pre-event.

Recovery of consciousness occurred within about 10 minutes, with return to performance of experiment measurements in about one hour.

Detailed analysis of the electrical events during the entire pre- and post-convulsive recovery periods is available.

VISUAL FUNCTIONS

A total of 18 subjects has been exposed to 3.0 ATA PO_2, with visual function measurements at intervals during exposure. The separate summaries below indicate the efforts to identify oxygen influences on acuity, accommodation, pupil size, retinal electrical function, visual fields, visual pathway, and visual cortex.

Acuity

With the exception of one in eighteen subjects, there were no detectable changes in visual acuity during or after O_2 exposures.

One subject, who subsequently had a generalized convulsion, reported a blurring of letters at 1:07 O_2-time. Measurement indicated acuity only slightly less than his normal 20/20. Subsequent measurement at 2:07 O_2-time showed visual acuity less than 20/30 but better than 20/40. At 3:00 hours O_2-time the subject convulsed, before a planned further measurement.

Perimetry (Visual Fields)

Twelve of eighteen subjects at 3.0 ATA PO_2 had visual field measurements at or close to the 3.5 hour limit for O_2 exposure. This summary includes these results. The rates of development and recovery for all subject exposures are now being analyzed, along with results obtained in other measurements of visual function.

Average decrement in visual fields at the points of maximum O_2 exposure for the overall group exposed for more than 3 hours was -49%, with a range from -89% to -12%.

Decrement in the individual subject who convulsed was not greater than the average, although acuity had decreased early in the exposure.

Onset. Typically, no changes in visual field areas were found early in the O_2 exposure. Changes usually began between 2.5 and 3 hours of the hyperoxic period.

Recovery. Rate of recovery of peripheral vision was quite rapid, even for the subjects experiencing the full 3.5 ATA O_2 exposure. In subjects with repeated post-O_2 exposure measurements, those with large field changes (-81 to -86%) were fully recovered within 45 minutes post-O_2. For subjects with smaller decrements (-12 to -39%), recovery was complete within 8 to 23 minutes.

Visual Evoked Cortical Potential

Visual evoked potential like visual acuity, is related largely to central vision. No significant identifiable changes were observed in any subject in either Latency or Amplitude of visual cortex potentials, by either the "Flash" or "Pattern" methods employed.

Electroretinogram (ERG)

Like visual fields, ERG is most influenced by peripheral retinal function. Electrical response of the dark-adapted retina to Strobe light flash (Amplitude of B-Wave) was distinctly decreased in only three of 18 subjects. In no instance was the ERG B-Wave amplitude significantly changed in the light-adapted eye.

Changes which did occur in ERG were not uniformly related to the decrements in visual fields. Considerable analysis of individual data is required for correlation of these and other visual function measurements.

Pupil Size

Six subjects exposed to oxygen at 3.0 ATA showed small increases in pupil diameter (0.5 to 2.0 mm Hg), beginning with the onset of oxygen breathing. Pupil size returned to normal by the final post-exposure module. Twelve other subjects in whom measurements were made showed either a minute decrease or no change.

Accommodation

Eleven of 18 subjects exposed to 3.0 ATA PO_2 showed an increase in accommodative near-point, ranging from 1.1 to 3.6 cm, during the first measurement module on oxygen. The remaining subjects showed no change.

The effect has little functional consequence. Measurement was necessary in part as a means of distinguishing retinal from refractive effects on possible change in acuity, if these occurred.

Color Vision

No changes were detectable.

AUDITORY/VESTIBULAR SYSTEM

Auditory Function

In the absence of O_2 effects on auditory function in an initial subject group at 3.0 ATA, methods were extended to include (a) measurement of high frequency auditory threshold (ultra-high octave frequencies of 8,000 to 16,000 Hz), and (b) performance of the measurements in the equivalent acoustic environment during one atmosphere air controls.

Results indicate that, with the possible exception of 8,000 and 10,000 Hz, mean thresholds for frequencies from 1,000 to 16,000 Hz did not change on the average during oxygen exposures. While analysis is not yet complete, no indication exists of residual decrement post exposure.

No change in Stapedius Reflex was found.

Vestibular Function

Preliminary analysis of records does not show spontaneous nystagmus or striking effect on vestibular function, in spite of active head movement involved in experiment measurement procedures. Nausea was a prominent symptom in only 3 of the 18 subjects.

MENTAL AND PSYCHOMOTOR FUNCTION (Changes in Memory, Cognition, Perception and Motor Performance)

Several elementary considerations to the Predictive Study V plan must be considered in relation to measurements of mental and psychomotor function, i.e.:

No adverse effects of hyperoxia should be expected early in exposure.

Subject fatigue unrelated to hyperoxia may decrease the quality of performance.

Unconsciousness accompanies convulsions.

A progressive chemical oxygen poisoning that leads to convulsive disruption of CNS function may be accompanied by progressive decrement in the higher expressions of CNS function.

Summary of Effects

Preliminary analysis indicates that oxygen exposure, even at 3.0 ATA for 3.5 hours, did not produce major disruption of mental or psychomotor function in any subject who completed the full period.

Up to the moment of convulsion the subject who convulsed appeared very capable of performing all experiment procedures, as well as performing the mental and psychomotor test functions before and after the convulsion. Generally, the analysis of changes during oxygen exposure as compared with the paired air breathing control did not show a severe performance failure in any of the four tests used. The importance of the 0.2 ATA PO_2 control was indicated by the existence of learning trend during air breathing, which was not as evident at 3.0 ATA PO_2. Detailed analysis against the 0.2 ATA PO_2 control may bring out effects not now identified.

MUSCLE STRENGTH

Possible occurrence of neural or muscle effects of oxygen, modifying muscle function, was appraised by two separate measures of muscle strength. One measured the forearm muscle group concerned with hand grip. The other measured maximal sustainable inspiratory and expiratory force generatable by respiratory muscles. No appreciable decrements in any of these measures were produced by oxygen exposure.

PULMONARY EFFECTS

Pulmonary function changes in this Program serve as (a) a cross-link to prior extensive investigations of pulmonary oxygen toxicity in man (12, 13, 14, 15, 16, 17), and (b) as the first quantitative measures of human pulmonary oxygen poisoning at oxygen pressure greater than 2.0 ATA.

The total of subjects now investigated for evidence of pulmonary oxygen poisoning at 3.0 ATA is 18 (13 for a full 3.5 hrs.). This allows definition of degree and variation at 3.0 ATA equivalent to the information available at 2.0 and 1.0 ATA.

The results in the overall group confirm predictions from previous Institute analyses and investigations that severe symptoms or prominent decrements in pulmonary functions should not be expected within several hours at 3.0 ATA PO_2.

The only significant changes observed in pulmonary functions were in fact small. They included: Forced Vital Capacity, One Second Forced Expired Volume, Percent of Forced Vital Capacity Expired in One Second, Forced Expiratory Flow at Mid-Expiration, Forced Inspiratory Vital Capacity, Forced Inspiratory Flow at Mid-Inspiration, and Inspiratory Capacity.

The approximately 3.5% decrease in Forced Vital Capacity, superimposed on Figure 1, indicates the close relationship of the present results at 3.0 ATA to the previous theoretical predictions derived (Oxygen Tolerance Curves) by IFEM from data of 2.0, 1.0., 0.8, and lower oxygen pressures.

This close relationship in turn strengthens the Institute concept whereby progressive development of pulmonary oxygen poisoning can be predicted in an exposure sequence (e.g., therapy or decompression) in which respired PO_2 varies with time (Cumulative Pulmonary Toxic Dose) (4).

CARDIOVASCULAR EFFECTS

Changes in measurable cardiovascular functions during continuous hyperoxia are included in the PS V Program to seek evidence of:

Alterations of Central Nervous System influence upon cardiac function (e.g. vagal, sympathetic activity).

Alterations of intrinsic electrical activity.

Changes in cardiac pump function.

Alteration of postural (baroreceptor) reflex function.

Measurements (see Methods) were made supine at rest, and on standing erect to elicit orthostatic circulatory reflex changes.

In this initial analysis, the present purpose has been served by providing the data on all subjects studied, where measurements were completed. In the complete analysis, information on average changes and individual changes will be provided with each subject serving as his own control.

Summary of Results.

The average results in supine rest show a pattern of initial effects, sustained throughout the full period of oxygen exposure, and promptly reversible on ceasing O_2 breathing. These include: slowing of heart rate (about 7 beats per minute), decrease in cardiac output, and increase in systemic peripheral resistance without important change in mean arterial blood pressure. These effects all appear to represent physiologic rather than progressive toxic (pathological) effects.

The reflex circulatory responses to standing also remained fully functional throughout the oxygen exposure, with at least normal increase in vascular resistance superimposed upon the above-mentioned effect of oxygen on vascular resistance in supine rest.

Electrical Activity. No repetition occurred of the prominent bradycardia and syncope observed at about 2.5 hrs. of O_2 breathing at 3.0 ATA in one of the initial subjects. This subject, included in the present Summary Tables, showed electrocardiographic patterns of increased vagal influence upon the SA node, raising the possibility of relation to a central nervous system (vagal center) effect of oxygen toxicity. Examination of the overall group has shown, in less than 20 percent of subjects, brief and intermittent slowing effects on cardiac rate, with disappearance of P wave or its reversal. These effects are minor, late, non-persistent, random and non-progressive. They are not yet fully analyzed but are not considered severe or limiting in the study of oxygen tolerance at rest.

As stated previously, cardiac functions are intentionally limited to rest in this Program. Since cardiovascular activity is influenced by autonomic neurological factors, conscious central nervous system function, physical activity, and by central and reflex respiratory states, it is considered necessary to determine cardiovascular tolerance and describe events in hyperoxic exposure for a resting state. Even at rest such an appraisal requires consideration of physiological as well as any progressive patho-physiologic effects of oxygen upon extrinsic neural, or hormonal, or intrinsic myocardial aspects of cardiovascular functions. It is considered that the present study has entered the O_2 exposure pressure/duration circumstances in which effects on cardiac function (probably indirect) may be occurring. Although these effects were relatively infrequent during the 3.5 hour oxygen exposures at 3 ATA, they may become more evident during longer exposures at lower oxygen pressure.

ENDOCRINE ACTIVITY

Blood sampling and plasma separation for hormone analysis according to Table 1 have been performed. Plasma samples are frozen pending chemical determinations. Analysis of results will follow.

TV UNDER HYPERBARIC CONDITIONS

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INTRODUCTION

The Japan Marine Science and Technology Center (JAMSTEC) has been using the following devices in deep sea diving experiments (saturation diving) to collect field data, namely, a small camera with strobe, a single-lens reflex camera for short range photography, an electronic clinical thermometer, an electronic sphygmomanometer for measuring a diver's body temperature and blood pressure, a radio cassette recorder for amusement (battery-supplied), a small stereo recorder, etc. In the present experiment, we tested a liquid crystal display (LCD) color TV for the divers to watch in the deck decompression chamber (DDC).

In 1971, JAMSTEC conducted "SEATOPIA," an undersea habitat project in which the 9-inch pressure-tight (13 kg/cm^2) CRT was developed and used for the habitat and DDC to receive monochrome TV images. However, the performance of the CRT system was limited by pressure, so that no TV could be used deeper than 100 meters.

In the meantime, TV sets with LCD have been developed. In 1984, an LCD color TV set was put on the market, as well as a monochrome set. The LCD is more advantageous to use under high pressure. Therefore, the author tested the LCD TV under high pressure in the laboratory and then used the LCD color TV in a trial under high pressure in the saturation diving experiment

Table 1.--Major specifications of LCD color TV

External dimensions	W 16 cm X H 8 cm X T 3.1 cm
Weight	450 g (incl. battery)
Screen size	2 inches
Display system	Transmissive type TN LCD panel
Number of pixels	52,800 pcs (vertical 220 X horizontal 240)
Light source	Internal light (small fluorescent lamp)
Power source	5 dry cells of R 6 (Ni-Cd batt.) 7.5 V
Power consumption	1.9 W

(simulation test) at 300 meters in the SEADRAGON-VI dives conducted by JAMSTEC from September to October 1984.

BRINGING TV INTO THE DECK DECOMPRESSION CHAMBER

LCD technology is widely used in table calculators, cameras, diver's watches, sphygmomanometers, clinical thermometers, game watches, etc. According to tests carried out by JAMSTEC on LCD's, such as pressure and helium gas penetration tests, etc., there are no practical problems with the LCD's during compression and decompression in saturation diving, although several problems occurred during rapid compression and decompression.

The major specifications of the LCD color TV set used for the experiment are shown in table 1.

The LCD color TV set was tested under hydraulic pressure in advance, to check the LCD and fluorescent lamp, the major components, in a 35 kg/cm^2 pressure-bearing test. In addition, the TV set was preliminarily tested for practical use in a 60-m saturation diving experiment (new SEATOPIA-III) and had been certified for use under 300-m pressure. However, various

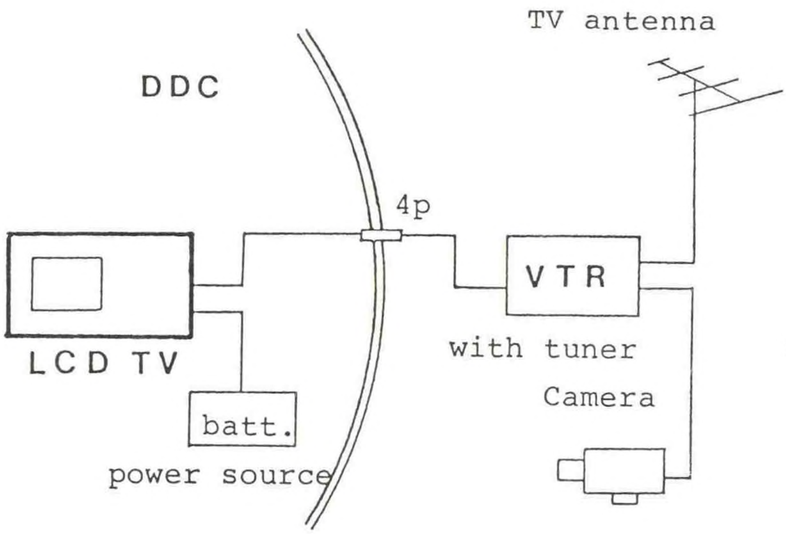

Figure 1.--TV wiring system in the DDC.

defects were expected, including that the helium gas would penetrate into the LCD under pressurization and cause spots because of swelling during the decompression period and that the fluorescent lamp and the dry cells might be interfered with by the penetration of helium. These potential troubles should be checked in advance.

The LCD color TV carried in the DDC was wired as shown in figure 1. For the wiring, precautions were taken to see (a) whether or not the image and voice from the camera and VTR could be seen and heard normally under a pressure of 300 m and during decompression, and (b) whether or not the image and voice of commercial TV programs could be seen and heard normally through the outdoor antenna.

Normally, the power supply of a LCD color TV set uses 5 dry cells (R 6). The R 6 dry cell often overheated, especially when subjected to a pressurizing test of 30 kg/cm^2, so these cells were replaced with 5 cells (R 20) that would be less influenced by pressure. As a result, the life of the cells could also be extended by about 8 times.

RESULTS

The LCD color TV set was placed in the high pressure helium environment (300 m) and used for the test. The results confirmed that (a) the image and voice from the camera and VTR were normal and (b) the image and voice from commercial TV programs via outdoor antenna were also normal.

The size of the LCD color TV set was as small as 2 inches. However, 4 divers could watch the TV simultaneously. The image was as bright as the level at which the characters could be satisfactorily read. The color tone was also fine, without any functional problems. During decompression, however, the screen became irregular and the fluorescent lighting did not operate normally in the range between 250 m and 200 m. However, the TV set soon recovered normal status, producing enjoyable TV programs until the end of decompression. The TV test scene in the DDC is shown in Photo 1.

SUMMARY

JAMSTEC tested a LCD color TV set in the DDC at a pressure of 300 m, without using a pressure-tight vessel. In the test, the transmission of TV images and voice was studied. As a result, it was proved that the TV set could function normally even under high pressure and that, in saturation diving, no vital problems

Photo 1.--LCD color TV set in the DDC, with external power supply in front.

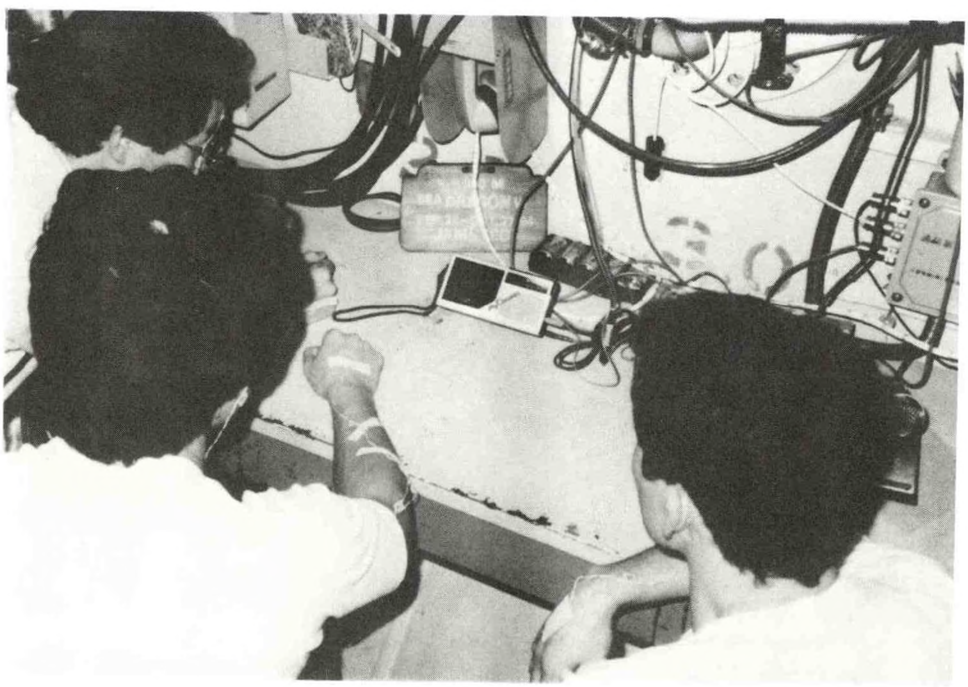

Photo 2.--Divers watching TV.

were observed during compression and decompression or as a result of helium penetration.

In consequence, the TV set can be effectively used for displaying diving work procedures and progress to waiting divers in the DDC. In addition, the image from the ROV can be presented directly to divers in the DDC, allowing the divers to watch working conditions and arrange their work procedures in advance. Furthermore, the divers can enjoy TV programs during long decompression times in the DDC (Photo 2). In the future, we hope to use the device in the SDC.

THE DIVING SCIENTIST AND UNDERSEA TECHNOLOGY FROM 1985 TO 2000

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INTRODUCTION

Upon reviewing the tasks performed by diving scientists over the past 5 to 10 years and comparing them with those anticipated during the next 15 years, it becomes apparent that the nature of the tasks probably won't change significantly, but changes will occur in the methods and equipment used to carry them out.

Before reviewing these new techniques, let's look briefly at some examples of the type of work performed by divers. Figure 1 shows examples of commercial, scientific, and archeological underwater tasks. Commercial tasks will continue to be related to oil and gas operations, bridge construction, mining, salvage, and related work. Diving scientists will continue to seek information about the environment as well as conducting biological and oceanographic investigations.

UNDERWATER WORK METHODS

The techniques used to conduct underwater studies include what I have referred to as remote blind operations utilizing trawls, dredges, seines, etc., as shown in figure 2. Current underwater work systems increasingly use remotely operated vehicles

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EXAMPLES OF UNDERWATER TASKS

<u>Commercial</u>

Oil and Gas Related

Bridges, Pile Driving

Tunnels

Ship Husbandry

Pipeline

Mining

Fishing Related

Construction

Surveying

<u>Scientific</u>

Environmental Monitoring	Geological Studies
Biological Studies	Chemical Studies
Coastal Benthic Pelagic	Geophysical Studies
	Physical Oceanography

<u>Exploratory/Archeological</u>

Deep Rifts/Vents	Wrecks
Seafloor Minerals	Historical Sites
Fishing Grounds	Early Sea Levels

Figure 1

UNDERWATER WORK SYSTEMS

<u>Remote Blind Operation</u>

Trawls

Seines

Nets

Grapples

Dredges

<u>Remote Visually/Acoustically Aided</u>

Unmanned Tethered Vehicles

Unmanned Towed Vehicles

Unmanned Free Swimming Vehicles

Bottom Crawling Vehicles

<u>Manned Undersea Systems</u>

Submarine

Diver Lockout Submarine

One Atmosphere Submersible

Diver Lockout Submersible

Wet Ambient Submersible

Atmospheric Diving Suits

Diving Bells

Ambient Pressure Habitats

Tethered Diver

Untethered Diver

Figure 2

(ROV's), which are fast becoming an effective extension of man's perceptual-motor capability. In addition to operating from the surface, current programs utilize a broad range of undersea systems. The major advances in the last few years have been in the use of atmospheric diving systems, research submersibles, and ROV's. It is my opinion that most manned ambient pressure diving in the future will be generally limited to depths less than 200 fsw.

Engineering advances with regard to robots and related systems, such as those just mentioned, have virtually eliminated the need for exposing humans to excessive pressure. The advances in miniaturization and control systems will further reduce the need for man to be exposed to deep ambient pressures. There is every reason to think that this trend in undersea technology will continue, and will perhaps grow at an exponential rate.

Even more radical changes in the future will be seen in the advances in on-site data acquisition and analysis techniques to augment the remotely controlled systems mentioned earlier. For example, relatively small, high resolution, color, underwater video systems capable of operating in extraordinarily low levels of illumination are now available. In addition, for conditions in which the water is turbid, new acoustic imaging systems have been developed and are being refined. Similarly, systems that are sensitive to small changes in temperature and that can be used as underwater imaging systems also will be improved over the next few years. Figure 3 illustrates some of these systems.

On-Site Acquisition

Manipulators

Photographic Systems

Video Systems

Acoustic Systems

Thermal Systems

Instrumentation

Samplers

Diver Tools

Figure 3

A developing area that is long overdue involves the production of seawater hydraulic hand tools for divers. For the first time, the U.S. Navy is developing a series of underwater tools designed specifically for divers, in contrast to the earlier practice of modifying tools designed for use on land and using them under water. A significant advance is the use of seawater motors in place of the traditional hydraulic oil motors. At the last panel meeting, one of the Japanese participants reported on the development of seawater hydraulic tools in Japan. An update of this report appears in the paper entitled "Sea Water Hydraulic Tool System for Diver Use." The advantages of seawater systems, such as the availability of fluid in remote locations and the elimination of pollution caused by the discharge of hydraulic oil, are obvious.

THE FUTURE

Figure 4 briefly summarizes some projected trends in the development of diver equipment, data acquisition systems, and recreational utilization of underwater technology.

In general, because of the development of advanced automated systems, the skills required of technical personnel will change. Instead of diving skills being the main focus, "undersea" operators of the future will serve mainly as system controllers and supervisors. Consequently, the type of personnel selected and the degree and nature of technical training also will change. Diving schools already are altering their curricula to reflect this trend.

EXAMPLES OF FUTURE DIRECTIONS

General Trends

Decline of Deep Ambient Pressure Diving

Divers Become System Monitors and Supervisors

In-Situ Sampling, Assay, Analysis

More Specialization of ROV's

Application of Low Light Level Technology

Diver Equipment

Integrated Life Support System

Personalized Decompression Profiles

Artificial Gills

Mini Diver Propulsion Systems

Data Acquisition Systems

Manipulators

Acoustic Systems

Instrumentation

Video

Real Time Analysis

Recreational

Observatories

Hotels

Cottages

Restaurants

Figure 4

Another general trend will be the increased use of systems providing the capability to obtain samples and to analyze these samples at sea in real time. This capability is becoming more important as the cost of conducting oceanographic research rises. The days of capturing samples, stowing them on board, returning to shore, and conducting an analysis "at a later time" are numbered. We can no longer afford the luxury of repeating cruises or dives simply because "we didn't know what we had at the time."

In the area of diving equipment, we already have seen the development of integrated display systems that present the diver with depth, air supply, and decompression information. Eventually, as our knowledge of the physiology of decompression increases, we should see the development of individual decompression profiles. Not only will this increase the safety of those individuals with slow tissue half times, but it also will allow those individuals who for some reason don't require the conservative decompression times currently used to decompress more rapidly.

Another technique being developed primarily for use with various types of underwater engines, which also can be applied to humans, is the use of artificial gills. These systems, which involve the use of a semipermeable membrane, allow oxygen to be transported in one direction and carbon dioxide in the other. During the next 15 years, there certainly will be advances in the use of artificial gills. In our lifetimes, we should see divers extracting oxygen directly from seawater instead of having to cope with the existing cumbersome diving equipment.

The final area I would like to address is recreational uses of underwater science and technology. With constantly increasing awareness of the fragile nature of our marine environment, people throughout the world are becoming more aware of the importance of understanding the realm of the oceans. As a result, more vacationers will learn about the oceans by utilizing underwater observatories, hotels, restaurants, and perhaps even small underwater cottages for their enjoyment.

All in all, the next 15 years should see enormous steps in the sophistication of undersea scientific equipment, an increase in the quality, validity, and timeliness of data obtained from the environment, and great strides toward the increased use of undersea recreational facilities.

For the imaginative developer, these goals are readily attainable, because the technology to accomplish them is here today.

DIVING OPERATIONS IN HEATED/CONTAMINATED WATER

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The encapsulation of divers, which is required to protect them from harmful substances or pathogenic micro-organisms in polluted waters, can lead to overheating in tropical and, in some cases, temperate waters. Diving in the heated effluents of power plants, and inside nuclear reactors, is becoming a more common requirement in commercial diving. Hyperthermia is an obvious problem in such cases.

During the early phases of the testing of polluted water diving apparatus by the NOAA Diving Program (NDP), hyperthermia became an obvious limiting factor to work load and dive duration at moderate temperatures (28°C). Diving suits normally limit or eliminate evaporative cooling of the skin. Breathing gas temperatures are approximately equal to water temperatures when using either scuba or surface-supplied diving equipment. Decontamination procedures following dives in contaminated water often require the diver to remain suited for up to 20 minutes, often in the hot sun.

As a part of a series of diving apparatus (USN MK 12 Helmet) integrity tests involving a 20-minute period of light exercise, which stressed the potential failure points of the apparatus, NOAA divers began to experience problems of overheating. Further tests were conducted to determine the upper temperature limits of

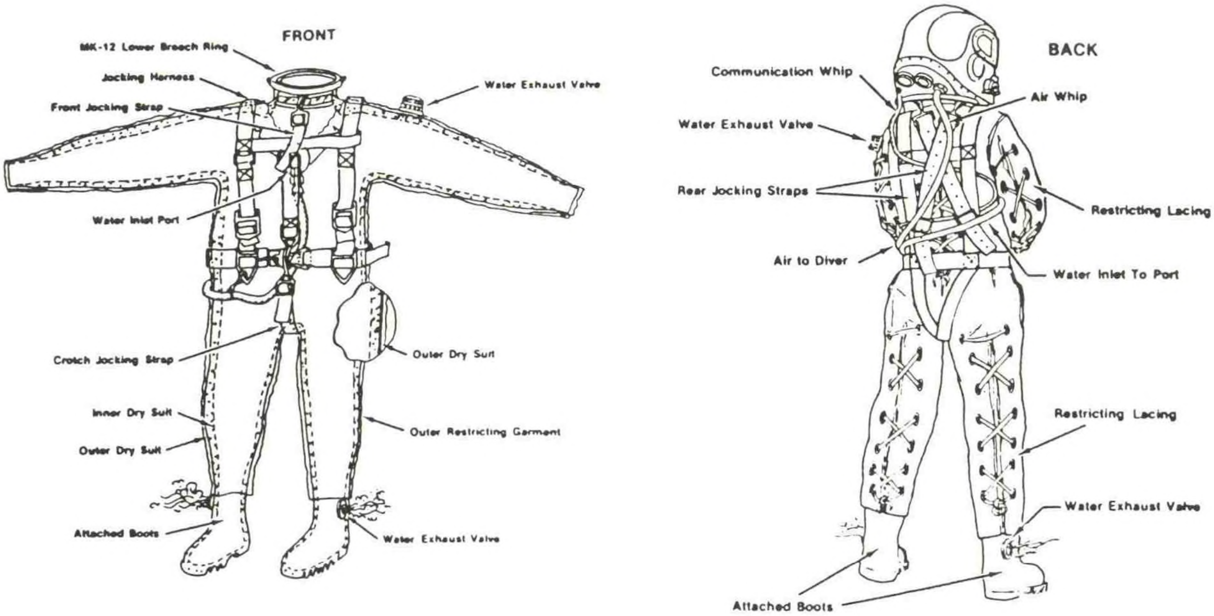

Figure 1.--The twin layers of the positive pressure "suit under suit" (SUS), with an inner foam neoprene neck-entry dry suit worn under a conventional dry suit with ankle exhaust valves, give double protection to the diver in contaminated waters and diminish the risk of hyperthermia.

the standard air-filled suits and of the more recently developed positive pressure water "suit under suit" (SUS) (fig. 1).

Helmet, skin, and rectal temperatures of the divers were monitored continuously. Electrocardiographic (ECG) tracings were obtained during brief rest periods. Signals from the sensors were sent to the surface monitoring equipment via a shielded cable exiting through the diver's helmet. Initial tests were conducted in conjunction with integrity/decontamination studies at the NOAA Experimental Diving Unit. These tests involved diving in heated ammonia/fluorescent dye solutions in a 12 foot deep tank. The temperatures were increased on a daily basis until upper thermal limits were achieved.

Diver discomfort in air-filled suits became significant at temperatures in excess of 38°C. Tests were terminated after 20 minutes in 42°C water due to rapidly rising rectal temperatures and high heart rates. Rectal temperatures continued to rise following the removal of the diver from the water, and during decontamination and undressing, suggesting an "afterrise phenomenon."

During the same series, divers were able to complete three consecutive exercise periods in 44°C water using the "SUS" apparatus perfused with 22°C water. Hyperthermia was not limiting in these tests and higher temperatures could not be obtained due to system heating limitations.

The potential applications of the "SUS" apparatus in nuclear reactor and other heated water diving situations stimulated the NDP to determine its true upper thermal limits. Optimum cooling water temperature and flow rates also needed to be established.

During the next series of tests, skin temperatures were measured on the chest, back, and crotch, as well as in the helmet, and rectal temperatures and periodic ECG tracings were taken. A heat exchanger was installed to provide temperature control of the cooling water. In-line flow meters were used to determine water and air flow to the diver. A standard air flow rate of 6 ACFM was used throughout the test. Water flow was set at 7.5 LPM of 22°C water. The same 20-minute light exercise series used in earlier tests was used in this new test series.

Initial tests in the 46° range were uneventful. At 49°C, an unanticipated incident resulted in a significant overheating of one of the divers. The cornstarch used on the outside of the inner suit to allow easy entry into the outer suit became "cooked" by contact with the hot outer suit and turned to "gravy." The "gravy" plugged the screens on the ankle exhaust valves and prevented adequate perfusion of the lower portion of the suit, causing a rapid heating of the diver. Although he was uncomfortable, the diver was unaware of the extent of hyperthermia that he was experiencing. The diver was removed from the water and cooled with cold water towels around the head, chest, and shoulders. The following day the same diver successfully completed a 1-1/2 hour dive in 50.5°C water with a stable rectal temperature and elevated heart rate. On a subsequent dive an older diver (44 years) exhibited a progressive increase in premature ventricular contractions (PVC's) as the dive progressed. The dive was terminated after 20 minutes.

Breathing a hot gas and having the head exposed to hot air while the body surface is maintained at a cool temperature is an unusual situation for humans. The PVC's experienced by one diver and the tachycardia experienced by another caused sufficient concern to terminate the test series and to consider 50°C the maximum acceptable temperature for divers breathing ambient temperature gas with body cooling. Cooling of helmet gas may allow a significant increase in the maximum operational temperature of diving.

CONCLUSIONS AND RECOMMENDATIONS

1. The highest recommended temperature for diving operations using helmets and air-filled suits is 40°C.

2. The highest recommended temperature for diving operations using helmets with ambient temperature breathing gases and body cooling is 50°C.

3. Divers' subjective feelings regarding their degree of hyperthermia are very unreliable, and a diver can easily extend his stay in hot water to the point of heat stroke. Reliable diver monitoring to determine the degree of hyperthermia is a recommended safety consideration when diving in heated water.

DEVELOPMENT OF A JAPANESE DEEP RESEARCH SUBMERSIBLE OF THE 6,000-METER CLASS

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INTRODUCTION

It is urgent for Japan to develop and utilize the ocean, which contains many biological and mineral resources and energy and has vast space.

The Japan Marine Science and Technology Center (JAMSTEC) developed the deep research submersible "SHINKAI 2000" and her support vessel "NATSUSHIMA" as an interim step in the development of a 6,000-m deep sea research submersible system, and since then, the research program has been gathering important data.

Meanwhile, the world's needs for deep-sea research have increased as the importance of research on deep hydrothermal deposits and on the slope of ocean trenches in relation to earthquake prediction have increasingly been recognized. The United States and France have already developed their 6,000-m deep submersibles (the SEA CLIFF and NAUTILE, respectively), and it is urgent for Japan, a maritime nation, to develop such a vehicle so that Japan has the capability to carry out research in 98% of the world's oceans or 94% of the Exclusive Economic Zone (EEZ) ocean around Japan.

JAMSTEC is therefore planning to develop such a submersible. The prospective schedule for development is shown below.

1985	1986	1987	1988	1989	1990	1991
Prelimi-nary Design		Construction		Sea Trial	Training Dive	Mission Dive

MAIN MISSIONS OF THE 6,000-M DEEP RESEARCH SUBMERSIBLE

RESEARCH ON THE DEEP SEA FLOOR ON THE PREDICTION OF EARTHQUAKES AND TSUNAMIS

Large earthquakes occur frequently around Japan and geophysicists predict that tremendously large earthquakes (with a magnitude greater than 8 on the Richter scale) will occur in the near future because of the sinking of the Pacific plate under the Asian plate at the Japan Trench. Tsunamis will also occur when large earthquakes occur at sea. These earthquakes and tsunamis cause tremendous damage to Japan; therefore, it is very important to predict the locations and times of these earthquakes and tsunamis.

One of the important missions of the 6,000-m deep research submersible will be to research the mechanisms of these natural phenomena.

RESEARCH ON DEEP SEA FLOOR MINERAL RESOURCES

Japan has scarce on-land mineral resources. However, after the implementation of the Law of the Sea Treaty, the EEZ around Japan will be 12 times the size of the country's land mass, and it is expected that many important mineral resources, such as those deriving from the manganese nodules and hydrothermal deposits on the ocean bottom, will be located in this zone. Of course, the mining of these mineral resources will be controlled by the United Nations under the Treaty; however, the information obtained from research on the distribution of these mineral resources will strengthen Japan's claim to mine them. Research using the 6,000-m deep research submersible will be very helpful for this purpose.

RESEARCH ON THE DEEP SEA ENVIRONMENT FOR INFORMATION ON FISHERY RESOURCES AND METEOROLOGY

Many aspects of the deep sea environment, such as water temperature, salinity, and current, have a large influence on fishery resources and meteorology. The new deep research submersible will be used to survey the deep sea environment closely.

RESEARCH ON THE UTILIZATION OF DEEP SEA MICRO-ORGANISMS

It is anticipated that deep sea micro-organisms will produce new and useful substances that cannot be produced by on-land micro-organisms, and that investigations of deep sea micro-organisms will also contribute to an understanding of ocean ecology. The new submersible will be used to investigate these deep sea micro-organisms.

DETAILS OF THE 6,000-METER DEEP RESEARCH SUBMERSIBLE

A feasibility study on the development of a 6,000-m deep research submersible recommended that:

(1) The maximum depth capability should be 6,500 meters, to

permit effective investigation of plate-tectonics theory and on the origins of large-scale earthquakes and tsunamis.

(2) The pressure hull should be made of titanium alloy (Ti-6Al-4V EL) material rather than 10NI-8CO steel (HY120 grade), considering the total strength-weight ratio.

(3) The inner diameter of the pressure hull should be 2.0 meters, so as to make the vehicle's weight light.

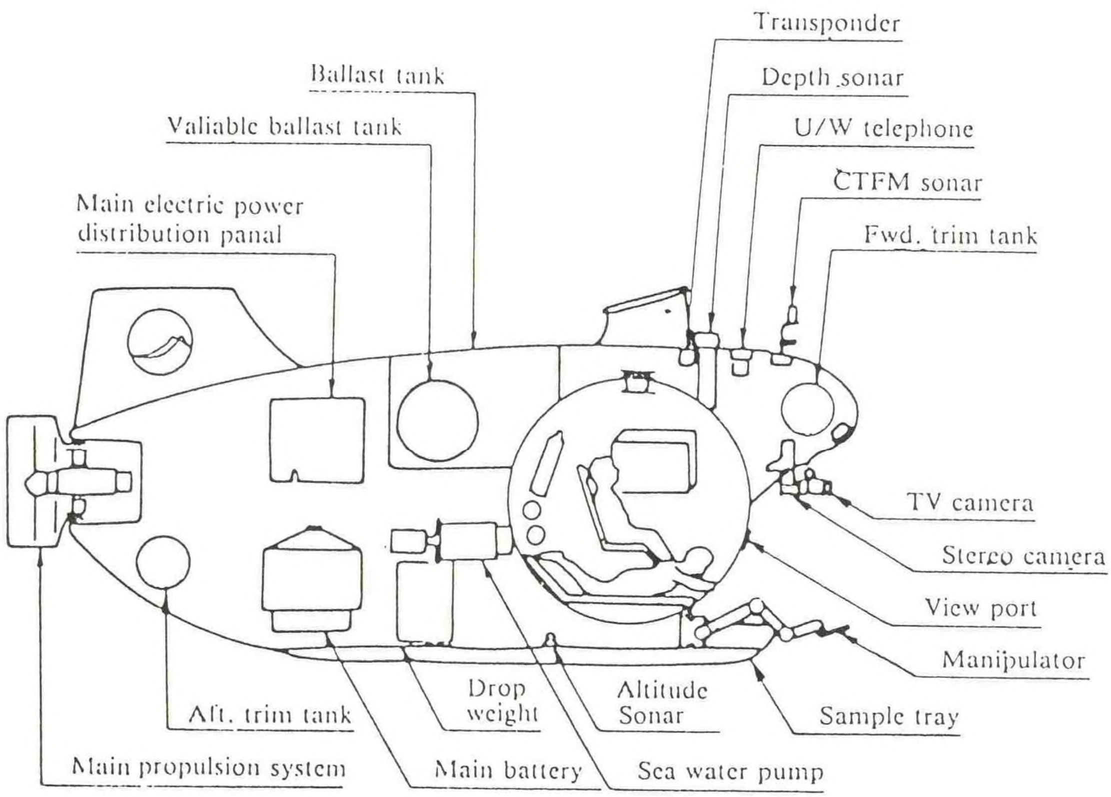
(4) The hydrodynamic drag coefficient of the vehicle for descent and ascent should be as small as possible so that longer observation times can be obtained. The sectional form of the vehicle will be improved if it is an ellipse whose longer axis coincides with a vertical line.

The specifications of the prospective Japanese 6,000-m deep sea research submersible are shown below.

PRINCIPAL PARTICULARS

Principal Dimensions:	Length: ab. 10 m Depth: ab. 3 m Breadth: ab. 3 m
Maximum Operating Depth:	ab. 6,500 m
Weight (air):	ab. 25 tons
Maximum Speed:	ab. 2.5 kts
Accommodation:	Pilot: 2 Observer: 1
Maximum Life Support Duration:	ab. 82 hrs
Pressure Hull:	Material: Ti-6Al-4V EL Size: ID 2 m Sphere Viewports: ab. ID 120 mm x 3 sets
Energy Source:	Oil-immersed type Silver-Zinc Battery
Propulsion System:	Main: Oil-immersed AC Motor x 1 set Auxiliary: Oil-immersed AC Motor x 2 sets

Weight and Trim Adjust System:	Variable Ballast Tank Drop Weight Trim Tank Main Ballast Tank
Hydraulic System:	Pressure Compensated Type
Navigation and Communication System:	Navigation: Transponder A/D Sonar CTFM Sonar Gyro Compass etc. Communication: U/W Telephone VHF Radio
Observation and Research System:	Viewports Manipulator and Grabber STD, etc.
Emergency System:	Dropping System * Drop Weight * Manipulator * Grabber, etc.



Conceptualization of the Submersible in Cross-Section

SOME PRACTICAL LESSONS LEARNED FROM SHALLOW WATER SATURATIONS

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St. Croix, USVI 00820

BACKGROUND

The NOAA Office of Undersea Research has operated HYDROLAB continuously in Salt River submarine canyon, just off the north shore of St. Croix, U.S. Virgin Islands, since 1978. Scientists from 89 major American universities and 9 foreign countries have come to HYDROLAB to live and work on the seafloor for 6 days, conducting scientific research of their own choosing. The facility is staffed on NOAA's behalf by Fairleigh Dickinson University, which has a satellite campus, West Indies Laboratory, on St. Croix. The operational staff consists of four marine engineers, a services coordinator, and a staff physician. There are two staff scientists. The habitat rests on a 52-foot bottom, with a hatch depth of 245.7 kPa (47 fsw). Air is the breathing medium for storage, excursions, and decompression. Upward excursions are limited to 224.2 kPa (40 fsw), downward excursions to 562.0 kPa (150 fsw). Since 1978, we have conducted 97 saturation missions, most of them 6 1/4 days (150 hours) in duration. These have involved 366 aquanauts and 57,872 saturation man-hours. About 25% of available time is spent in the water column; 10.6% of the time is spent in decompression.

SOME LESSONS LEARNED

I will briefly describe a few practical clinical observations we have made over our 7 1/2 years of operation. None is very profound, none is substantiated by data, but each may help operators of future habitats to deal with scientist aquanauts.

1. During the first 2 years of our operation, our aquanauts ate freeze-dried food as their major source of calories. Nearly every aquanaut lost weight during saturation and weight losses of 2 to 3 kg were not unusual. Since then, we have been potting a normal diet to the aquanauts each day in sealed plastic bags, which are then reheated in the habitat prior to consumption. This change has nearly eliminated weight loss during saturation. A study is currently underway to estimate total daily caloric intake by our saturated scientists. Preliminary data suggest that intake is high but is sufficient to meet metabolic requirements.

2. We have been able to nearly eliminate skin and external auditory canal problems by meticulous attention to skin and ear care. We ask our scientists to bathe with soap and fresh water after every excursion, and then to dry carefully with a clean, dry towel. In addition, to avoid urine and urine by-product retention in wet suit bottoms, we ask our scientists to carefully wash the crotch of their wet suit bottoms at least every other day with a washing detergent, which we provide. Similar care is lavished on the external auditory canal. Prior to saturation, I remove all excess cerumen from the external auditory canal. At the end of every excursion, we ask our scientists to gently lavage

the external auditory canal with fresh water, allow the water to drain out, and then dry the pinna with a towel and blow dry the external auditory canal with a conventional hair dryer. Then, at the end of each excursion day, they are asked to flush each external auditory canal with a special solution of ethanol and acetic acid, which we provide. We have yet to be required to abort a single excursion due to otitis externa. Rarely, when otitis externa does develop, it has always been successfully managed with antibiotic ear drops, and, if there is an accompanying lymphangitis, with orally administered tetracycline.

3. Reflux esophagitis is seen frequently among our aquanauts. Immediately upon the report of heartburn, we recommend the prophylactic use of an oral antacid, either tablet or liquid, taken prior to each excursion, and have been able to prevent recurrence.

4. Substernal burning and difficulty getting a deep breath is a common complaint of many, but not all, aquanauts early in the saturation. It usually develops on the second day and is gone by the fourth day. It has never been severe enough to compromise the research. This syndrome has been reported in other saturation situations and has been called "work lung."

5. Winter water temperature in St. Croix may get as low as 25.5° C (78° F). Summer water temperatures reach 29° C (84° F). Despite this warm water and the protection offered by full 1/4-inch wet suits and hoods, when scientists work in the water for 6 or 8 hours a day they become uncomfortably cold, shivering

becomes distracting and complicates manipulations, and, late in the mission, the enthusiasm for entering the water diminishes significantly. We feel they are becoming cold-soaked. The habitat itself is uninsulated, and we feel that even while in the habitat, with an air temperature equal to the water temperature, they are losing body heat to the cooler walls through radiation. They are asked to wear sweatsuits while in the habitat, slippers to keep their feet off the moist carpet, a knit cap is recommended, and the regular ingestion of warm beverage is encouraged. "Warm water" can make you very cold. We have found that wearing a leotard under the wet suit helps greatly in the conservation of body heat. In addition, it makes the donning and doffing of the wet suit much easier and nearly eliminates skin chafing due to wet suit abrasion. Initially, there is often some reluctance to wear the garment, but we have made many converts.

6. Over the years, I have sutured many skin lacerations in the habitat. I have found that the eventual result can be quite good even if the scientist continues to swim, if great care is taken to achieve good approximation of the stratum germinativum. Then, even if the epidermis imbibes water during excursions, and the wound edges become soft and macerated, the eventual scar will be thin and have a satisfactory cosmetic appearance. To attempt to reduce imbibition, prior to excursions, we ask the scientist to cover the wound with a petrolatum base ointment, and then occlude with an adhesive bandage.

7. For the first 6 1/2 years of our operation, our decompressions were conducted solely on air, using NOAA Table 12-10: 16 hours and 19 minutes from 239.5 kPa (45 fsw) to the surface. During that period, the recovered scientists generally slept most of the day of recovery. We attributed this to accumulated fatigue, cold, and a long decompression. In mid-year of 1984, we introduced two 20-minute oxygen breathing cycles, 20 minutes on oxygen, 20 minutes on air, early in the decompression. Calculations indicate that this regimen will reduce the 480 minutes half-time compartment inert gas load by about 6 kPa (2 fsw). Since instituting this practice, the scientists have noted increased alertness and improved ability to work on the day of recovery. We now feel that the lethargy the earlier groups exhibited was very likely due to mild decompression sickness, which these two short oxygen exposures are sufficient to prevent.

8. Although we have no substantiation, there is no question in the minds of our staff, who interact daily with the aquanaut scientists, that the aquanauts exhibit nitrogen narcosis, even at our storage depth of 245.7 kPa (47 fsw). Many of the scientists themselves report unusual jocularity and slowness with mathematical computations while saturated, and most report clearing of these manifestations through the course of decompression.

BIOMECHANICAL ASSESSMENT OF MK 12 DIVE SYSTEM

NOAA MODIFICATION FOR ANTI-CONTAMINANT USE IN CONTAMINATED WATERS

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INTRODUCTION

The history of human factors engineering research in diving equipment is a short history indeed. In 1967, Hugh Bowen and James Miller presented an overview of problems in human factors in underwater performance at an international conference in England, reporting on such aspects as the U.S. Navy SEALAB II experience. In 1969, perhaps the first thorough statement of the range of problems was developed in a Japanese paper by Hori (1969), but actual research conducted in human factors at that time was virtually nonexistent. In 1975, a paper was presented to the Third Joint Meeting of the UJNR reporting the collaborative research comparing the MARK V diving system with the prototype MARK XII (Bachrach 1977). In this paper the collaboration between UCLA and the Naval Medical Research Institute was discussed, emphasizing the human factors studies of biomechanical analyses comparing the two diving systems. UCLA, with support from NMRI, developed a set of biomechanical, anthropometric measures (figs. 1, 2), which were used to quantify range of motion measures to

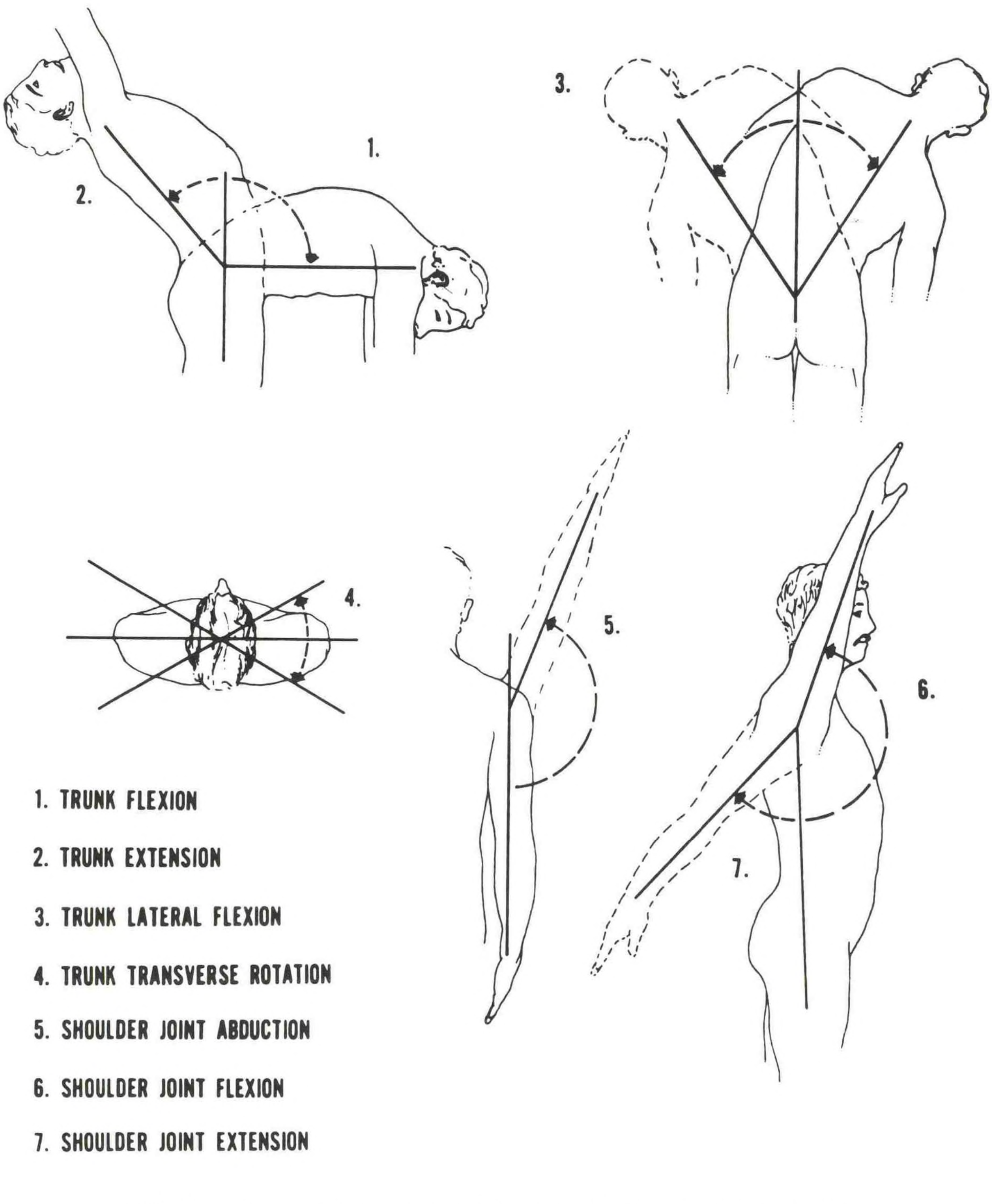

Figure 1.--Biomechanical anthropometric measures

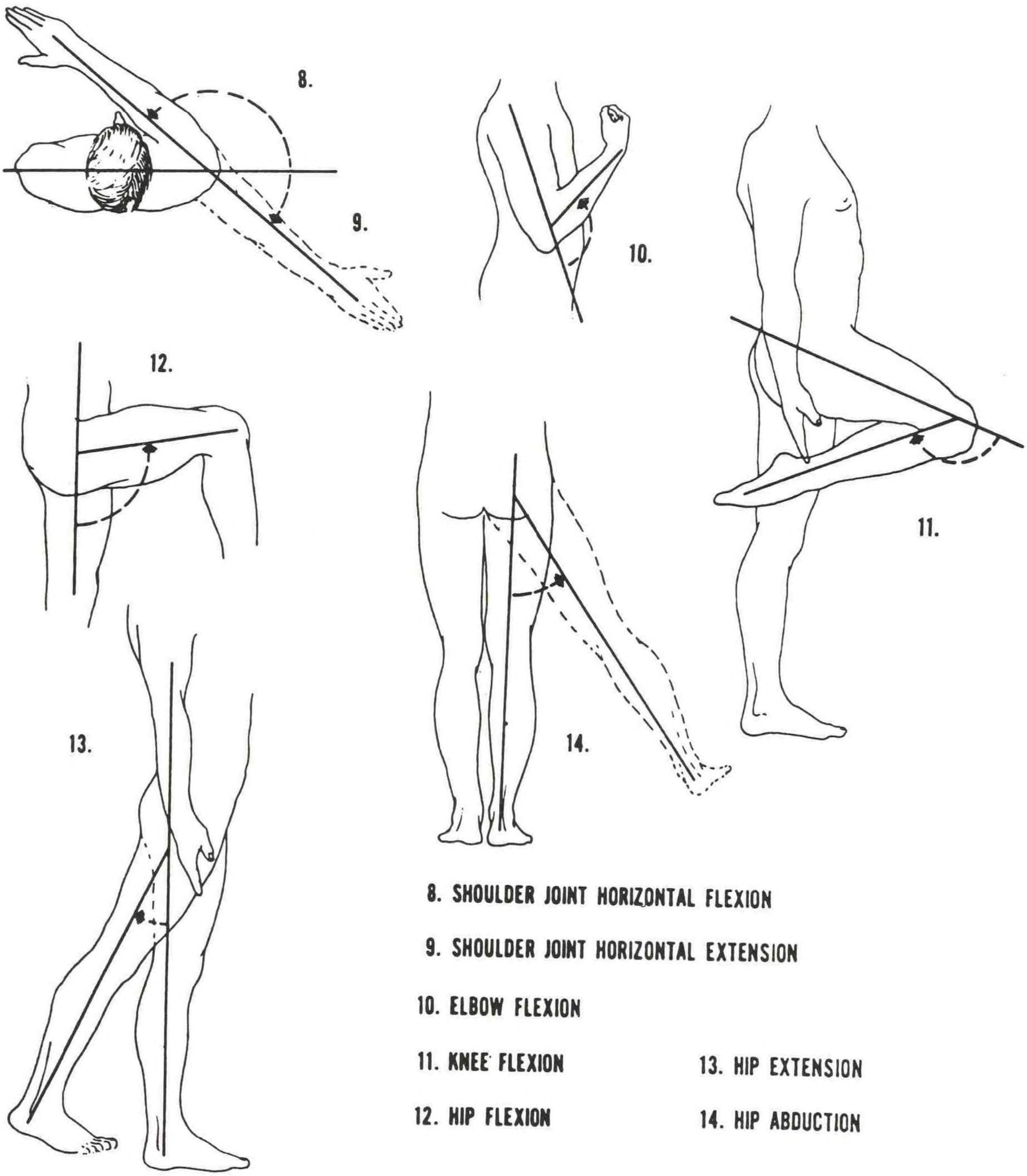

Figure 2.--Biomechanical anthropometric measures

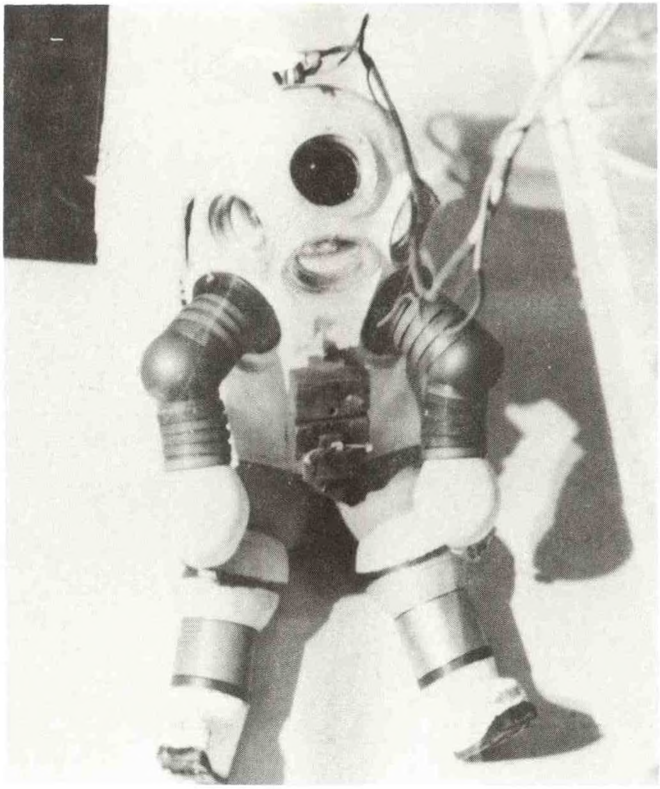

Figure 3.--Biomechanical measure operator in JIM-4

assess the impact of the diving gear itself on movement and performance (Bachrach et al. 1975). The measures shown in figures 1 and 2 were taken in swimsuits (as baselines) in each system, and then in water wearing the MARK V and the MARK XII, respectively. The divers also performed tasks such as the UCLA pipe assembly, and physiological measures were taken (primarily heart rate to assess the physiological cost of working in the gear). The results of the series of studies completed showed an overall superiority of the MARK XII over the MARK V in range of motion and in lowered physiological cost (Bachrach et al. 1975).

These measures have since become standard in many research projects in which biomechanical assessment is important. In the

Navy biomedical assessment (Bachrach 1981) of JIM-4, the one-atmosphere diving system, measures appropriate to the performance of JIM in the water were taken, also after a swimsuit baseline series (fig. 3). The U.S. Navy Coastal Systems Center used the measures in studies of the development of thermal protection for divers (Nuckols 1980). When the Naval Medical Research Institute, UCLA, and NOAA's Diving Program Office embarked on a collaborative project to assess the NOAA modification of the MARK XII for use in contaminated waters, use of these biomechanical measures was clearly indicated.

All measures were taken in swimsuit baselines. Figure 4 illustrates a diver performing Trunk Flexion in surface baseline; figure 5 shows a diver performing the same movement under water in the MARK XII. A similar comparison, this time of Trunk Extension, is illustrated in figures 6 and 7. The use of the grid and the floor radial plot allowed for reasonable quantification of the measures. Recording of the movements was accomplished by video and still photography. The water measures were taken at 30 feet of seawater in the Tower test facility at the Naval Surface Weapons Laboratory, White Oak, as were the surface baselines. A report of the preliminary analysis was presnted at the Oceans '85 Conference (Egstrom et al. 1985). Results indicated that there were no significant decrements in range of motion when the diving system was used, compared with swimsuit baseline measures. Losses were in the range of less than 20%, indicating that the decrements resulting from the diving dress did not appear to be of a magnitude

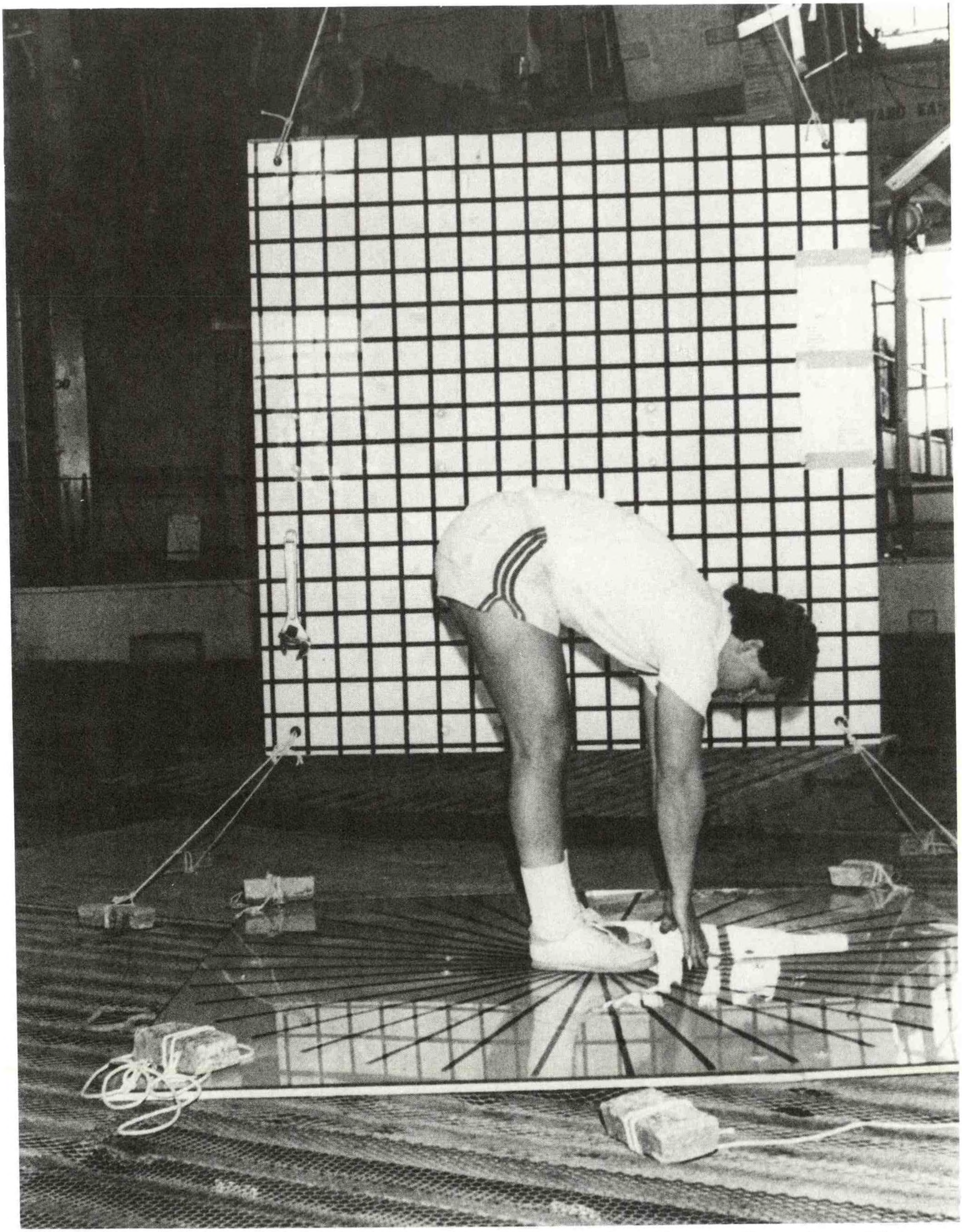

Figure 4.--Diver performing Trunk Flexion in surface baseline

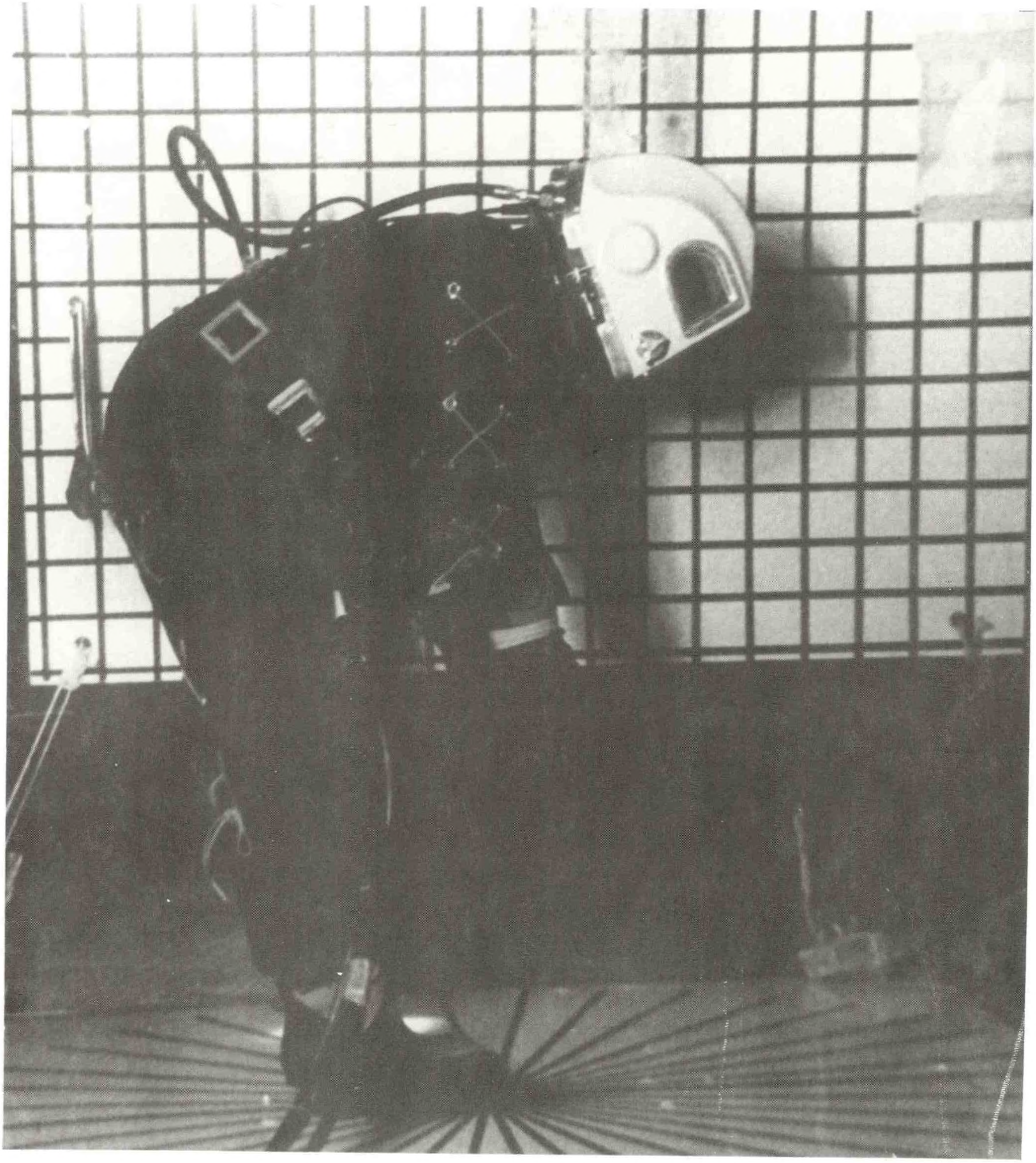

Figure 5.--Diver performing Trunk Flexion under water in the MARK XII

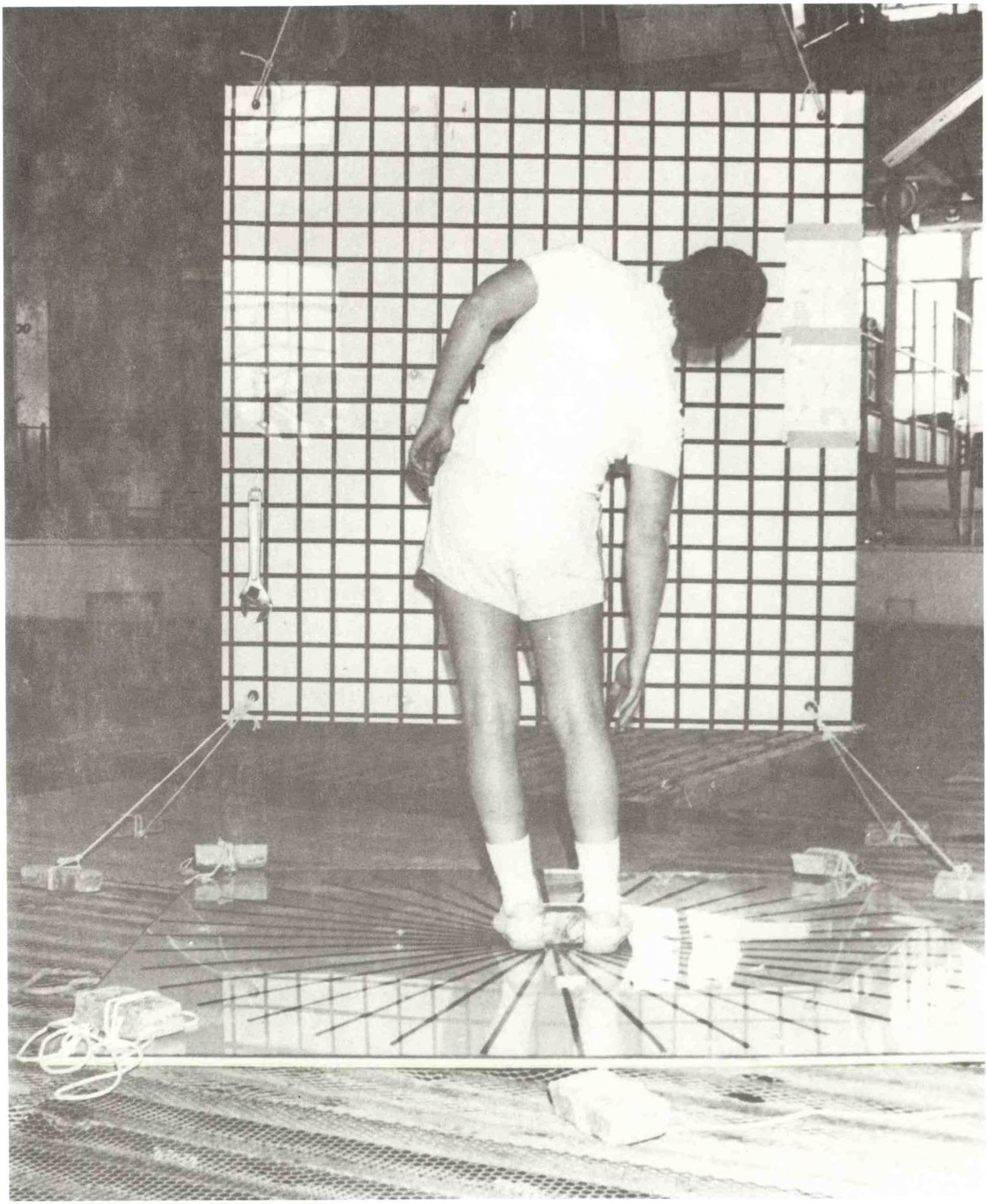

Figure 6.--Diver performing Trunk Extension in surface baseline

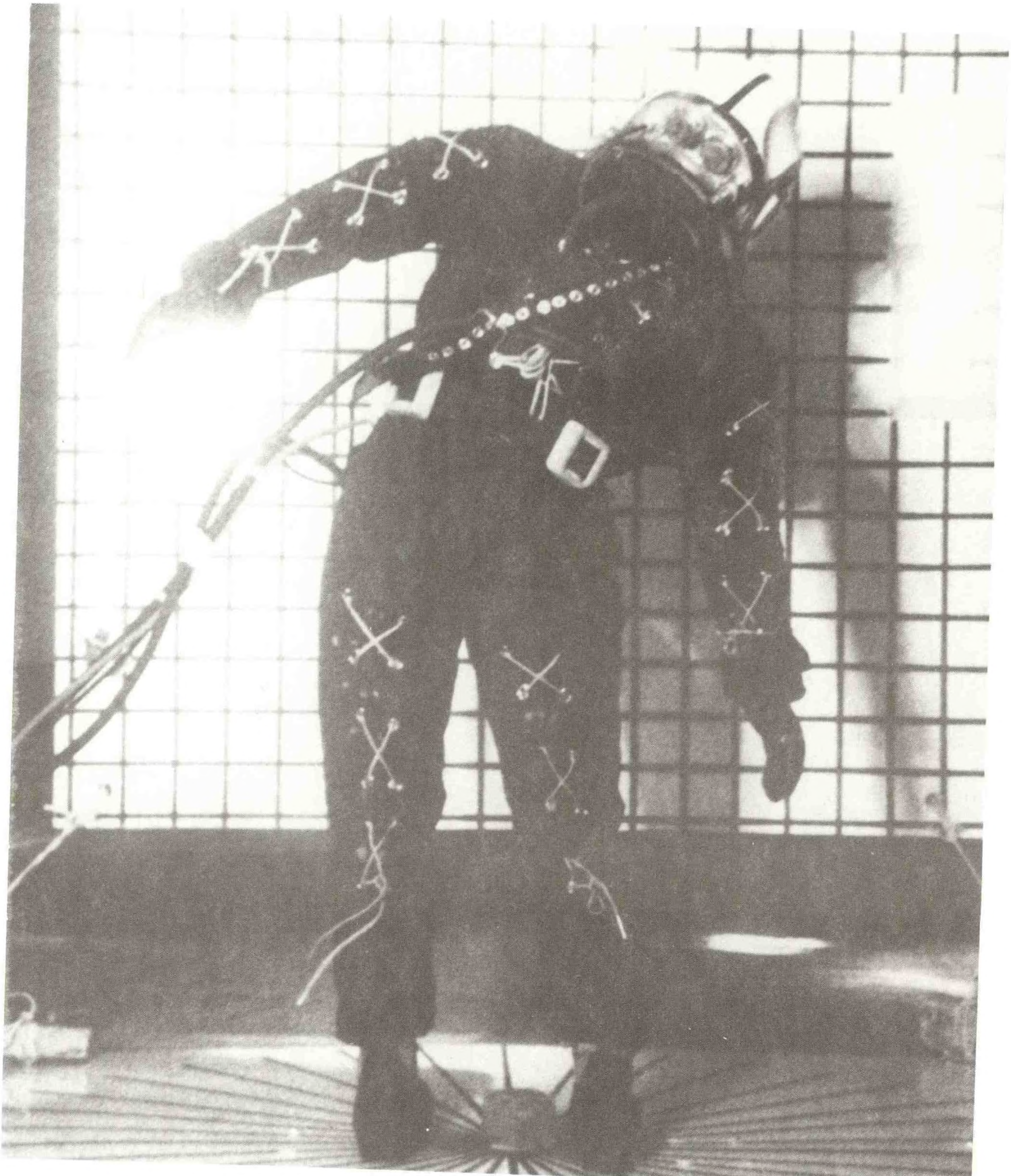

Figure 7.--Diver performing Trunk Extension under water in the MARK XII

that would limit routine underwater work. One finding of interest was that the shortest of the three NOAA divers showed the greatest flexibility in range of motion, suggesting that the sizing of suits and the selection of divers for specific tasks needs full consideration.

It is our firm belief that the various studies briefly noted in this discussion, along with related research, support the importance of human factors analyses of diving equipment. In his excellent review of human factors applications related to underwater activities, Hori stresses that it is important to study research related to "the protection of the body and maintenance of posture underwater, posture and movement at time of work, methods of supporting the body, the assessment of protective tools, clothing, gloves and shoes at time of work" (Hori 1969). The methods described for biomechanical and physiological assessments can contribute significantly to such a goal.

ACKNOWLEDGMENT

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REFERENCES

Bachrach, A. J. 1977. "Human Factors and Diving Equipment Design." In: Proceedings, Third Joint Meeting of the Panel on Diving Physiology and Technology. Kawaski, Japan; Ministry of Labour, Nat. Inst. of Ind. Health, pp. 17-25.

Bachrach, A. J. 1981. "A Biomedical Assessment of a One Atmosphere Diving System: JIM-4." Final Report. Naval Medical Research Institute, Naval Research and Development Command, Bethesda, Maryland 20814. Work Unit M00099PN.003.3030.

Bachrach, A. J., G. H. Egstrom, and S. Blackmun. 1975. "Biomechanical Analysis of the U.S. Navy Mark V and Mark XII Diving Systems." Human Factors 17(4):328-336.

Egstrom, G. H., A. J. Bachrach, and J. M. Wells. 1985. "Range of Motion Studies in Anti-Contaminant Diving Dress." Oceans '85 Conference Proceedings, Vol. 2, pp. 956-958, November 1985, Marine Technology Society, Washington, DC.

Hori, Motoyoki. 1969. "Human Factors Engineering in Undersea Activities." Japanese Journal of Ergonomics 5:217-250.

Nuckols, L. 1980. "The Development of Thermal Protection Equipment for Divers." In: L. Kuehn, ed., Thermal Constraints in Diving: The Twenty-Fourth Undersea Medical Society Workshop. Bethesda, Maryland: Undersea Medical Society.

SMALL ROVS DEVELOPED BY JAMSTEC

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ABSTRACT

Since 1979, two types of small ROVs have been developed by JAMSTEC. They are the JTV-1 (200 m water depth) and the HORNET-500 (500 m water depth). The JTV-1 was completed in 1980 and the JTV-2 (the prototype commercial vehicle) was completed in 1981. After that, 8 DLT-300's were delivered by Q. I. Co., Ltd. as the commercial type of JTV vehicle.

Recently, a JTV-2 and divers were used to survey artificial fish reefs. The results of the survey were described.

The HORNET-500, which utilized fiber optic tether cable, was completed in early 1984. A sea-going test of the vehicle was carried out in June of 1984, at depths between 30 and 300 meters. The vehicle showed superior operability, but it was lost in an accident. A HORNET-500-2 is under fabrication and will be completed by the end of 1985.

INTRODUCTION

Two types of small ROVs have been developed by JAMSTEC. One of the purposes of this development is to utilize highly maneuverable ROVs to show the effectiveness of ROVs through operations, because ROV development was rather slow in Japan in the early 80's. Through the efforts of JAMSTEC and some other companies, there have recently been several advancements in the development and utilization of ROVs in Japan.

The utilization of ROVs in Japan is somewhat unique because they are seldom used to support the offshore oil industry. They are used for geological and biological surveys, surveys of artificial fish reefs, inspections of the OTEC pipeline, and diver support for fisheries surveys.

The DLT-300's were used for such operations as archaeological surveys of lakes, biological surveys of Antarctica, fisheries, harbor engineering, dam sites, and diver support activities. A unique usage for the DLT-300 was to perform manipulative work in a low-level radioactive waste pool.

DIVER SUPPORT WORK WITH THE JTV-2

The JTV-2 was used to survey artificial reefs in November 1984. The purpose was to compare the ability of an ROV with that of divers and to establish practical operational procedures for the diver/ROV team. The survey was largely funded by the Secom Science and Technology Foundation.

The vehicle was equipped with a CCD color TV, a 2 x 200 W light, a 35-mm still camera, and a strobe. The dimensions of the vehicle were 68 (L) x 63 (W) x 52 (H) cm, and it weighed 50 kg.

The vehicle is shown in figure 1. The tasks of the ROV were as follows:

- o Provide topside monitoring of diver operations.
- o Document the divers' work with both TV and still camera.
- o Provide lighting for the divers.
- o Provide topside monitoring and VTR records of the dive site prior to the divers' deployment. After that, the

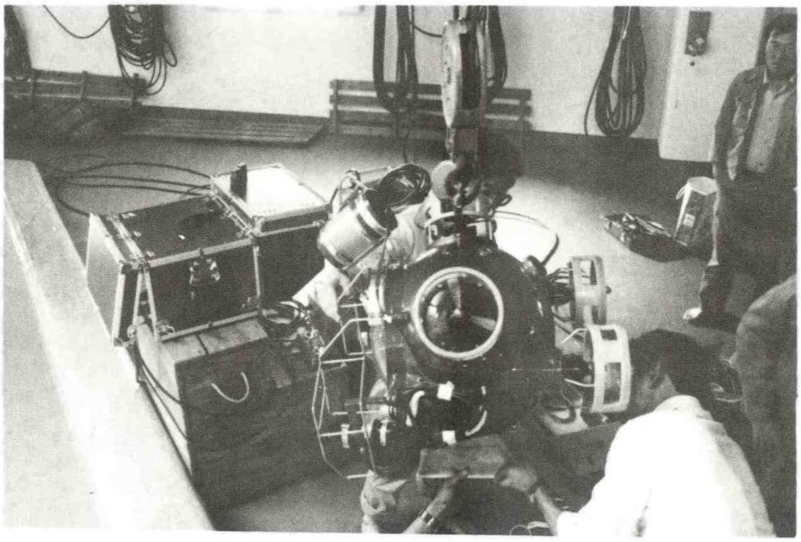

Figure 1.--JTV-2 vehicle

ROV dives to locate the precise dive site and then the divers deploy along the cable of the vehicle.

A scenario of diver and ROV tasks was outlined first and several practice runs of the scenario were carried out in the diving training pool of JAMSTEC. Figures 2 and 3 show pictures of the practice session.

After the practice, a sea-going test was carried out at Tago Bay, in the western part of the Izu Peninsula. Figure 4 shows the locations of Tago Bay and the artificial reefs surveyed. Depths of the diving sites ranged from 10 to 36 meters.

The diver/ROV team was composed of 2 groups of divers, and 1 group for operation of the ROV. A total of 6 dives were carried out at the 4 diving sites shown in figure 4. The times for each dive were 20 minutes for divers and 120 minutes for the ROV. Figure 5 shows the launch of the ROV from a small ship.

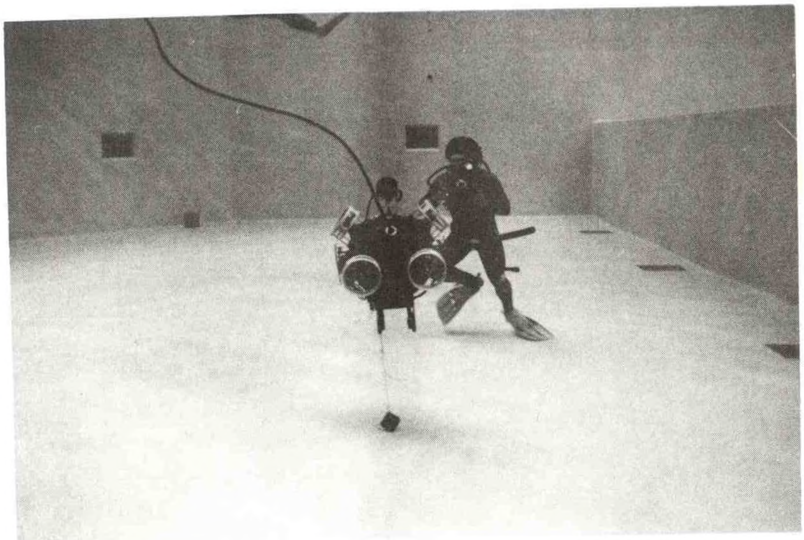

Figure 2.--The diver/ROV team practice in the diving training pool

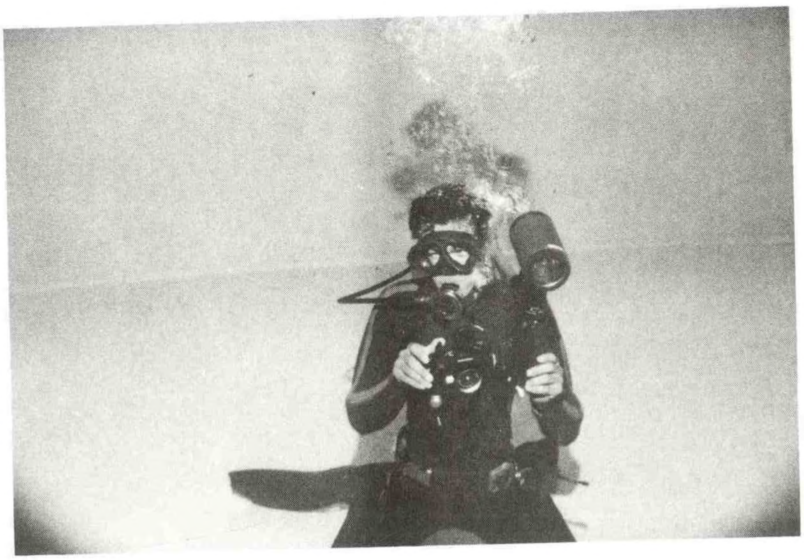

Figure 3.--A picture of diver taken by the still camera of ROV

Figures 6 to 8 show pictures of the ROV taken by the divers. Figures 9 to 11 show pictures of the ROV taken by the 35-mm still camera.

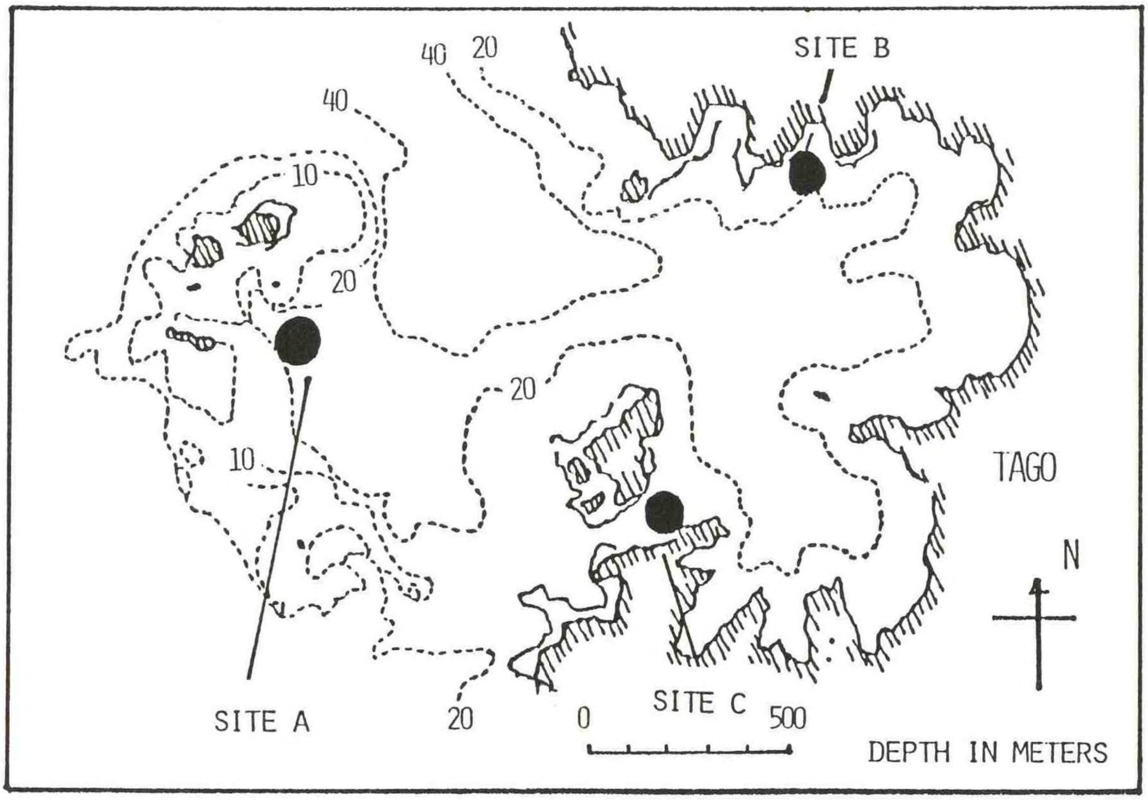

Figure 4.--The depth contour map of the Tago Bay showing the locations of diving sites

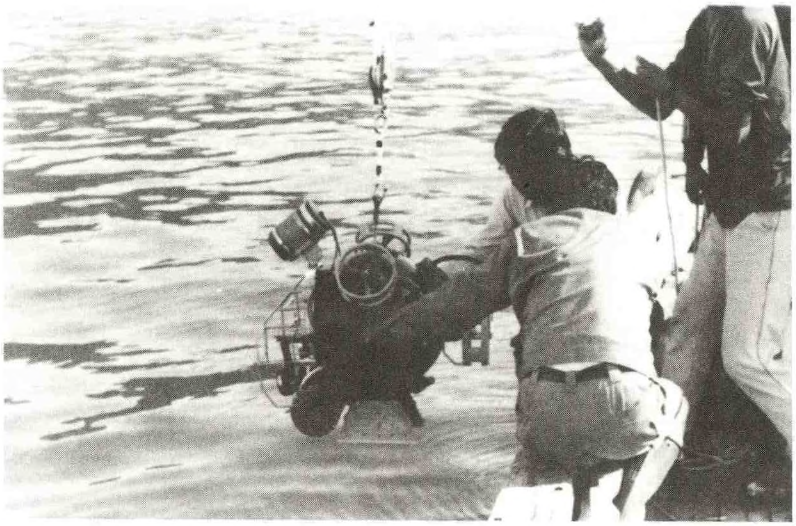

Figure 5.--Launching of JTV-2 from a small ship

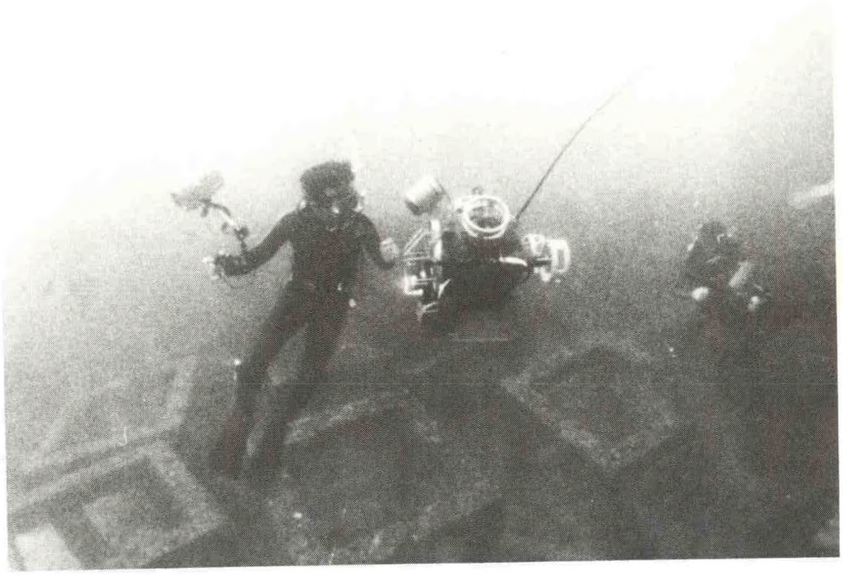

Figure 6.--ROV and divers on the artificial reefs

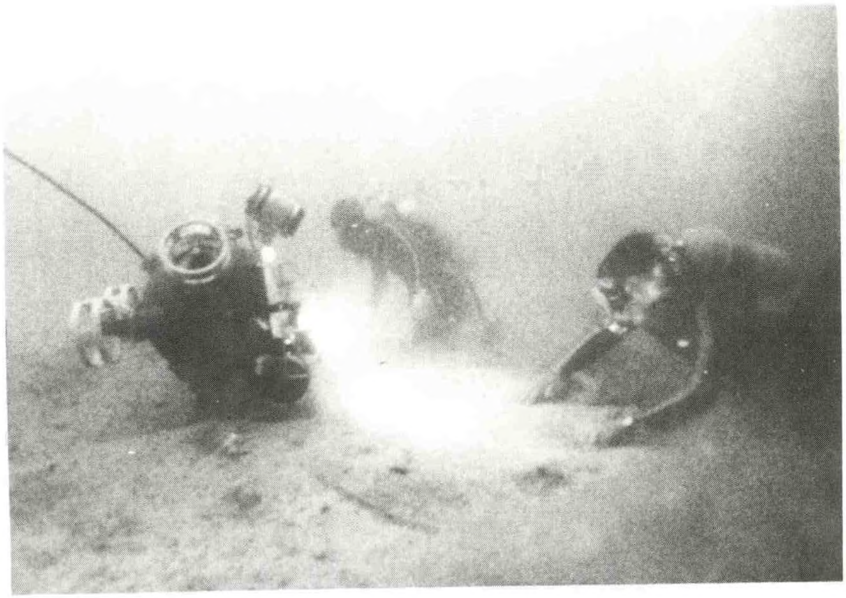

Figure 7.--ROV provides light for divers

An analysis of the results of the study of the fish around artificial reefs is now underway. The first results of the comparative trial of the diver/ROV teams are shown below:

- o The ROV provided good TV pictures and depth information on the dive sites before diver deployment, so divers were

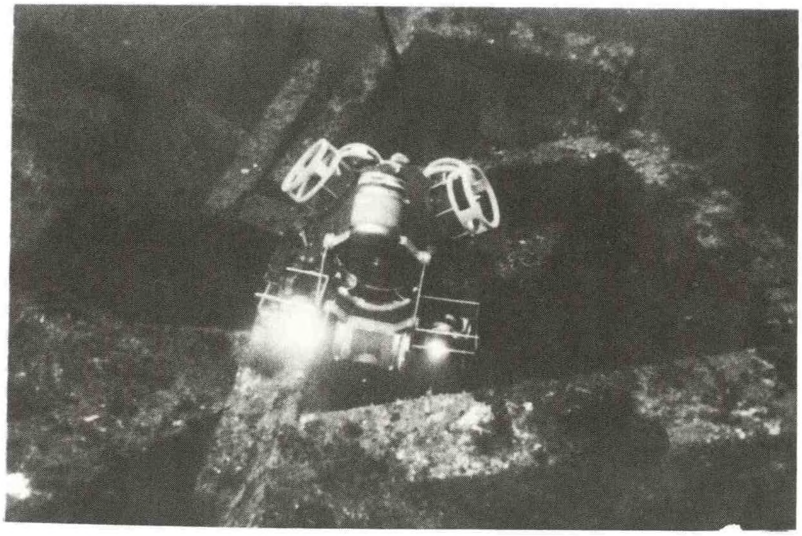

Figure 8.--ROV flying over the artificial reefs

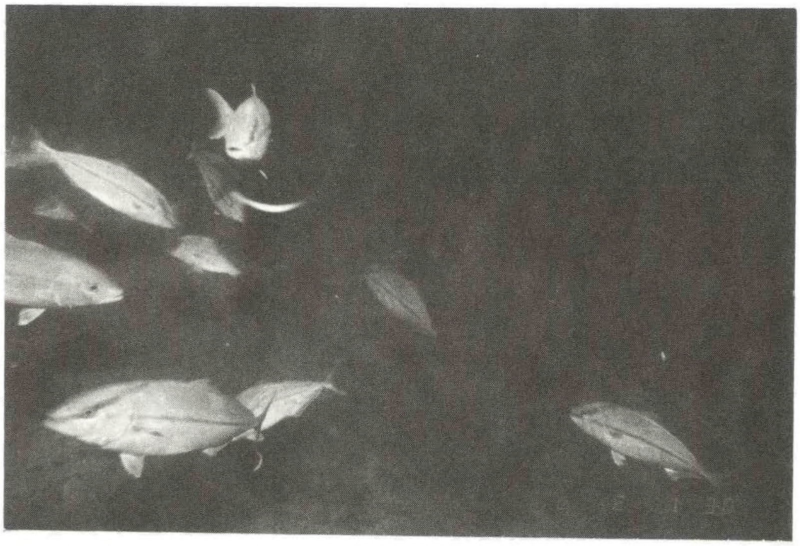

Figure 9.--Amberjacks taken by the still camera of ROV

able to have an adequate diving plan before diving. After that, divers could dive along the cable of the ROV.

- The vehicle provided TV pictures of the divers for the topside monitor. VTR records and pictures were also taken to document the divers' work.

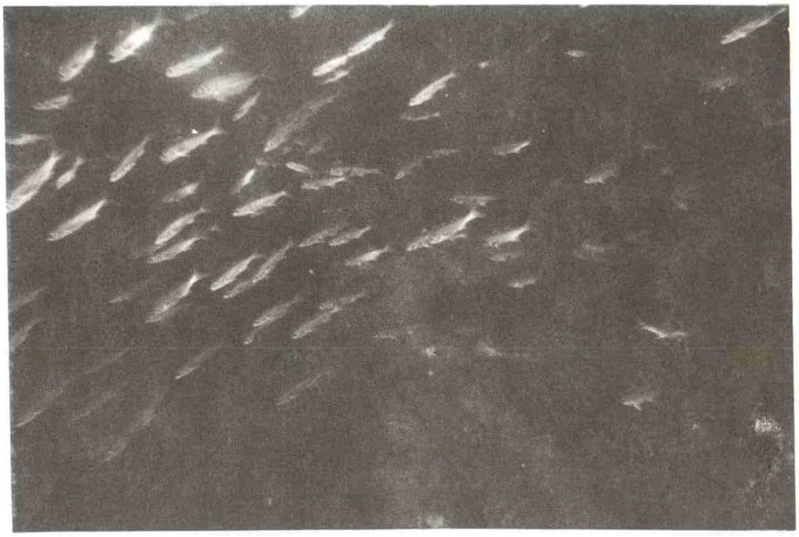

Figure 10.--A school of Scombrops boops taken by the still camera of ROV.

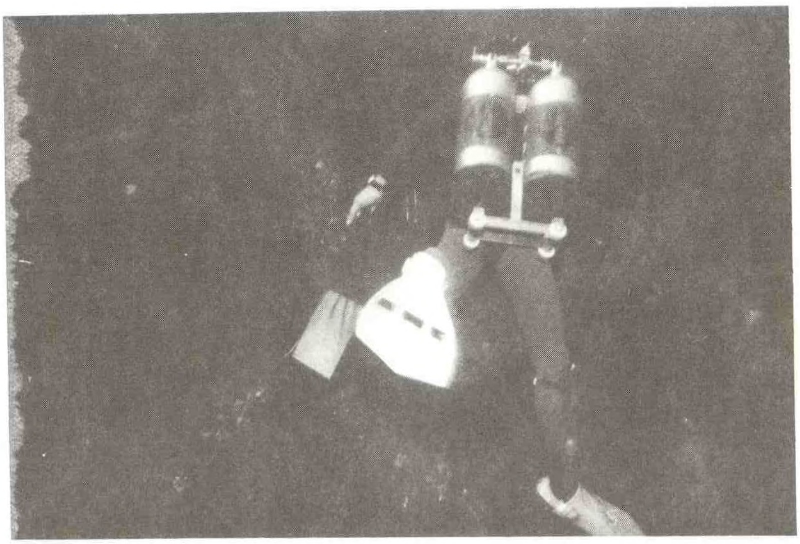

Figure 11.--A diver working around the artificial fish reefs taken by the still camera of ROV

- o The vehicle also provided lighting for divers.
- o By performing these functions, the vehicle increased the safety of the divers.

- It is also concluded that observations of artificial fish reefs and bottom dwelling animals can be successfully performed using an ROV. The ROV is confirmed to be very effective both in support of the divers and in independent investigations.

DEVELOPMENT OF HORNET-500

The HORNET-500 is a fiber optic tethered vehicle completed in early 1984 (Aoki et al. 1984). Specifications of the HORNET-500 are shown below:

Operational depth	:	500 m
Dimensions	:	120 (L) x 95 (W) x 56 (H) cm
Weight	:	120 kg
Buoyancy	:	1 kg
Speed	:	2.7 kt
Structure	:	2 cast aluminum spheres with acrylic dome port; the spheres are center joined by an aluminum cylinder
Power Source	:	AC 100 V, 3 kV
Thrusters	:	Rare earth cylinder type magnetic torque coupling thrusters DC 100 V, 120 W x 2 DC 80 V, 80 W x 2
Instrumentation	:	Color TV camera (ENG), sensitivity 80 lux b/w after TV camera, sensitivity 0.3 lux Halogen lamp 300 W x 3, 150 W x 2 Depth sensor, compass, rate gyro

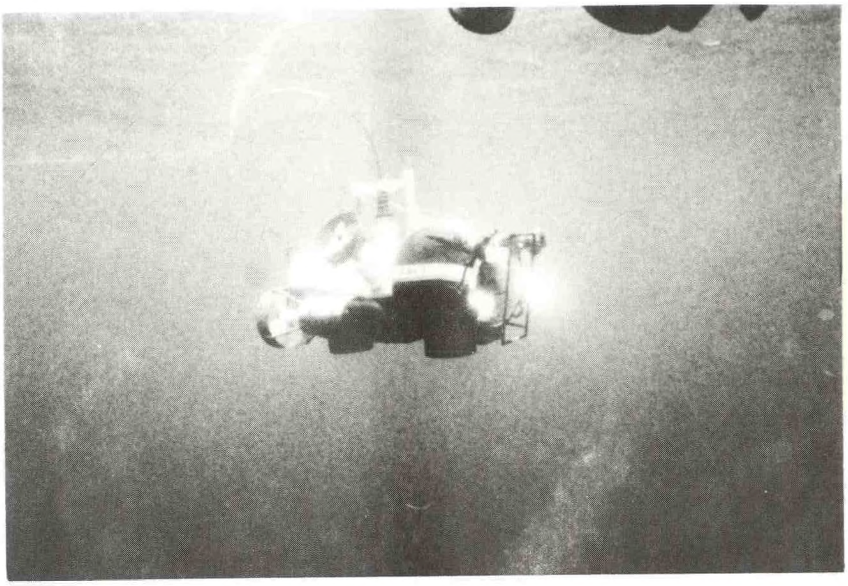

Figure 12.-- HORNET-500 vehicle under sea-going test

Deck equipment : Computer control unit, optical fiber communication unit, VTR, monitor TVs, power unit, winch

A sea-going test of the vehicle was carried out in June of 1984, at depths between 30 and 300 meters. The vehicle showed superior operability and there were no problems with any system. In particular, the fiber optic transmission system and the ENG color TV camera provided very clear pictures. Figure 12 shows the HORNET-500 undergoing a sea trial, and figure 13 shows the winch with optical rotary connectors and a high voltage electric slip ring.

Unfortunately, the vehicle was lost in an accident. This involved a kind of entanglement (Marine Technological Society 1984) caused by an unexpected abrupt change in current.

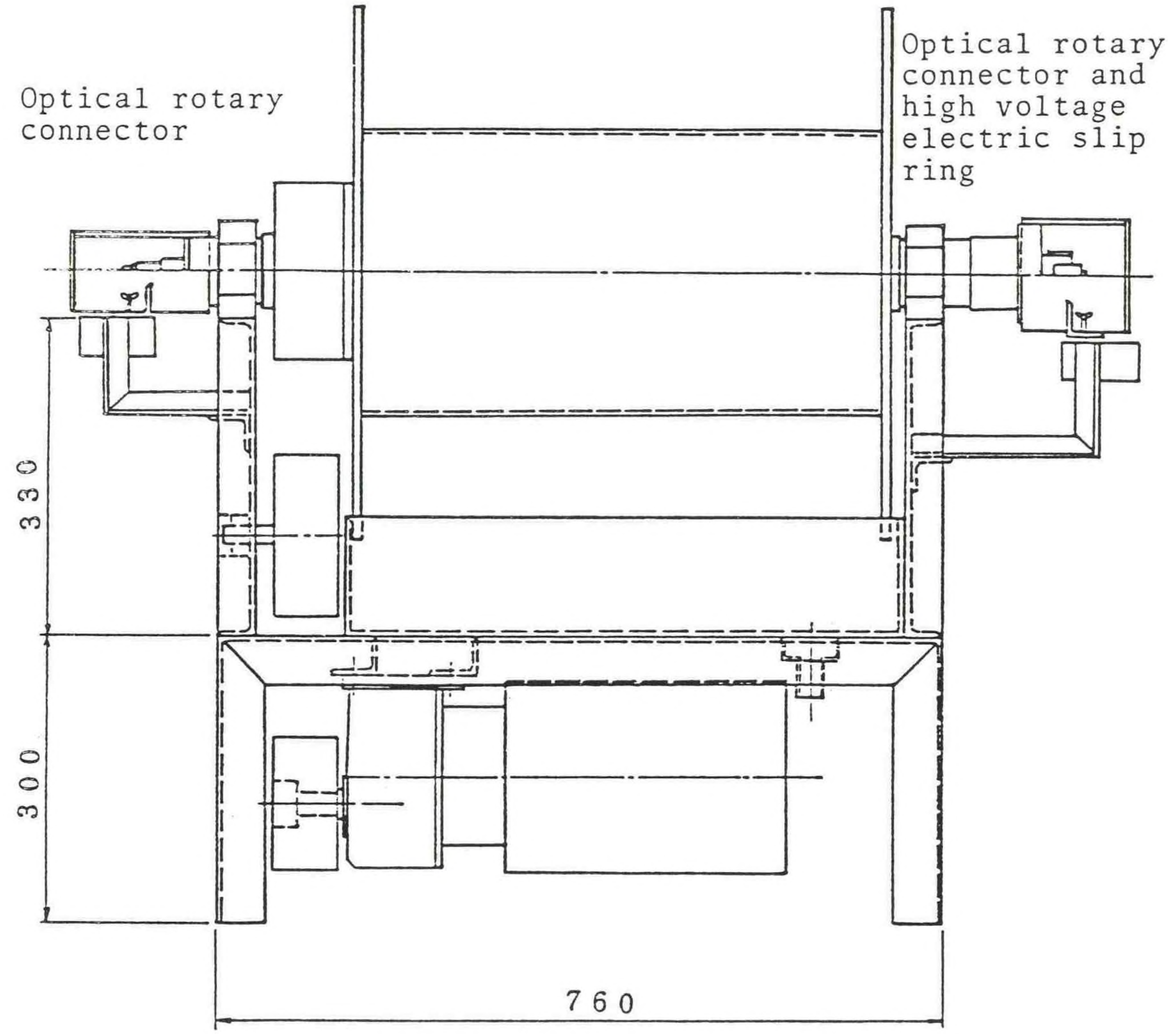

Figure 13.--The winch with optical rotary connectors and a high voltage electric slip ring

The HORNET-500-2 is under fabrication and will be completed in the early winter of this year.

FUTURE DEVELOPMENT

At present, JAMSTEC owns 2 JTV-type vehicles: the JTV-2 and the DLT-300-C, which was delivered by Q. I. Co., Ltd. The HORNET-

500-2 will be completed this year. The practical operational procedures for the diver/ROV team will be established in the near future through more trials.

REFERENCES

Aoki, T., Hattori, M., and Takahashi, K. 1984. "Fiber-Optic-Tethered Vehicle 'HORNET-500,'" Marine Technology Society, pp. 59-62.

Marine Technological Society, 1984. Operational Guidelines for ROVs, Marine Technology Society.

OUTFITTING AN UNDERSEA HABITAT

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HISTORY OF PROJECT

In June of 1980, in keeping with its history of active involvement in marine research, the National Oceanic and Atmospheric Administration accepted a proposal from the University of Southern California to establish an undersea laboratory in the temperate waters of Santa Catalina Island off the California coast.

The original proposal called for a four-part program leading to operational readiness by the fall of 1984. The proposal called for an initial conceptual engineering phase, a detailed engineering phase, a fabrication phase, and a testing phase ending in certification and classification by the American Bureau of Shipping.

In January of 1984, only slightly behind the original target dates as outlined in the USC proposal to the government, the RFP was announced and a prebid conference held at the main USC campus in Los Angeles. Both because of the detail required by the RFP and the impact of inflation since project inception, the proposal bids exceeded the available funds. USC and NOAA decided to review the project thoroughly and to reduce the overall scope to that of the habitat pressure vessel and its outfitting and support equipment. It was generally considered that, with this major system in hand and capable of starting minimum operations, other alternative methods of funding the balance of the desired optional systems and equipment could be obtained.

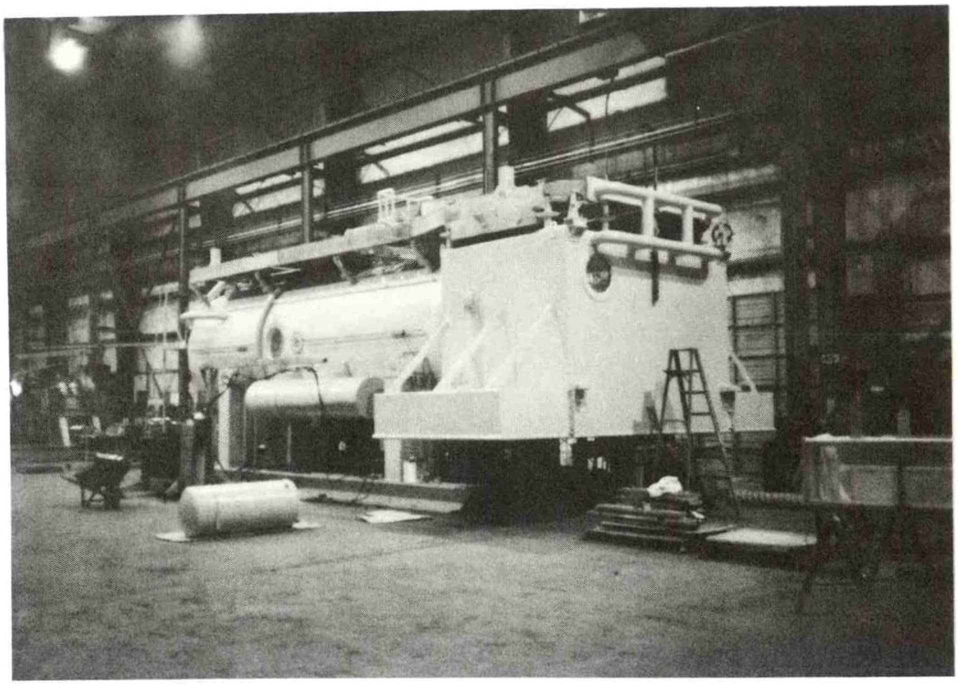

Figure 1.--GEORGE F. BOND undersea habitat under construction.

In June of 1984, a revised RFP was issued and there were several quality bids within the existing budget constraints. The proposed team of VMW Industries, Inc., of Victoria, Texas, and Mechidyne Systems of Houston, Texas, was accepted and on September 4, 1984, contracts were signed and work commenced on the construction of the GEORGE F. BOND undersea habitat (fig. 1).

SCOPE OF PROJECT

VMW Industries and Mechidyne Systems proposed a review of existing engineering drawings to deal with potential errors and omissions caused by the changing scope of the project. The contractors also proposed to use data base management techniques to establish baseline information about the habitat systems and materials. The purposes of the proposed data base, or data bases as it turned out, were to reduce costs and perform reliability analysis. Throughout the review, attention was directed to:

(1) Safety;

(2) Simplicity; and

(3) Life Cycle Costs and Logistics.

RE-ENGINEERING OF SPECIFIC EQUIPMENT ITEMS OR FEATURES

To meet changing mission tasks, specific changes in pressure vessel features, subsystem deletions, and re-engineering of outfitting material were required. Some required changes to the systems had been brought about by changes in technology and the marketplace. Some of the hardware had become commercially available, thus obviating the need to construct one-off specials. (Specials might have been required under the original engineering specifications; one-off specials would be hard to maintain and replace, and their cost is prohibitive. Such items could also be critical components of the operation, threatening the completion of a mission if they failed.)

MAJOR CHANGES

During the proposal preparation effort by VMW and Mechidyne, it became obvious to the fabrication team that altering the design of the habitat to allow easy removal of the wet porch, the lower support structure, and the upper structure would enhance both the construction effort and operation of the habitat in terms of life cycle flexibility and operational cost control. The advantages to making these items removable during manufacture were obvious, e.g., allowing modular construction and the use of two different manufacturing plants as well as permitting the external hydrotesting of the vessel in existing shore-based test facilities rather than performing this essential task at sea.

From the government's position, making these items removable meant that the basic habitat pressure vessel could be altered in the future to accept different baseplate and wet porch configurations that might be required in the future by as yet undefined undersea research programs. The upper support structure required enlarging and changing to accommodate different equipment than that originally specified. The ability to remove this portion of the habitat allows repairs or replacement to be made without having to transport the entire habitat back to the mainland.

Other changes to the configuration of the habitat were:

(1) Addition of a passive system for dealing with the sea surge in the wet porch caused by operation of the habitat in extreme sea states.

(2) Relocation and resizing of the ballast tanks.

(3) Relocation of the battery pods.

(4) Relocation of the power supply pod.

NUMBERING SYSTEM

One of the first problems that had to be addressed concerned a parts tracking system. The government wanted a system that would lend itself to being used both during the fabrication project and in the continuing operation of this and other habitat programs. Because of the evolutionary nature of this project, the engineering contractor had not been asked to address requirements beyond fabrication and had been operating on the assumption that the entire system would be fabricated at one time. In addition, the drawings and parts tracking systems of the two contractors were unique to each company, and neither company's system was adequate. Consequently, an interim data base was decided on that would include the normal data available on the drawings and some additional vendor and inventory information. Further, it was decided that only information on items that could be removed from the habitat proper or might conceivably require replacement would be entered into the data base.

We chose the dBase II program because of its flexibility and power, and because it incorporates a programming language that allows the writing of command programs, tailored to user needs, to insulate the user and make the program transparent. This was important because the personnel using the data base were not likely to be computer experts. We then settled on the Micro Soft operating system, which is used by the IBM PC and similar machines. Further additions, enhancements, or modifications of the data base structure were added after the initial data had been entered. We found it was important to be consistent when working with computers to incorporate engineering drawings.

THE DATA BASE AS A TOOL

After the raw data were entered and available for analysis, we sorted the data by manufacturer and manufacturer's part number.

Several interesting things became apparent. For one, we were able at a glance to determine how many of each unique part there were and on what drawings the part appeared. We were also able to determine, as for example in the case of ball valves, that we had quite a few made by different manufacturers and that even for the same manufacturer we had quite a few different models and configurations. Through this type of analysis, we were able to reduce the number of valve types and configurations from one manufacturer from 18 to 6. The impact of this reduction on the life cycle of the habitat can be readily seen: Fewer spares are required and from a safety viewpoint, the operations manager will not have to worry about the wrong valve being put in the wrong service.

In terms of the process of outfitting the habitat, the data base approach to the management of this important aspect of the project is of immense value. It has allowed us to analyze the habitat systems and make critical decisions regarding the quality and quantity of selected items used. It makes the procurement process cleaner, and for the owner it creates a dynamic history of the project.

THE DATA BASE

OBJECTIVE

Data base routines were designed to provide ready access to the descriptive data of the GEORGE F. BOND undersea habitat's hardware components. Data base access is desirable to locate replacement parts from spare parts inventory rapidly or to identify qualified vendors. Cost control of the spare parts inventory is also improved by an ordered data base approach.

The data base procedures operate interactively with the user on an IBM PC or PC compatible personal computer. The user will be able to query for specific data, prepare reports that will be displayed on the computer terminal or be printed, and revise the data bases.

APPROACH

The data base procedures access three separate but interrelated data bases. One data base contains the as-built component information, another has spare parts data, and the third is the vendor information data base.

All data base access is from menu selection. Data requested of the user are entered from the keyboard. The user is guided through successive menus as needed. In general, the data required of the user involve a single character entry, although specific data such as a part number may be necessary.

The user is presented four options: to search for some component, to generate a report on the data base status, to edit the data base, or to revise the data base. Although the procedures are written in dBASE II, the user need not be an experienced programmer. (Some familiarity with edit commands must be developed.) A tutorial has been developed to assist in familiarization and training of users.

CONCLUSION

In conclusion, our experience has led us to strongly recommend the use of microcomputer data base management as a tool for any construction project related to the ocean. We recommend that it be an integral part of the project from the start in order to maximize its positive impact.

Specific attention should be given to consistency in naming of components. Special attention should be given to the engineering document control system used and to systems with flexibility and compatibility with electronic data processing techniques, to capture fully the inherent value of this type of tool.

DESCRIPTION OF DATA BASES

AS-BUILT COMPONENTS

This data base will contain the following information about the as-built components:

Identification by engineering or fabrication contractor drawing and item number,

Identification by generic description with qualifiers,

Identification by manufacturer and part number,

Vendor, quantity and units, and cost,

Number of times repaired and most recent repair.

It is noted that the engineering or fabrication contractor drawing number coupled with the item number is a unique identifier for a specific component or group of components. The generic description and the manufacturer's designation may not be, however.

Because of this ambiguity, the user may be required to select from options or refer to the drawings.

This data base will be used to aid in the identification of an existing component. If the component is already known by generic description, the user can proceed to inquiry of the spare parts data base.

SPARE PARTS DATA BASE

The spare parts data base will contain the inventory of replacement parts for the original components. It will include:

Identification by generic category and qualifiers,

Quantity on hand and location,

Reorder point for inventory,

Cost, and

Names of qualified vendors.

If the user cannot locate a spare part in stock, two possibilities are that the part is not kept in the spares inventory or that the last spare has been used. If the spare part is not kept in stock, the user must return to the as-built data base to find a vendor. If the spare part has been consumed, the replacement can be ordered from a vendor in the vendor data base.

VENDOR DATA BASE

The vendor data base contains the names, addresses, and telephone numbers of qualified vendors. Specifically, all component suppliers will be listed by:

Name

Address

Telephone and telex numbers

Contact person

PROGRAMMED OPTIONS

Select Option:

1. Search for component
2. Find spare part
3. Locate vendor
4. Revise data base

Search for Component Against:

1. Drawing and item number
2. Manufacturer name and number
3. Generic descriptor with qualifiers
4. Manufacturer name
5. Manufacturer number
6. Printed report

Printed Reports:

1. Entire data base sorted by drawing numbers
2. Entire data base sorted by generic description
3. All components from a vendor
4. All components with a generic descriptor

Spare Parts Selection:

1. Stock on hand
2. Printed report

Spare Parts Report:

1. All spare parts sorted by generic descriptor
2. All spare parts sorted by vendor

Locate Vendor.

Revise data base.

NEW REPETITIVE NO-STOP EXCURSION PROCEDURES FOR NITROX SATURATION DIVING

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A. Abstract

The NOAA OPS procedures for excursion diving with air from an undersea habitat having nitrox as the breathing gas are efficient for reaching the depth range 60-200 fsw. However, the current procedures do not make provision for repetitive excursions; this project is to provide such capability. Using neo-Haldanian techniques based on calculated gas loadings and the ascent limits developed and used for NOAA OPS with adjustments for recent experience, we have calculated a set of new and more conservative no-stop limits. Also, we have taken a new approach to providing allowable no-stop times for repetitive excursions. Based on numerous repetitive calculations, these are determined by the number in the repetitive sequence and the time in the habitat since the last excursion. Representative values show an excursion to 105 fsw from storage at 50 fsw could be 296 min with a fresh diver (after 16 hr) but the second dive can be only 98 min and subsequent excursions are limited to 49 min. We have developed a technique for adjusting the allowed times to account for submaximal excursions; in this case the allowable time on the second excursion is shortened in proportion to the fraction of allowed time used on the first.

B. Introduction

Aquanauts in early sea floor habitats were considerably restricted in the vertical excursions they could perform while on a habitat mission. This was improved somewhat in 1973 by the introduction of the NOAA OPS excursion procedures (Hamilton et al. 1973). These allowed for no-stop excursions in both directions--above and below--the habitat.

A severe limitation has prevailed in that these procedures make no specific provision for repetitive excursions; although some ad hoc procedures have been developed, in most situations a diver was basically limited to one dive per day. There has never been any reason why repetitive excursions could not be performed, it was just that no procedures had been developed (Miller et al. 1976). This project is to fill that need.

C. Arriving at the Method of Calculation

The method used for calculation is that developed in our laboratory and based on the work of Haldane, Workman, and Schreiner in particular. We rationalized the use of gas loading analysis because, first, all the repetitive tables we know of use some variation of the classic methods and consider primarily the residual gas in calculating a repetitive dive. Bubbles are clearly involved, however, but we know of no established model or technique based on bubbles that could do this job (see Berghage, 1978).

Bubbles present something of a dilemma in repetitive diving. The first dive may either remove bubble nuclei or may cause bubbles to form, and the real effect is not known for sure. One thing seems clear, that bubble activity appears to be related to or affected by the gas loading. Therefore, even though an accurate model of bubble behavior might be more relevant, gas loading remains the definitive analytical approach.

For calculations we used a variation of the DCAP program, which has evolved over the years in our laboratory (Hamilton and Kenyon, 1982).

D. Calculation of repetitive tables

The method of calculating repetitive dive procedures is intimately intertwined with the method of displaying such procedures, that is, telling the diver or operator what to do. The prevalent methods either add some bottom time to the second dive, or get the same effect by multiplying the allowable time for the second dive by a factor greater than 1.

1. Multiple repetitive sequences

We took a different approach. We noted in calculating a series of repetitive no-stop dives, dives repeated over and over again with the gas loadings retained between dives, that the allowable times were reduced substantially in the second and perhaps third excursions, but that after that they seemed to stabilize or level out and make little change thereafter. It looked as if the allowable times as they became stable were determined by the interval between the excursions. We felt we should be able to set the repetitive limit in this manner, as a function solely of the interdive interval. However, this analysis was done with the old NOAA OPS matrix (of ascent-limiting M values), and when we revised and smoothed the matrix we found the tendency to stabilize after the second or third excursion was not so clear. Even so, we felt the method could be used to produce a set of no-stop excursions that would account adequately for repetitive dives and be easy to use.

One premise of this approach is the concept that the worst possible dive to have done before a given dive is one just like it. That is to say, a second dive to the same depth and for a similar bottom time will tend to load the same gas compartments that constrained the first dive. Both to confirm this and to find out what the limiting times were we computed a series of multiple repetitive dive sequences having the same bottom times and excursion distances from a set storage depth. These were done for various interdive "habitat" intervals. We chose 14 almost arbitrarily as the number of dives in a repetitive sequence to establish the limits. Fourteen seemed enough to establish a pattern if there were one, and is more than a diver would be likely to do in a row without a break. In most cases the times stabilize long before 14 excursions.

We then adjusted the DCAP program to print the results of 14 individual repetitive dives in a table without printing comments, instructions, stop times etc. We examined these and determined that there was no abrupt levelling like we had noted earlier, but that by the time a few dives had been done the changes were slight thereafter. A sample printout of some of these is included as Table I.

Table I.
Sequences of repetitive dives

Table shows sequences of 14 dives performed from a saturation storage depth of 60 fsw to 3 selected excursion depths. Each row holds 14 dives separated by the indicated interdive or habitat intervals. The first, second, and 14th excursions are used.

Repeat excursion tables; MF0805.DCP STORAGE DEPTH 50. FSW

RWH/DJK 29-MAY-85 SATURATION MIX NORMOXIC
Base Case: D55RO0.K08 and .K09

HAB INTVL	1ST EXC	2ND EXC	3RD EXC	4TH EXC	5TH EXC	6TH EXC	7TH EXC	8TH EXC	9TH EXC	10TH EXC	11TH EXC	12TH EXC	13TH EXC	14TH EXC
DEPTH 100 FSW														
30	458	131	121	72	72	72	72	72	72	72	72	72	72	72
60	458	205	148	131	131	131	131	131	131	113	107	107	107	107
120	458	292	223	221	221	221	217	197	197	197	197	197	197	197
240	458	374	343	340	340	340	340	340	340	340	340	340	340	340
480	458	431	431	431	431	431	431	431	431	431	431	431	431	431
DEPTH 110 FSW														
30	201	85	63	53	53	53	50	38	38	38	38	38	38	38
60	201	124	93	92	86	70	70	70	70	70	70	70	70	70
120	201	162	145	143	124	124	124	124	124	124	121	115	115	115
240	201	189	189	189	189	189	189	189	189	189	189	189	189	189
480	201	200	200	200	200	200	200	200	200	200	200	200	200	200
DEPTH 120 FSW														
30	116	54	46	46	34	33	33	33	33	32	25	25	25	25
60	116	77	72	62	59	59	55	48	48	48	48	48	48	48
120	116	103	100	99	97	91	87	87	87	87	87	87	87	83
240	116	116	116	116	116	116	116	116	116	116	116	116	116	116
480	116	116	116	116	116	116	116	116	116	116	116	116	116	116

2. Times for first, second, and 3+ dives

The above tables determined three no-stop dive times for each excursion depth from each storage depth. The first of these is the excursion time allowed for the fresh diver who has made no previous excursions. The second time is for divers who have made one previous excursion, and the third (designated as "3+") is the time allowed for an indefinite number of excursions (up to 14).

These sequences were calculated under the premise that the repetitive dive time could be determined solely on the basis of the interdive habitat interval and the number the dive is in the sequence, and that it is independent of the type of dive that was done before. We then tested this with a number of different types of combinations to verify that it held up under a widely different combination of dives. We could not prove that it would always be true, but we showed it would prevail for many different combinations, and further that if there were violations they would be for no more than a few minutes and could be considered inconsequential.

To further ensure that these assumptions would result in safe profiles we added some additional restrictions, covered below.

Thus, in summary, in a sequence of repetitive dives the most important changes take place early in the sequence. After a number of similar dives interrupted by specific interdive intervals the times begin to stabilize and any subsequent changes are small and inconsequential. Thus the major factors affecting a repetitive dive are the number of the dive in the sequence and the habitat interval, the duration of time spent in the habitat since the previous dive. For repetitive tables we are using the first, second, and 14th dive in the sequence, and the diver uses the time appropriate to his situation. In arriving at this we were presuming that the worst impact on a subsequent dive is by a dive of the same type; representative calculations showed this to be true in all cases tested.

A sample of the no-stop repetitive tables is shown in Table II.

3. Restrictions

As a further conservatism we recommend certain restrictions on the use of these procedures. These are partly to help prevent an unusual and unanticipated combination of events from exceeding safe limits, but are also to provide a practical limit on some aspects of the divers' exposure.

a. 12 hour excursion limit

The maximum time a diver is allowed to stay in the water in the decompression range in any 24 hour period is 12 hours. The "decompression" range is any depth deeper than the "oxygen window" below the habitat. This allows the diver to excurse below the habitat by an amount equal to the partial pressure of oxygen in the habitat. Thus a diver could attend to the matters in the close vicinity of the habitat without having to count

Table II.
No-stop repetitive excursion tables

Table shows values and manner of presentation for all no-stop excursions available from a storage depth of 50-55 fsw.

NO-STOP EXCURSIONS **STORAGE DEPTH 50 FSW**

85JUL Base cases: D55RO0.K08, .K09. Matrix: MF0805

Allowable time (min) at each excursion depth (fsw)

Intrvl	Excn#	65	70	75	80	85	90	95	100	105	110	115	120	125	130
16+ hr	1st	480	480	480	480	480	480	480	458	**296**	201	158	116	92	77
1/2-1	2nd	480	480	480	480	480	480	419	131	**98**	85	59	54	50	44
"	3+	480	480	480	480	480	241	480	72	49	38	30	25	22	19
1-2	2nd	480	480	480	480	480	480	462	205	142	124	91	77	68	60
"	3+	480	480	480	480	480	427	480	107	78	70	57	48	42	37
2-4	2nd	480	480	480	480	480	480	480	292	200	162	123	103	86	72
"	3+	480	480	480	480	480	480	307	197	145	115	95	83	75	67
4-8	2nd	480	480	480	480	480	480	480	374	262	189	147	116	91	77
"	3+	480	480	480	480	480	480	480	340	253	189	147	116	91	77
8-16	2nd	480	480	480	480	480	480	480	431	294	200	157	116	92	77
"	3+	480	480	480	480	480	480	480	431	294	200	157	116	92	77

Intrvl	Excn#	135	140	145	150	155	160	170	180	190	200	220	240
16+ hr	1st	67	54	45	40	35	32	27	23	19	16	11	08
1/2-1	2nd	37	34	31	28	26	24	20	17	15	14	11	08
"	3+	17	18	17	16	15	14	12	10	09	08	07	06
1-2	2nd	51	45	41	37	33	30	25	21	19	16	11	08
"	3+	33	30	27	25	23	21	19	17	15	14	11	08
2-4	2nd	62	53	45	39	35	32	27	23	19	16	11	08
"	3+	60	53	45	39	35	32	27	23	19	16	11	08
4-8	2nd	66	54	45	40	35	32	27	23	19	16	11	08
"	3+	66	54	45	40	35	32	27	23	19	16	11	08
8-16	2nd	67	54	45	40	35	32	27	23	19	16	11	08
"	3+	67	54	45	40	35	32	27	23	19	16	11	08

that time against the 12 hour limit. This limit is at the far end of what a diver-scientist might need for an occasional project, but we expect that it will rarely be a factor; it is particularly unlikely to be used in cooler water.

b. 14 dive limit

Because the only limits repeatedly checked with definitive calculations were based on sequences of 14 consecutive excursions, we recommend divers be limited to no more than 14 dives in a row without a 16-hour break.

c. 16 hour recovery

Calculations covering all the excursions given here show that in almost all repetitive sequences a 16 hour period is sufficient for a diver to begin counting a new sequence of repetitive dives. In a few cases a dive calculated to follow a 16 hour habitat period was a few minutes shorter than one in which there was no previous gas loading. In these cases the shorter time is the one listed in the table. The 16 hour recovery period is analogous to the 12 hours used in US Navy rules for repetitive dive calculations.

E. Submaximal excursions

Although the set of a repetitive excursion times would greatly increase the capability of divers working in the nitrox saturation excursion diving situation, restrictions would be unnecessarily burdensome in cases where the diver used only a part of his allowable time. It has therefore been desirable to develop a protocol for adjusting the following dive for a dive before it that has used less than the allowable time, a "submaximal" excursion.

Intuitively one might expect that the proportion of allowable time used would reduce the allowable time for the following dive in a manner proportional to the time that would otherwise be allowed. This is in fact what happens in exact calculations. The calculation required of the diver to effect this saving involves a certain complexity, but it is straightforward, linear, and applies throughout the entire range of excursions.

This description of the rule applies to a given excursion depth from a given saturation storage. The rule is that a submaximal excursion shortens the next one in the same proportion to the total limitation of a preceding excursion as the time of the submaximal excursion is to the total allowable time.

For a specific place in the dive sequence (1st, 2nd, or 3+) and a specific habitat interval, an excursion shortens the allowable time of the next excursion. A submaximal excursion shortens the next one in the same proportion that the time used holds to the time allowed.

As an example, using the values given in Table 2, it can be seen that for a 1/2 hr habitat interval the first dive from 50 fsw to 105 fsw is 296 min, and the second would be limited to 98 min. The difference is 198 min; this value is the one modified by the submaximal rule. If the first dive is only 99 min or 1/3 of the allowable time, then the second is shortened by 1/3 of 198 or 66 min; 230 min would be allowed instead of the listed 98 min.

We intend to prepare a graphical aid for making this calculation.

F. Additional work

A number of other procedures are being prepared. Among these are excursions with stops, and various methods of returning to the surface during both routine and emergency conditions. A particular effort is being put into developing a satisfactory plan for the saturation decompression.

REFERENCES

Berghage TE, editor. Decompression Theory. UMS Publ. 29WS(DT)6-25-80. Bethesda, MD: Undersea Medical Society, 1980.

Hamilton RW, Kenyon DJ. DCAP: Decompression computation without a computer expert. In: Proceedings, International Diving Symposium '82. Gretna, LA: Association of Diving Contractors, 1982.

Hamilton RW, Kenyon DJ, Freitag M, Schreiner HR. NOAA OPS I and II: Formulation of excursion procedures for shallow undersea habitats. UCRI-731. Tarrytown, NY: Union Carbide Corp., 1973.

Miller JW, Adams GM, Bennett PB, Clarke RE, Hamilton RW, Kenyon DJ, and Wicklund RI. Vertical excursions breathing air from nitrogen-oxygen or air saturation exposures. Rockville, MD: Natl. Oceanic Atmospheric Admin., May 1976.

REDUCED ORTHOSTATIC TOLERANCE IN HYPERBARIC ENVIRONMENTS: PARTIAL RESULTS FROM A UJNR COOPERATIVE DIVE, SEADRAGON VI

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Cardiovascular deconditioning occurs in weightlessness (Blomqvist 1983, Bungo and Johnson 1983, Dietlein 1975, Johnson et al. 1976, Sandler 1976), bed rest (Birkhead et al. 1963, Chobanian et al. 1974, Convertino et al. 1982, Greenleaf et al. 1982, Greenleaf 1984, Kollias et al. 1976). An expanded central venous blood volume exists under these diverse conditions. In the hyperbaric environment, breathing high-density gases causes increased airway resistance, which causes, in turn, negative-pressure breathing and thus an increase in central blood volume (Smith et al. 1977). Associated with this condition is a diuresis that persists throughout the period of hyperbaric exposure (Hong 1975, Hong et al. 1977, Nakayama et al. 1980, Shiraki et al. 1984), similar to that which occurs in head-out water immersion (Epstein 1974, Greenleaf 1984) and during bed rest (Greenleaf 1984, Hargens et al. 1983). These similarities have caused us to suspect that circulatory deconditioning may also occur during hyperbaric exposure. The evidence for this, however, is not presently available.

This study was designed to examine whether circulatory deconditioning occurs during hyperbaric exposure to a depth equivalent to 1,000 feet of seawater (31 atmospheres absolute, or 31 ATA). If deconditioning exists, it is important to determine whether its cause is due to the effect of pressure exposure or to prolonged physical confinement. We approached this problem by instituting an orthostatic tolerance test (a 90° body-tilt) for the divers prior to and immediately upon arrival at the target depth, on the seventh day of exposure to 31 ATA, during decompression, and immediately upon returning to sea level.

METHODS

Facility, Subjects, and Dive Profile

This simulated 300-m saturation dive, code named SEADRAGON VI, was carried out in September-October of 1984 in the chamber system at the Japan Marine Science and Technology Center (JAMSTEC), in Yokosuka, Japan. The dive consisted of a 5-day predive control period, 7.5 days at 31 ATA, a 12-day decompression period, and a 3-day postdive period (table 1). Three male subjects ranging in age from 23-32 years and weighing between 55-65 kg participated in the orthostatic tolerance tests (table 2). The fourth diver acted as the experiment coordinator for this portion of the study and was responsible for drawing all blood samples from all

Table 1.--Experimental schedule for orthostatic tolerance test during a 7-day, 300 m saturation dive (SEADRAGON VI)

Date	Activity
Oct. 2	Divers entered the chamber at 10 a.m.
Oct. 3	Pre-dive tests*
Oct. 4	Pre-dive tests
Oct. 6	1st day at 31 ATA, tests
Oct. 11	7th day at 31 ATA, tests
Oct. 12	Decompression started, 7 a.m.
Oct. 14	24 ATA, tests**
Oct. 15	21 ATA, tests**
Oct. 23	Decompression completed at 1:30 p.m.
Oct. 24	Post-dive tests
Oct. 27	Divers emerged from the chamber at 10 a.m.

*The orthostatic tolerance tests consisted of 3 tests per day, 8-10 a.m., 3-5 p.m. and 8-10 p.m. The 300 m heliox simulated saturation dive, code named Seadragon VI, was carried out at the Japan Marine Science and Technology Center (JAMSTEC) between September and October 27, 1984.

**No blood samples.

experimental subjects. A detailed description of the experimental design, objectives, and scope of the entire SEADRAGON VI dive has been presented in a separate paper by Nakayama, Murai, and Hong (1985).

Tilt Table

A padded tilt table measuring 0.7 m (width) by 1.9 m and

Table 2.--Physical characteristics of the subjects

Measurements	A	B	C	Mean
Age, years	32	28	23	27.7
Body weight, kg	65.4	55.0	60.2	60.2
Height, cm	173	164	167	168.0
Chest circ., cm	80	88	87	85.0
Body surface area, m^2	1.78	1.59	1.68	1.68

equipped with a footrest and belts across the chest and the abdomen was used. A center axle allowed for manual rotation of the table from the horizontal to the vertical position. A 90° rotation can be accomplished within 2 seconds. The table was located in the wet pot of the chamber system, where the vertical height exceeds 2 m.

Orthostatic Tolerance Test

The test consisted of passive standing for 15 min unless this period was interrupted by the subject's fainting. After preparation for the necessary physiological measurements (see below), subjects assumed a supine posture on the table for 10 min. Control measurements were made during the last 5 min of the pretilt period, after which the table was rotated to the vertical position. The subject was trained and instructed again just before the experiment to remain passive in the standing position. He could, of course, signal the approach of fainting; in such a case, the table can be returned immediately to the horizontal position.

Tilt tests were performed three times on each test, at 8-10 a.m., 3-5 p.m., and 8-10 p.m. The total number of tests for each of the three subjects was 21 (3 times on each of 2 predive days, 3 times on the 2 days at 31 ATA, 3 times on the 2 decompression days, and 3 times each on the single postdive day).

During the test, the following measurements were made: heart rate and arterial blood pressure at 1 min intervals and stroke volume and systolic time intervals by impedance cardiography at the end of the horizontal control period and at the 5th, 10th, and 15th min of passive standing. In addition, venous blood samples were taken, in selected experiments, at the end of the 5-min horizontal control period and at the end of the 15-min passive standing period. Hematocrit (and thus, relative plasma volume changes) and humoral responses were measured (Matsui et al. 1985). However, blood samples were obtained only during the morning and evening tilt tests and were not available for the decompression period.

Impedance Cardiography

Conventional 4-band electrodes and an impedance cardiograph (Nihon-Koden, AI-601G) were used for estimating stroke volume. We used disposable tape-on twin mylar electrodes of uniform spacing (Nihon-Koden). The total width of the tape measured 5 cm and the electrodes were spaced 3 cm apart. The electrode was constructed of 1.0 mil (0.001 in) aluminum deposited in parallel on an adhesive polyester film. This type of construction allows four electrodes to be positioned with only two pieces of tape. In addition to saving time, use of the twin-electrode tape guarantees uniform spacing between the inner and outer electrodes.

Of the two inner electrodes, one was placed around the base of the neck and the other at the level of the xiphisternal joint. The two outer electrodes serve to conduct the sinusoidal current source, 4 mA, 100 kHz, through the chest. The two inner electrodes detect impedance changes by way of a high impedance amplifier (Nihon-Koden AI-600G). Results of an ECG (standard lead II placement) were displayed on a Nihon-Koden cardiofax and then recorded onto a Watanabe recorder (Watanabe Instruments Corp., Japan). This arrangement was chosen for the convenience of displaying the ECG record for the impedance pneumographic study concurrently (see below) and because it permitted monitoring by a physician to detect any sudden adverse changes in cardiac rhythms during the orthostatic tests. A phonocardiogram (PCG) was obtained with a small microphone (Panasonic omnidirectional condenser microphone, P9932) sealed into a metal stethoscopic head with a plastic diaphragm. A multichannel Watanabe Mark VII recorder registered the ECG, PCG, and impedance cardiogram (ICG). The stroke volume (SV, in ml) was calculated according to the empirical formula of Kubicek et al. (1970):

$$SV = p(L/Zo)^2 T(dZ/dt)min \tag{1}$$

where p represents the resistivity of blood in ohm-cm, which was assumed in healthy Japanese subjects to be 135 ohm-cm at 100 kHz and to be constant during the experiment; L defines the mean distance in centimeters between the inner pair of electrodes; Zo indicates the basal thoracic impedance in ohms; (dZ/dt)min is the minimum rate of change of impedance in ohm/sec; and T is the ventricular ejection time in seconds, as obtained from the dZ/dt wave form (Kubicek et al. 1970). This method of obtaining T was checked against heart sound procedures and results of the two methods were indistinguishable. The average value of the distance between the two inner electrodes at the anterior and posterier midlines yields a mean L value. Average values of relevant impedance data over three cardiac cycles were used for calculation of SV. Impedance was measured during brief apnea at FRC. Cardiac output (CO) was then calculated by multiplying SV by heart rate (HR).

Arterial Blood Pressure and Heart Rate

A solid state B300E sphygomomanometer (Stanly) with digital indicators for blood pressure and heart rate was used to determine systolic and diastolic blood pressure and heart rate. These values were recorded manually at 1-min intervals.

Cardiovascular Index of Deconditioning

Systolic arterial blood pressure (sABP) decreases, diastolic pressure (dABP) increases, and heart rate (HR) increases upon assuming upright posture. In comparison to the predeconditioned state, subjects in a deconditioned circulatory state exhibit greater changes in sABP, dABP, and HR during passive standing.

Accordingly, an index of circulatory deconditioning can be compiled by summing these changes and comparing this value to the pretreatment condition. Bungo and Johnson (1983) proposed a cardiovascular index of deconditioning (CID) that is calculated as follows:

$$CID = \Delta HR - \Delta sABP + \Delta dABP$$

where Δ HR is heart rate standing postexposure minus HR standing pre-exposure, and ΔsABP and ΔdABP represent systolic and diastolic blood pressure differences between post- and pre-exposures, respectively. The same result is obtained by a two-step procedure; that is, ΔHR, ΔsABP, and ΔdABP in response to standing is summed (CID) first for each condition, and then CID's are compared for the various exposure conditions. The CID as originally proposed can be represented by:

$$\begin{aligned} CID = & [(HR_T - HR_S)_2 - (HR_T - HR_S)_1] \\ & - [(sABP_T - sABP_S)_2 - (sABP_T - sABP_S)_1] \\ & + [(dABP_T - dABP_S)_2 - (dABP_T - dABP_S)_1] \\ = & [(HR_T - HR_S)_2 - (sABP_T - SABP_S)_2 + (dABP_T - dABP_S)_1] \\ & -[(HR_T - HR_S)_1 - (sABP_T - sABP_S)_1 + (dABP_T - dABP_S)_1]. \end{aligned}$$

This is the same as

$$CID = CID_2 - CID_1$$

where subscripts S and T represent each variable respectively in the supine and response-to-tilt postures, and the subscripts 1 and 2 denote pre- and post-exposures, respectively. A greater difference in the numerical value of CID signifies greater circulatory deconditioning. Similarly, we propose to use a modified CID to accommodate the ability to vasoconstrict during circulatory perturbation, so that:

$$\text{Modified CID} = \Delta HR - \Delta sABP + \Delta dABP - \Delta TPR$$

where TPR stands for total peripheral resistance. For reasons described later, the ability to vasoconstrict appears to be a major factor in orthostatic tolerance.

Experimental Design and Statistical Treatment

Orthostatic tolerance tests were performed on two successive predive days, on the 1st and 7th days at 31 ATA, on two consecutive days during decompression (21-24 ATA, no blood sample taken on either day), and, finally, on surfacing (the 27th day since entering the chamber). With the exception of the decompression days, blood samples were available for the morning and evening tilt tests; responses to passive standing were compared on the basis of paired Student-t tests. We rejected the null hypothesis if p was equal to or less than 0.05.

RESULTS

Arterial Blood Pressure and Heart Rate

Figure 1 illustrates the typical temporal response of the circulatory system to a 15-min head-up tilt (passive standing) during a predive trial. Typical responses consisted of depressed sABP, elevated dABP, tachycardia, and an unchanged mean ABP. (Also shown are changes in stroke volume (SV), cardiac output (CO), and total peripheral resistance (TPR). These parameters will be considered separately in later sections.) Absolute levels of these parameters differed significantly among subjects (fig. 2,

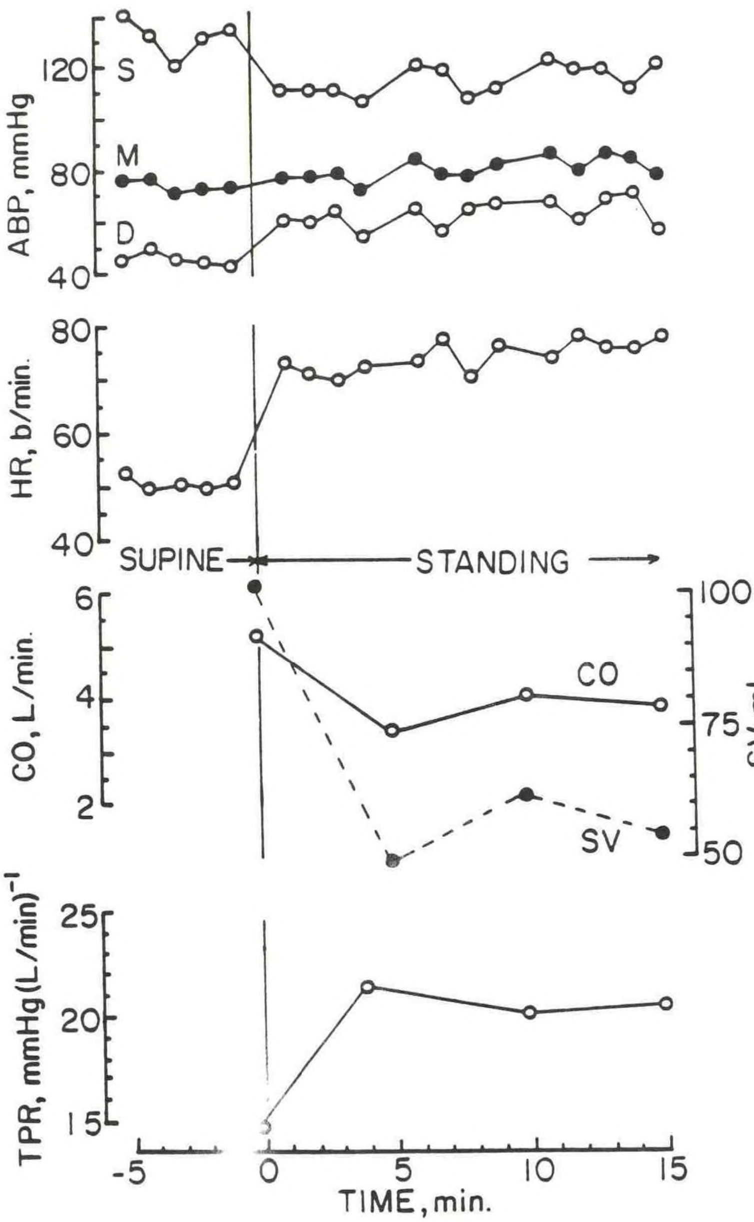

Figure 1.--Typical responses to head-up tilt (passive standing). This example was obtained from subject A (32 yr, 173 cm ht, and 65.4 kg) during precompression period. Abbreviations are: S, M, D, ABP = Systolic, mean, and diastolic arterial blood pressure; HR for heart rate; CO for cardiac output; SV for stroke volume; and TPR for total peripheral resistance.

left panel), whereas diurnal variations had little influence on circulatory responses to orthostatic challenge (fig. 2, right panel). For this reason, we averaged all test results, and to

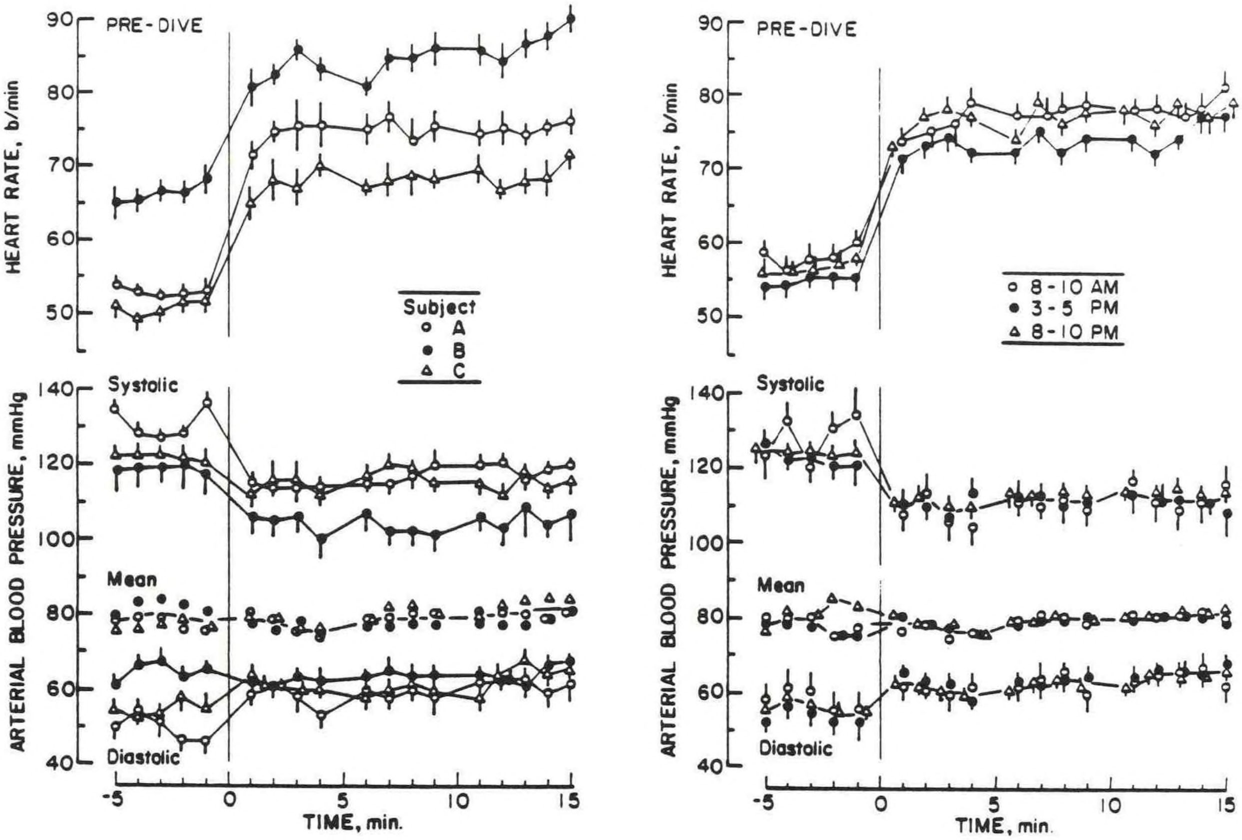

Figure 2.--Subject variation and diurnal influence on circulatory responses to a 15 min head-up tilt (passive standing). Passive standing begins at time zero. Each point represents average and standard error of six tests in each subject (left panel) or for each test period (right panel) over 2 days. Tilt tests were performed three times: 8-10 a.m., 3-5 p.m., and 8-10 p.m. on each test day.

take care of between-subject variations we used paired t-statistics. Furthermore, it is clear from these data that responses were stable over the entire 15 min of passive standing (figs. 1 and 2). Therefore, for comparisons between test conditions we elected to average the response over the entire 15 min of passive standing. Responses to standing at pressure and to standing immediately after return to sea level were quantitatively similar (fig. 3).

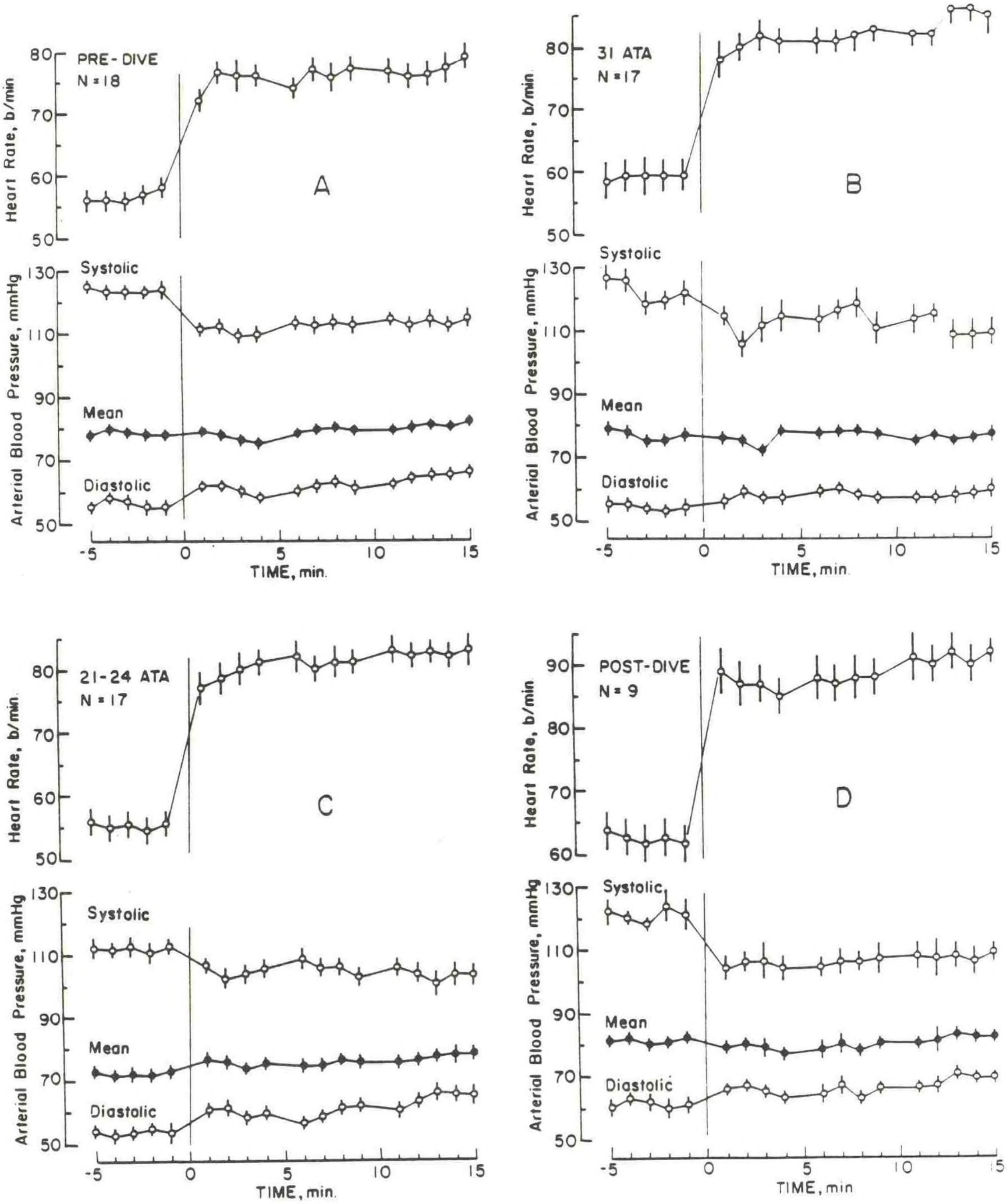

Figure 3.--Arterial blood pressure and heart rate response to 15-min passive standing during predive (A), at 31 ATA (B), during decompression to between 21-24 ATA (C), and immediately after the dive (D). Each point represents mean $\pm$ SE of 18 tests for A, 17 tests for B and C, and 9 tests for D in 3 male subjects.

All data presented as group means excluded two trials that produced fainting; the fainting cases are described separately (see below).

Table 3 summarizes responses to passive standing in various pressure environments. (Again, this summary excludes the two tests that produced fainting.) Passive standing from the supine posture caused systolic hypotension, elevation of diastolic blood pressure, tachycardia, vasoconstriction (indicated by increases in TPR and diastolic hypertension), reduced SV, and a decreased CO level despite the presence of tachycardia. With the exception of mABP, all changes on standing were significantly different ($p < 0.05$) from supine values, based on paired t-tests. The greatest systolic hypotensive response was observed immediately after the dive (table 3). Passive standing caused elevations in diastolic pressure of the same magnitude in all pressure environments. Mean blood pressure was not affected by passive standing. Both supine and standing values of TPR decreased, relative to the predive state, during and after pressure exposure.

Figure 4 compares the relative changes in circulatory parameters during passive standing predive (A), at 31 ATA (B), during decompression (C), and immediately after the return to 1 ATA (D). There were no qualitative differences in the responses to standing in the various conditions, with minor quantitative differences. Passive standing in hyperbaric environments produced greater tachycardia ($p < 0.05$), which persisted until the postdive period. Cardiac output showed a lesser drop at 31 ATA. Coincident with this was a lesser elevation in specific thoracic impedance,

Table 3.--Summary of circulatory changes during 15 minutes of passive standing

Measurements		Predive (n = 18)	31 ATA (n = 17)	21-24 ATA (n = 17)	Postdive (n = 17)
HR, bt/min	Supine[a]	57 ± 1.8	59 ± 3.0	55 ± 2.0	63 ± 2.9
	Standing[b]*	77 ± 2.0	82 ± 3.9†	81 ± 2.3†	89 ± 2.1†
sABP, mmHg	Supine	124 ± 2.4	122 ± 3.8	112 ± 2.6	122 ± 3.8
	Standing	112 ± 2.4	112 ± 4.2	104 ± 3.2†	106 ± 4.3
dABP, mmHg	Supine	56 ± 2.3	54 ± 2.3	54 ± 2.1	61 ± 3.0
	Standing	62 ± 1.8	58 ± 2.2	62 ± 2.3	66 ± 1.9
mABP, mmHg	Supine	79 ± 1.4	77 ± 1.6	72 ± 1.7	81 ± 1.6
	Standing	79 ± 1.3	76 ± 1.6	76 ± 1.8	80 ± 2.3
SV, ml	Supine	104 ± 8[c]	105 ± 9	121 ± 10†	106 ± 14
	Standing	56 ± 5	62 ± 6	68 ± 7	66 ± 9
CO, L/min	Supine	5.91 ± 0.33[c]	5.96 ± 0.39	6.93 ± 0.44	7.00 ± 0.83
	Standing	4.10 ± 0.30	4.72 ± 0.26	4.99 ± 0.32	5.13 ± 0.43
TPR, mABP/CO	Supine	13.2 ± 0.74[c]	12.9 ± 0.84	10.5 ± 0.67†	11.6 ± 1.38†
	Standing	19.2 ± 1.40	17.1 ± 0.94†	15.4 ± 0.99†	15.5 ± 1.29†
Zo/L, Ω/cm	Supine	0.93 ± 0.02[c]	0.93 ± 0.01	0.92 ± 0.02	0.90 ± 0.03
	Standing	0.99 ± 0.02	0.98 ± 0.02	0.99 ± 0.02	0.97 ± 0.04

Values are means ± SE for n measurements in 3 subjects. Number of measurements (n) represents 3 tests per day in 3 subjects for 2 days (n - 3 x 3 x 2) or for 1 day (n - 3 x 3 x 1). The n = 17 figure denotes that 1 subject fainted; the fainting cases are presented separately. (a) average over the 5 min prestanding measurements; (b) integrated over the entire 15 min passive standing period. (c) based on 15 determinations, due to equipment failure in 1 test period. *With the exception of mABP, all responses upon standing differ statistically ($p < 0.05$) from supine values, based on paired t-tests. †: differ significantly from predive responses.

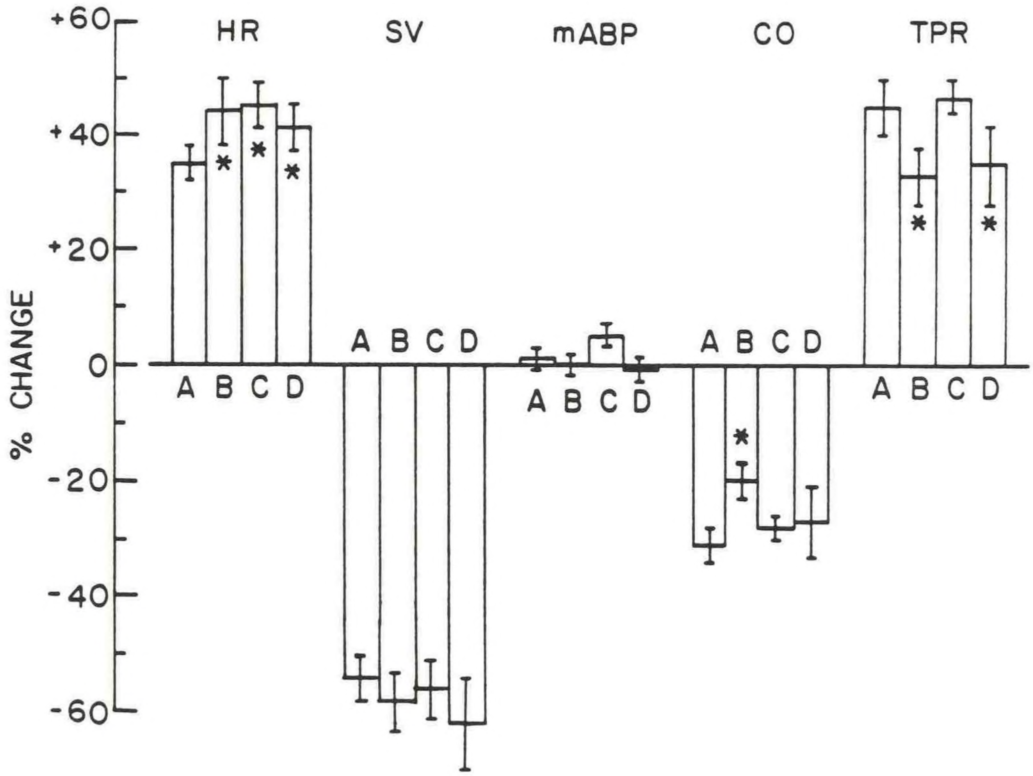

Figure 4.--Relative changes in circulatory parameters during 15-min passive standing predive (A), 31 ATA (B), during decompression (C), and immediately following completion of decompression (D). Values are means $\pm$ SE for 15 determinations in A, 17 determinations in B and C, and 9 measurements in D in 3 male subjects, 3 times daily over 2 days. Asterisks indicate statistical differences between A and other test conditions.

Zo/L, at 31 ATA during standing (table 3), which could signify a lesser reduction in thoracic blood volume. Mean ABP values at depth varied less than 5% from their respective control values.

Stroke Volume, Cardiac Output, and Vascular Resistance

Overall circulatory responses to standing were similar in all conditions (fig. 5). The decrease in stroke volume during standing was similar in all conditions, ranging from 54% to 62% below control values (table 3 and fig. 4). Despite tachycardial

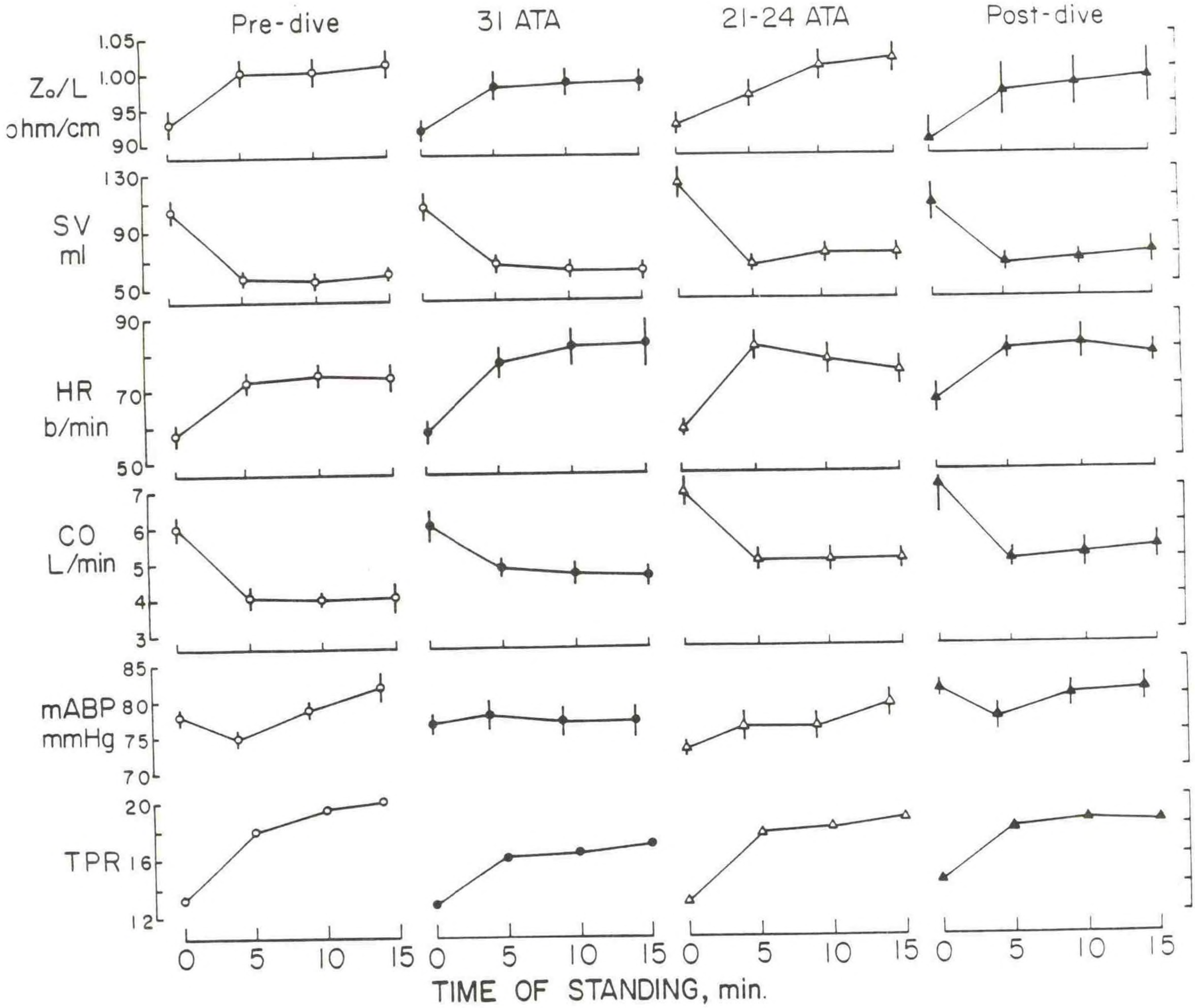

Figure 5.--General hemodynamic responses to 15-min passive standing. Values are means ± SE of measurements made 3 times daily in 3 subjects over 2 days. Number of determinations were: predive 15, 31 ATA 17, 21-24 ATA 17, and 9 in postdive.

responses during standing, the CO level decreased significantly, to levels ranging from 20% to 31% below control values. Relatively, CO showed a lesser reduction in the 31 ATA environment. Since mABP values did not vary significantly from control values, the reduction in CO levels signifies peripheral vasoconstriction. The ability to vasoconstrict decreased during exposure to pressure and at postdive (tables 3 and 5). In relative terms, however, the elevation of TPR during decompression was not different from TPR during predive conditions (fig. 4).

Fainting During Orthostatic Tolerance Tests

Only one subject, Subject C, fainted during the standing tests. He fainted twice: once in the morning of the first day at 31 ATA, and once in the morning on the third day of decompression at 24 ATA. Otherwise, he completed all other tests (19 out of a total of 21 tests, see table 1) without fainting. This subject's circulatory responses for these two occurrences are presented in figure 6; greater tachycardia, greater systolic hypotension, and failure to maintain mean ABP levels were observed in this subject just prior to fainting on both occasions, compared to this subject's mean responses at 1 ATA (6 tests over 2 days at 1 ATA). The magnitude of the reduction in SV (20% at 31 ATA and 29% at 24 ATA, table 4) and in CO (23% at 31 ATA and 7% at 24 ATA) on these two occasions was in fact less than occurred for this subject in trials during which no fainting occurred (tables 3 and 4). The inability to sustain peripheral vasoconstriction appears to be responsible for the failure to maintain ABP (table 4), which causes fainting. Although tests in the other two subjects did not result in syncope, these subjects reported a sensation of dizziness and discomfort during the standing tests at 31 ATA and during

Table 4.--Circulatory status of subject C prior to fainting during standing test

Measurements	October 6, 1984, 31 ATA 0	5 min	10 min	October 11, 1984, 24 ATA 0	5 min
HR, b/min*	57	67	54	52	72
sABP, mmHg	119	104	86	110	94
dABP, mmHg	40	60	38	58	56
mABP, mmHg	67	75	55	75	69
SV, ml	121	73	97	164	116
CO, L/min	6.83	4.86	5.26	8.89	8.31
TPR, mmHg/(L/min)	9.81	15.4	10.45	8.44	8.30

* This is the heart rate measured in conjunction with a determination of stroke volume measured by impedance cardiography. Temporal responses of heart rate and blood pressure are shown in figure 6. Note the failure to maintain vasoconstriction just prior to fainting.

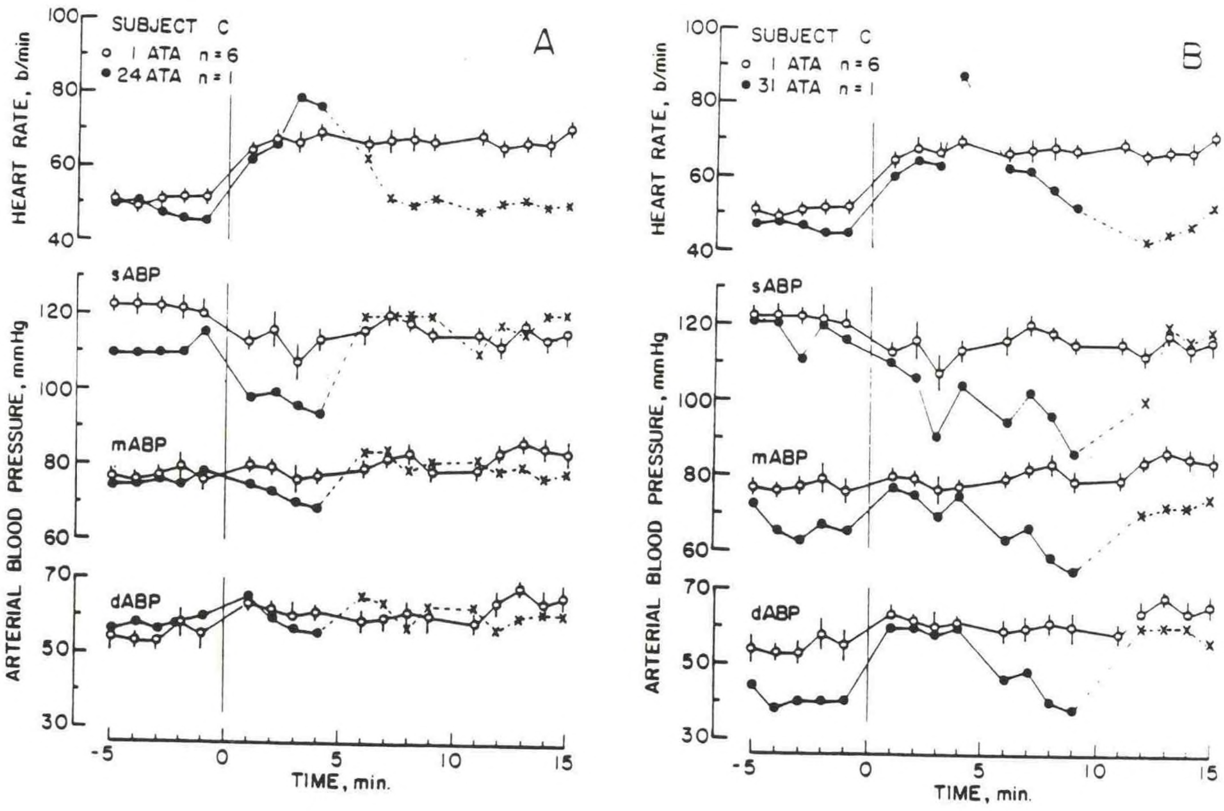

Figure 6.--Circulatory responses of fainting subject just before fainting.

decompression but did not report such sensations before or after the pressure exposure. The responses of these subjects therefore reflect circulatory strain under the same stress that caused the one subject to faint.

Estimate of Circulatory Deconditioning

Syncope represents a definitive indicator of cardiovascular deconditioning. What index to use to indicate circulatory deconditioning short of fainting during orthostatic tolerance tests, however, remains uncertain. The ability to respond appropriately during circulatory stress offers some insight into this problem: the following responses may be useful, since there is no single indicator that adequately defines the deconditioned circulatory state.

Tachycardia: a greater tachycardial response to circulatory perturbation may indicate inadequate stroke output for the required responses. A greater increase in HR occurred during the orthostatic test during and after hyperbaric exposures compared to HR values during the pre-exposure tests (tables 3 and 5, fig. 5).

Systolic hypotension: This reflects inadequate stroke output in relation to circulatory capacitance during circulatory perturbation. Generally, there was no difference in sABP responses to passive standing except during decompression (table 3).

Diastolic hypertension: This indicates qualitatively the degree of peripheral vasoconstriction. There was no difference in this parameter under the different test conditions.

Stroke volume and cardiac output: Stroke volume during passive standing did not change under various conditions, either in absolute (tables 3 and 5) or in relative terms (fig. 4). SV changes were also similar for fainting and nonfainting trials (table 5) in the subject who fainted. Changes in CO levels were also similar for all conditions, except for one subject in the nonfainting trials at 31 ATA and in one fainting trial during decompression, where CO reductions were smaller than they were in other trials (table 5).

Total peripheral resistance: This indicator shows the degree of vasoconstriction quantitatively. The ability to vasoconstrict decreased after hyperbaric exposures (tables 3, 4, and 5).

Table 5.--Cardiovascular responses to head-up tilt and indices of cardiovascular deconditioning during and following exposure to 31 ATA for 7 days

Measurements	Predive (n = 18)	31 ATA (n = 17)	31 ATA (n = 1)	21-24 ATA (n = 17)	21-24 ATA (n = 1)	Postdive (n = 17)
ΔHR, b/min	19.4 ± 0.8	25.9 ± 2.6†	42	25.2 ± 0.8†	32	26.0 ± 0.9†
ΔsABP, mmHg	-11.1 ± 1.8	-9.7 ± 2.2	-33	-7.7 ± 1.7†	-16	-15.4 ± 1.9†
ΔdABP, mmHg	6.2 ± 0.6	4.0 ± 0.5†	-2	8.2 ± 0.8	-2	5.4 ± 0.6
ΔSV, ml	-48 ± 4	-43 ± 4	-48	-53 ± 5	-48	-40 ± 5
ΔCO, L/min	-1.81 ± 0.13	-1.24 ± 0.07†	-1.17	-1.94 ± 0.12	-0.58	-1.87 ± 0.22
ΔPV, % pretilt*	-6.6 ± 0.7	-6.9 ± 1.1	-5.9	---	---	-6.8 ± 1.8
ΔTPR, mmHg/(1/min)	6.0 ± 0.42	4.2 ± 0.24†	0.64	4.9 ± 0.30†	-0.14	3.9 ± 0.46†
CID**	37	40	73	41	46	47
modified CID***	31	36	72	36	46	43
ΔHR/ sABP, b/min·mmHg	-1.75 ± 0.28	-2.67 ± 0.61†	-1.27	-3.27 ± 0.72†	-2.0	-1.68 ± 0.21

* From Matsui et al. (1985).
** CID = HR - dABP, according to Bungo and Johnson 1983.
*** Modified CID = HR - sABP + dABP - TPR.
†P < 0.05, compared to predive values.

Baroreceptor sensitivity: A change in HR relative to a given change in ABP is an indicator of the sensitivity of the baroreceptor response. To compensate successfully for a low stroke output state, the heart must beat faster if the circulatory system is compromised. This is indicated by greater ΔHR/ΔsABP values in the nonfainting subjects during hyperbaric exposure (table 5). Failure to increase ΔHR/ΔsABP produces an inappropriate response to a low cardiac output state. Depressed baroreceptor sensitivity was observed in the two fainting episodes (table 5).

CID: A method of summing the magnitude of the circulatory changes that occur during standing tests would be useful as an index of circulatory deconditioning. The cardiovascular index of deconditioning (CID) proposed by Bungo and Johnson (1983) consists of the sum of the changes in HR, sABP, and dABP, i.e., CID = ΔHR - ΔsABP + ΔdABP. Computations based on nonfainting trials showed that the CID increased during pressure exposures and immediately after the dive (table 5).

Modified CID: As mentioned above, the ability to maintain vasoconstriction was affected on the trials that produced fainting in one subject. The CID could therefore be improved by including this parameter. Like the CID, values obtained by using this modified CID rose during and after pressure exposures, although the difference between results obtained under pressure and those obtained at predive increased somewhat when the modified CID was used.

CID in syncope: Since the responses in syncope did not reach a steady state (fig. 6), the calculation of a CID is somewhat subjective. When peak ΔHR was taken and summed with the changes in blood pressure before the subject fainted, the CID equals 73 at 31 ATA and 46 at 24 ATA (table 5). Both cases showed higher values than was true for the predive trials. TPR dropped back to supine levels just before the subject fainted. The ΔTPR was, therefore, practically zero in these two cases (table 5). The inability to maintain vasoconstriction, reflected in the changes of TPR and dABP (a decrease instead of an increase), represents the most significant indices for circulatory deconditioning (table 5).

DISCUSSION

The fact that one subject fainted during the passive standing test (head-up tilt) during hyperbaric exposure and that no such episode occurred before or after the exposure indicates that hyperbaria can evoke inappropriate orthostatic reflexes. This result cannot be explained simply by the reduced physical activity over the period of confinement. A failure to maintain appropriate vasoconstriction appears to be the mechanism involved in this fainting, since the reduction in SV and CO was no greater in the fainting subject than in the same subject in nonfainting trials. The failure to maintain vasoconstriction was shown in this study by a reduction in TPR and diastolic hypotension in a situation where an increase in TPR and diastolic hypertension would be appropriate.

Indications of cardiovascular deconditioning include orthostatic intolerance, reduced cardiac dimensions, elevated resting heart rate, contracted intravascular volume, and diminished exercise capacity (Dietlein 1975, Henry et al. 1977, Johnson et al. 1976, Sandler 1976). Syncope during the orthostatic test indicates definitively the existence of circulatory deconditioning. Without such an endpoint, however, it is uncertain as to what index or indices could be used to define the state of circulatory deconditioning adequately. Because of experimental limitations, we could not determine cardiac dimensions as well as blood volume. However, exercise capacity was shown in an earlier study to be reduced during a 300-m simulated saturation dive (Ohta et al. 1981, Salzano et al. 1970). Furthermore, Ohta et al. (1981) concluded that neither ventilatory nor cardiac limitations offered a satisfactory explanation for the decrement in VO_2 observed at 300 meter depths. These authors' conclusion suggests the existence of an undefined deconditioning during hyperbaric exposure. The cause for the depressed maximal tolerable work load at 31 ATA was not elucidated in their study. It is possible that a host of composite factors as a whole bring out "cardiovascular deconditioning," while depressed work capacity is but one of the expressions of circulatory deconditioning.

The results of the present study show no hyperbaric bradycardia in the supine posture at rest. Since bradycardia often appears under hyperbaric conditions, especially when hyperoxia is present (Fagraeus et al. 1974, Flynn et al. 1972, Salzano et al. 1970, Shida and Lin 1981) and a deconditioned circulatory state results in a higher resting heart rate, it is possible that an unaltered heart rate in a hyperbaric environment in itself represents a deconditioned state. Further investigation of this point is justified.

Studies of quantitative cardiovascular responses to circulatory perturbation may yield information concerning the circulatory state after exposure to an experimental condition. We chose the orthostatic tolerance test to produce perturbation of the circulatory system. Cardiovascular responses to orthostatic challenges are mediated mainly by cardiopulmonary baroreceptors and by arterial baroreceptors. Therefore, quantitative cardiovascular responses to orthostatism, which reflect the integrity of the orthostatic reflexes, could serve as indices for the quantification of circulatory deconditioning. The present study compiled various parameters of orthostatic reflexes (tables 5 and 6). These included tachycardia, systolic hypotension, diastolic hypertension, reductions in SV and CO, peripheral vasoconstriction, various combinations of the above changes, and an estimate of baroreceptor sensitivity (table 5). In addition, hypovolemia and altered humoral responses could also play a role (Matsui et al. 1975). In the trials in which the subject did not faint, a greater tachycardia, reduced vasoconstriction, and elevated CID, modified CID, and increased baroreceptor sensitivity were observed during orthostatism subsequent to hyperbaric exposure, compared to this subject's predive responses (table 5). On the trial that resulted in syncope, greater tachycardia and systolic hypotension, reduced dABP and TPR, elevated CID and modified CID occurred during the orthostatic tests, and the subject's baroreceptor sensitivity was either reduced or unchanged compared to his predive responses (table 5). Based on these changes and the observation of reduced work capacity (Ohta et al. 1981), we conclude that cardiovascular deconditioning existed during and subsequent to hyperbaric exposure, and that cardiovascular deconditioning can be documented in the absence of syncope as an endpoint.

Although cardiovascular deconditioning can be demonstrated by several indices, the question remains as to how hyperbaric exposure causes circulatory deconditioning. We cannot as yet offer an obvious explanation for this phenomenon. The present study did not allow us to determine whether the afferent, efferent, or effector of the orthostatic reflex, or all of these, were involved. Although the cause of the impaired reflex during head-up tilt in the hyperbaric environment remains unclear, we postulate that, based on the knowledge of a common physiological state that could be observed from a variety of diverse conditions, circulatory neurohumoral adaptation to an expanded intrathoracic volume is the mechanism involved.

First of all, by recognizing that there exists a common physiological state in such diverse conditions as hyperbaric exposure, head-out water immersion, bed rest, negative pressure breathing, and exposure to weightlessness, it can be seen that the physiological adjustments in these conditions are similar:

cephalic blood shift and postexposure hypovolemia. Cardiovascular function is essentially normal so long as the redistribution of blood volume is not great. However, in the physiological responses that demand redistribution of blood toward the periphery, cardiovascular dysfunction may appear. A prominent example of this is the circulatory collapse that occurs during unprotected re-entry into the earth's gravity and the orthostatic intolerance that occurs shortly thereafter (Dietlein 1975, Sandler 1976). Circulatory deconditioning has also been documented following participation in various weightlessness simulation techniques at normal gravity (Greenleaf 1984).

An expanded central blood volume leads to an increased urinary output without an appropriate and concurrent thirst drive; one of the results of this effect is a negative fluid balance during hyperbaric exposure. Hyperbaric diuresis, especially that of nocturia, has been well documented (Claybaugh et al. 1984, Hong 1975, Hong et al. 1977, Makayama et al. 1980; Shiraki et al. 1984). This diuresis is in agreement with our current understanding that pulmonary vascular engorgement is induced by negative pressure breathing in response to the breathing of a high-density gas mixture in a hyperbaric environment (Smith et al. 1977). The engorged pulmonary vascular compartment enhances the activity of the cardiopulmonary receptors and leads to diuresis (Claybaugh et al. 1984, Gauer and Henry 1976, Hong et al. 1977, Leach et al. 1973). The fact that in the present study both faintings occurred in the morning trials suggests the involvement of a reduced plasma volume caused by nocturnal diuresis. This notion was partially supported by changes in relative plasma volume. Plasma volume decreased by 15% from the predive level during the initial phase of compression and arrival at 31 ATA, but it gradually returned to the control level (Shiraki et al. 1985). Plasma volume returned to the control level by the end of the stay at 31 ATA (Matsui et al. 1985). This explanation is weakened, however, by the fact that one fainting episode occurred during the decompression phase, when plasma volume had returned to its predive level.

It is generally recognized that circulating blood volume plays an important role in circulatory responses to orthostasis. Acute hypovolemia, induced either by head-out water immersion or by blood withdrawal, leads to orthostatic and acceleration intolerance, while drinking fluid or a blood infusion partially restores this tolerance in hypovolemic subjects (Bergenwald et al. 1977, Greenlead et al. 1977). A diminished blood volume reduces the mean circulatory pressure and produces a reduced venous return and stroke volume. Cardiac output is thus compromised, especially under stress, unless it is compensated for by a greater tachycardia (Nadel et al. 1980, Sjostrand 1953). This view is, however, not uncontroversial. The blood volume loss observed during space flight and ground level simulations, and the loss that occurs in the adaptive state of hyperbaric exposure is modest or nonexistent. The degree of circulatory deconditioning seems disproportionately great. Furthermore, volume-to-volume replacement achieves only a partial correction of orthostatic intolerance (Blomqvist et al. 1980, Blomqvist and Stone 1983). Taken together, these results suggest that a factor or factors, in addition to reduced blood volume, must be responsible for the observed cardiovascular deconditioning.

The centralization of blood during head-out water immersion, bed rest, or weightless exposure initiates a decrease in peripheral venous tone (Echt et al. 1974), vasodilation in general (as shown by the present study) and that of the muscular vessels in particular (Arborelius et al. 1972), reduced sympathoadrenal activity (Bonde-Petersen et al. 1984, Goodall et al. 1964, Deroanne et al. 1979, Leach et al. 1982), and reduced sympathetic efferent activity (Clement et al. 1972, Mano et al. 1985, Gilmore and Zucker 1980). The stimulation of cardiopulmonary and arterial baroreceptors by the expanded central blood volume initiates regulatory changes that correct hypervolemia, i.e., elimination of fluid and selective vasodilation. Consequent to these changes, a peculiar circulatory state exists, consisting of circulatory and neurohumoral adaptations to an expanded central venous capacity and a reduced total blood volume. Orthostatic reflexes require an enhanced sympathetic drive. However, the low level of sympathetic drive existing at the pretilt stage may cause insufficient velocity in compensation, and symptomatic expressions of orthostatic intolerance, such as excessive tachycardia, weak peripheral vasoconstriction, systolic hypotension, and even syncope may occur.

Conventional views hold that first and foremost orthostatic reflexes strive to maintain mABP and a rational distribution of blood flow that favors hypoxia-intolerant tissues, such as those of the brain. To accomplish this in the face of reduced stroke output, tachycardia and selective vasoconstriction must occur. Subnormal levels of these responses lead to syncope. Whether it is the sensitivity of the baroreceptors or the ability to vasoconstrict that changes in cardiovascular deconditioning should be examined.

The proper degree of baroreceptor sensitivity must be present to maintain an appropriate level of tachycardia during orthostatism. Our results demonstrated that inappropriate circulatory responses and syncope occurred in tests where baroreceptor sensitivity remained unchanged, compared to predive control levels. On the other hand, in the nonsyncope trials the subject exhibited elevated baroreceptor sensitivity and thus the ability to maintain an above-normal degree of tachycardia (table 5). Ideally, baroreceptor sensitivity should be studied in a beat-to-beat manner (Ebert et al. 1984, Eckberg and Eckberg 1982). In the present study only values for the steady state response were available, which grossly underestimate the true sensitivity. However, this study was designed only to identify relative changes, and we have quantified sensitivity in the same manner for all trials. We suggest that elevated tachycardial responses by way of increased baroreceptor sensitivity could serve as an index of cardiovascular deconditioning even in the absence of syncope.

The ability to vasoconstrict in the face of reduced CO is the most important process in maintaining ABP. Vasoconstriction during tilt was demonstrated in this study by the elevation of TPR and an increase in dABP. We have shown that the ability to vasoconstrict decreases following hyperbaric exposure, and that TPR failed to rise in trials that resulted in fainting. Therefore, we propose to add this variable to the CID that was originally proposed by Bungo and Johnson (1983). The question remains, however, as to what causes the reduced ability to vasoconstrict in a circulatory deconditioned state. An examination of the changes in circulatory levels of vasoactive substances may yield information on this question.

The inability to vasoconstrict sufficiently after hyperbaric exposure may be related to plasma ADH changes. The ADH level fell prominently during hyperbaric exposure and was still depressed, to a lesser degree, after the dive. Furthermore, the ADH level failed to rise during tilt at 31 ATA, although a significant elevation was observed both before and after the dive (Matsui et al. 1985); in this study we also examined plasma renin activity (PRA), angiotensin I (A-1), serum aldosterone (Aldo), and cortisol at the end of a 15-min passive standing period, and compared these values to pretilt values. Of these, PRA, A-1, and cortisol showed significant rises as a result of circulatory challenge. Furthermore, the magnitude of change was greater during and after hyperbaric exposure. The depressed ADH response to tilt deserves further investigation. Drastic rises in PRA and A-1 as well as ADH were observed in the fainting case (Matsui et al. 1985). Even with elevated levels of vasoconstrictive hormones, TPR showed either a decrease or no change at all in the syncope trial. Vagal activation is suggested, although its trigger remains obscure.

Stella and Zanchetti (1977) suggested that the elevation of peripheral resistance and the subsequent regulation of blood pressure during tilt may be related to angiotensin-mediated vasoconstriction via the sympathetic stimulation of renin release by the kidney. This implies that a low level of PRA correlates with orthostatic intolerance. This view has its supporters (Goldwater et al. 1980) as well as its opponents (Convertino et al. 1984); the latter have shown that there is no difference in PRA levels between untrained controls and subjects physically trained as regards orthostatic intolerance.

In summary, cardiovascular deconditioning was documented in this study by changes in a variety of indices without using syncope as an endpoint. These changes, combined with previously demonstrated evidence of reduced work capacity at 31 ATA, demonstrate the existence of cardiovascular deconditioning at depth. Among these indicators, the inability to vasoconstrict adequately provides a clear signal of the existence of cardiovascular deconditioning. Insufficiency of vasomotion in the hyperbaric environment was shown to be related to a low level of plasma ADH and its failure to rise during orthostatic stress. It is recognized that the combined data demonstrate the multifactorial nature of orthostatic intolerance following hyperbaric exposure. The subtle expression of cardiovascular deconditioning resembles that of exposure to weightlessness and to many ground-based simulations. We postulate that cardiovascular deconditioning occurs in these conditions as an expression of cardiovascular and neurohumoral adaptation to an expanded central blood volume and a reduced total blood volume.

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REFERENCES

Arborelius, M., Jr., U. I. Balldin, B. Lilja, and C. E. G. Lundgren. 1972. "Hemodynamic Changes in Man During Immersion With the Head Above Water." Aerospace Med. 43:592-598.

Bergenwald, L., U. Freyschuss, and T. Sjostrand. 1977. "The Mechanism of Orthostatic and Haemorrhagic Fainting." Scand. J. Clin. Lab. Invest. 37:209-216.

Birkhead, N. C., G. J. Haupt, and R. N. Myers. 1963. "Effect of Prolonged Bed Rest on Cardiodynamics." Am. J. Med. Sci. 245:118-119.

Blomqvist, C. G., J. V. Nixon, R. L. Johnson, Jr., and J. H. Mitchell. 1980. "Early Cardiovascular Adaptation to Zero Gravity, Simulated by Head-Down Tilt." Acta Astron. 7:543-553.

Blomqvist, C. G. 1983. "Cardiovascular Adaptation to Weightlessness." Med. Sci. Sports Exercise 15:428-431.

Blomqvist, C. G., and H. L. Stone. 1983. "Response to Stress: Gravity," pp. 1025-1063. In: J. T. Shepherad and F. M. Abboud (eds.), Handbook of Physiology, Peripheral Circulation and Organ Blood Flow, American Physiological Society, Bethesda, Md.

Bonde-Petersen, F., P. Norsk, and N. J. Christensen. 1984. "Plasma Catecholamines and Central Hemodynamics During Simulated Zero Gravity (Head-Out Water Immersion) in Humans." The Physiologist 27:S65-S66.

Bungo, M. W., and P. C. Johnson, Jr. 1983. "Cardiovascular Examinations and Observations of Deconditioning During the Space Shuttle Orbital Flight Test Program." Aviat. Space Environ. Med. 54:1001-1004.

Claybaugh, J. R., S. K. Hong, N. Matsui, H. Nakayama, Y. S. Park, and M. Matsuda. 1984. "Responses of Salt- and Water-Regulation Hormones During a Saturation Dive at 31 ATA (SEADRAGON IV)." Undersea Biomed. Res. 11:65-80.

Chobanian, A. V., R. D. Little, A. Tercyak, and P. Blevins. 1974. "The Metabolic and Hemodynamic Effects of Prolonged Bed Rest in Normal Subjects." Circulation 49:551-559.

Clement, D. L., C. L. Pelletier, and J. T. Shepherd. 1972. "Role of Vagal Afferents in the Control of Renal Sympathetic Nerve Activity in the Rabbit." Circ. Res. 31:824-820.

Convertino, V. A., L. D. Montgomery, and J. E. Greenleaf. 1984. "Cardiovascular Responses During Orthostasis: Effect of an Increase in VO_2..." Aviat. Space Environ. Med. 55:702-708.

Convertion, V. A., D. J. Goldwater, and H. Sandler. 1982. "Effect of Orthostatic Stress on Exercise Performance After Bed Rest." Aviat. Space Environ. Med. 53:652-657.

Deroanne, R., Y. Hault, J. Juchmes, D. Tsalos, A. Cession-Fossion, and J. Lecomte. 1979. "Influence de l'immersion horizontale dan l'eau a 38 C, sur l'elimination urinaire des catecholamines." C. R. Soc. Bio. 173:660-663.

Dietlein, L. F. 1975. "Skylab: A Beginning," pp. 795-814. In: R. F. Johnson and L. F. Dietlein (eds.), Proceedings of the Skylab Life Sciences Symposium, Houston, Texas, NASA TMX 58154.

Ebert, T. J., J. J. Hayes, J. Ceschi, K. J. Kotrly, J. Van Brederode, and J. J. Smith. 1984. "Repetitive Ramped Neck Suction: A Quantitative Test of Human Baroreceptor Function." Am. J. Physiol. 247:H1013-H1017.

Echt, M., L. Lange, and O. H. Gauer. 1974. "Changes of Peripheral Venous Tone and Central Transmural Venous Pressure During Immersion in a Thermo-Neutral Bath." Pfluegers Arch. 352:211-217.

Eckberg, D. L., and M. J. Eckberg. 1982. "Human Sinus Node Responses to Repetitive, Ramped Carotid Baroreceptor Stimuli." Am. J. Physiol. 242:H638-H644.

Epstein, M. 1978. "Renal Effects of Head-Out Water Immersion in Man: Implications for an Understanding of Volume Homeostasis." Physiol. Rev. 58:529-581.

Fagraeus, L., C. M. Hesser, and D. Linnarsson. 1974. "Cardiorespiratory Responses to Graded Exercise at Increased Ambient Air Pressure." Acta Physiol. Scand. 91:259-274.

Flynn, E. T., T. E. Berghage, and E. F. Coil. 1972. "Influence of Increased Ambient Pressure and Gas Density on Cardiac Rate in Man." U.S. Navy Exp. Diving Unit Report 4-72, Washington, DC.

Gauer, O. H., and J. P. Henry. 1976. "Neurohumoral Control of Plasma Volume," pp. 145-190. In: A. C. Guyton and A. W. Cowley (eds.), International Review of Physiology, Cardiovascular Physiology II, Vol. 9. University Park Press, Baltimore, MD.

Gilmore, J. P., and I. H. Zucker. 1980. "The Contribution of Neural Pathways to Blood Volume Homeostasis in the Subhuman Primate." Basic Res. Cardiol. 75:281-288.

Goldwater, D. J., M. De Lada, A. Polese, L. Keil, and J. A. Luetscher. 1980. "Effect of Athletic Conditioning on Orthostatic Tolerance After Prolonged Bedrest." Circulation 65 (Suppl): 287.

Goodall, McC., M. McCally, and D. E. Graveline. 1964. "Urinary Adrenaline and Noradrenaline Response to Simulated Weightless State." Am. J. Physiol. 206:431-435.

Greenleaf, J. E. 1977. "Cardiorespiratory Responses to Exercise After Bed Rest in Men and Women." Acta Astron. 4:895-905.

Greenleaf, J. E. 1984. "Physiological Responses to Prolonged Bed Rest and Fluid Immersion in Humans." J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 57:619-633.

Greenleaf, J. E., P. J. Brook, R. F. Haines. S. A. Rositano, L. D. Montgomery, and L. C. Keil. 1977. "Effect of Hypovolemia, Infusion, and Oral Rehydration on Plasma Electrolytes, ADH, Renin Activity, and +Gz Tolerance." Aviat. Space Environ. Med. 48:693-700.

Greenleaf, J. E., L. Silverstein, J. Bliss, V. Langenheim, H. Rossow, and C. Chao. 1982. "Physiologic Responses to Prolonged Bedrest and Fluid Immersion in Man: A Compendium of Research (1974-1980)." NASA TM-81324.

Hargens, A. R., C. M. Tipton, P. D. Gollnick, S. J. Mubarak, B. J. Tucker, and W. H. Akeson. 1983. "Fluid Shifts and Muscle Function in Humans During Acute Simulated Weightlessness." J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 54:1003-1009.

Henry, W. L., S. E. Epstein, J. M. Griffith, R. E. Goldstein, and D. R. Redwood. 1977. "Effect of Prolonged Space Flight on Cardiac Function and Dimensions," pp. 366-371. In: R. S. Johnson and L. F. Dietlein (eds.), Biomedical Results From Skylab. NASA.

Hong, S. K. 1975. "Body Fluid Balance During Saturation Diving," pp. 127-140. In: S. K. Hong (ed.), International Symposium on Man-in-the-Sea. Undersea Medical Society, Bethesda, MD.

Hong, S. K., J. R. Claybaugh, V. Frattali, R. Johnson, F. Kurata, M. Matsuda, A. A. McDonough, C. V. Paganelli, R. M. Smith, and P. Webb. 1977. "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. III. Body Fluid Balance." Undersea Biomed. Res. 4:247-265.

Johnson, R. L., A. E. Macogossian, S. A. Bergman, Jr., and G. W. Hoffler. 1976. "Lower Body Negative Pressure: The Second Manned Skylab Mission." Aviat. Space Environ. Med. 47:437-453.

Kollias, J., D. Van Derveer, K. J. Dorchak, and J. E. Greenleaf. 1976. "Physiologic Responses to Water Immersion in Man: A Compendium of Research." NASA TMX-3308.

Kubicek, W. G., A. H. L. From, R. P. Patterson, D. A. Witsoe, A. Castaneda, R. C. Lillehei, and R. Ersek. 1970. "Impedance Cardiography as a Noninvasive Means to Monitor Cardiac Function." J. Assoc. Adv. Med. Instr. 4:79-84.

Leach, C. S., W. C. Alexder, C. L. Fischer, C. J. Lambertsen, and P. C. Johnson. 1973. "Endocrine Studies During a 14-Day Continuous Exposure to 5.2% O_2 in N_2 at Pressure Equivalent at 100 fsw (4 ATA)." Aerospace Med. 44:855-859.

Mano, T., H. Miwa, Y. C. Lin, and H. Nakayama. 1985. Seadragon VI: A 7-Day Dry Saturation Dive at 31 ATA. VI. Sympathetic Nerve Activities During a 90° Body Tilt.

Matsui, N., J. R. Claybaugh, K. Shiraki, H. Nakayama, S. K. Hong, and Y. C. Lin. 1985. Seadragon VI. A 7-Day Dry Saturation Dive at 31 ATA. VII. Plasma Volume and Hormonal Changes During a 90° Body Tilt.

Nadel, E. R., S. M. Fortney, and C. B. Wenger. 1980. "Effect of Hydration State on Circulatory and Thermal Regulations." J. Appl. Physiol. 49:715-721.

Nakayama, H., S. K. Hong, J. R. Claybaugh, N. Matsui, Y. S. Park, Y. Ohta, K. Shiraki, and M. Matsuda. 1981. "Energy and Body Fluid Balance During a 14-Day Saturation Dive at 31 ATA (SEADRAGON IV)," pp. 541-554. In: A. J. Bachrach and M. M. Matzen (eds.), Underwater Physiology VII. Undersea Medical Society, Bethesda, MD.

Nakayama, H., T. Murai, and S. K. Hong. 1985. Seadragon VI: A 7-Day Dry Saturation Dive at 31 ATA. I. Objectives, Design, and Scope.

Ohta, Y., H. Arita, H. Nakayama, S. Tamaya, C. E. Lundgren, Y. C. Lin, R. M. Smith, R. Morin, L. E. Farhi, and M. Matsuda. 1981. "Cardiopulmonary Functions and Maximal Aerobic Power During a 14-Day Saturation Dive at 31 ATA (Seadragon IV)," pp. 209-221. In: A. J. Bachrach and M. M. Matzen (eds.), Underwater Physiology VII. Undersea Medical Society, Bethesda, MD.

Salzano, J., D. C. Rausch, and H. A. Saltzman. 1970. "Cardiorespiratory Responses to Exercise at a Simulated Seawater Depth of 1,000 Feet." J. Appl. Physiol. 28:34-41.

Sandler, H. 1976. "Cardiovascular Effects of Weightlessness," pp. 227-270. In: P. N. Yu and J. G. Goodwin (eds.), Progress in Cardiology. Lea & Febriger, Philadelphia, PA.

Shida, K. K., and Y. C. Lin. 1981. "Contribution of Environmental Factors in Development of Hyperbaric Bradycardia." J. Appl. Physiol. 50:731-735.

Shiraki, K., S. Sagawa, N. Konda, H. Nakayama, and M. Matsuda. 1984. "Hyperbaric Diuresis in a Thermoneutral 31 ATA He-O_2 Environment." Undersea Biomed. Res. 11:341-353.

Smith, R. M., S. K. Hong, R. H. Dressendorfer, H. J. Dwyer, E. Hayashi, and C. Yelverton. 1977. "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. IV. Cardiopulmonary Functions." Undersea Biomed. Res. 4:267-281.

Sjostrand, T. 1953. "Volume and Distribution of Blood and Their Significance in Regulating Circulation." Physiol. Rev. 33:302-328.

Stella, A., and A. Zanchetti. 1977. "Effects of Renal Denervation on Renin Release in Response to Tilting and Furosemide." Am. J. Physiol. 232:H500-H507.

A DIVE PROFILE RECORDING SYSTEM

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It is very important to obtain precise dive profiles for use in preventing or treating decompression sickness (DCS), as well as for analyzing the causes of diving accidents. From these points of view, we have been developing a dive profile recording system (DPRS).

THE SYSTEMS

We have two types of DPRS. The DPRS-1 is used in diving. It consists of a diving memory recorder (DMR), an interface, and a hand-held computer (HHC) (figures 1 and 2). The DMR is carried by the diver during his (her) dive.

The data on dive profiles are stored in the random access memory (RAM) of the DMR. It can record up to 16 hours of dive profiles. After the final dive, the DMR is connected to the HHC through the interface. The data stored in the RAM are read out and transferred to the HHC, through which they are recorded permanently on tape. They can then be analyzed or transferred again to the floppy disk of a personal computer (PC).

The DPRS-2 is used in compressed air work. It consists of a pressure sensor with an amplifier, a cable, an A/D converter and a PC. When the pressure sensor is fitted to the man-lock of a caisson or compressed-air tunnel, electric (analog) signals produced in the sensor due to the pressure of the man-lock are

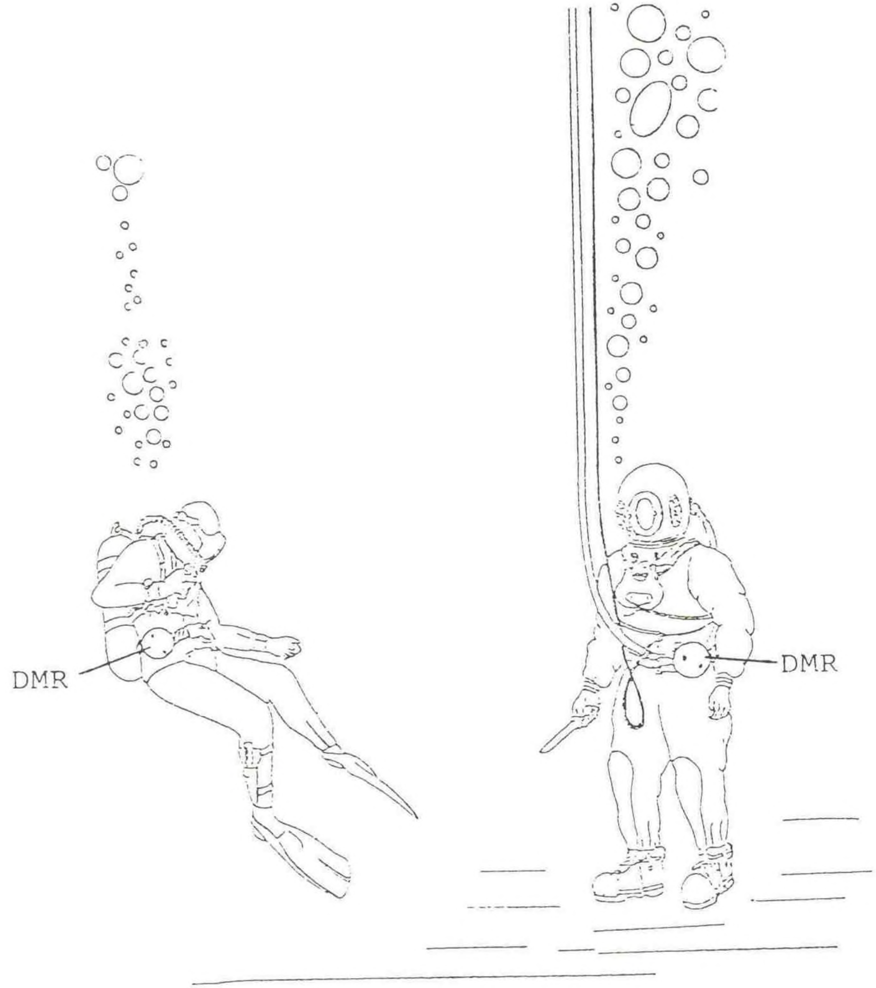

Figure 1.--Use of DMR in SCUBA and helmet diving.

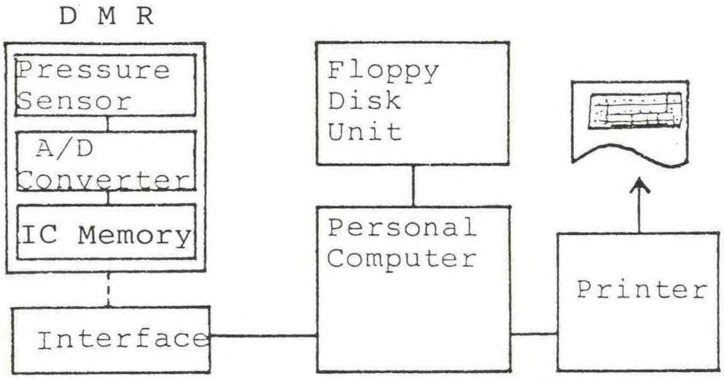

Figure 2.--Block-diagram of DPRS-1.

transmitted to the A/D converter through the cable (figures 3 and 4).

The pressure (depth) signals are picked up every 30 seconds, changed into digital signals, and then stored on the floppy disk of a PC. One disk can record three weeks of data on dive profiles.

RESULTS OF TESTS

Figure 5 shows an example of the dive profiles of shellfish divers who used diving helmets to gather abalones on the Pacific coast of the Boso Peninsula. In these dives, the deepest depth in each dive was 16 to 36 meters and constant fluctuations in diving depth occurred at the bottom; these fluctuations were probably due to the rocky bottom, which caused the divers to move up and down as they gathered abalones.

Figure 6 shows an example of the dive profiles for a harbor diver who was engaged in laying the stones that had previously been thrown on the sea bottom evenly as the foundation of a break-water in Onahama Harbor. The dives were carried out at an almost constant depth of 16 meters.

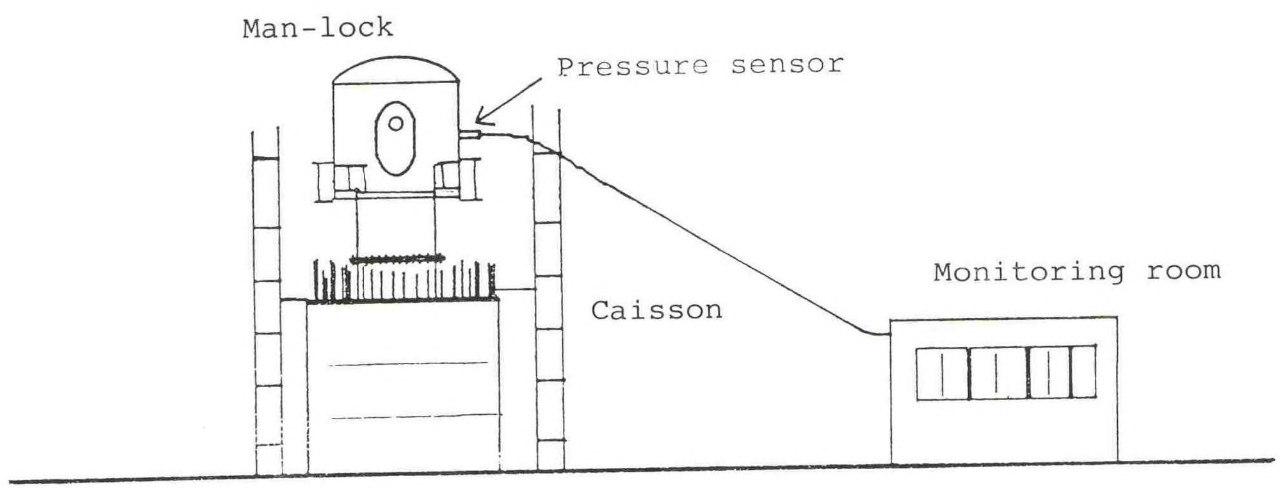

Figure 3.--Use of DPRS-2 at the construction site of caisson.

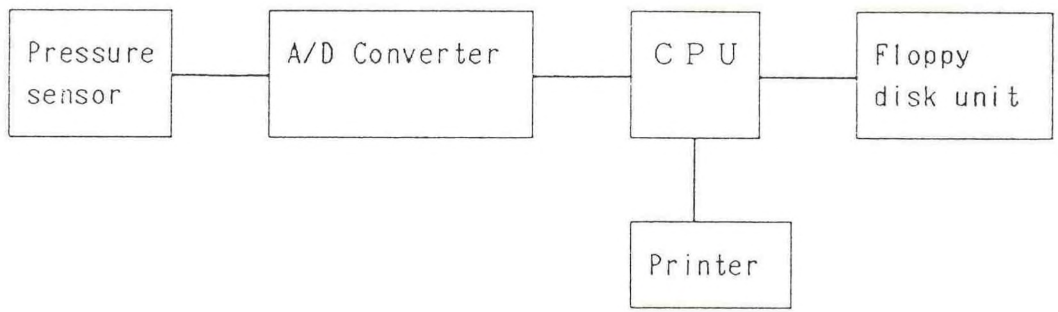

Figure 4.--Block-diagram of DPRS-2.

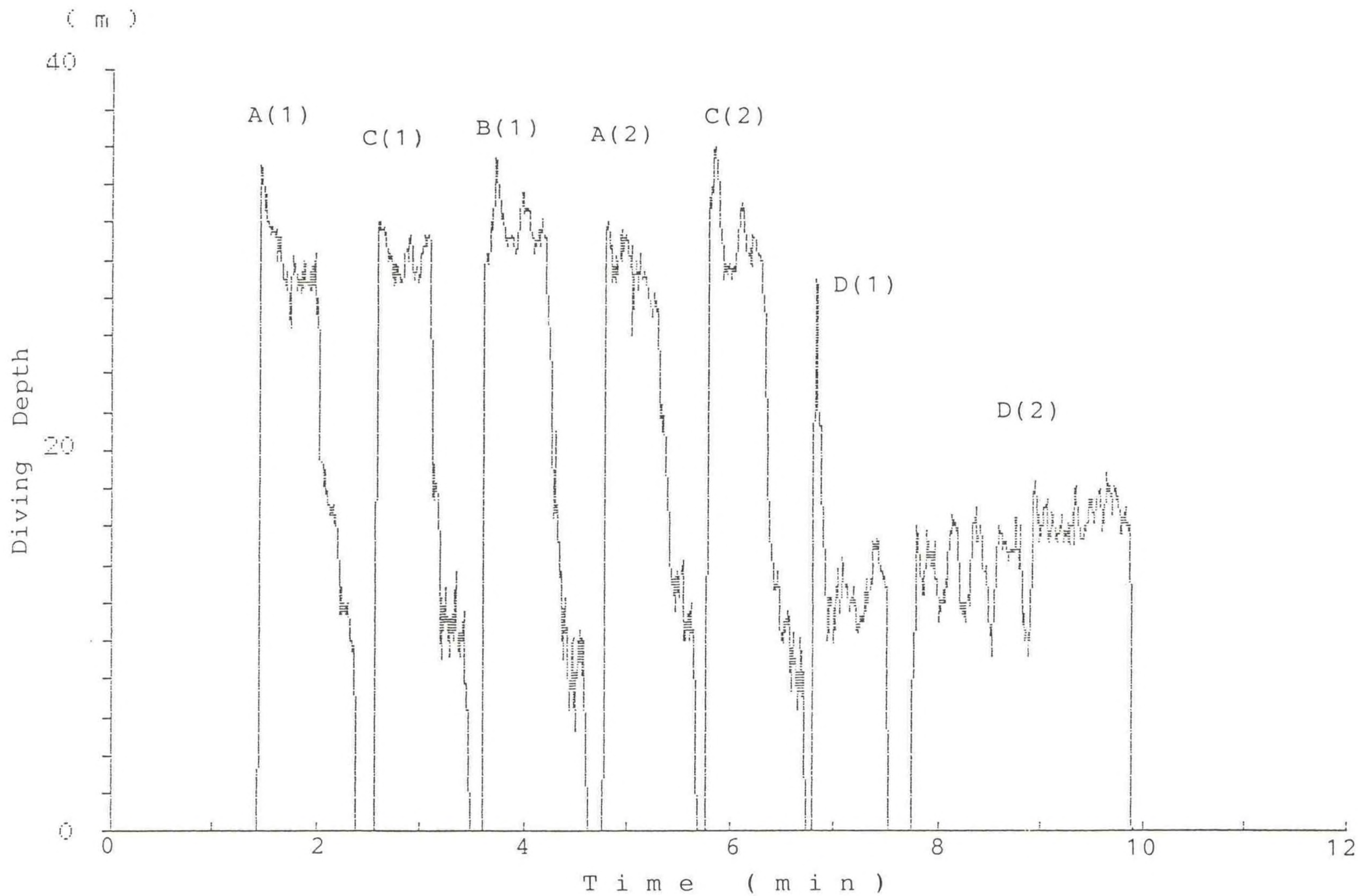

Figure 5.--Daily profiles of shellfish divers. Alphabet is used instead of diver's name. In the graph (1) and (2) represent the first and the second dive respectively.

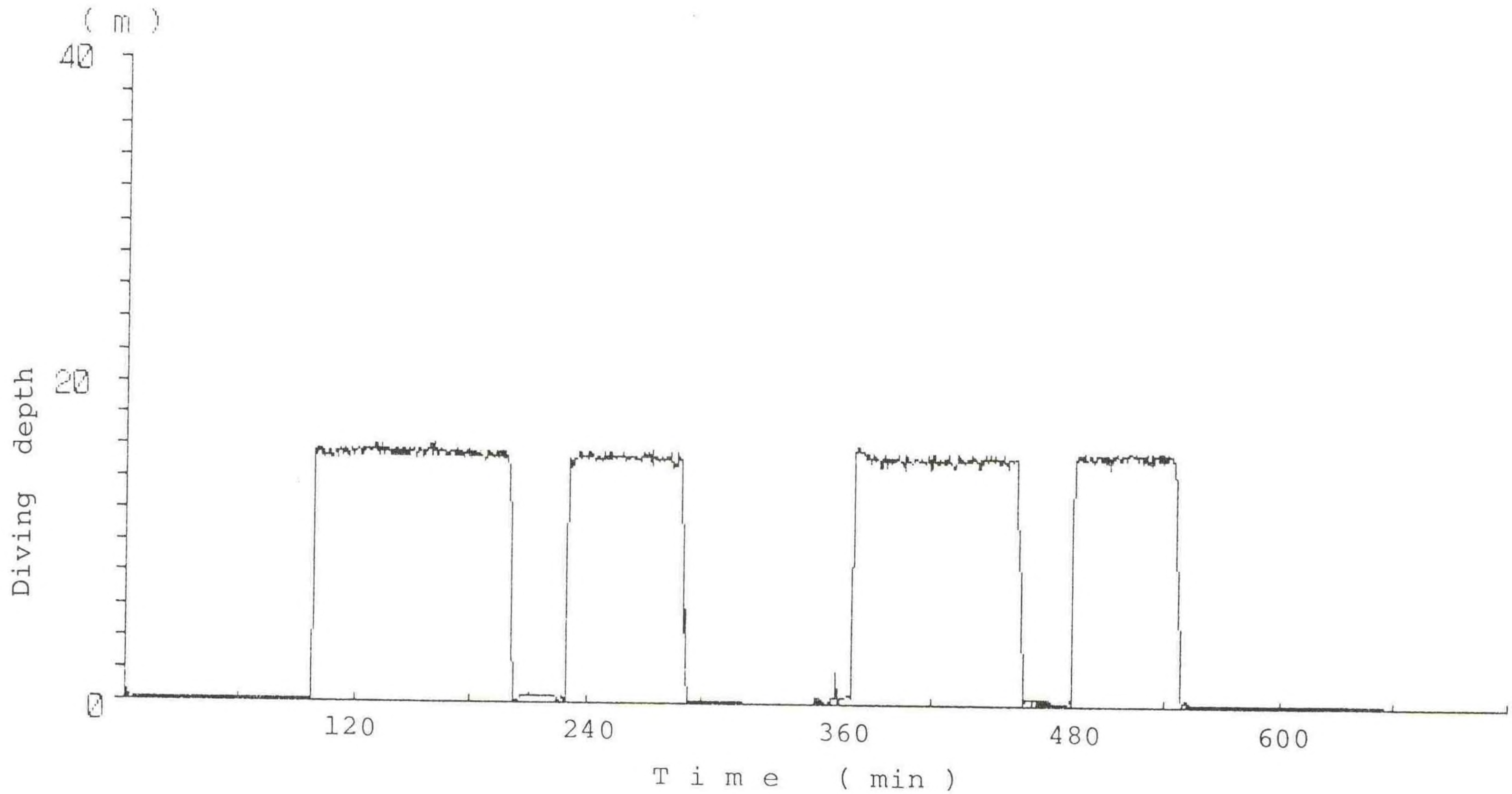

Figure 6.--Dive profiles of a harbor dive.

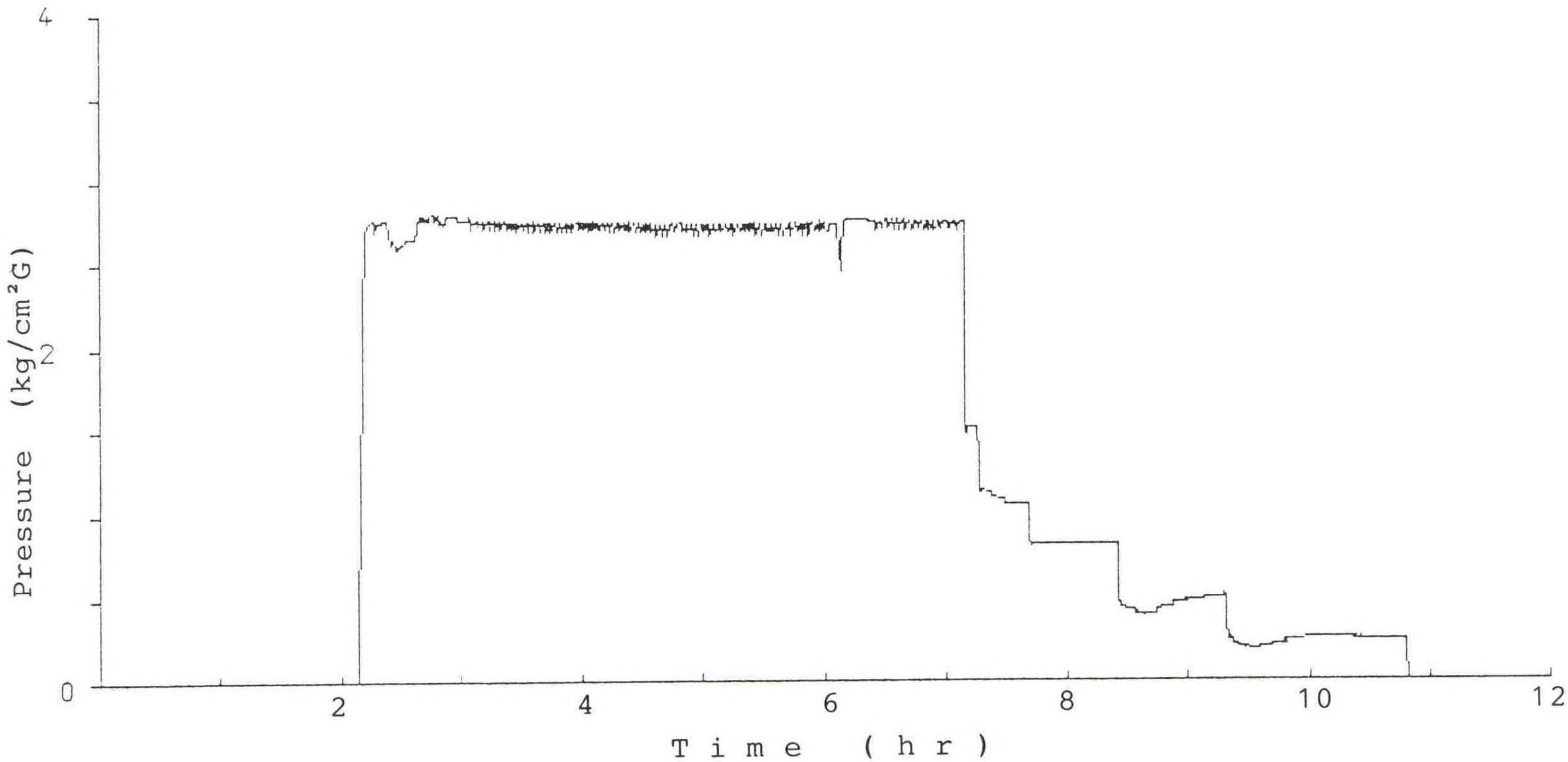

Figure 7.--Dive profile of caisson workers.

Figure 7 shows an example of a dive profile of compressed air workers who worked in a pneumatic caisson. It is clear from the dive profile that they followed the working schedule (including working-time and decompression schedule) of the regulations on compressed air work in Japan. This probably accounts for the low bends rate there.

It seems reasonable to conclude from the results of our tests that the DPRS will serve as an extremely useful tool in the practice of diving or compressed air work as well as in research on these topics.

SPECIAL PROBLEMS OF TREATING DECOMPRESSION SICKNESS IN HABITAT DIVING

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A. Abstract

Treatment of DCS in habitat diving uses current procedures or their derivatives as much as possible, with modifications to suit the equipment capabilities. Treatment comprises diagnosis, therapy, and return to the habitat storage pressure or saturation profile. Therapy is primarily recompression and oxygen breathing cycles, and is more aggressive for symptoms of a serious nature or occurring quickly. Recompression is in steps with waiting periods, to be adequate but not excessive; a protocol is provided. Treatment mixtures are breathed for a few cycles past relief, with a "soak" if necessary. Return to storage depth is by saturation profile, or if in saturation the ascent is resumed but possibly at a slower rate.

B. Introduction

Decompression sickness (DCS) is a possibility in virtually all types of diving, and any responsible decompression plan will include provisions for dealing with it. We are preparing procedures for excursion diving from a nitrox-based habitat, with the main emphasis on repetitive excursions and the final saturation decompression. Since habitat diving imposes special problems in the event treatment for DCS is needed, we are addressing that as a specific topic. This paper describes the problem and how we are approaching it.

C. Treatment steps

Decompression sickness treatment comprises three steps. First is **diagnosis,** the recognition that DCS is present and an assessment of the extent of the involvement needed to guide the treatment. Next is **therapy,** the procedures used to relieve or cure the signs and symptoms and treat any possible effects that may not be obvious. The final step is the **return** of the diver to the surface or habitat storage pressure.

1. Diagnosis

There is little special about the details of diagnosing DCS in the habitat diver with DCS--the signs and symptoms are the familiar ones--but it is especially important that it be done, and because of several factors the diagnosis needs to be careful and thorough. First, the isolation of the habitat will usually mean that guidance from the supervisor and/or physician at the surface is limited at best. Also, because a treatment will affect the mission, it is important that it be correct and appropriate. Lastly, although the treated diver can probably go back to work, he (or she) does face a final decompression from nitrox saturation; because this is the most difficult aspect of decompression in habitat diving everything possible needs to be done to avoid compromising it.

One important aspect of diagnosis is to ensure that a diver believed to be suffering from pain-only DCS does not in fact have neurological involvement. A neurological exam should be performed on any diver being treated for DCS, however mild it may seem to be. At the surface the exam would normally be performed quickly before recompression, but in the habitat it would depend on the circumstances.

2. Therapy

The traditional DCS therapy is still applicable in the habitat situation, but its implementation requires some special effort. Therapy for DCS consists of repressurization and oxygen breathing, plus supportive fluids and sometimes drugs. As much as possible the procedures will resemble those used at the surface, specifically the USN Tables 6 and 6A. Determining the optimal recompression and how to implement it are most likely to be the major problem areas. How to administer oxygen or hyperoxic mixtures may be troublesome as well, depending on the equipment and other resources available.

In a habitat operation it will be necessary to allocate a lock for recompressing a diver needing treatment. Ideally this will be done so as to minimize disruption of the mission.

It is also necessary to decide which other divers should be recompressed with the diver being treated. The diver with DCS should be attended even if the symptoms are minor or relieved, because he will be breathing high oxygen mixtures. Normally only the "hit" diver needs to breathe treatment mixtures, unless other divers are known to have missed some required decompression. If the tables are regarded as safe and are followed properly it should not be necessary for other divers on the same profile as the one having DCS to be treated. However, if the therapy phase of the treatment calls for exposure to inert gases followed by return to the habitat by means of a required or "staged" decompression profile, then some accounting needs to be made for the decompression of all those exposed to the treatment profile. If the therapy takes too long to allow staged decompression and a saturation return has to be used, then it is not necessary for the attendants to breathe high oxygen mixtures.

3. Return

Treatment is not really over until the diver is returned to a stable pressure, which will be the surface in normal diving and the storage depth in habitat diving. Normally the therapy profile will provide for return. In a habitat operation it may be possible to compress the living chamber to meet the treated diver, then continue a saturation return to storage depth during the night.

In commercial diving it is normally considered acceptable for a diver with pain-only symptoms to dive again the next day after a successful and uncomplicated treatment; this seems acceptable for habitat diving as well.

D. Therapy

1. Principles

The therapy should follow the same general principles used in treating cases of decompression occurring at the surface. However, one distinction needs to be made concerning much published information on DCS treatment. Many of the interesting cases that have been reported deal with DCS that has gone untreated (or without proper treatment) for many hours or a few days. The situation in habitat diving is--except possibly for DCS occurring after the final surfacing--that the diver will be treated within minutes of the first symptoms. This makes the job much easier. DCS is a normal component of diving, and though every effort is made to minimize it, when it does happen it should be handled promptly in a routine way.

As much as possible conventional treatment with USN Tables 6 or 6A should be used. The deep stages of these can be used as given in the manual, with return to the habitat depth or saturation profile, when this depth is 45 fsw or less. It is more effective to treat with pure oxygen--which can only be done in the neighborhood of 60 fsw--instead of a nitrox mixture, because the nitrogen in the mixture then has to be eliminated. Some compression is needed, and we advocate normally compressing to 100 fsw if the diver is deeper than 45 fsw when the symptoms are first encountered.

It is important that the treatment be adequate. Recurrences are disrupting and often harder to treat. Further, if treatment is inadequate the risk of late effects is greater.

2. Recompression

Recompression should be adequate, but no more than necessary. Determining when recompression is optimal may not be easy, so we provide an algorithm or set of steps to follow.

3. Oxygen breathing

Oxygen or a treatment mixture is breathed on all treatments. The mixture should be selected to provide 1.5 to 2.5 atm of PO_2, optimally 2.0. Treatment mix is breathed in cycles of 20 minutes on mix alternated with 5 minutes off, when the diver breathes the chamber atmosphere. A maximum of 6 cycles is breathed at one time; if therapy is not complete then the diver should "soak" or wait at the treatment pressure for 12 hours and begin cycles again. Cycles are started as soon as possible, and timing goes right on, independent of other events; it may be necessary to adjust the mixture to account for changes in chamber pressure. Breathing oxygen is carried on a few cycles past relief (see algorithm).

4. Fluids and drugs

Where treatment is planned as part of the operation and can begin promptly, the response should be quickly effective (except in the case of something like an accidental surfacing or embolism). Therefore the fluids and drugs used for treating serious DCS should not normally be needed. They should, of course, be kept on hand in the habitat.

E. Recompression procedures

1. Ascending excursions

Normally all that is required if symptoms begin to develop while a diver is above the habitat (at a lower pressure) is to return to habitat pressure and breathe treatment mix. If symptoms are relieved by the time habitat pressure is reached the diver should be observed and treated if symptoms recur; if symptoms are bad enough to cause return to the habitat then at least one cycle should be breathed. If relief is after returning to habitat and within 10 minutes, breathe 1 cycle. If relief is not complete within 10 minutes during the first cycle, treat with recompression as if from a descending excursion.

2. DCS following a descending excursion

Normally symptoms resulting from excursions will not be noticed until the diver is back at the habitat. If DCS symptoms appear while a diver is still in the water on an excursion the diver returns to the habitat; the symptoms are treated as "serious DCS."

With storage or onset deeper than 45 fsw, the diver begins breathing treatment mix and recompresses according to the algorithm. Return to storage depth is by saturation profile.

3. Shallow occurrence

If storage is less than 45 fsw, or if symptom onset is at that depth or shallower during saturation decompression, use Table 6 or 6A for the oxygen breathing pattern. If deeper than 30 fsw, perform the 30 fsw breathing at storage depth or after returning to the saturation profile.

4. DCS in saturation

DCS occurring in saturation decompression normally requires minimal recompression for relief, as long as recompression is prompt. "Return" in this case consists of resuming the saturation ascent, possibly on a slower profile.

5. Recompression algorithm

If the diver is too deep to breathe pure oxygen, recompression should be adequate but not excessive. To facilitate this, recompression is in steps that allow an appropriate time for relief of symptoms. "Onset" is the depth at which symptoms were first noticed. The time between the end of the excursion and symptom onset is a factor in selecting the therapy to be used, on the concept that symptoms occurring rapidly indicate more severe stress.

	1st step, fsw	Wait, min	Next steps, fsw	Max depth	# clean cycles	Soak, hr
Saturation or 2 hr after excursion						
Pain only	5	6	5	Onset + 60	2	4
Serious	10	4	10	Onset + 100	4	12
DCS in water or 2 hr after excursion						
Pain only	30	20	10	Max + 30	2	4
Serious	60	10	20	Max + 60	4	12

Notes

Compression rates 5-30 fsw/min

"Clean cycles" are cycles after complete relief of symptoms. Maximum number of cycles in one session is 6; if total of relief + clean cycles exceeds 6 then soak and continue cycles.

"Max" is maximum depth attained on any recent (8 hr) excursion.

Return to storage depth is by saturation profile.

Embolism is always serious.

Diving medical doctor should be consulted in serious cases.

F. Use of heliox

Decompression from helium is much easier than with nitrogen, and in tough cases it may be worth the effort to make a switch. Because of counterdiffusion a switch to heliox **must** involve recompression. This should be at least 20% of the prevailing absolute pressure. Procedures are the same otherwise, except that heliox saturation ascent rates can be used after saturation with helium (36 hr after the switch).

PREVENTION OF DYSBARIC OSTEONECROSIS

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OVERVIEW OF DYSBARIC OSTEONECROSIS

In Japan, women divers called Ama have been diving for more than one thousand five hundred years. Helmet diving was introduced in the beginning of the Meiji Period (1895) by diver fishermen in Chiba Prefecture. They taught their diving technique to the fishermen of Taneichi in Iwate Prefecture in 1898. Since then the number of divers in Taneichi has increased and they have promoted the spread of diving all over Japan. The Fishermen of Ohura in Saga Prefecture began diving around 1897. Their diving methods have been handed down from generation to generation.

Bone changes in workers exposed to compressed air were first described by Borstein and Plate and independently by Bassoe in 1911. In 1939, Kahlstrom, Burton, and Phemister reported on four cases of multiple bone lesions in caisson workers. An autopsy was performed on one of these patients and the pathological changes of the bone were described.

The first case of a diver with bone necrosis was reported by Grutzmacher in 1941. Since then there have been a number of reports including those of Dale (1952), Alnor (1963), Kirjakov (1964), Elliot and Harrison (1972), Fagan and Beckman (1974), and Walder (1976). In Japan, there have been reports by Kinoshita et al. (1958, 1959, 1961), Kimura et al. (1959), Nagai and Ibata

(1965), Asahi et al. (1968), and Ohiwa and Itoh (1978). From the Kyushu Rosai Hospital, Ohta and Matsunaga (1974) reported on 152 cases of aseptic bone necrosis found among 301 divers, and Kawashima et al. (1973) found 72 cases of bone necrosis among 135 patients who were admitted for the treatment of decompression sickness.

As we reported previously at the past UJNR meeting, 421 divers (56.4%) among 747 divers in Kyushu had at least one type of osteonecrosis. Comparing these figures with those of other surveys, the occurrence of bone lesions in Japanese divers is generally higher than in divers of other countries (table 1).

Osteonecrosis in Japanese diving fishermen is now a social problem. These divers stay at 20 meters depth for 5 hours, and come up to the surface within 30 minutes. They repeat this diving twice a day. Some of them still utilize the surface

Table 1.--Age levels of men surveyed and bone lesion

Age (years)	With bone lesion	Without bone lesion	Total
16-19	16 (0) 43.2%	21 56.8%	37 100.0%
20-29	131 (32) 46.3%	152 53.7%	283 100.0%
30-39	149 (44) 61.1%	95 38.9%	244 100.0%
40-49	90 (34) 66.2%	47 33.8%	137 100.0%
50 and over	35 (11) 76.1%	11 23.9%	46 100.0%
Total	421 (121) 56.4%	326 43.6%	747 100.0%

d.f. = 4 $X^2 = 29.0894$ $P < 0.01$; ( ) = juxta-articular lesion.

Table 2.--Bends and bone lesions

	Number of men with bone lesion	Number of men without bone lesion	Total
With previous experience with bends	259 67.6%	143 50.0%	402 60.1%
Without previous experience with bends	124 32.4%	143 50.0%	267 39.9%
Total	383 100.0%	286 100.0%	669 100.0%

d.f. = 1; $X^2 = 21.4199$; $P < 0.01$

decompression chamber; this method is very dangerous. We have treated many severe cases of decompression sickness caused by the use of this method.

As many authors have described, there is a significant relationship between dysbaric osteonecrosis and bends. In our surveys at Kyushu, 67.6% of divers with osteonecrosis were known to have been treated for bends. In the group without osteonecrosis, 50.0% were known to have been treated for bends.

The difference between these groups was statistically significant ($P < 0.01$) (table 2).

Osteonecrosis in Japanese diving fishermen seems to be caused by inadequate decompression, and therefore education is very important for them.

We established a divers' union in the Kushu area in 1975. Educational programs have been carried out for them since then. 3000 divers have already listened to our medical lectures. The number of serious decompression cases decreased rapidly. The number of bends cases is now decreasing. We expect that the number of divers with osteonecrosis will reduce in the near future in Japan. Overly hard work and inadequate decompression seem to result in the development of osteonecrosis in Japanese divers. A short exposure to compressed air on the bottom and slow decompression using a universal standard table might decrease either the development or the prevalence of osteonecrosis.

ETIOLOGY OF OSTEONECROSIS

Beginning in the first half of the nineteenth century, there have been many attempts to advance a theory that would explain the symptoms after decompression. These theories may be grouped according to cause as follows: first, exhaustion and cold; second, mechanical congestion; third, the current theory of gas embolism (Bell et al. 1942).

The gas-embolism theory actually dates from the work of Robert Boyle (1662), who was the first to observe gas bubbles in the blood of animals subjected to suddenly decreased air pressure. Paul Bert (1878) studied the symptoms of decompression caused by air bubbles; Chryssanthou, Tiechner, Goldstein, Kalberer, and Antopol (1971) reported the symptoms caused by vasospasm; Swindle (1937) and End (1938) reported the agglutination of erythrocytes; Philp (1964), Philp, Schacham, and Gowdey (1971), and Hallenbeck, Bove, and Elliott (1976) reported the aggregation of platelets; and Cockett, Pauley, Saunders, and Hirose (1971) studied fat embolism.

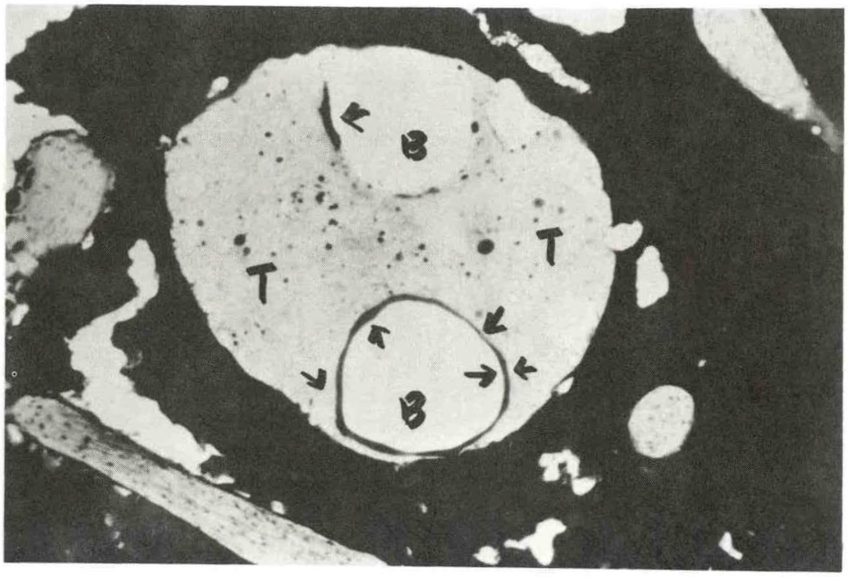

Figure 1.--Dilated sinusoid in the femoral head of autopsied case. Accumulation of fat (arrows), and aggregation of platelets (T) and air bubbles are noted (B). Oil red O.

The pathogenesis of osteonecrosis is still not clear. Recently, Stegall and Smith (1972) and Smith, Stegall, and D'Aoust (1975) succeeded in producing osteonecrosis in miniature pigs after repeated decompression. They noticed increased platelet aggregation and suggested that microthrombi may cause osteonecrosis. The appearance of bubbles in conjunction with histopathological developments such as platelet aggregation, erythrocyte sludging, and microthrombus formation may provide a clue to the pathogenesis of osteonecrosis in divers.

Furthermore, fat was found the the dilated sinusoids in our autopsied case (fig. 1). We considered this fat to have resulted from fat cell rupturing secondary to bubble formation. Fat enters the bloodstream coincidentally with other products of tissue disintegration, such as fatty acids, serotonin, and other tissue products. These substances, along with bubbles, tend to alter the secondary and tertiary configurations of blood proteins, leading to activation of the blood-clotting system, platelet aggregation, releasing of basoconstrictive substances, and finally, disturbance of blood circulation.

While the sinusoid system of the bone marrow is a large venous blood pool in which there are many anastomoses, the volume of the sinusoid system is abundantly greater than that of the arteries supplying the regions it drains. Therefore, the sinusoid system differs from other vein systems. It is not simply a conduit transporting blood toward the heart, but a relatively stagnant pool in which the rate of flow is ordinarily sluggish. As a result, after decompression, the sinusoid system of bone marrow can easily become obstructed by intravascular bubbles that collect, coalesce, and grow: as Hallenbeck said, "by analogy with freezing water, lakes freeze, rivers do not freeze" (fig. 2).

In the sinusoid system, bubbles probably exert both direct mechanical effects and also indirect effects due to various thrombogenic activities.

In conclusion, the early stage of osteonecrosis of divers might be intimately related to circulatory disturbances, especially in the sinusoid system. There are many kinds of anticoagulant drugs. Antiplatelet agents, such as vitamin E, aspirin, and dipyridamole might be useful in the prophylaxis of decompression sickness and osteonecrosis in divers.

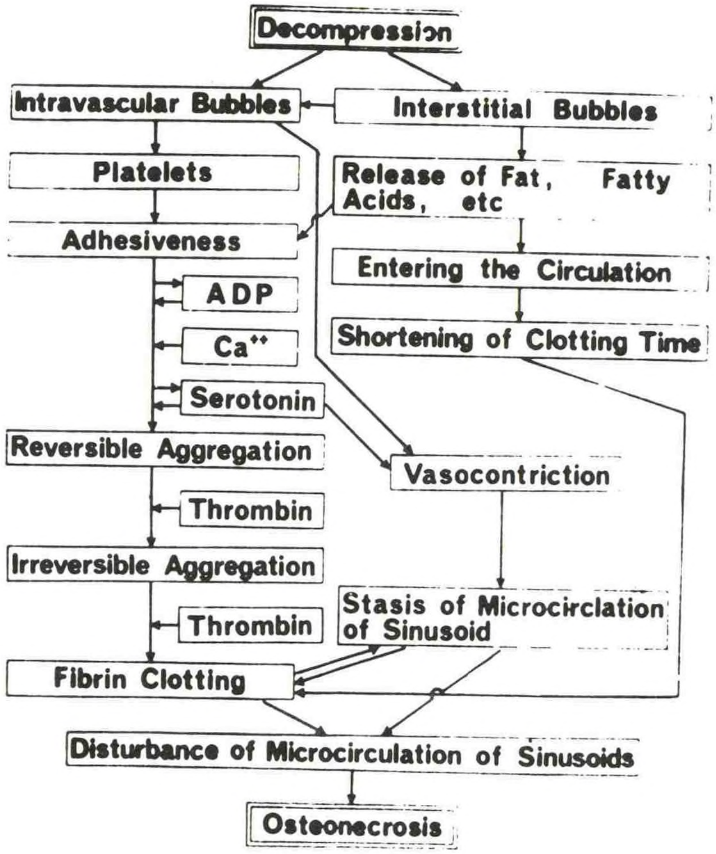

Figure 2.--Mechanism of etiology of dysbaric osteonecrosis.

Behnke proposed oxygen decompression with isobaric transport of N_2 from tissue. However, it is very difficult for divers to utilize oxygen in Japan. It might be possible to inhale pure oxygen after the diving.

Many kinds of trials for the prophylaxis of dysbaric osteonecrosis should be performed in the future.

REFERENCES

Alnor, P. C. 1963. "Chronic Changes in the Bone Structure of Divers." Bruns' Beitr. Klin. Chir. 207:475-485.

Asahi, S., H. Ohiwa, and I. Nashimoto. 1968. "Avascular Bone Necrosis in Japanese Diving Fishermen." Bull. Tokyo Med. Dental Univ. 15:247-257.

Bassoe, P. 1913. "The Late Manifestation of Compressed-Air Disease." Am. J. Med. Sci. 145:526.

Bell, A. L., G. N. Edson, and N. Hornick. 1942. "Characteristic Bone and Joint Changes in Compressed-Air Workers: A Survey of Symptomless Cases." Radiology 38:698-707.

Bert, P. 1878. Barometric Pressure: Researches in Experimental Physiology. Translated from French by M. A. Hitchcock and F. A. Hitchcock, 1943. Republished 1978, Bethesda, MD: Undersea Medical Society, Inc., pp. I-1-27 to I-1-63.

Chryssanthou, C., F. Teichner, G. Goldstein, J. Kalberer, Jr., and W. Antopol. 1971. "Studies on Dysbarism III. A Smooth Muscle Acting Factor (SMAF) in Mouse Lungs and Its Increase in Decompression Sickness." Aerosp. Med. 41:864-867.

Cockett, A. T. K., S. M. Pauley, J. C. Sanders, and M. Hirose. 1971. "Coexistence of Lipid and Gas Emboli in Experimelntal Decompression Sickness." In: Lambertsen, C. J. (ed.). Proceedings of the Fourth Symposium on Underwater Physiology. London: Academic Press, pp. 245-250.

Fagan, C. J., and E. L. Beckman, with J. B. Galletti, Jr. 1974. "Sample Survey of Osteonecrosis in Gulf of Mexico Commercial Divers." In: Beckman, E. L., and D. H. Elliott (eds.). Dysbarism-Related Osteonecrosis. U.S. Dept. of Health, Education, and Welfare, National Institute for Occupational Safety and Health.

Grutzmacher, K. T. 1941. "Changes of the Shoulder As a Result of Compressed-Air Sickness." Roentgenpraxis 13:216-218. (Translated from the German.)

Hallenbeck, J. M., A. A. Bove, and D. H. Elliott. 1976. "Decompression Sickness Studies." In: Lambertsen, C. J. (ed.). Underwater Physiology V. Proceedings of the Fifth Symposium on Underwater Physiology. Bethesda, MD: Federation of American Societies for Experimental Biology, pp. 273-286.

Kahlstrom, S. C., C. C. Burton, and D. B. Phemister. 1939. "Aseptic Necrosis of Bone." Surg. Gynecol. Obstet. 68:129.

Kawashima, M. 1974. "Avascular Bone Necrosis in Caisson Workers." West-Jap. Orthop. Trauma 23:15.

Kawashima, M. 1976. "Aseptic Bone Necrosis in Divers." Bull. Tokyo Med. Cent. Univ. 23:71.

Kawashima, M. 1977. "Histopathology of the Early Stage of Osteonecrosis in Divers." Undersea Biomed. Res. 4:409.

Kawashima, M. 1978. "Pathological Review of Osteonecrosis in Divers." Clin. Orthop. 130:107.

Kawashima, M. 1983. "Osteonecrosis in Divers: Prevention and Treatment." In: Shiraki, K., and S. Matsuoka (eds.). Hyperbaric Medicine and Underwater Physiology. Kitakyushu, Japan: University of Occupational and Environmental Health.

Kawashima, M., T. Torisu, K. Hayashi, and Y. Kamo. 1974. "Avascular Bone Necrosis in Japanese Diving Fishermen." In: Trapp, W. G., E. W. Bannister, A. J. Davison, and P. A. Trapp (eds.). Fifth International Hyperbaric Congress Proceedings. Burnaby (Canada): Simon Fraser University.

Ohiwa, H., and A. Itoh. 1978. "Aseptic Bone Necrosis in Japanese Navy Divers." In: Shilling, C. W., and Beckett, M. W. (eds.). Underwater Physiology VI. Proceedings of the Sixth Symposium on Underwater Physiology. Bethesda, MD: Federation of American Societies for Experimental Biology, pp. 299-305.

Ohta, Y., and H. Matsunaga. 1974. "Bone Lesions in Divers." J. Bone Joint Surgery 56B:3-16.

Philp, R. B., P. Schacham, and C. W. Gowdey. 1971. "Involvement of Platelets and Micro-Thrombi in Experimental Decompression Sickness: Similarities With Disseminated Intravascular Coagulation." Aerospace Med. 42:494-502.

Stegall, P. J., and K. H. Smith. 1972. "The Etiology and Pathogenesis of Decompression Sickness: Radiologic, Hematologic, and Histologic Studies in Miniature Swine." In: Abstracts of the Fifth Symposium on Underwater Physiology. Freeport, Bahamas, p. 26.

Walder, D. 1964. "Some Dangers of a Hyperbaric Environment." In: Proceedings of the Second International Congress on Hyperbaric Oxygenation.

FETAL AND MATERNAL BUBBLES DETECTED NONINVASIVELY IN SHEEP AND GOATS FOLLOWING HYPERBARIC DECOMPRESSION*

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Increasing numbers of women are entering the labor force as professional divers; in addition, there are many female sport and research divers. Pregnant airline passengers and the effect of rapid cabin decompression are also of concern; what should be an appropriate course of action?

In the fetus, the pulmonary filter is not functioning, and bubbles, generated by either fetal tissue or placental tissue, will pass through the foramen ovale into the fetal arterial circulation from whence they can proceed to embolize organs, the cord, and the brain.

We wanted the ultrasound monitoring to answer two questions:

1. Did the fetus produce bubbles in dives that did not result in decompression sickness for the mother?
2. If fetal bubbles were produced, were there more or less than for the mother?

METHODS

Domestic goats and sheep purchased locally were used as subjects; a total of 20 dives were made. Two goats (one at

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approximately the middle of the second trimester, the second in the early third trimester) were used extensively and dived on a series of titrated profiles. In the entire series, a total of 6 young were born.

All simulated dives were conducted in a chamber using air as the compression gas. All compressions and decompressions were made at the standard rate employed by divers, i.e., 0.31 m/s (1 ft/s). The time spent at maximum pressure (bottom time) ranged from 5 to 15 minutes. All dives were made to a simulated depth of 49 msw.

All subjects were unanesthetized and free-standing during the measurements to allow for the assessment of decompression sickness. In quadrupeds, this manifests itself first as rocking from side to side indicating discomfort in the limbs (Type I decompression sickness). More severe forms (Type II) are evidenced by the inability of the animal to stand or by frank convulsions (indicative of cerebral gas embolism).

Noninvasive Doppler ultrasonic techniques were employed to monitor the mother and fetus for postdecompression gas bubble formation.

RESULTS

Following decompression, maternal precordial Doppler ultrasound gas bubble signals increased in a predictable manner in that precordial grade increased with tissue gas loading (time at bottom). Maternal bubble signals could be detected within 5 min from the start of decompression. Doppler ultrasound gas bubble signals detected from the fetal circulation also were found to increase with increased tissue gas loading, but were (a) found to be less in number than the mother and (b) appeared at a later time following decompression (10-15 min postdecompression) and ceased before the disappearance of the maternal precordial bubble signal. Bubbles in the fetal circulation generally were first detected when the maternal precordial grade reached III. At the time when the mother had reached a grade IV, the fetal grade was an (F) III.

Our fetal Doppler grades [(F)I-(F)V] are not equivalent to adult precordial Doppler grades. A greater density of bubbles can be present in the maternal pulmonary artery and not detected because of the cardiac motion sounds, whereas in the umbilical artery, the signal-to-noise ratio is very high and individual bubbles can be detected quite easily. We are confident that we have a high sensitivity for detecting fetal gas bubbles and that considerably fewer bubbles were present when compared to the maternal venous return.

A precordial grade of 0 to III in adult goats or sheep is seldom associated with decompression sickness; this was also found to be true in this series of dives. Slight problems of decompression sickness were noted, however, when the maternal grade reached IVa or IVb. In these cases, the subjects rocked to-and-fro on their hind limbs, which is indicative of pain-only decompression sickness (Type I). At this point, the fetal grade had increased to a (F)IV. The general relationship of maternal

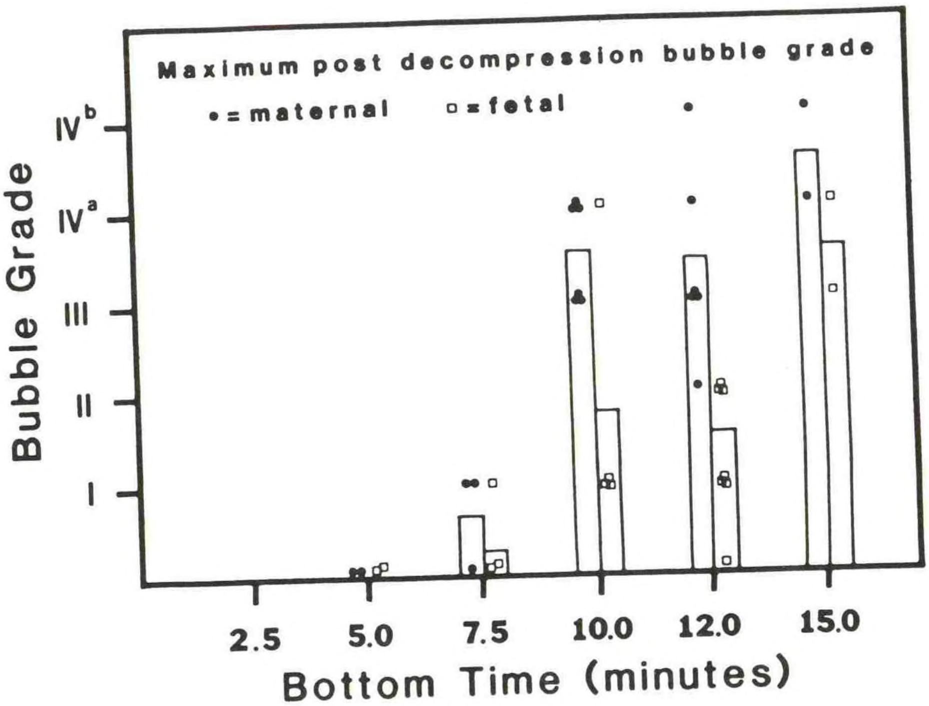

Figure 1.--Maternal and fetal Doppler ultrasound bubble grade, detected transcutaneously, as a function of bottom time at 49 msw (160 fsw).

precordial bubble grade to the fetal grade is shown in Figure 1. In one experiment (dive 14) it was evident that cardiac arrhythmias in the fetus were appearing, and recompression was instituted immediately to 18.5 msw on oxygen. Following treatment, the mother recovered uneventfully. The lamb was born 4 d later with weakness in its hind legs, and subsequently died. Another pain-only case occurred in the mother who was treated at 49 msw on a 50% to 60% oxygen-nitrogen mixture. In this case, the lamb was born 8 d later; it was normal and was subsequently released to a farm.

In the series with the 2 goats exposed on the titrated profiles, triplets were born to one and a singleton to the other. The singleton was normal, but triplets appeared weak though normal at birth; however, one triplet died 2 d later of apparent respiratory failure. Because they were triplets, which is somewhat unusual for this species, their postpartum survival was in jeopardy, and the fact that one died cannot be directly attributed to the effects of the decompression and bubble formation per se.

DISCUSSION

In our study, fetal gas bubbles were detected following decompression when the bottom time was as short as 10 min. This is approximately within the limits of the U.S. Navy decompression table as being a safe dive for humans. In one fetal subject (#9), the number of detectable bubbles was large. This is within the commonly noted variability for gas phase formation in a dive even when suitable decompression tables are followed.

The work of Willson et al. (1983) has shown that fetal abnormalities can be found when the mother has been subjected to dives that resulted in signs of decompression sickness. Our study indicates that, in these cases, there should have been considerable numbers of gas bubbles present in the fetal circulation.

All gas bubbles in the fetal circulatory system are potential arterial embolizing agents. Consequently, no "safe bubble limits" can be determined for fetal decompression. In general, human divers suffer few problems when the precordially measured bubble grade is less than III. This reflects both minimal gas phase formation (avoidance of "the bends" because of insignificant gas phase formation in joint tissue) and the integrity of the pulmonary filter (avoidance of arterial gas embolism).

CONCLUSION

On the basis of these 20 dives with 4 subjects and their 6 young, we can make the following tentative conclusions: (a) Gas bubble formation does occur following decompression in both second and third trimester fetuses; (b) fetal gas bubble formation occurs following a dive which is easily tolerated by the maternal sheep and goat; (c) the detectable level of gas bubble formation in the fetus is considerably less than that which can be determined precordially in the maternal venous return because of the favorable signal-to-noise ratio; (d) fetal gas bubble formation occurs at a later time than it does in the mother postdecompression and does not persist as long as gas bubbles in the maternal venous return;

(e) the absence of the pulmonary filter makes the fetal system far less tolerant of gas bubbles than is the maternal system; (f) fetal problems appear earliest as fetal cardiac arrhythmias; (g) in cases where the mother is displaying obvious signs of decompression sickness (in the sheep and goat at least), the fetus is usually experiencing cardiac arrhythmia.

REFERENCES

Willson, J. R., W. B. Blessed, and P. J. Blackburn. 1983. "Hyperbaric Exposure During Pregnancy in Sheep: Staged and Rapid Decompression," Undersea Biomedical Research, 1:11-15.

THE NEWEST DIVER TOOL SYSTEM

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INTRODUCTION

It is well known that it is preferable for diver power tools to be driven by seawater rather than oil or air. Using pressurized water as the activating fluid has many advantages, which are described in the proceedings of the 7th UJNR Diving Panel. In the U.S.A., the Naval Civil Engineering Laboratory has the program to develop these tools, and in Japan, JAMSTEC does.

In this paper, we present the newest model, which JAMSTEC and the Sugino Machine Co. developed cooperatively.

SEAWATER MOTOR

The seawater motor, which is the heart of these tools, consists simply of a nozzle-and-runner turbine motor and transmission. There are therefore no problems of contamination of the working fluid or overloaded output. However, the motor cannot be rotated reversely, which would require an impact wrench, etc. Photos, specifications, and performance characteristics of the immersion-type motor are shown below.

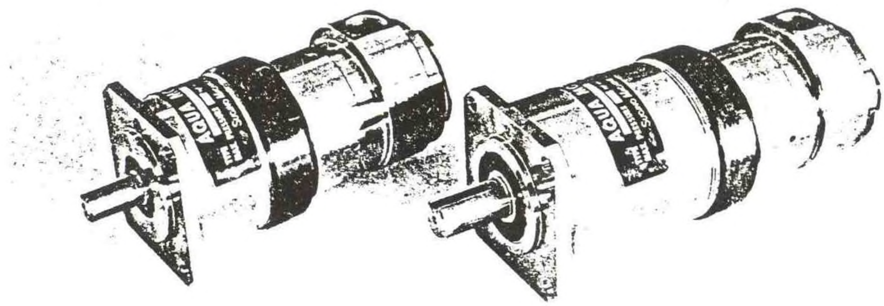


Figure 1.--Aqua motor (Standard model, left; low-speed model, right)

Table 1.--Specifications of Aqua motor (immersion type)

Sugino Aqua Motors		Model	Max. output (hp)	At max. output Torque (ft·lb)	Speed (rpm)	Stall torque (ft·lb)	Max. speed (rpm)	Max. pressure (psi)	Water consumption (gal/min)	Weight (lb)
Immersion type	Standard models	WM-4021-300	0.8	2.39	1,750	3.6	3,000	857	5.81	4.4
		WM-4032-300	1.0	3.25	1,600	5.1	3,000	571	8.98	4.4
		WM-4046-300	1.5	4.84	1,600	6.5	3,000	571	12.70	4.4
		WM-4060-300	2.0	6.07	1,700	9.4	3,000	571	17.20	4.4
	Low-speed models	WML-4021-300	0.8	23.10	180	34.0	310	857	5.81	6.0
		WMG-4021-300	0.8	12.30	340	19.0	560	857	5.81	6.0
		WMG-4032-300	1.0	17.30	300	26.0	560	571	8.98	6.0

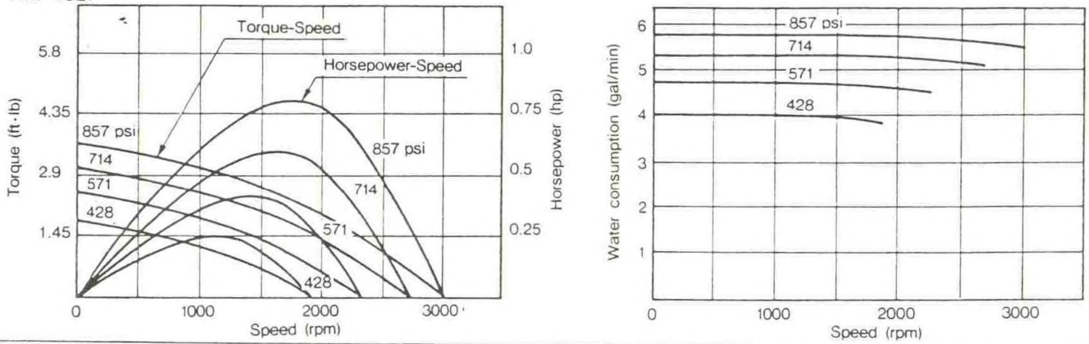
SYSTEM CONSTITUTION

The essential circuit of this system is shown in Figure 3, and the practical assembly is shown in Figure 4. This system consists of five parts:

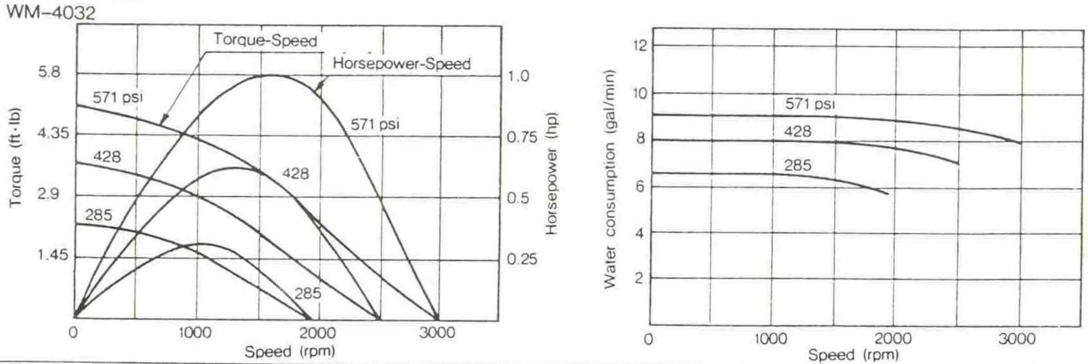
Water supply pump;
Water compression pump;
Hose reel;
Hoses;
Tools.

The water supply pump and hose reel are used temporarily. Any hose that endures the water pressure and offers the needed water flow will be available. Details of the water compression pump and tools are described below.

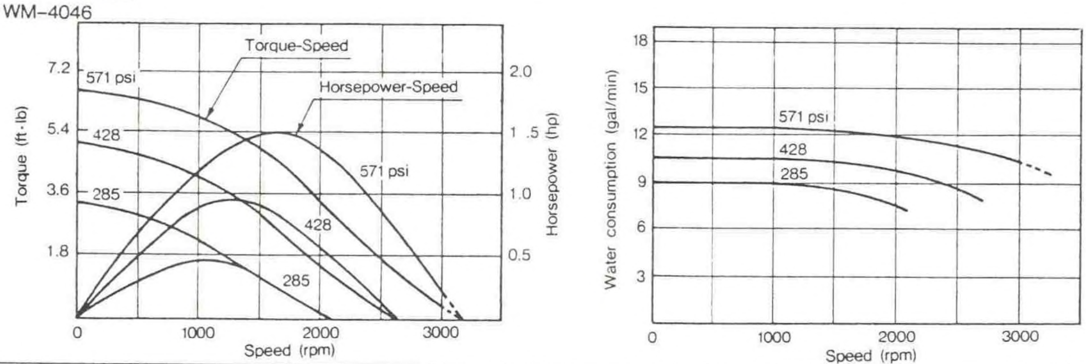
● WM-4021-300
WM-4021



● WM-4032-300
WM-4032



● WM-4046-300
WM-4046



● WM-4060-300
WM-4060

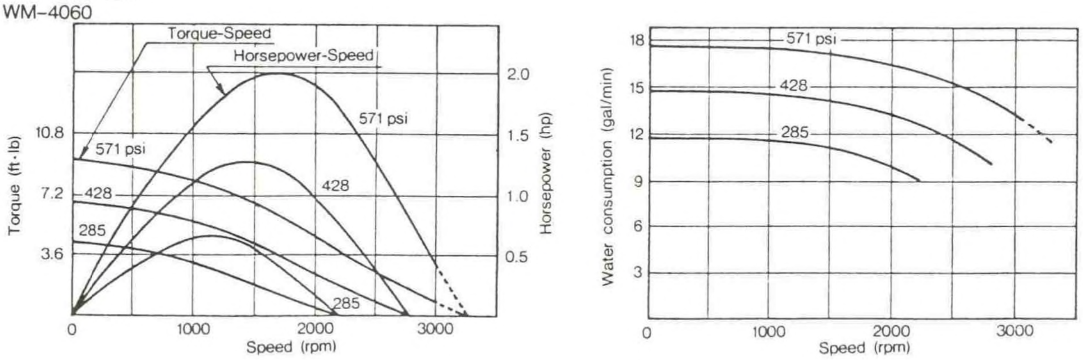


Figure 2.--Performance of Aqua motor (immersion type)

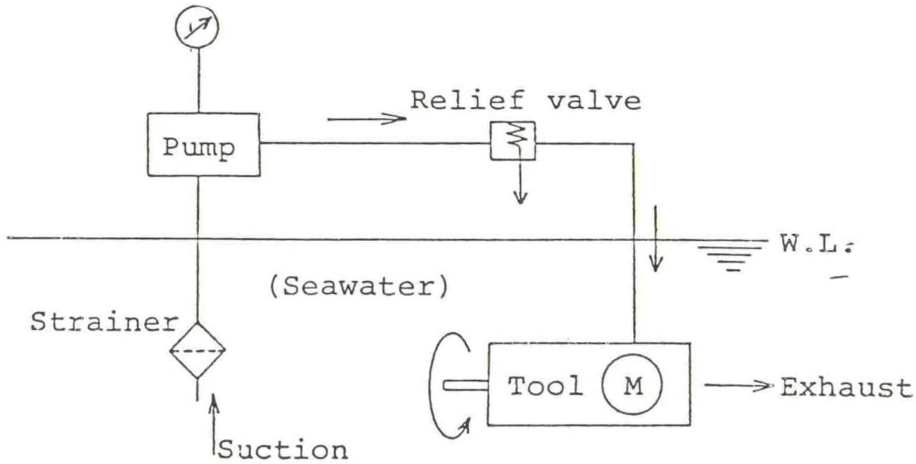


Figure 3.--Essential system circuit

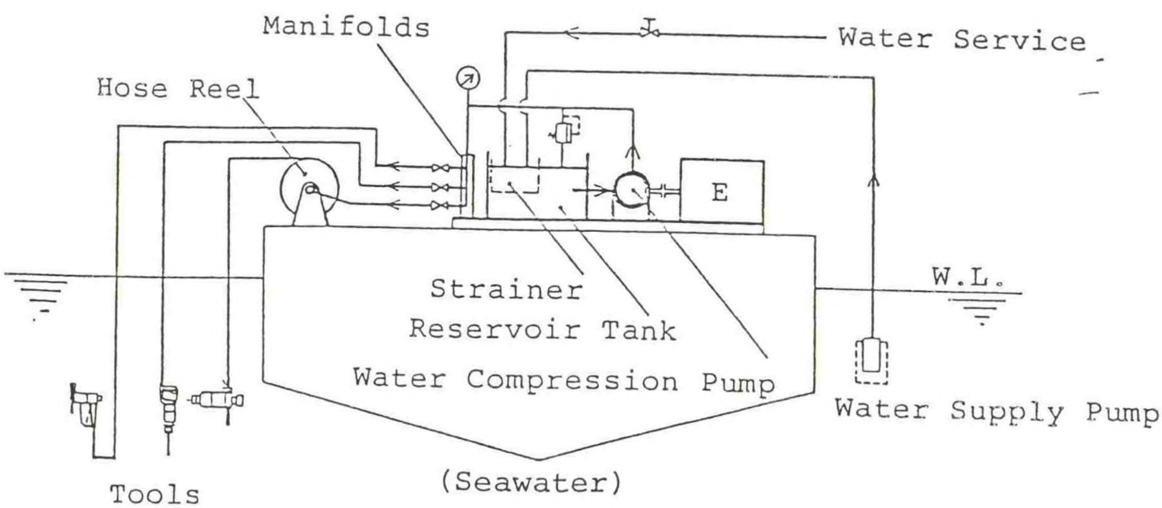


Figure 4.--Practical system circuit (JAMSTEC model)

WATER COMPRESSION PUMP

The pump is shown in Figure 5. It has three manifolds to drive three tools at a time. Because it will operate on the support vessel in the oil field, it is designed to work 8 hours without refueling, to extinguish exhaust sparks, and to run on an inclined (up to 15 degrees) deck via the naval diesel engine.

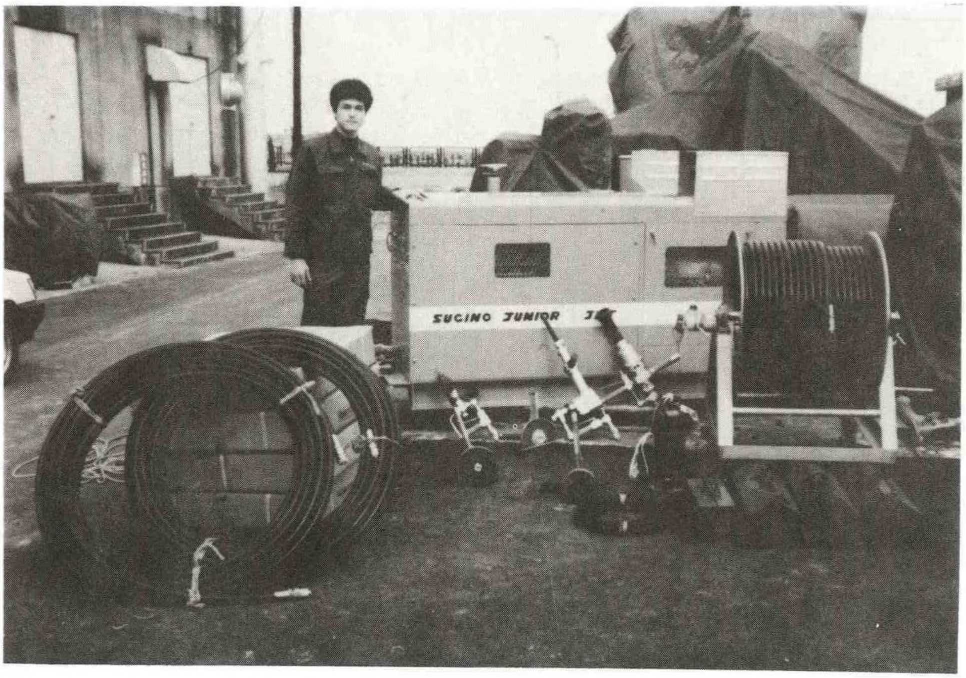


Figure 5.--Water compression pump and other parts

Specification	Pump type	Horizontal 3 plunger
	Maximum pressure	930 psi
	Flow rate	40 gal./min.
	Occupied area	2.5 x 7 ft
	Weight	3,100 lbs
	Engine	4 cycle, 3 piston 32 ps, diesel
	Fuel tank	13.2 gal.
	Reservoir tank	52.8 gal.

TOOLS

We have four types of tools now, and they are used in six ways by changing attachments. These tools are designed to be operated at a depth of 980 fsw.

The grinder, brush-cleaner, and cut-off saw are the same type of tool and have different attachments. A photograph and specifications for these tools are presented below.

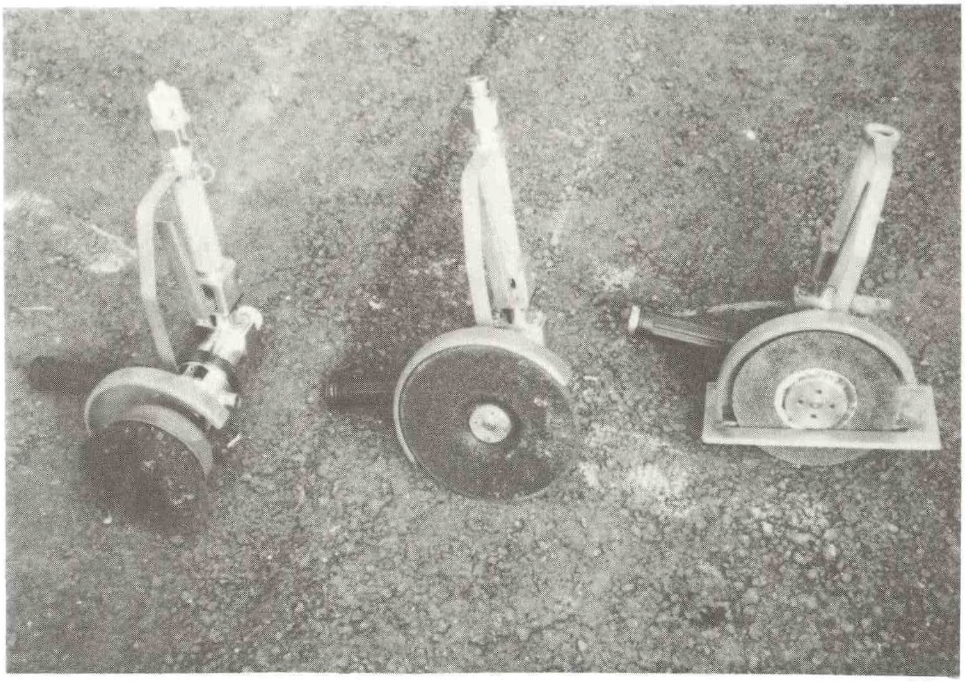


Figure 6.--Brush-cleaner, grinder, and cut-off saw

Specifications

	Power	1.5 ps
	Max. rpm	4,300 rpm
	Water pressure	570 psi
	Optimum flow	12.7 gal./min.
	Weight (in air)	9.6 lbs
	(in water)	8.0 lbs
	Porting	1/2 in.
	Diameter of grinder	6, 7.2 in.
	Diameter of saw	7.2 in.
	Motor model	WM-4046-300

The drill has the most simple structure of all the tools in this tool series. Figure 7 shows the drill, which makes a 1/2 in. hole; another drill (WD-1023) has the ability to bore a hole that is 1.5 inches in diameter.

An impact wrench (Figure 9) is the most useful tool for undersea work. Offshore structures use a bigger bolt and nut than those used on land. Our impact wrench has the ability to tighten and loosen a bolt as large as 1.5 inches in diameter.

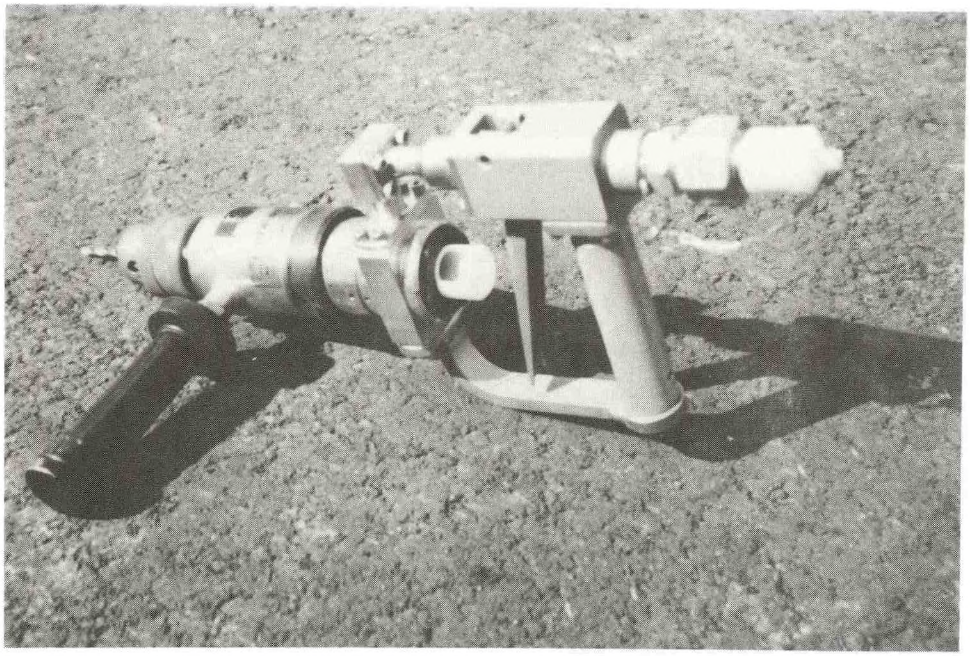


Figure 7.--Drill

		Standard type	Low-speed type
Specifications	Drill chuck capacity	1/2 in.	3/2 in.
	Power	1.0 ps	1.0 ps
	Max. rpm	1,100 rpm	560 rpm
	Water pressure	570 psi	ditto
	Optimum flow	9.5 gal./min.	ditto
	Weight (in air)	11.1 lbs	ditto
	(in water)	9.3 lbs	ditto
	Porting	1/2 in.	ditto
	Motor model	WM-4032-300	WMG-4032-300

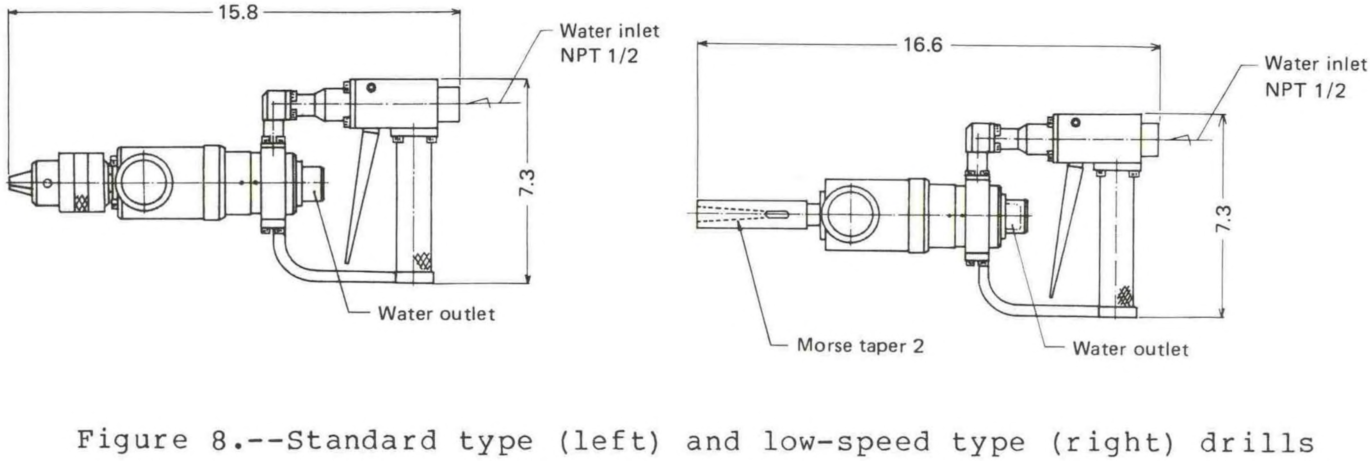


Figure 8.--Standard type (left) and low-speed type (right) drills

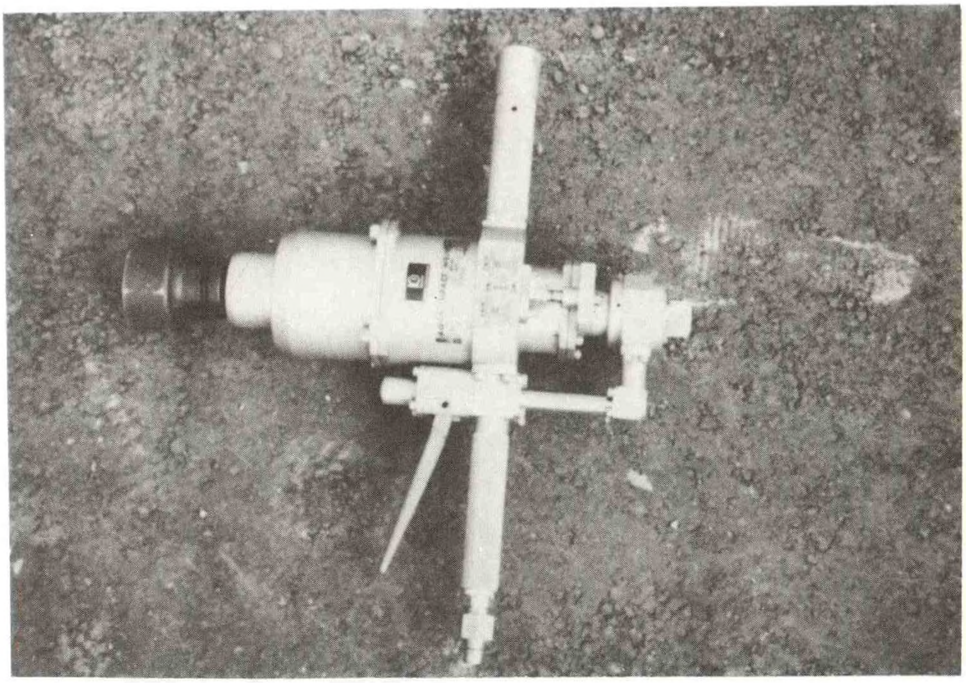


Figure 9.--Impact wrench

Specifications	Power	1.0 ps
	Beat frequency	2,100 beat/min.
	Water pressure	570 psi
	Optimum flow	9.0 gal./min.
	Weight (in air)	20.0 lbs
	(in water)	17.3 lbs
	Porting	1/2 in.
	Motor model	WM-4032-300

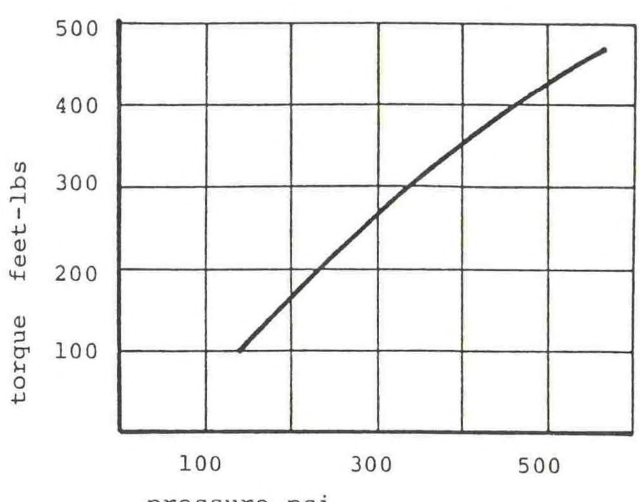


Figure 10.--Torque-pressure diagram of impact wrench

The universal joint socket is prepared for small flanges, and torque control is accomplished by regulating the water pressure. Figure 10 shows the torque-pressure diagram.

A rock breaker (Figure 11) is used for breaking rock or concrete. The chisel is moved back and forth but not rotated, which means that this tool cannot be adapted to bore holes to insert dynamite.

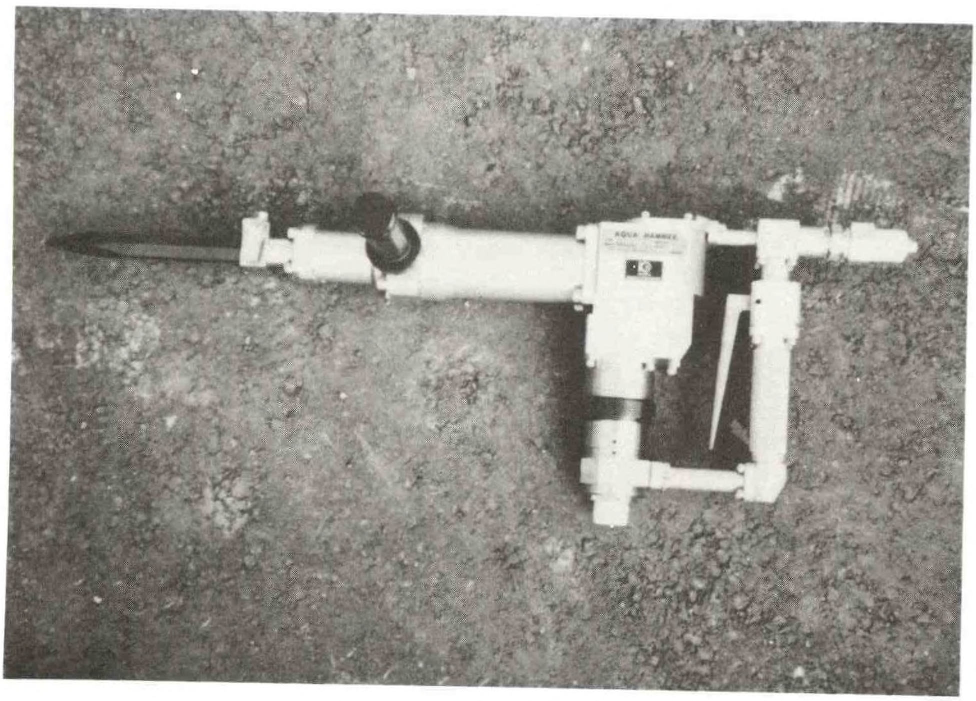


Figure 11.--Rock breaker

Specifications	Power	1.0 ps
	Beat frequency	2,100 beat/min.
	Water pressure	570 psi
	Optimum flow	9.0 gal./min.
	Weight (in air)	20.0 lbs
	(in water)	17.3 lbs
	Porting	1/2 in.
	Motor model	WM-4032-300

FUTURE PLANS

We have developed six types of seawater-driven diver tools, but to reduce the relative cost of the total system, more useful tools should be developed. These are, for example, rock drills, wire or cable-cutters, and chain-saws.

We think that the most significant matter to research now is data to decide what the design goals should be for undersea machines for diver use.

We have therefore begun to study human engineering as it applies to the undersea environment, and are stressing the engineering rather than the medical aspects. In the future, we will test these tools to ensure that they have the optimum design in terms of human performance.

POLYMETALLIC SULFIDES--A RENEWABLE MARINE RESOURCE [1,2]

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ABSTRACT

Active ocean floor hydrothermal vents have been observed to date along ridge crest segments of the Juan de Fuca and Explorer Ridges located off North America, the East Pacific Rise, and the Galapagos Ridge as well as on submarine volcanoes of the ridge crests and hot spots. Vents that are currently generating polymetallic sulfide mounds and chimneys with "smoker" activity are found to be active in ridge crests or segments with medium (5-9 centimeters per year) and fast (9-16 centimeters per year) spreading rates. A detailed submersible-based study was carried out over large inactive hydrothermal polymetallic sulfide deposits located at the crest of the Galapagos Ridge. This study suggests that prolonged hydrothermal activity on a ridge crest can develop an ore-sized massive sulfide body on contemporary oceanic crust. The geology, size, and mineralogy of the Galapagos massive sulfide body resemble massive sulfide ore bodies found on subaerial segments of fossil oceanic crust. The study also suggests that the size of massive sulfide bodies that may be found along the crest of the mid-ocean ridge systems may vary from a few meters to 2,000 meters in length. (Commercially viable ore-sized bodies, however, may be rare.) To date, contemporary oceanic analogues of massive sediment-hosted ore bodies have not been detected along the mid-ocean ridge crests but may well be found along the marginal basins of the Western Pacific in the future.

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[1] HIG Contribution No. 1590

[2] Also based on work done at National Ocean Service, NOAA, Rockville, Maryland

INTRODUCTION

Since 1978, following the initial discoveries of hydrothermal vent communities along the Galapagos Ridge axis (Ballard et al. 1981), a large number of research teams from several nations have continued working on the problem of massive sulfide deposition and hydrothermal mineral formation on the ocean floor. Research work by the author and his colleagues on the geology of the Galapagos and Juan de Fuca Ridges resulted in the discovery of several large polymetallic sulfide deposits located along the axes of these ridges (Malahoff et al. 1983). An array of instruments and facilities were used, including multibeam echo-sounding vessels, such as the NOAA ship Surveyor, and the submersible ALVIN, equipped with bottom transponder navigation and bottom photography. The comprehensive field techniques used in this research area are vital for success because, whereas manganese nodules form large slow-growing deposits over extensive areas of the abyssal floors of the ocean, polymetallic sulfides form small rapidly growing deposits located in rugged fresh rock terrain.

The distribution of hydrothermal activity and polymetallic sulfide deposition is a function of the nature and rate of volcanic processes along the world ridge crest system. The active hydrothermal vents are found within the rift valleys of the ridges, a system extending over 60,000 kilometers (fig. 1). This system includes ridge systems found within marginal basins of the Pacific such as the Bismarck Sea, the Lau Basin, the Fiji Basin,

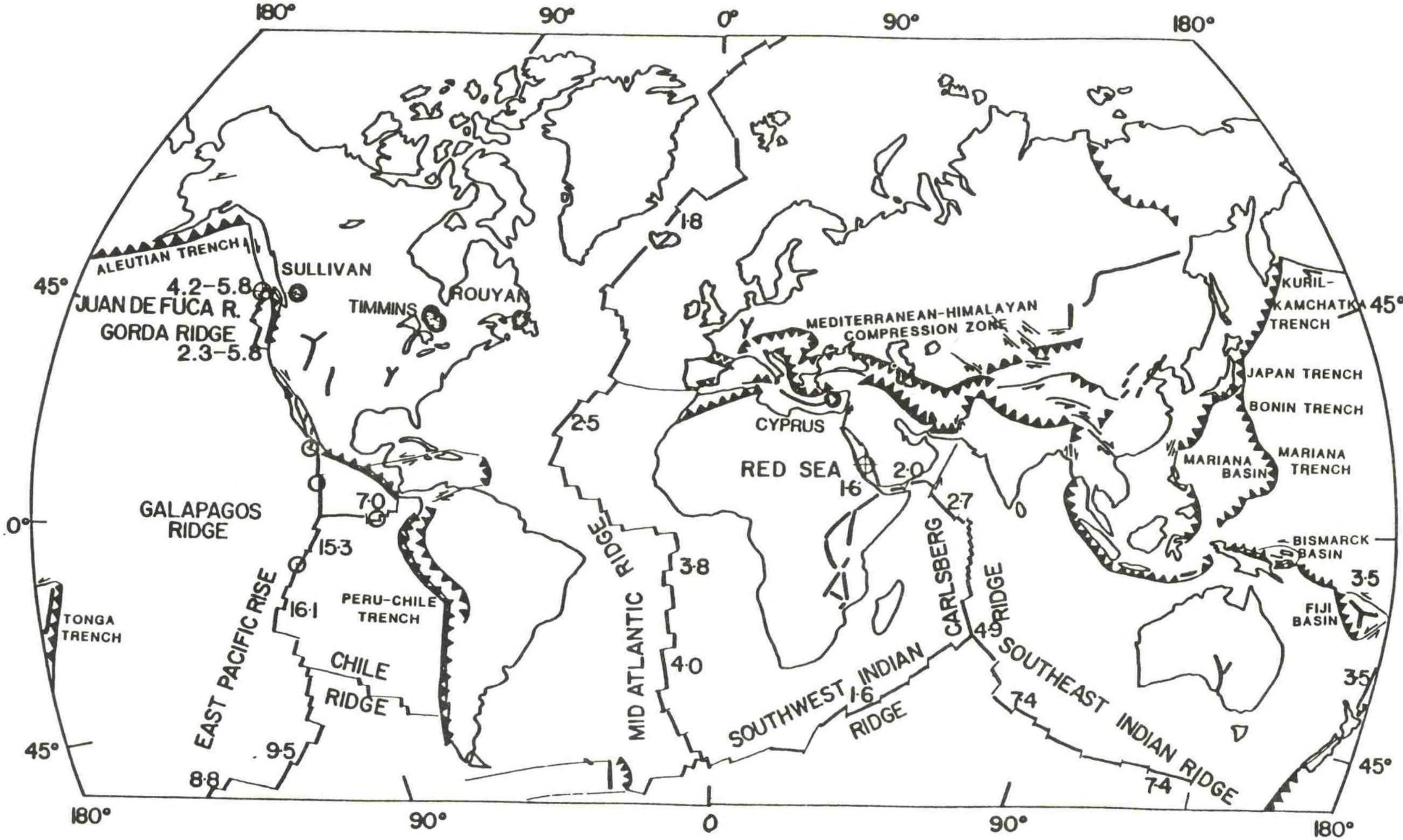

Figure 1.--The midocean rift systems, subduction zones, and principal regions of crustal compression. Figures listed along the axis of the rift system are full spreading rates in centimeters per year. The subduction zones and underthrust belts are shown as heavy lines with triangles pointing in the direction of underthrusting. The Mediterranean-Himalayan crustal compression zone is designated by the location of the principal planes of underthrusting. Open circles show locations of known submarine massive polymetallic sulfide deposits. Solid circles show locations of subaerially mined polymetallic sulfide deposits discussed in this paper.

and the Mariana Basin. Despite the great extent of this area, only about 500 of the 60,000 kilometers of the world ocean ridge system have been studied in detail. So far, every segment of the Pacific Ocean ridge crest system that has been studied by U.S., Canadian, and French teams has shown either active or inactive polymetallic sulfide deposition.

When the first high temperature hydrothermal vents and smokers were discovered along the East Pacific Rise at 21°N by Robert Ballard (Ballard et al. 1981) of the Woods Hole Oceanographic Institution, it was assumed that the polymetallic sulfides were only formed at fast-spreading ridge crests (with spreading rates in excess of 9 cm/year). To date, no massive sulfides have been found on the slow-spreading mid-Atlantic Ridge segments and only low temperature hydrothermal manganese crusts have been mapped and described there. However, recent research done by Rona (1985) does suggest the presence of hydrothermal activity along the crest of the mid-Atlantic Ridge. The best-mapped hydrothermal deposits found to date along a slow-spreading ridge segment are the metalliferous sediments of the Red Sea (Backer 1982). Backer calculated that about 30 million tons of iron and 2.2 million tons of zinc are deposited in an area of 60 square kilometers along the Atlantis II Deep of the Red Sea. Studies of a medium-spreading (6 to 7 cm/year) ridge crest along the Galapagos Ridge (Malahoff 1982) showed the presence of what is apparently one of the largest polymetallic sulfide bodies found to date, located on the Galapagos Ridge, about 400 kilometers east of the Galapagos Islands.

Submersibles such as the DSRV ALVIN, equipped with corers, water bottles, video and still cameras, thermometers, manipulator arms, and baskets have been used extensively in the study of hydrothermal mineral formation on the ocean floor. In most cases, the dive sites have been defined by high resolution multibeam bathymetric maps. It is this combination of techniques that has allowed the detailed mapping and sampling of the polymetallic sulfide deposits found within the rift segments of the Eastern Pacific.

Biologic Communities Associated With Polymetallic Sulfide Deposits

Active hydrothermal vents on the ocean floor are all characterized by associated biologic communities consisting of a variety of specially adapted biota. Wherever there is warm or hot water permeating through the ocean floor in a diffuse manner, with a temperature two or three degrees above ambient, hydrothermal vent-associated clams and mussels may be present (Williams et al. 1981, Jones 1981). Dense populations of clams have been observed along the Galapagos Rift Valley (Ballard 1982). The presence of dead clam shells at several sites suggests that these populations died with the cessation of hydrothermal water circulation. The biology of the clams has proved to be quite exotic. The clams bear hemoglobin-type blood and are able to process bacteria-laden water containing H_2S (Rau 1981). Clam beds are associated with low temperature hydrothermal activity on the ocean floor (Grassle 1982). Their average life span--a good indicator of the duration of the hydrothermal systems--is about 14 years. Clearly, they must spawn profusely to establish new communities in new hydrothermal areas. Thus, at any given time, the hydrothermal areas are not site specific but are distributed widely throughout the currently volcanically and hydrothermally active ridge crest area.

With an increase in the hydrothermal temperature to 30°C, diverse biological communities develop around the vents. Frequently, a diverse population is seen to occupy a spongy base composed of oxidized sulfides left over from the high temperature phase of the vent (Ballard et al. 1979, Enright et al. 1981). Giant clams as well as large vestimentiferan tube worms (Jones 1981), annelid worms (Desbruyeres and Lanbier 1980), bacterial mats (Karl et al. 1980), and vent crabs form some of the more prominent groups within the population. The worms appear to be adapted to rapid maturity, quick reproduction, and mass mortality. The outer skeleton of the worms consists of a hard, flexible tube, and 60% of their body tissue is bacteria. There is no alimentary tract associated with the tube worms (Enright et al. 1981), and their only true animal tissues are concentrated largely around the reproductive organs. The worm survives through a symbiotic relationship with the bacteria contained in a trophosome (Jones 1981) which processes the hydrogen sulfide (and possibly methane) extracted from the hydrothermal water and absorbed in the blood of the worm. H_2S is normally highly toxic to animal life, yet Grassle's (1982) observations suggest that hot vents contain some of the most intense biota on the face of the earth.

Formation of Submarine Polymetallic Sulfide Deposits and Hydrothermal Vents

The phenomenon of mineral formation along the volcanically active mid-ocean ridge segments located at depths between 1,600 meters, such as on the Juan de Fuca Ridge Axial Volcano (Canadian-American Seamount Expedition 1985), and 2,600 meters, such as the Galapagos Ridge (Ballard et al. 1981), is related directly to the heating of the circulating seawater by magma located under the axis of the mid-ocean ridge. Along the mid-ocean ridges, magma produced by partial melting of the mantle rises to the surface in response to the passive parting of the adjacent plates on either side of the axis of the mid-ocean ridge.

The magma arrives on the floor of the trough-shaped rift valley 1) in the form of basaltic sheet flows if the volume and flow rate are great (Macdonald 1982), 2) in the form of lobate lavas during medium flow and volume rates, or 3) in the form of pillow basalts if the flow rate and volume of the magma are relatively low (Ballard 1979). The magma arrives on the ocean floor at a temperature of 1200°C and solidifies rapidly, forming new ocean floor. The new lava, especially the sheet and lobate flows, probably forms a temporary cap rock over the underlying hot magma. Ocean water circulating down through the adjacent colder crust near the axial rift encounters the hot magma underlying the axis of the ridge. At a depth of a few hundred meters to two kilometers below the floor of the rift axis, the percolating seawater is heated to temperatures of up to 400°C and begins to migrate upward, where it tends to be trapped under pressure beneath the newly formed capping rock of sheet or lobate basalt overlying the axial rift (Ballard et al. 1979). The oceanic crust is basalt, largely an aluminum silicate rock, free of quartz, rich in iron and manganese, and containing a large variety of low percentage metallic elements.

During its residence time and upward passage below the cap rock, the 300° to 400°C heated ocean water undergoes the following reaction: superheated water begins to concentrate cations of Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}, and traces of Fe^{+2}, Mn^{+2}, and anions of SO_4^{-2}, HCO_3^{-}, and Cl^{-} from the constituents of the seawater (Edmond and Von Damm 1983). The release of hydrogen, hydrochloric acid, and silicic acid during this passage makes the seawater more corrosive. The superheated seawater then leaches positively charged anions of metals such as cooper, zinc, manganese, and cobalt (which are normally trace constituents in the basalt) out of basalt, transporting these components to the surface of the basaltic crust. En route, chemical reactions take place in the crust, precipitating $CaSO_4$, $Hg(OH)SiO_3$, SiO_2, FeS_2 (pyrite), and Fe_3O_4 within the crust. Gases such as H_2S, CO_2, and H^+ are formed during the process; they move upward together with anions such as Cu^{+2}, Fe^{+2}, Mn^{+2}, Zn^{+2}, and Ca^{+2}. Near the surface, FeS and CuS are deposited.

The superheated water with many elements in solution is trapped beneath the surface of the new crust and exits under pressure only where the crust has been fissured by either renewed rifting along the ridge axis or displacement by normal fault motion along the boundaries of the axial rift valley. When the superheated (300° to 400°C) water encounters oceanic water at an ambient temperature of 2°C, immediate cooling of the heated water takes place, followed by a chemical reaction wherein the contained cations and anions combine to form minerals. Because of the overburden pressure of over 2 kilometers of seawater, no boiling of the water takes place, despite the high temperatures encountered. The mineral-laden water exits at velocities of between 0.5 and 2 meters per second.

Hekinian (1984) calculated that for a vent with a diameter of 3 centimeters, the flow rate is between 3.5 and 14 liters per second. As the fluid exits, the precipitating minerals build up sulfide chimneys around the hydrothermal vent (fig. 2). The "black smoker," so named because of the smokelike consistency of the effluent exiting from the hydrothermal vents, precipitates FeS (the "black smoke"), MnO_2, and FeO(OH) as well as metalliferous sediment into the water column surrounding the vent. SiO_2 and CO_2 also exit from the vent. Within the chimney, SO_4^{-2} from the seawater combines with the Ca^{+2} from the hydrothermal fluid to form $CaSO_4$. Cations of other metals combine with SO_4^{-2} to form FeS_2 (pyrite), CuS, and ZnS. These compounds, comprising the bulk of the chimney, are the principal constituents of polymetallic sulfides found on the ocean floor, and also form the major constituents of polymetallic sulfides found on segments of ancient ocean floor now exposed as subaerial lava terrain within Canada (Franklin et al. 1981) and Cyprus (Adamides 1980).

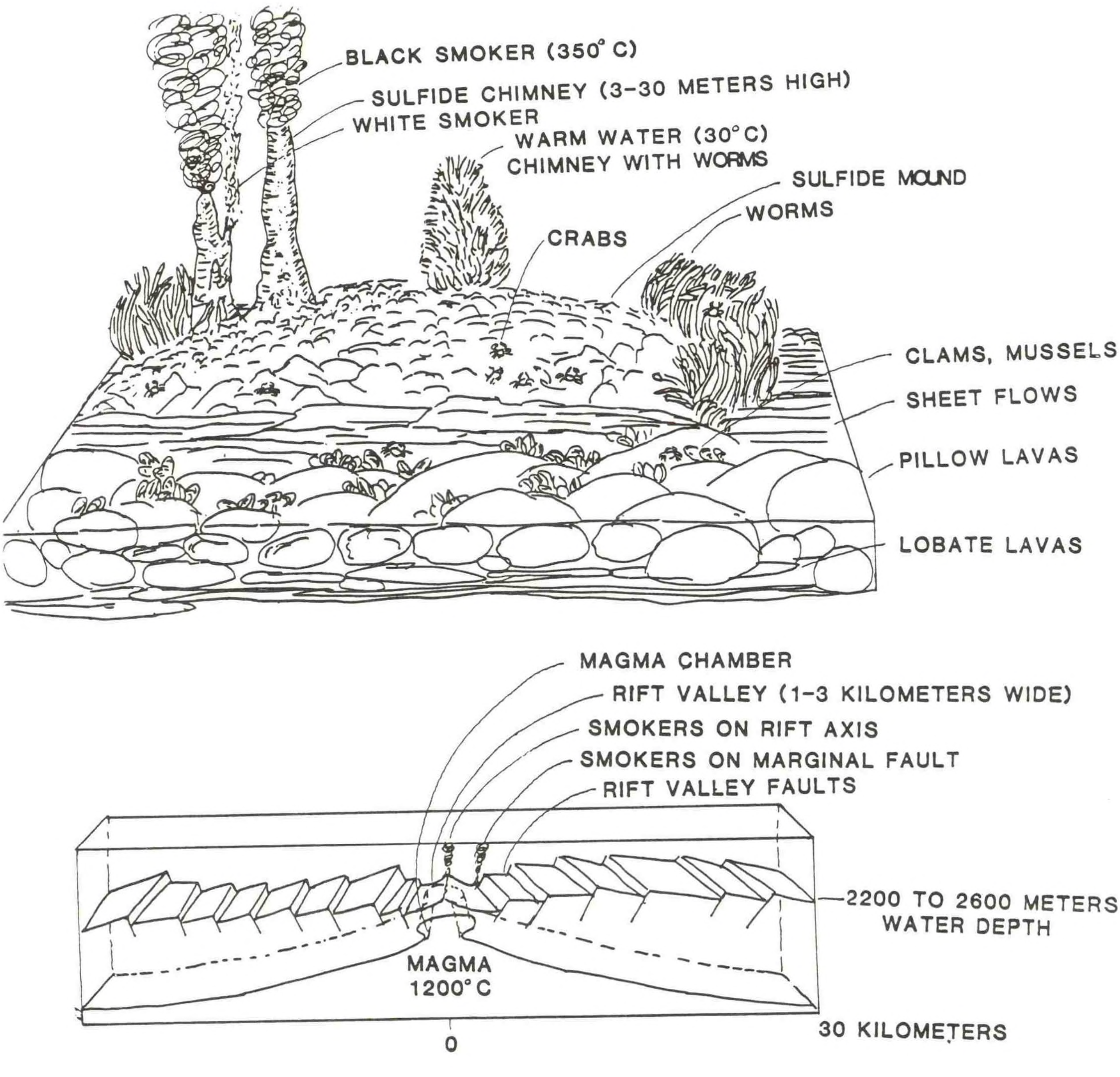

Figure 2.--Schematic diagram showing the morphology of a typical hydrothermal vent found along the axes of margins of the rift valleys of the East Pacific, Galapagos, Gorda, Juan de Fuca, Endeavor, and Explorer Ridges. Lower diagram shows the structural and magmatic model of the rift valley (Macdonald 1982).

It is interesting to note that the copper and zinc content of fresh basalt is about 100 and 150 parts per million (ppm). When the metals are transported as sulfides, their concentration increases by ten thousand times. Hekinian (1984) calculated that to produce a polymetallic sulfide deposit 3 cubic meters in volume and containing 50% zinc, it would be necessary to percolate the superheated hydrothermal water through 1,500 cubic meters of basalt with a normal zinc content of 100 ppm. Cobalt and silver are also found associated with minerals such as pyrite, chalcopyrite, and sphalerite. The bulk content of silver may go as high as 400 ppm in some of the sulfides, corresponding to an enrichment of five thousand times more than the concentration in the parent basalt. Hekinian also calculated that for a chimney with a flow rate of 10 liters per second, the mass precipitation of metalliferous deposits is 100 kilograms per day. Some of this precipitated material is deposited in chimneys, some of the material is dispersed by the oceanic water mass and is deposited as metalliferous sediments nearby or elsewhere. This process appears active at medium to fast mid-ocean ridge segments, according to the most recent studies along the East Pacific Rise (Edmond and Von Damm 1983) and the Juan de Fuca Ridge (Canadian American Seamount Expedition 1983).

At hydrothermal water temperatures of 300° to 400°C, "black smokers" may be encountered at the vents, and at temperatures between 200° and 300°C "white smokers" (with the white "smoke" consisting of anhydride) may be observed. Frequently, white "smoke" is found emanating from the same chimney as black "smoke." Through the process of hydrothermal activity, rigid chimneys and surrounding blankets of sulfide-rich hydrothermal sediments are precipitated around the hydrothermal vents. Chimneys with heights up to 30 meters commonly develop at the vent sites. After hydrothermal activity ceases, the massive sulfide deposits remain behind in the form of chimneys and chimney mounds. Hydrothermal activity at any particular vent site may last from a few months to a decade. Areas of extensive hydrothermal deposits such as those observed by the author along the Galapagos Ridge (Malahoff 1983) may have been built through continuous hydrothermal activity at the site over a period of 100 years or more. Nevertheless, on a geologic time scale, all massive polymetallic sulfide deposits of the mid-ocean ridge systems are "instantly" formed deposits. Accordingly, sulfides may be regarded as renewable resources.

The Galapagos Ridge sulfides and others observed to date show similar processes of deposition. All sites show the presence of a capping rock beneath the hydrothermal vents. Normally, the capping rocks associated with the high temperature vents are basaltic sheet flows or lobate flows. Pillow basalts are too porous, so the hot hydrothermal water probably dissipates and never reaches the 350° to 400°C temperatures required to leach, transport, and precipitate polymetallic sulfides. The hydrothermal activity appears to cease when renewed lifting breaks up the capping rock and the local hydrothermal circulation system.

If Hekinian (1984) is correct in estimating that 3 cubic meters of sulfide with a 50% zinc content are deposited as a result of hydrothermal fluid circulation through 1,500 cubic meters of basalt, almost 2 million cubic meters of basalt would have to be leached by the circulating fluids in order to build hydrothermal deposits similar to the ones observed along the Galapagos Ridge (i.e., a mound measuring 30 meters high, 5 meters wide, and 10 meters long, containing about 1,500 cubic meters of sulfide). After deposition, the massive sulfide deposits and their underlying crust move away from the rift as a result of seafloor spreading. Two phenomena may take place during this motion of the sulfide-capped plate away from the axis of the rift valley: 1) The dissolution of the sulfides may take place by the way of oxidation. The oxidized deposits may be scavenged by ocean water circulating downward near the vicinity of the next generation of hydrothermal vents and redeposited back at the new hydrothermal sites of the rift valley. 2) Preservation of the sulfides may occur through sedimentation, transport on the mobile oceanic crust, and possible abduction on land, as in the case of ophiolite-associated massive sulfide deposits. A typical marine massive sulfide deposit may contain the following characteristics (derived from detailed chemical analyses on 10 samples from the Galapagos polymetallic sulfide deposit):

1) Elemental analysis: 7% silica, 30% iron, 40% sulfur, 17% silica, 1% zinc, and manganese under 0.5%. Variation from sample to sample can be large, with the copper

percentage as high as 27%.

2) Mineralogy: abundant pyrite surrounded by chalcopyrite replaced by bluish covelite (copper and iron sulfide) with alteration to bornite; low temperature deposits yield abundant talc as well.

3) Average density: 4.1 g/cc and largely nonporous.

4) Fossil biota: dense worm pseudomorphs (largely pyrite infill) indicative of intimate and abundant association of the worms with the process of sulfide deposition until such time as excessive heating or cooling kills them off.

5) Average crystal size: a millimeter (coarsely crystalline).

6) Crystal surface morphology: large pyrite crystals with smaller crystals indicative of the continuous state of crystallization during sulfide deposition. The simultaneous appearance of surface pitting suggests intermittent episodes of dissolution and deposition (due perhaps to heat fluctuations, effluent rate, or changes in carrying capacity of the fluid).

Seen together, the changes in mineralogy, biota, crystal size, and surface morphology suggest complex thermal histories within each smoker. Large temperature swings are probably the rule rather than the exception.

Fossil Submarine Polymetallic Sulfide Ore Deposits

Modern mines located in ancient ocean floor terrain such as the Kidd Creek and Timmins mines in Northern Ontario (Walker et al. 1975), extract several tens of thousands of tons of polymetallic sulfide ore per day. Characteristically, such modern mines, as well as the ancient copper mines of Cyprus (Adamides 1980), are located over ore bodies that barely exceeded several hundred meters in cross section and are characteristically associated with volcanic pillow lava sequences and fossil faults. The size of such currently operating mines ranges from 1 million tons to perhaps as much as 80 million tons per deposit. The age of the seafloor-associated mineral deposits ranges from as old as 1.8 billion years for the sulfides of Noranda (Rouyan District of Quebec) and Kidd Creek (Northern Ontario), to 80 million years for the Cyprus ores (Adamides 1980), to possibly 100 to 1,000 years for the Galapagos sulfide deposits (Malahoff 1982).

All polymetallic sulfides, whether recovered by dredge or submersible from the ocean floor or recovered from land-based mines, have one chemical trend in common: although diverse in metallic content, the chemistry of these mineral deposits is very simple--all the principal components of the mineral body are metallic sulfides. Therefore, by composition, sulfur may account for as much as 40 percent of the content, iron for about 20 percent, copper for up to 20 percent, and zinc for up to 20 percent. The zinc-copper-iron ratio is highly variable within any one polymetallic sulfide deposit, as well as from deposit to deposit. The sulfides mined at Noranda, in Quebec, typically have a 3 percent copper and 1 percent zinc component, with silver extracted at 30 grams per ton and gold at 0.4 grams per ton

(Spence and De Rosen-Spence 1975). The size of the polymetallic sulfide lenses mined within the Millenbach mine ranges from 4,000 tons to 181,000 tons, and polymetallic sulfide deposits located within the "stringer" or hydrothermal feeders range in size from 5,000 to 1,000,000 tons, for a total regional ore volume in excess of 2 million tons. The important fact to observe from these figures is that commercial mines like Millenbach consist of several small deposits not unlike those that may be found on the ocean floor in the form of individual or coalesced smokers (fig. 2). A typical cross-section of a Millenbach ore body is illustrated in figure 3, with dimensions close to those of the ridge crest polymetallic sulfide mounds described by Ballard et al. (1981) and Hekinian et al. (1981) for the East Pacific Rise sites.

The massive polymetallic sulfide ore bodies of Archean age found in Canada also appear to have developed through high temperature hydrothermal activity in a geological setting of seafloor pillow lavas, volcanic talus, and volcanic breccia, located along faults and in small volcanic mounds. Geochemical and petrological studies show these to have been largely intermediate to acidic in composition (Franklin et al. 1981). The sulfides appear to have been formed on the floor of a rift located within a continental crust that widened to a width of perhaps 200 kilometers and a length of perhaps 800 kilometers during the Archean, forming a grabenlike basin that was subsequently flooded by the sea to a water depth of perhaps a few hundred to a thousand meters. The sulfide bodies were apparently deposited in the form

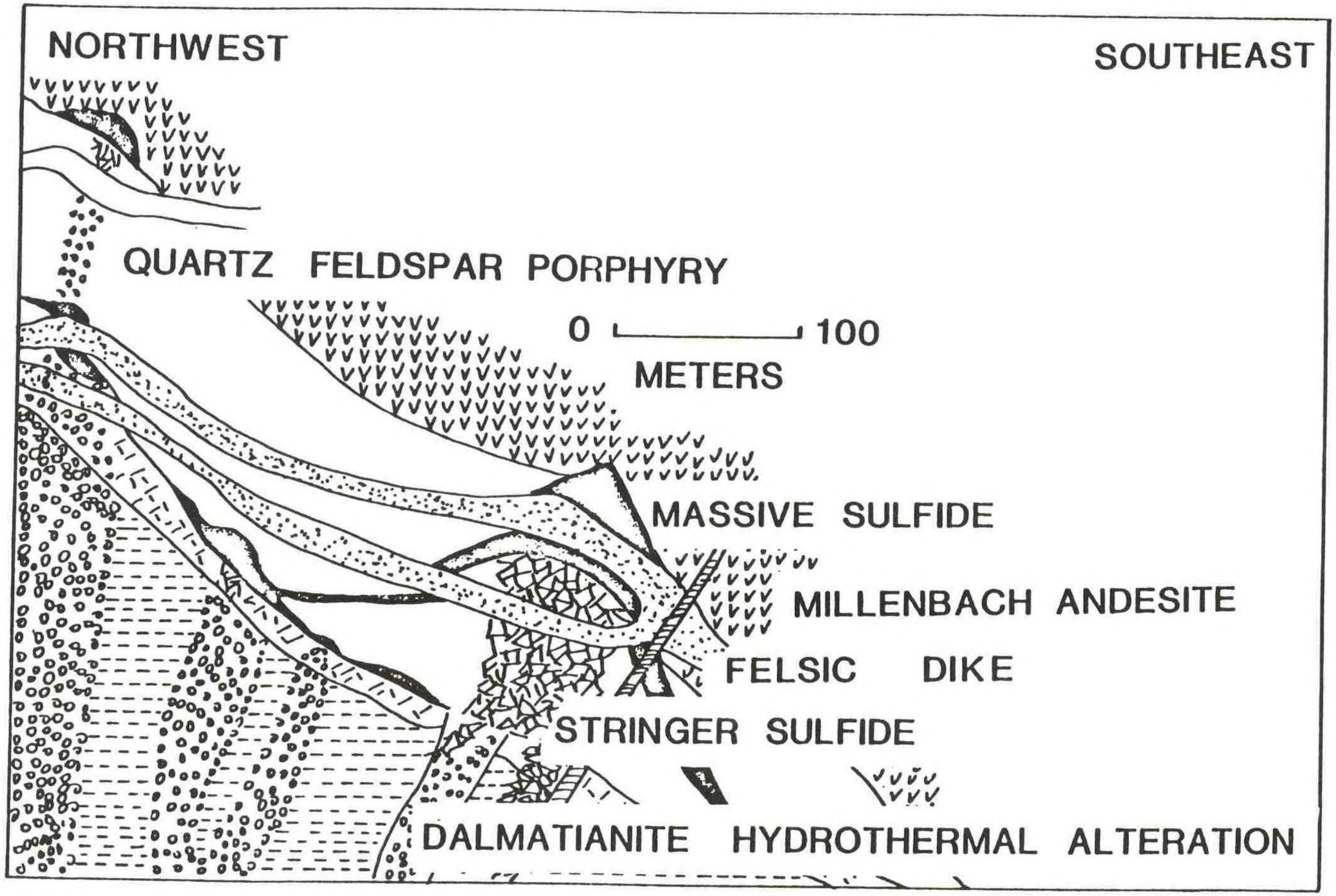

Figure 3.--Cross-section of a massive polymetallic sulfide ore body mined at Millenbach Mine, in the Rouyan district of Quebec, Canada (Kinskey et al. 1982).

of mounds or lenses consisting of pyrite, chalcopyrite, and sphalerite, with the sphalerite usually occupying the outer margins of the mound or lens. Geological examination of the stringer deposits shows these to be the solidified channels through which the hot hydrothermal fluids migrated upward to the surface of the ocean floor, prior to precipitating the solid polymetallic sulfide phases on the ocean floor upon contact with the seawater.

Polymetallic Sulfides of the Galapagos Ridge

Unlike the sulfides observed along the East Pacific Rise at 21°N that were formed along the axis of the rift valley (Hekinian 1984), the sulfides located along the Galapagos Ridge were formed along a major marginal fault of the rift valley whose axis is devoid of hydrothermal deposits. The Galapagos Ridge deposit appears to have been formed as a string of chimneys located along the fault. Recent fault motion which terminated the hydrothermal cycle also exposed the stock work of the hydrothermal vents (stringer sulfide) located beneath the massive sulfide deposit (fig. 3). Scientists in the submersible ALVIN have observed hydrothermal sulfide deposits located at the northern end of the Juan de Fuca and Explorer Ridges (Merge Group 1984) that formed along marginal faults of the rift valley and are not unlike those of the Galapagos Ridge (fig. 5).

Details of the geologic setting of the Galapagos Ridge sulfides are as follows. The Galapagos Ridge extends eastward from the East Pacific Rise with which it forms a triple junction.

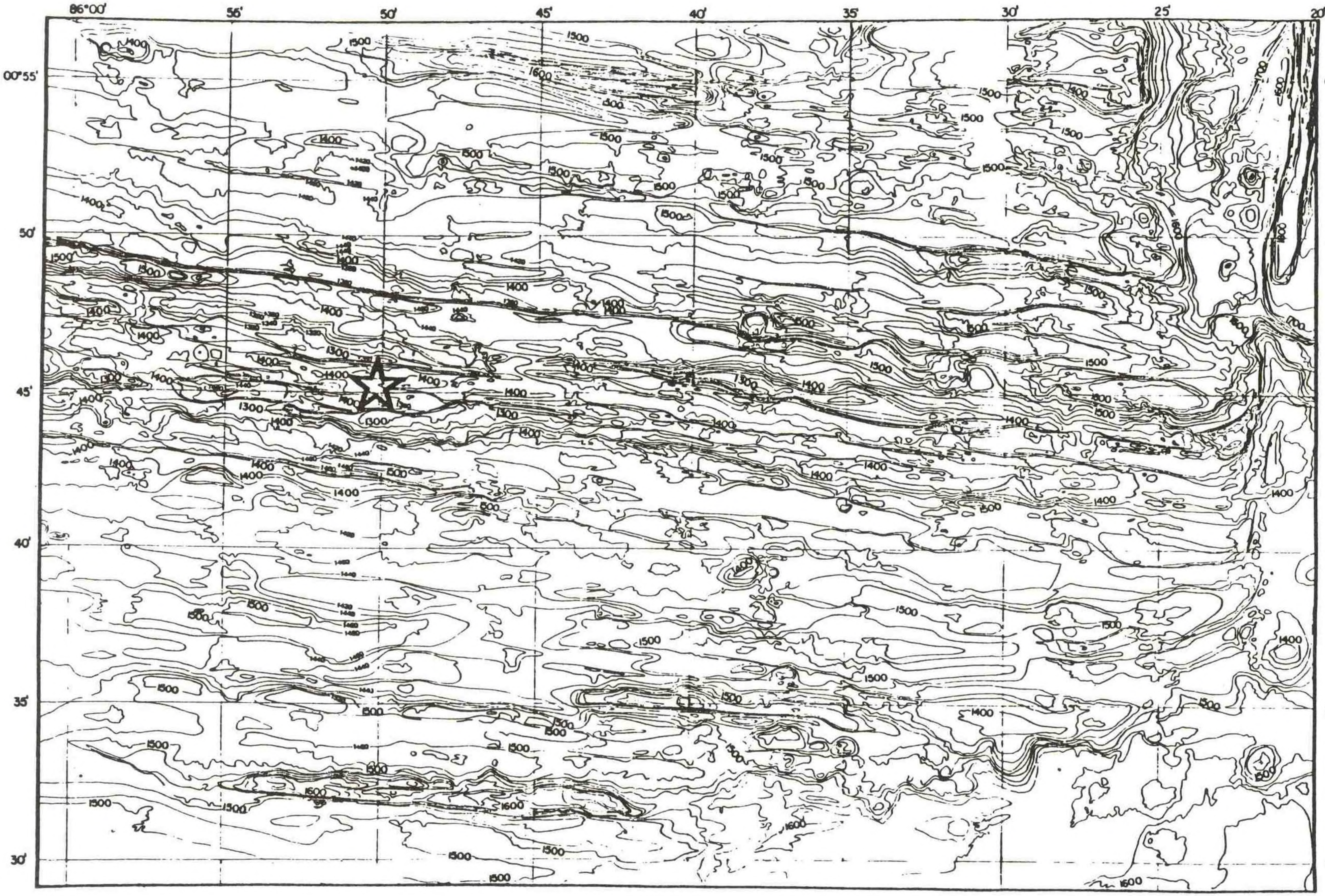

Figure 4.--Bathymetric map of the eastern end of the Galapagos Rift system. Depths in fathoms. Map drawn from a SASS multibeam survey of the area constructed by the U.S. Navy. Location of the massive polymetallic sulfide deposit described in this text is shown by a star.

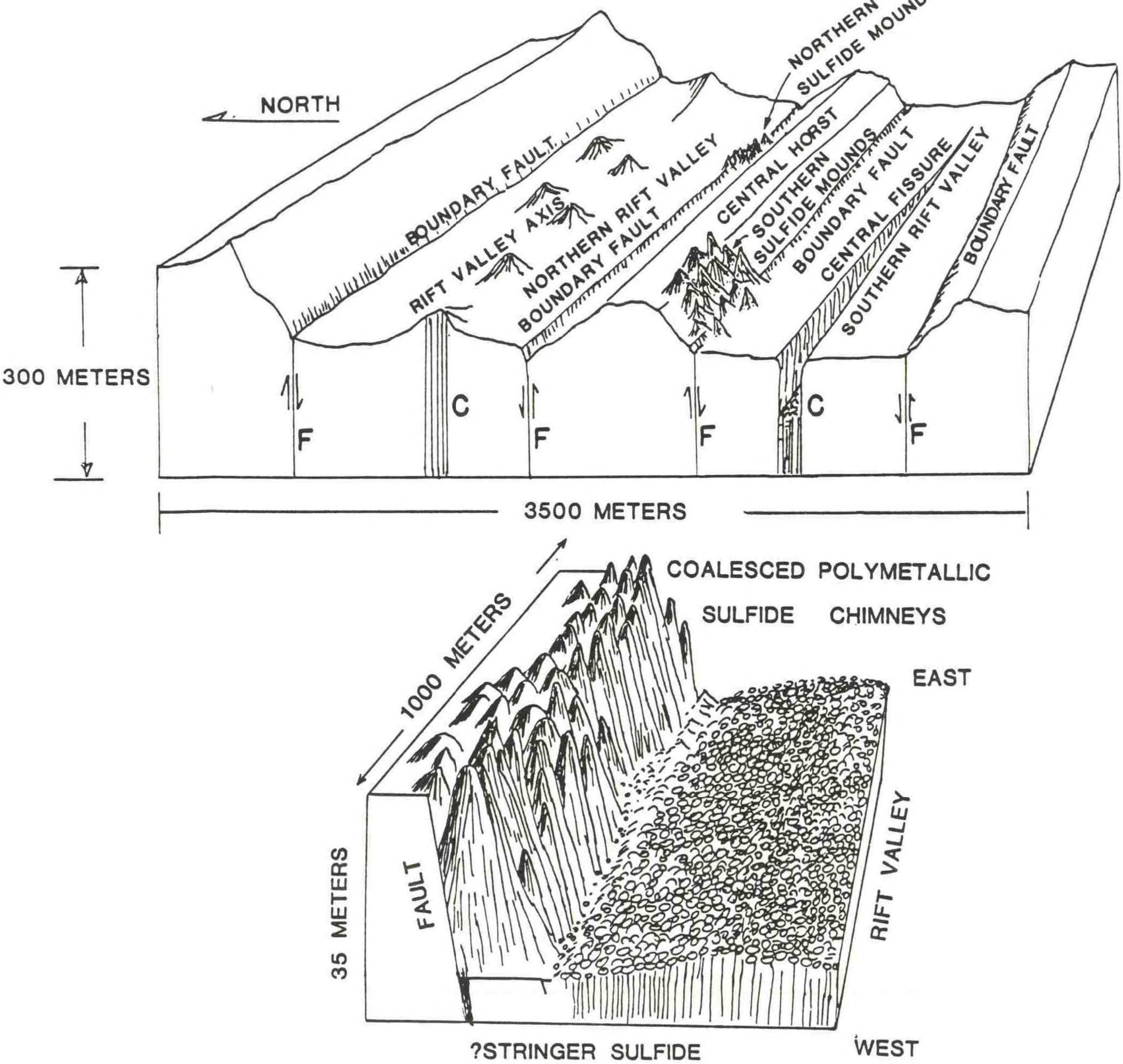

Figure 5.--Schematic view of the location (upper diagram) and morphology (lower diagram) of the Galapagos Ridge massive polymetallic sulfide deposit.

The average spreading rate of the ridge is 7 centimeters per year. The Galapagos Ridge terminates against the Inca Fracture Zone which strikes in a north-south direction located at 80°20'W (fig. 4). The crest of the ridge is located at an average water depth of 2,300 meters, while the floor of the rift valley at 85°50'W, 0°45'N is located at a water depth of 2,600 meters. The valley is between 1 to 2 kilometers wide and is bounded to the north and south by normal faults, 35 meters high, dipping toward the rift axis. Detailed bathymetric analysis of a 130-kilometer segment of the Galapagos Rift, extending west from the Inca Fracture Zone, has been made possible through the use of multibeam, high-resolution bathymetric data prepared by the U.S. Navy. The U.S. Navy SASS system was used for this purpose and provided an excellent bathymetric road map for submersible-based expeditions by U.S. scientists to several sites along the rift.

Examination of the bathymetry suggests a symmetry of fault development along the ridge. At 85°50'W and 0°45'N the axial rift valley appears to have undergone a jump or the magma chamber appears to have tapped an older adjacent rift segment to the south (fig. 6). A detailed examination of the SASS data for this area shows the presence of two rift valleys whose axes are separated by a distance of 2 kilometers. The northern valley is characterized by the presence of several volcanic mounds located along the length of the rift valley, while the southern valley is characterized by the presence of a recently formed 50-meter-deep central fissure (fig. 5). The horst located between the two rifts was

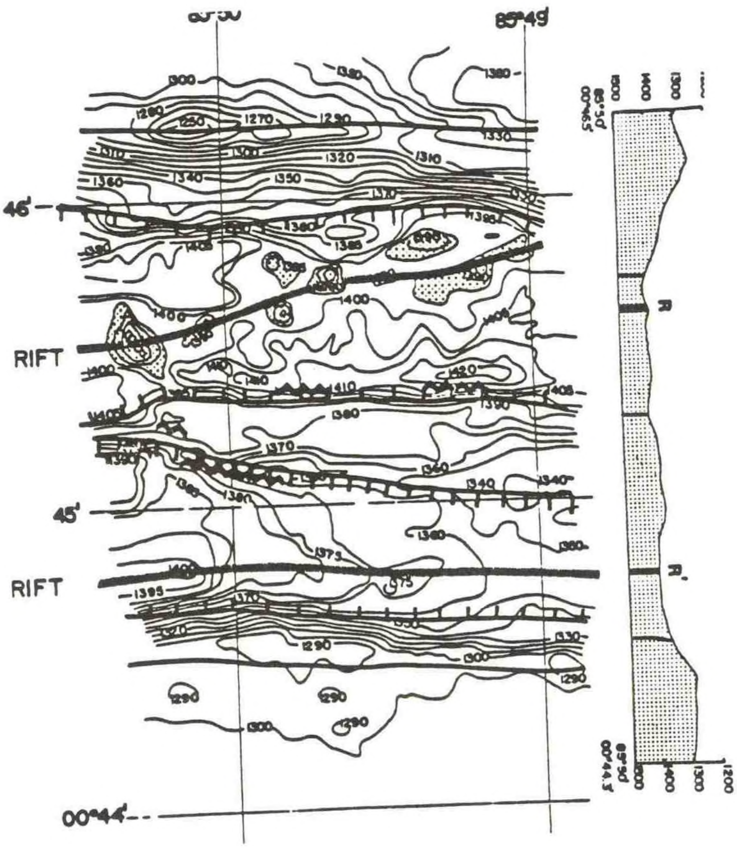

Figure 6.--Detailed bathymetry of the double rift of the Eastern Galapagos Ridge, showing the sites of the polymetallic sulfide deposits (zig-zag lines), located along the margins of the rift valleys.

examined for sites of possible hydrothermal activity by the author and his colleagues. We hypothesized that the horst may have acted as a hydrothermal "wick," allowing fluids to rise from depth to the ocean floor along normal faults which had been kept active through isostatic recovery motion of the horst trapped between the two active rifts.

Four ALVIN dives were carried out during two expeditions in 1980 and 1981. Three sites of hydrothermally inactive polymetallic chimney formations were observed extending along the boundary faults of the rift valleys (fig. 7). The largest deposit mapped during the dives is located over the northern fault of the southern rift valley. It consists of coalesced inactive chimneys 35 meters high, extending over a width of 20 meters and a length of perhaps 1,000 meters. Samples were recovered from this site by using the ALVIN manipulator arm to dig a 2-meter-long trench along the top of a mound, and by sampling the younger individual chimneys. The largest chimney examined was 35 meters tall. The largest sample recovered was taken from the top of a smaller chimney and weighed 350 kilograms. After cutting the sample, a detailed chemical and mineralogical traverse was conducted across the specimen, which showed the presence of numerous pseudomorphs of small vent worms whose outlines are now filled with chalcopyrite and pyrite.

Study of the samples suggests that as the chimneys grew, successive hot water phases killed off the neighboring worms attached to the outside of the chimney, thus incorporating their

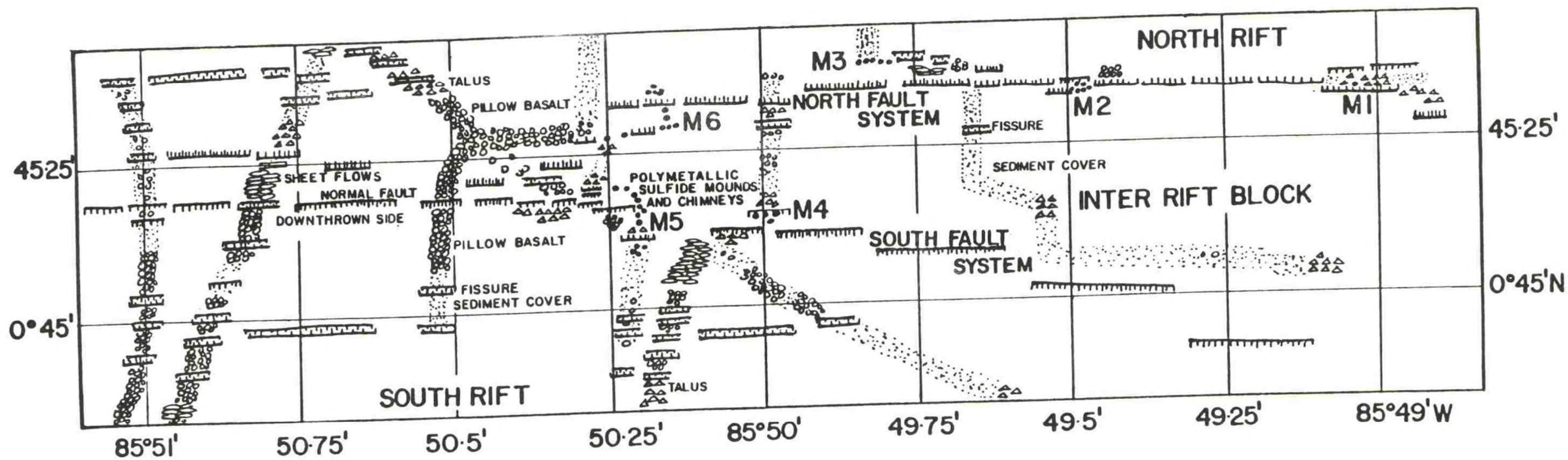

Figure 7.--Location of the principal polymetallic sulfide mounds (M1 to M5) along the marginal faults of the double axial rift valley within the eastern Galapagos Ridge (see fig. 6). Geology of the site was constructed from visual observation and sampling from the submersible ALVIN. The bands of geological observations are marked along the submersible traverses.

remains into the polymetallic sulfide mass of the growing chimney. The worm tubes are preserved in the form of cylindrical vesicles, with the morphologic details of the tube preserved by pyrite replacement. Quantitative chemical analyses of seven samples, taken from both the trench dug on top of the massive sulfide and from individual chimneys, show an average specific gravity of 4.1 gm/cm^3 for the sample and a composition consisting of 40 percent sulfur, 30 percent iron, 6.5 percent copper, 7 percent silica, 1 percent zinc, 0.5 percent manganese, 0.3 percent aluminum, 360 ppm selenium, 250 ppm cobalt, 270 ppm magnesium, 181 ppm molybdenum, 215 ppm lead, 45 ppm arsenic and barium, and less than 40 ppm of cadmium, chromium, phosphorus, mercury, nickel, tin, vanadium, uranium, and tungsten. Gold is less than 0.2 ppm and silver averages around 21 ppm, with palladium less than 0.05 ppm. Optical examination of the individual minerals shows various phases of dissolution and precipitation of all mineral phases, especially chalcopyrite. These observations suggest that the mineralogy of the individual chimneys, and indeed the deposit as a whole, was changing rapidly during the period of formation which may have lasted from a few decades to a hundred years.

Other Sites of Potential Polymetallic Sulfide Ore Bodies on the Contemporary Ocean Floor

Recently, massive sulfides have also been discovered off the west coast of North America (Canadian-American Seamount Expedition 1985). The Gorda/Juan de Fuca Ridge system, located off California, Oregon, and Washington and Canada's British Columbia, offers many

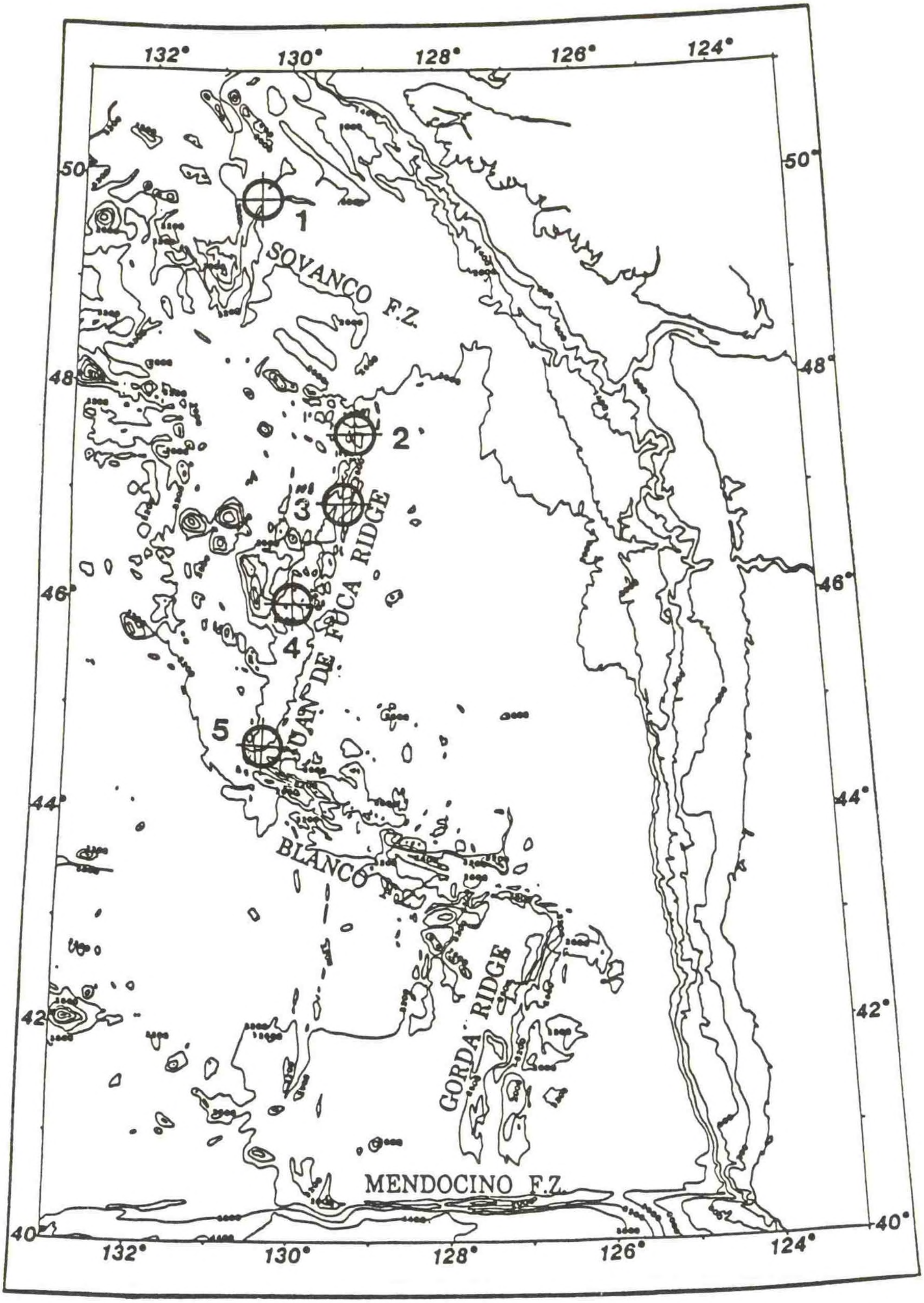

Figure 8.--Sites of polymetallic sulfide deposits and the location of active hydrothermal vents along the Juan de Fuca Ridge system are as follows: 1. Explorer Ridge, 2. Endeavor Ridge, 3. Northern Juan de Fuca Ridge, 4. Axial Volcano, 5. Southern Juan de Fuca Ridge.

potential sulfide sites (fig. 8). Multibeam mapping of this ridge system shows a geological structure similar to that observed over the Galapagos Ridge. Geochemical anomalies have been located over several active hydrothermal sites (Canadian-American Seamount Expedition 1985; Normark et al. 1982). Dredging and submersible sampling have yielded zinc sulfides with up to 50 percent zinc and 290 ppm of silver (Normark et al. 1982). Recent detailed mapping and submersible-based dives have shown these hydrothermal vent and sulfide sites to be ubiquitous along the Juan de Fuca, Endeavor, and Explorer Ridges. Delaney et al. (1984) observed temperatures of 400°C within sulfide mound chimneys 5 to 18 meters high, at a depth of 2,200 meters on the Endeavor Ridge. Hammond et al. (1984) observed black smokers as well, emanating from vents at the top of Endeavor Ridge chimneys, some of which were 15 to 20 meters high.

The northernmost ridge segment of the Gorda and Juan de Fuca Ridges is marked by the Explorer Ridge, a separate ridge segment with a calculated spreading rate of 4.2 centimeters per year (Riddihough 1983). On the shallowest segment of the ridge, located at a depth of 1,800 to 1,950 meters, Scott et al. (1984) observed the presence of 40 sulfide deposits along an 8-kilometer-long segment located between 49°42'N and 49°46'N. The shallowest high temperature active hydrothermal vent was observed by Malahoff et al. (1984), and was located at a depth of 1,560 meters within the caldera of Axial Volcano, Juan de Fuca Ridge at 45°58'N. This particular vent consisted of both black and white smokers, which had a maximum temperature of 293°C, as recorded by the ALVIN thermometer. Low temperature hydrothermal vent deposits, consisting of iron oxide and nontronite, surround the vent for a distance of several hundred meters (McMurtry et al. 1984). The extensive ocean floor hydrothermal activity located at sites along the Juan de Fuca, Endeavor, and Explorer Ridges (fig. 8) is also characterized by the presence of excessive iron and manganese particulate matter contained in a midwater hydrothermal plume detected tens of kilometers away from the ridge crest (Massoth et al. 1984).

It is particularly interesting to note that although the Juan de Fuca (5.8 cm/year), Endeavor (6.0 cm/year), and Explorer (4.2 cm/year) Ridge systems show the morphologic characteristics of a medium rate spreading system (Riddihough 1983), extensive hydrothermal vents are located on all three of these ridges. The separation between the individual hydrothermal vent sites appears to be on the order of tens of kilometers. Comprehensive research conducted during the past 2 years along the Juan de Fuca, Endeavor, and Explorer Ridge systems suggests that the extent of hydrothermal activity and polymetallic sulfide deposition along oceanic ridge systems is more a function of that particular segment's episodic magmatic phase than the spreading rate of the ridge as a whole. Therefore, at any given time, a ridge segment with medium (or even slow) average spreading rate may show active hydrothermal venting as extensive as that found along segments with fast spreading rates.

Comparative observations between extent of hydrothermal activity and spreading rate suggest that the period between (1) active magmatic cycles marked by extensive extrusion of lava and (2) hydrothermal activity accompanied by polymetallic sulfide deposition is shorter for fast spreading segments than for medium to slow segments. The interval between magmatic constructional cycles is marked by tectonic activity and extension of the crust with the axial rift. Long extensional periods lead to the development of deep and wide rift valleys--extensively rifted and faulted --along the crests of slow spreading centers such as the mid-Atlantic Ridge (Macdonald 1982). The relatively frequent magmatic constructional cycles observed along the fast spreading segments of the East Pacific Rise obliterate most tectonic features. A high ridge crest with a narrow, shallow, and frequently nonexistent rift valley results (Macdonald 1982). Accordingly, massive polymetallic sulfide deposits may indeed be present along slow spreading ridge segments, but they are probably separated by greater time and distance intervals.

Volcanically active seamounts may also show sites of hydrothermal deposition. Lonsdale et al. (1982) observed extensive sulfide deposits located on "red" and "green" volcanoes of the East Pacific Rise. Loihi submarine volcano, located a kilometer below the ocean surface within the 200 nautical mile EEZ of the Hawaiian Archipelago, marks the latest phase of Hawaiian hot spot activity. The active seamount is located along the Hualalai-Maunaloa volcanic trend of Hawaii (fig. 9). The slopes of the

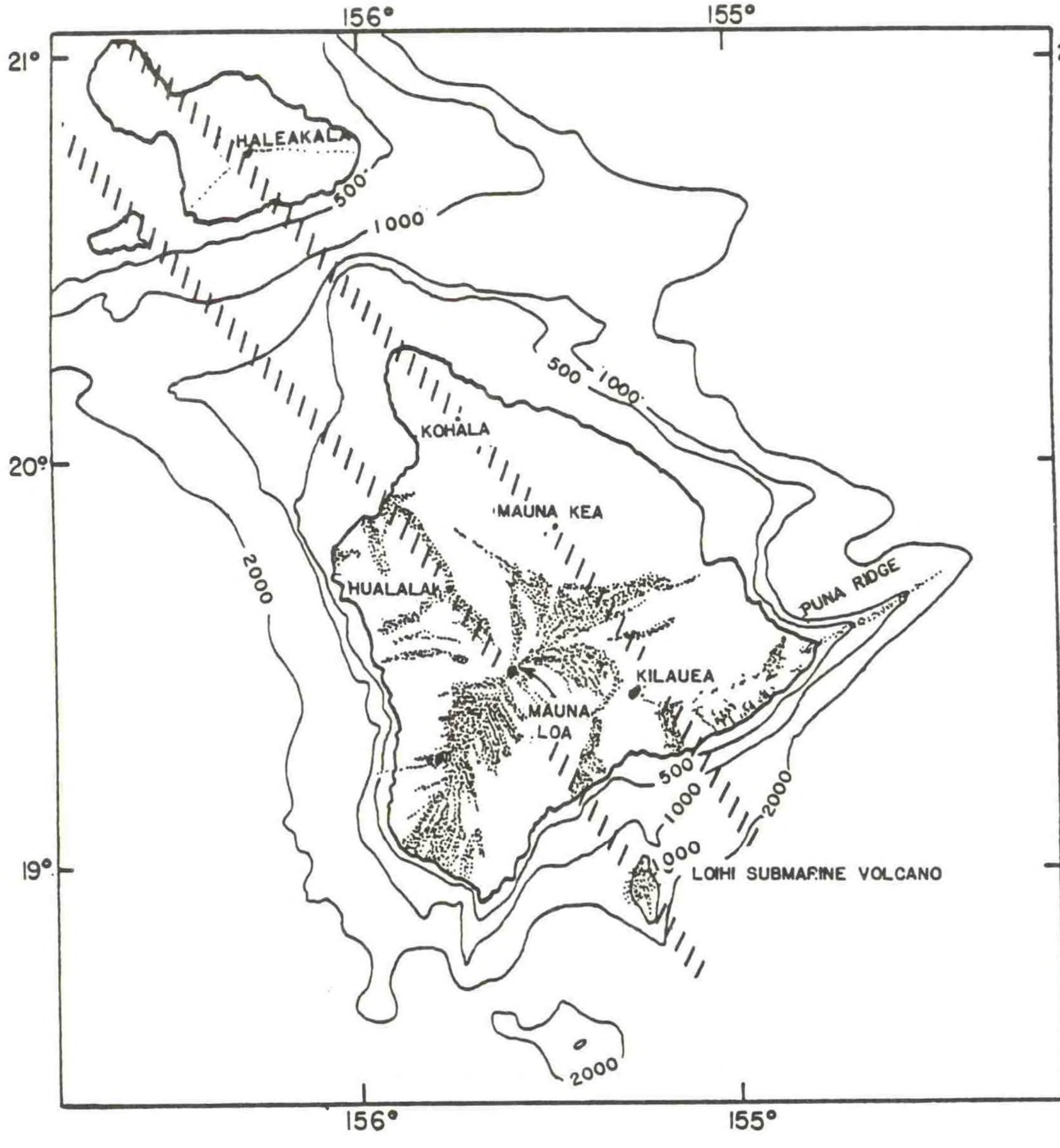

Figure 9.--Location of the Loihi submarine seamount adjacent to the island of Hawaii.

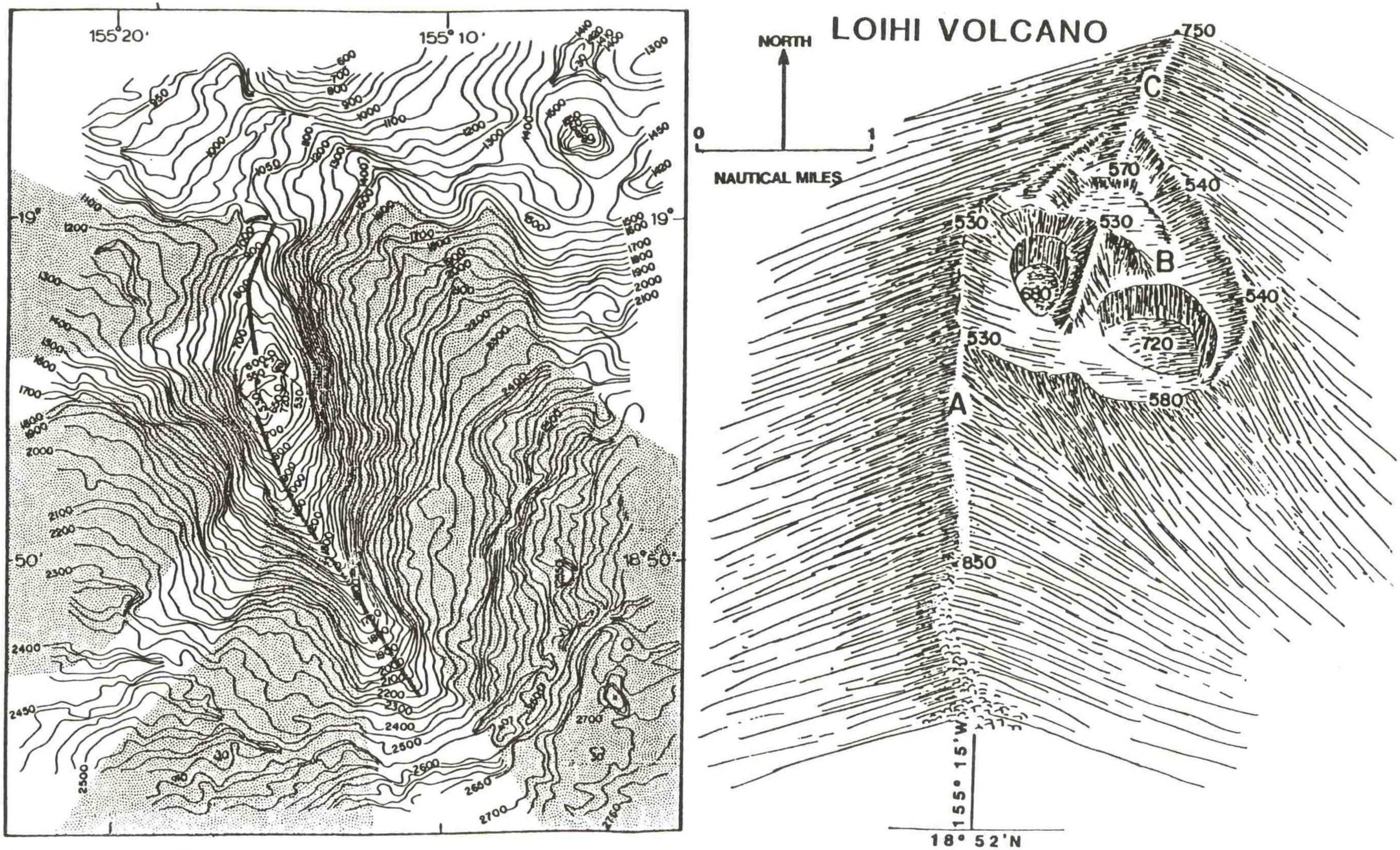

Figure 10.--Detailed bathymetric map of Loihi, based on multibeam surveys by the U.S. Navy with the SASS system (water depths in fathoms), together with a schematic drawing of the summit of Loihi, showing the distribution of rifts and craters.

volcano show erosion through mass sediment-wasting of talus. Analyses of a high resolution multibeam bathymetric survey (fig. 10) and bottom photographic data over the volcano show the presence of a large calderalike crater, two rifts, two pit craters (about half a kilometer in diameter), abundant talus, and recent lava flows, around which are located 7 acres of hydrothermal fields with abundant hydrothermal chimneys 1 to 3 meters high. Throughout the talus slopes, there is evidence of hydrothermal fluid which permeated up through the talus and deposited nontronite. Temperature anomalies of 1° to 2°C were observed 5 meters above the chimneys recorded in the photographs (Malahoff et al. 1982).

Research Frontiers and Future Economic Potential

Although marine polymetallic sulfide deposits may themselves prove to be a valuable resource, the current scientific value of ocean floor sulfides lies in their contribution to our understanding of their unique genetic processes and the help they may give in discovering analogous deposits on land, where there is abundant evidence of massive fossil marine polymetallic sulfide deposits. Cyprus, Noranda, and Kidd Creek, Canada, are all mining sites for polymetallic sulfides and all areas show the presence of underlying oceanic crust. Visiting the past by studying the present has led to the unravelling of the mechanisms by which this very important class of long-utilized minerals and ores was formed.

The ocean floor itself is the site of a wide range of precipitated hydrothermal minerals with possible future economic potential. These deposits range from the currently mined metalliferous brines of the Red Sea, to the active "smokers" of the East Pacific Rise, to the massive polymetallic deposits of the Galapagos Rift, to the zinc sulfide deposits of the Juan de Fuca Ridge. All these deposits have one factor in common--they have all been formed very recently along the presently active mid-ocean rift system of the world, some of which is located within the exclusive economic zones of the United States, Canada, and many Pacific Isles.

The discoveries of massive marine polymetallic sulfides of the ocean floor during the past 5 years may have a lasting effect on many segments of society. The United Nations' Law of the Sea negotiations are only now taking these recent scientific discoveries into account. Manganese nodules, whose distribution on the ocean floor has been relatively well mapped, represent a "two dimensional," largely nonrenewable deposit and may no longer constitute the prime mineral resource of the ocean floor. Their commercial importance may be overshadowed by the economic potential of the renewable polymetallic sulfide deposits or the nonrenewable cobalt-rich manganese crusts of Pacific Basin seamounts. Since this resource is renewable, "harvesting" of ocean floor polymetallic sulfide deposits may be a more appropriate term than "mining."

The technology of marine mining may take a dramatic turn from broad area "combing" of the seafloor for manganese nodules to precision spot mining or harvesting of polymetallic sulfide deposits. It may even be possible to utilize the energy available in higher temperature hydrothermal vent waters. The relatively simple geochemical composition of polymetallic sulfides, compared to that of manganese nodules, taken together with the availability of land-based plants currently processing polymetallic sulfides, may make the harvesting of seafloor polymetallic sulfides an even more attractive proposition in the future.

Sediment-hosted massive polymetallic sulfides, such as those that form the largest zinc ore bodies found in British Columbia's Sullivan Mine (Hamilton 1983), have yet to be observed on the ocean floor. This is primarily due to the fact that the research emphasis to date has been focused upon midocean ridge crest processes. Possible sites of active polymetallic sulfide precipitation of the lower temperature sediment-hosted zinc variety may be located within active rifts of Western Pacific marginal basins such as the Lau Basin, the north Fiji Basin, the Bismarck Sea, the Mariana Basin, and the Bonin-Ogasawara Trough (fig. 1). The marginal basins of the Western Pacific mark the new frontiers in the study of polymetallic sulfide deposition.

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REFERENCES

Adamides, N. G. 1980. "The Form and Environment of Formation of the Kalawasos Ore Deposits--Cyprus," Proceedings of the 1979 International Ophiolite Symposium, Cypriot Ministry of Agriculture and Natural Resource Geological Survey Department, Nicosia, pp. 117-127.

Backer, H. 1982. "Metalliferous Sediments of Hydrothermal Origin from the Red Sea," Proceedings of the Conference, Clausthal, West Germany, pp. 102-135.

Ballard, R. D., Holcomb, R. T., and Van Andel, T. H. 1979. "The Galapagos Rift at 86°W: Sheet Flows, Collapse Pits and Lava Lakes of the Rift Valley," Journal of Geophysical Research 84, pp. 5407-5422.

Ballard, R. D., Francheteau, J., Juteau, J., Rangan, C., and Normark, W. 1981. "East Pacific Rise at 21°N: The Volcanic, Tectonic and Hydrothermal Processes of the Central Axis," Earth and Planetary Science Letters 55, Amsterdam, pp. 1-10.

Ballard, R. D., Van Andel, T. H., and Holcomb, R. T. 1982. "The Galapagos Rift at 86°W: Variations in Volcanism, Structure and Hydrothermal Activity Along a 30 km Segment of the Rift Valley," Journal of Geophysical Research 87, pp. 1149-1161.

Canadian-American Seamount Expedition. 1985. "Hydrothermal Vents on an Axis Seamount of the Juan de Fuca Ridge," Nature 313, pp. 212-214.

Desbruyeres, D., and Laubier, L. 1980. "Alvinella pomfejana, Ampheretidac Aberrand des Sources Hydrothermales de la Ride Est-Pacifique," Oceanologica Acta 3, 3, pp. 267-274.

Edmond, J., and Von Damm, K. 1983. "Hot Springs on the Ocean Floor," Scientific American 248, 4, pp. 78-93.

Enright, J. J., Hewman, W. A., Hessler, R. R., and McGowan, J. A. 1981. "Deep Ocean Hydrothermal Vent Communities," Nature 289, pp. 219-220.

Franklin, J. M., Lydon, J. W., and Sangster, D. M. 1981. "Volcanic-Associated Massive Sulfide Deposits," Economic Geology 75, pp. 485-627.

Grassle, J. F. 1982. "The Biology of Hydrothermal Vents: A Short Summary of Recent Findings," Marine Technology Society Journal 16, 3, pp. 33-38.

Hamilton, J. M., Delaney, G. D., Hanser, R. L., and Ransom, P. W. 1983. "Geology of the Sullivan Deposit, Kimberley, B. C., Canada," Sediment-Hosted Stratiform Lead-Zinc Deposits, D. F. Sangster (ed.), Mining Association, Canada.

Hammond, S. R., Lee, J. S., Malahoff, A., Feely, R., and Embley, R. W. 1984. "Discovery of High-Temperature Venting on the Endeavor Segment of the Juan de Fuca Ridge," EOS 65, 45, p. 1111.

Hekinian, R., Fevrier, M., Bischoff, T. L., Picot, P., and Shanks, W. C. 1980. "Sulfide Deposits from the East Pacific Rise Near 21°N," Science 207, pp. 1433-1444.

Hekinian, R. 1984. "Undersea Volcanoes," Scientific American 251, 1, pp. 46-55.

Jones, M. 1981. "Riftiapachypitilia Zones: Observations on the Vestimentiferan Worms from the Galapagos Rift," Science 213, pp. 333-336.

Karl, D. M., Weisen, C. O., and Jannash, H.W. 1980. "Deep Sea Primary Production at the Galapagos Hydrothermal Vents," Science 207, pp. 1345-1347.

Knuckey, M. J., Comba, C. D. A., Riverin, G. 1985. The Millenbach Deposit, Noranda District, Quebec--An Update on Structure, Metal Zoning and Wall Rock Alteration, Geological Association of Canada Special Paper (in press).

Lonsdale, P., Batiza, R., and Simkin, T. 1982. "Metallogenesis at Seamounts on the East Pacific Rise," Marine Technology Society Journal 16, 3, pp. 54-60.

Macdonald, K. C. 1982. "Mid-Ocean Ridges: Fine Scale Tectonic, Volcanic and Hydrothermal Processes within the Plate Boundary," Annual Reviews of Earth and Planetary Science 10, pp. 155-190.

Malahoff, A. 1982a. A Comparison of the Massive Polymetallic Sulfides of the Galapagos Rift With Some Continental Deposits," Marine Technology Society Journal 16, 3, pp. 39-53.

Malahoff, A. 1982b. "Geology and Chemistry of Hydrothermal Deposits from Active Submarine Volcano Loihi, Hawaii," Nature 298, 5871, pp. 234-239.

Malahoff, A., McMurtry, G. M., Hammond, S., and Embley, R. W. 1984. "High Temperature Hydrothermal Fields--Juán de Fuca Ridge Axial Volcano," EOS 65, 45, p. 1112.

Malahoff, A., Embley, R. W., Cronan, D. S., and Skirrow, R. 1983. "The Geological Setting and Chemistry of Hydrothermal Sulfides and Associated Deposits from the Galapagos Rift at 86°W," Marine Mining 4, 1, pp. 123-137.

Massoth, G. J., Baker, E. T., Feely, R. A., and Curl, H. C. 1984. "Hydrothermal Signals Away from the Southern Juan de Fuca Ridge," EOS 65, 45, p. 1112.

McMurtry, G. M., Malahoff, A., Feely, R. A., and Massoth, G. J. 1984. "Geology and Chemistry of the Hydrothermal Nontronite Deposits from the Juan de Fuca Ridge," EOS 65, 45, p. 1112.

McMurtry, G. M., Epp, D., and Karl, D. M. 1983. "Project Pele: Studies of the Hydrology, Chemistry and Microbiology of Geothermal Systems on the Submarine Rift Zones of the Hawaiian Chain," Sea Grant Quarterly 5, 4, pp. 1-8.

The Merge, 1984. "Regional Setting and Local Character of Hydrothermal Field/Sulfide Deposit on the Endeavor Segment of the Juan de Fuca Ridge," EOS 65, 45, p. 1111.

Normark, W. R., Lupton, J. E., Murray, J. W., Delaney, J. R., Johnston, H. P., Koski, R. A., Clague, D. A., and Morton, J. L. 1982. "Polymetallic Sulfide Deposits and Water-Column of Active Hydrothermal Vents on the Southern Juan de Fuca Ridge," Marine Technology Society Journal 16, 3, pp. 46-53.

Rau, G. H. 1981. "Hydrothermal Vent Clams and Tube Worms 13-C/12-C: Further Evidence of Non-Photosynthetic Food Sources," Science 213, pp. 338-339.

Riddihough, R. 1983. "Poles of Motion, Gorda and Juan de Fuca Ridges," Special Publication Map Series, open file 83-6; Pacific Geoscience Center; Earth Physics Branch; Energy, Mines, and Resources, Canada.

Rona, P., Bostrom, K., Widenfalk, L., Cronan, D. S., and Jenkins, W. J. 1984. "Asymmetric Hydrothermal Activity and Tectonics of the Mid-Atlantic Ridge 11° to 26°N," EOS 65, 45, p. 974.

Scott, S. D., Barrett, T. J., Hannington, M., Chase, R. L., Fouquet, Y., and Juniper, K. 1984. "Tectonic Framework and Sulfide Deposits of the Southern Explorer Ridge, Northeastern Pacific Ocean," EOS 65, 45, p. 1111.

Spence, D., and De Rosen-Spence, A. F. 1975. "The Place of Sulfide Mineralization in the Volcanic Sequence at Noranda, Quebec," Economic Geology 70, pp. 80-89.

Walker, R. R., Matulich, A., Amos, A. C., Watkins, J. J., and Mannard, G. W. 1975. "The Geology of Kidd Creek Mine," Economic Geology 70, pp. 80-89.

Williams, P. M., Smith, K. L., Druffel, E. M., and Linich, T. W. 1981. "Dietary Carbon Sources of Mussels and Tube Worms from Galapagos Hydrothermal Vents Determined from Tissue 14-C Activity," Nature 292, pp. 449-449.

Useful hydrothermal/polymetallic reviews:

The Summer 1983 issue of Canada's GEOS (Ottawa) 12/3, pp. 1,3; article by Mungall, C., "Pacific Coast Ridge."

Hydrothermal Deposits at Seafloor Spreading Centers, P. A. Rona, K. Bostrom, L. Laubier, and K. L. Smith (eds.), Plenum Press, New York and London. NATO Conference Series IV:12, 800 pp., 1983.

The Fall 1982 issue of the Marine Technology Society Journal 16, 3, entire issue.

The July/August 1980 issue of NSF's Mosaic 11, 4, pp. 8-21.

The Fall 1984 issue of Woods Hole Oceanus 27, 3, entire issue.

OVERVIEW OF NOAA'S UNDERSEA PROJECTS

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ABSTRACT

With man's ever-increasing reliance on the earth's oceans and their vast resources, undersea research and its management have become increasingly vital. Because of the high costs and complex operational support required to implement undersea projects, most marine scientists are unable to support this type of research on their own. To alleviate this, the National Oceanic and Atmospheric Administration's Office of Undersea Research (OUR) makes available to the marine science community an ensemble of undersea facilities and capabilities that allow these scientists to conduct their research successfully. These facilities range from basic scuba and surface-supported tethered diving systems to highly sophisticated submersible and underwater habitat systems.

Through these university-based operations, the marine scientist now has access to unique research opportunities in such diverse locations as the mid-Pacific archipelagoes, tropical coral reefs, mid-Atlantic rift zones and Pacific trenches, fresh waters of the Great Lakes, marine canyons off the New England coast, and areas of the Atlantic Continental Shelf.

NOAA has been actively involved in undersea activities since 1971. At present, NOAA is involved not only in the operation of the five independent facility programs initiated in 1980 but also in the extensive use of submersibles for research, in the research and development of specific areas related to diver safety, and in the development of undersea technology. The future holds great promise, with plans for the expansion of OUR's activities to include Pacific Northwest areas, more extensive investigation of the Great Lakes, cruises into the Western Pacific, and the development of a Caribbean Basin undersea program.

Since the establishment of OUR's undersea facility programs in 1980 at the University of Hawaii (UH), University of Southern California (USC), University of North Carolina at Wilmington (UNC-W), and Fairleigh Dickinson University (FDU) at St. Croix, and the initiation of the University of Connecticut (UCon) project in 1983, NOAA's support of the marine science community in undersea research has expanded greatly. Each of these programs has grown in capabilities, facilities, personnel, range of research locations, and scientific opportunities. Extensive and highly sophisticated equipment, such as saturation habitats, deep diving submersibles, surface support platforms, mixed-gas diving systems, and remotely operated vehicles, is being used increasingly. With these new systems, the programs are permitting scientists to explore worldwide undersea locations at depths and for durations not formerly possible.

University of Southern California

To allow scientists the opportunity to dive and spend extended periods of time on the seafloor in either temperate or tropical waters, NOAA has developed an undersea program that will use a manned saturation habitat, the GEORGE F. BOND, built for temperate water science operations. Using this facility both as a home and a laboratory, 6 scientists will be able to live saturated on the seafloor for an average mission duration of 10 days and a maximum duration of 30 days. The habitat will be located at depths ranging from 60 feet of seawater (fsw) to 120 fsw and will allow the aquanauts to excurse from the habitat to a maximum depth of 200 fsw on tethered diving units.

At the deeper depths (greater than 50 fsw), a special breathing gas mixture, NITROX, will be used in the habitat. However, while excursing either on tether or scuba, the aquanauts will breathe normal air instead of NITROX. Divers will initially swim from the surface to the habitat. Once saturated, they must remain at

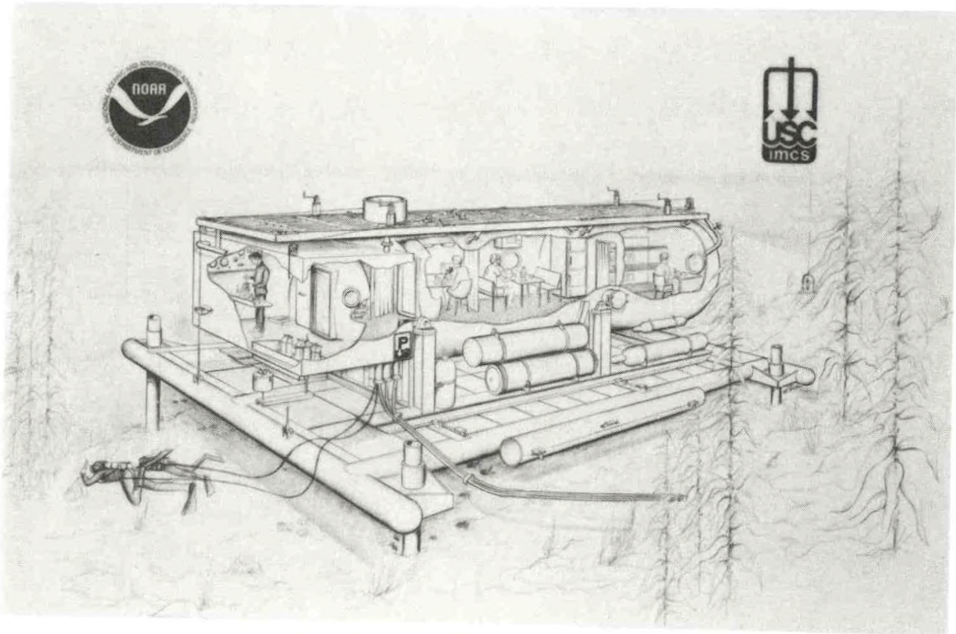


Figure 1.--GEORGE F. BOND habitat located on the seafloor with aquanauts conducting undersea research missions

that depth until the mission is completed, at which time they will go through the decompression process in the habitat; when the dive is completed, they will then return from the seafloor to the surface. At the habitat's maximum saturation depth of 120 fsw, the time for decompression could be as much as 3 days. In the event of an emergency while using NITROX, a Personnel Transfer Capsule (PTC) will be used to transfer the saturated aquanauts to a surface decompression chamber. Figure 1, an artist's conception of the GEORGE F. BOND, shows aquanauts working inside, while table 1 provides detailed specifications for the system.

The system, presently under construction at the Victoria Machine Works (VMW), Victoria, Texas, is scheduled to be completed in January 1986. Figure 2 shows the top assembly; figure 3, the

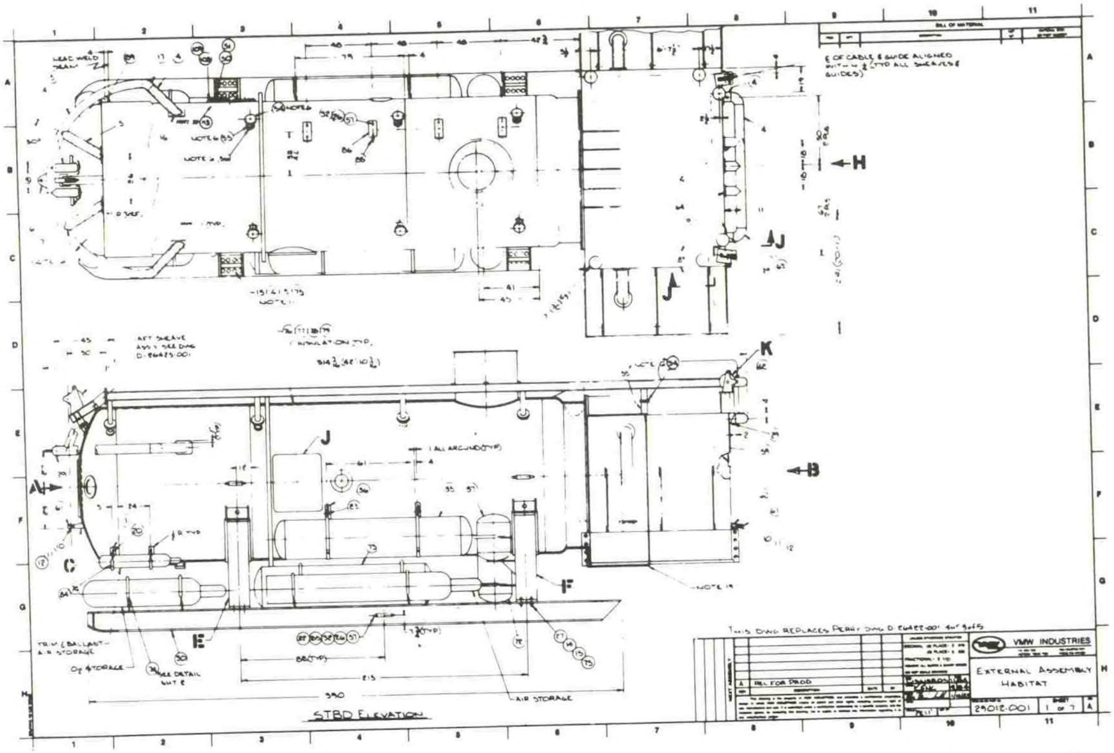


Figure 2.--External top assembly drawing showing plan and elevation views of BOND habitat

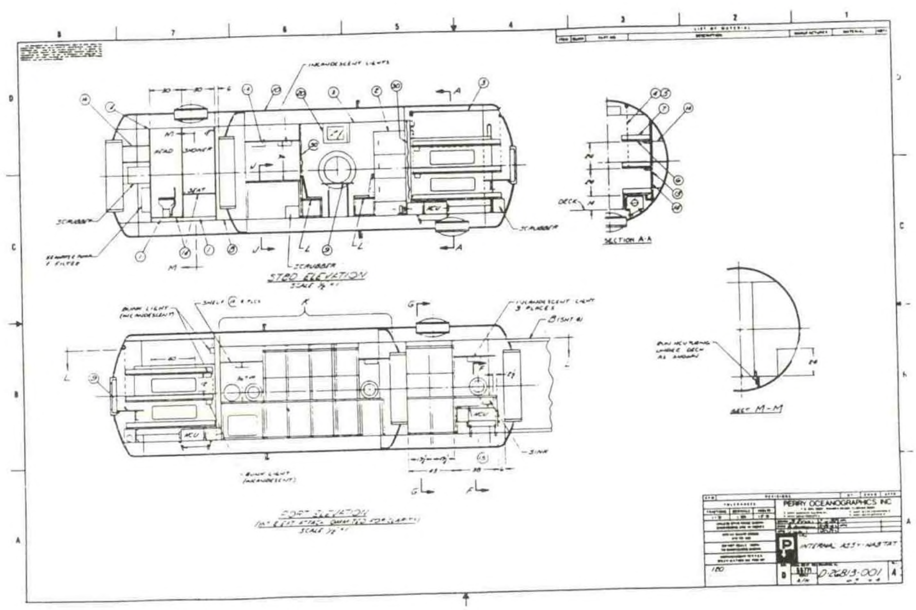


Figure 3.--Internal arrangement of GEORGE F. BOND habitat

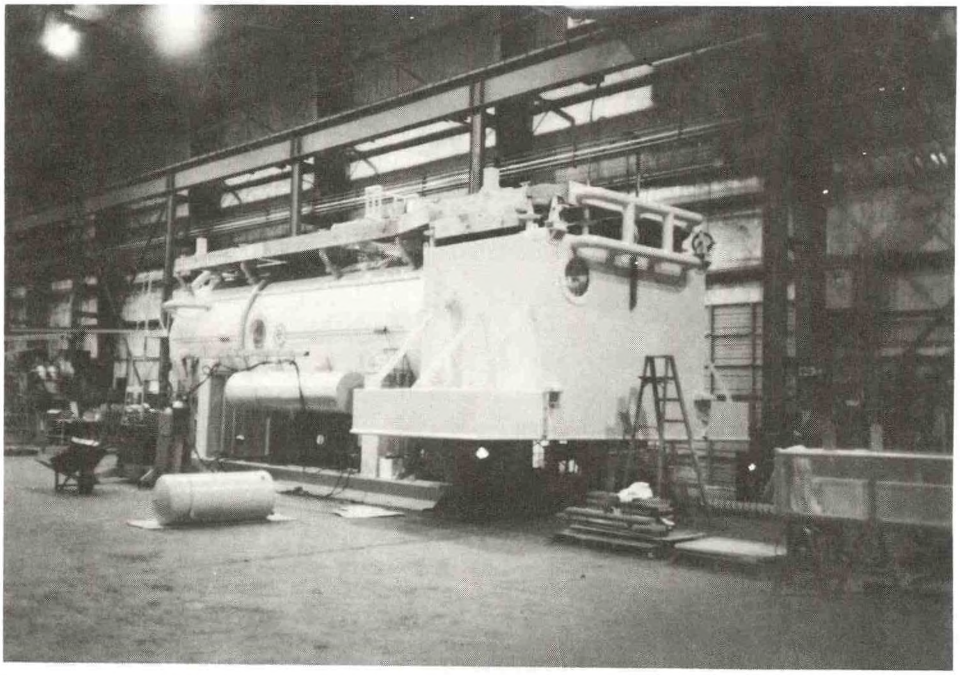


Figure 4.--GEORGE F. BOND habitat under construction at Victoria Machine Works

internal arrangement; and figure 4, the system while under construction at VMW.

The basic habitat is a double-lock chamber capable of both bottom and surface decompression and with the ability to be towed to another location without major modification of the structure. It will operate independently of shore support, with life-support functions supplied by a life support barge located overhead on the surface. The habitat will be deployed by a mobile Launch, Retrieval, and Transport (LRT) system. Control of all habitat functions will be in the hands of habitat occupants, while decompressions will be controlled by the program support staff on the surface.

The entrance to the habitat system is a "wet porch"--an enclosed ambient pressure chamber providing direct access to the sea through a large rectangular hatch. The wet porch area will be used for "suiting" up divers, filling tanks, rewarming divers with hot showers, and bringing daily supplies from the surface. It will also contain a "wet" sorting tray and aquaria for use by the scientists.

The habitat's main compartment will have sleeping and galley accommodations, while shower and bathroom facilities are located in the entrance lock chamber. Scientific facilities will feature a well-equipped underwater laboratory complete with microscopes, dissection equipment, aquaria, and computer equipment permitting real-time data analysis. The computer will be used to catalog samples and specimens and to plot trend graphs, as well as to monitor internal habitat conditions and critical operational parameters. If need be, it could also be integrated via the communications system with a main-frame system located topside or at a university.

The in-situ working range of the aquanauts will be extended by the use of underwater way-stations. These stations are open diving bells equipped with communications, breathing gas supplies, hot water, and electrical power. They consist of a heavy metal base with a plastic dome or "bubble" mounted above the base on metal struts. The bubble is filled with fresh breathing gas via a umbilical from the habitat, allowing the aquanaut to climb inside, remove his mask, and talk or rest.

The program anticipates that the habitat will be used for 12-16 saturation research missions per year, with the first mission starting in late 1986. Since it is readily towable, the system will be located at research sites selected in accordance with scientific needs. It will initially be located off St. Croix in the U.S. Virgin Islands. This new laboratory/habitat is the first of its kind built for both the temperate coastal zones and tropical waters of the United States.

University of Hawaii

NOAA's Undersea Research Program at the University of Hawaii, also known as the Hawaiian Undersea Research Laboratory (HURL), is headquartered at the university's main campus, with the facility operations based at the Makai Research Pier, Makapuu Point, on the island of Oahu. Since 1980, the program has used the two-man submersible MAKALI'I, which has a maximum depth capability of 1,200 fsw. During this period the submersible has been extremely effective; it has been used for many missions within the Hawaiian Islands and for three extensive scientific cruises to the mid- and western Pacific. Based on experience with the MAKALI'I to date and the expressed needs of the science community, it is apparent that a system with deeper capability is needed. To this end, the Hawaii program is obtaining a submersible with greater depth capability in 1986 and is presently negotiating the purchase of the PISCES V submersible. This sub, which is capable of carrying three men (one pilot and two scientists), has a maximum depth limit of 6,600 fsw and a maximum mission time of 6 to 8 hours. Table 2 describes the system's detailed specifications and capabilities.

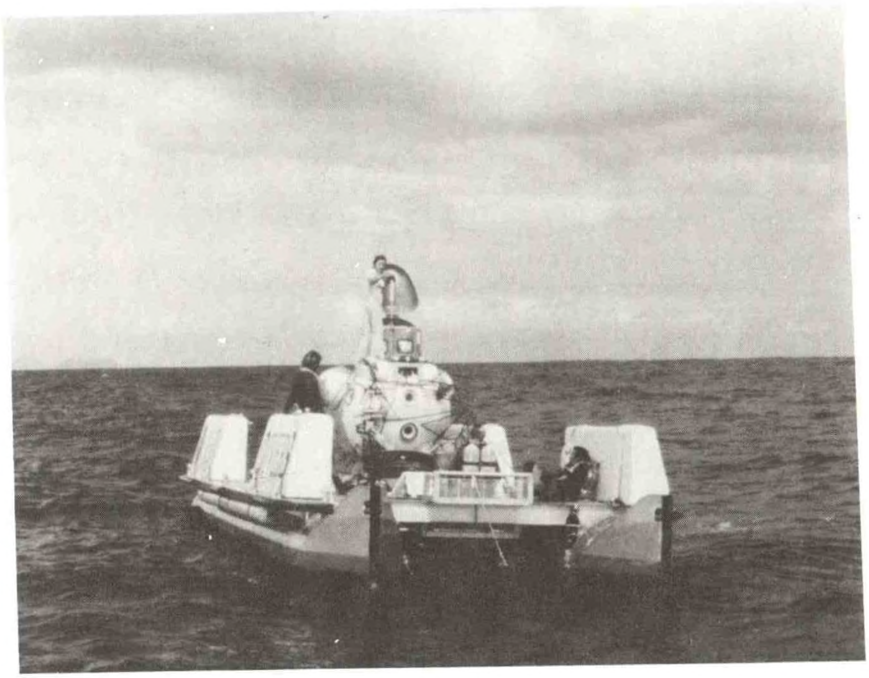


Figure 5.--University of Hawaii's shallow submersible, MAKALI'I, on its Launch, Retrieval, and Transport (LRT) vehicle

Because of the PISCES' greater weight (compared to that of the MAKALI'I) (12 tons versus 5 tons), a new LRT vehicle will have to be designed and built for the new submersible. The system will be deployed and recovered in a manner identical to that used in MAKALI'I operations. The submersible rests on the LRT while in transit to the dive site, as shown in figure 5. Prior to launching, scuba divers go aboard the LRT and control its descent, figure 6, with the submersible still attached--through the air-sea interface. After reaching the proper launch depth at approximately 50 feet, divers release the submersible, figure 7, which then backs off the LRT and carries out its planned mission. While the submersible is conducting its mission, the LRT surfaces and awaits the sub's return. With its mission completed, the

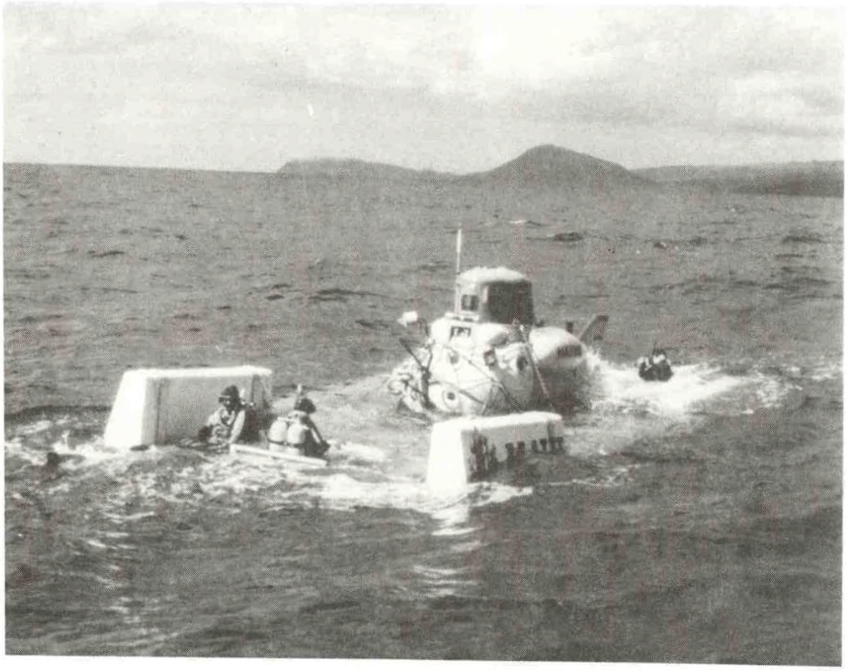


Figure 6.--Submersible MAKALI'I and LRT being submerged by divers in preparation for launching submersible

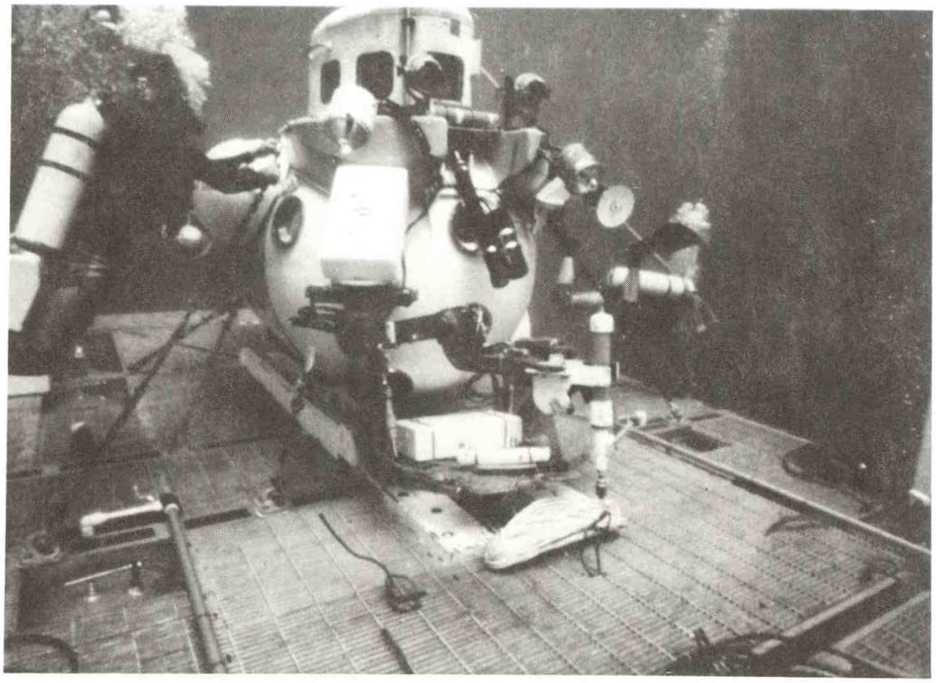


Figure 7.--Divers at 50 ft water depth releasing MAKALI'I from LRT for launching

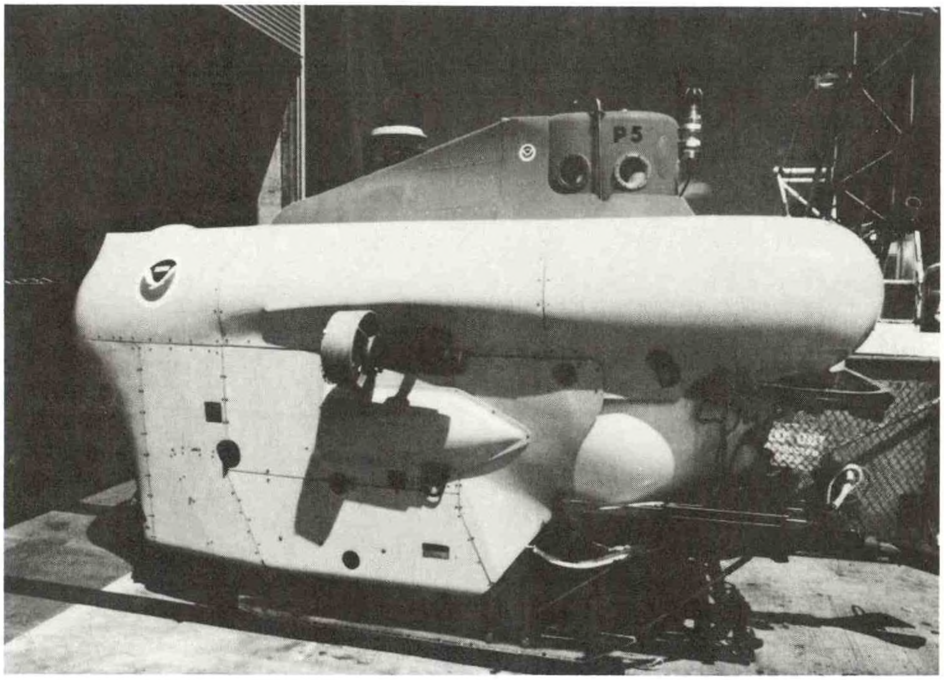


Figure 8.--PISCES V submersible operated as part of NOAA's Undersea Research Program at the University of Hawaii

submersible returns to a depth of 50 feet, the LRT is submerged, and the submersible is retrieved. During this entire operation, the LRT is at all times tethered to the tow ship. Figure 8 shows the PISCES V outside its hangar in Hawaii.

With the ability to dive to 6,600 fsw and to carry two scientists plus a pilot, the Hawaii-based science program will be expanded to cover the entire Pacific area, including the western regions. Scientists will be able to study the tops of seamounts (normally about 2,000-3,000 fsw under water) and to descend part of the way down the sides of the seamounts. Deep-water mineral deposits, such as those of polymetallic sulfides and cobalt, that were previously inaccessible because of depth, will be accessible for direct observation, sampling, and monitoring.

After the purchase of the PISCES and the construction of its LRT in 1986, scientific operations are planned to begin in late 1986. Research areas emphasized by this program will include:

- o Fisheries: ecosystem assessment and dynamics; habitat degradation and enhancement; harvesting impact; animal behavior; and gear development
- o Pollution: manner and physical effects of waste disposal; behavioral, biochemical, and physiological responses of marine organisms to pollutants
- o Seafloor properties and processes: geological, geochemical, and geophysical aspects, including gradients in the water column near the seafloor, sediment transport, stability, fluxes, and mineral resources
- o Ocean technology and services: marine sanctuary monitoring; engineering; equipment testing and recovery; medical and diving physiology; and archaeology.

Fairleigh Dickinson University

Prior to 1976, the saturation habitat HYDROLAB was owned and operated by Perry Oceanographics, Inc.--off Freeport Island in the Bahamas--through a grant with NOAA. With the termination of that project in 1976, NOAA purchased the habitat and refurbished it. It was placed back into operation, as shown in figure 9, in 1978 off the coast of St. Croix in the U.S. Virgin Islands. Located approximately 1/2 mile off the northeastern shore of St. Croix, the habitat was positioned at a depth of 50 fsw in the head of the Salt River Submarine Canyon. During the period of

Figure 9.--Aquanauts working in-situ next to saturation habitat, HYDROLAB, off St. Croix, USVI

scientific operations beginning May 1978 and ending July 1985, 99 HYDROLAB missions were conducted involving 331 scientists, who logged a total of 55,056 hours of saturation; all of these hours were devoted exclusively to undersea and marine-related research.

Because of the facility's age and the expense associated with complying with American Bureau of Shipping (ABS) refurbishment requirements, it was decided that it was more cost-effective to terminate HYDROLAB operations in 1985 and to replace the habitat with a new and more modern and capable habitat. This new system will use the LRT from the old AEGIR habitat originally belonging to the Navy. The newly constructed and outfitted GEORGE F. BOND habitat, originally constructed for operations off the California coast, will be sent to St. Croix and mounted on the AEGIR's LRT. The detailed specifications and capabilities of the system, shown in table 1, are also applicable to the St. Croix-based operation of this habitat.

The new habitat will have considerably greater mobility than the HYDROLAB. Because the pressure vessels are mounted on the LRT, the system can be towed by a support vessel. The LRT functions in a manner similar to the methods used to launch and retrieve the submersible in the Hawaii system. It has onboard ballasting and trim systems that are controlled externally by support divers, which allows the entire system to be raised and lowered from the seafloor. In contrast, the HYDROLAB was permanently located in Salt River Canyon and the scientific program was centered only in that area. Because the new system is mobile, the science program will encompass the entire Caribbean basin area and may involve as many as 15 different countries. The new habitat system will be moved to and located at research sites in response to scientific needs and the importance of the science projects that can be developed at various sites. The system will remain at each location for a period of 6 to 12 months.

Refurbishment of the AEGIR system has already begun at St. Croix. The habitat system is expected to be in the water in

October 1986 for tests and evaluation, and the first scientific mission is scheduled for December 1986.

University of Connecticut

NOAA's undersea research program at the University of Connecticut is the newest of OUR's five facility programs; it was started in mid 1983 and conducted its first scientific missions in 1984. In 1985, an extensive science program was initiated that involved conducting shallow water (less than 3,000 fsw) submersible cruises both in the Gulf of Maine off the New England coast and in the Great Lakes. This was the first time NOAA has conducted submersible operations in the Great Lakes. Because of the difference in buoyancy between fresh and salt water, certain modifications had to be made to the JOHNSON SEA-LINK II, the submersible from the Harbor Branch Foundation (HBF) that was used to dive to Lake Superior's seafloor. Figures 10 and 11 show both the submersible and HBF's new support ship, the R/V SEWARD JOHNSON.

A total of 23 days of scientific dives were conducted. These dives were extremely successful and productive, providing scientists with data, new insights, and considerable information on conditions in and ecosystems of the lake. Diver scientists from 8 universities and 6 state government agencies and NOAA made a total of 45 manned dives at 25 locations through the central and eastern regions of Lake Superior--logging more than 225 man-hours of "bottom time."

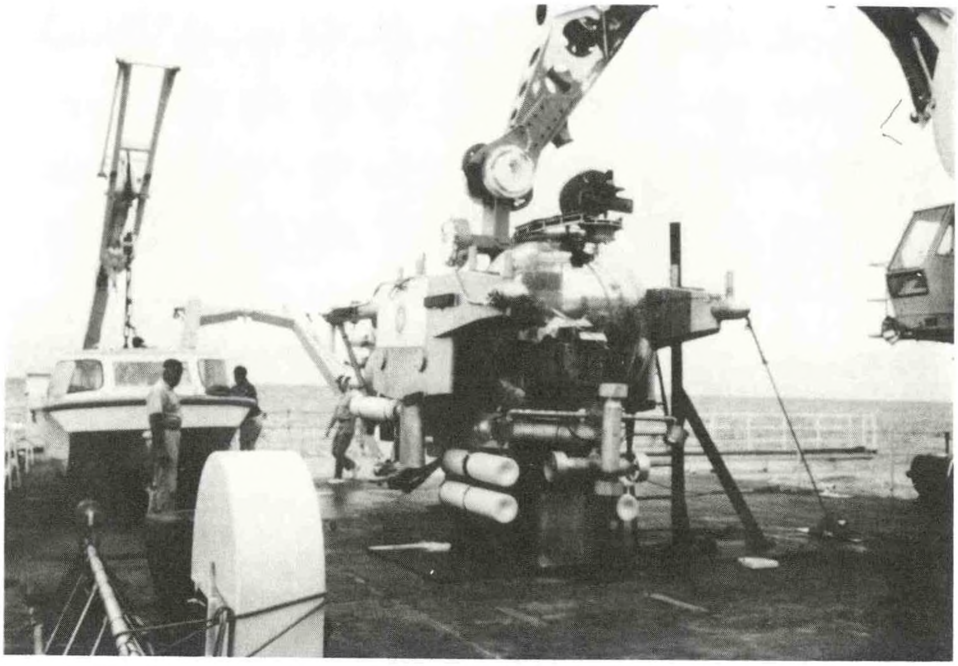


Figure 10.--JOHNSON SEA-LINK submersible being prepared for launching on deck of support ship

Figure 11.--Harbor Branch Foundation's new support ship R/V SEWARD JOHNSON used for operational support of JOHNSON SEA-LINK submersibles

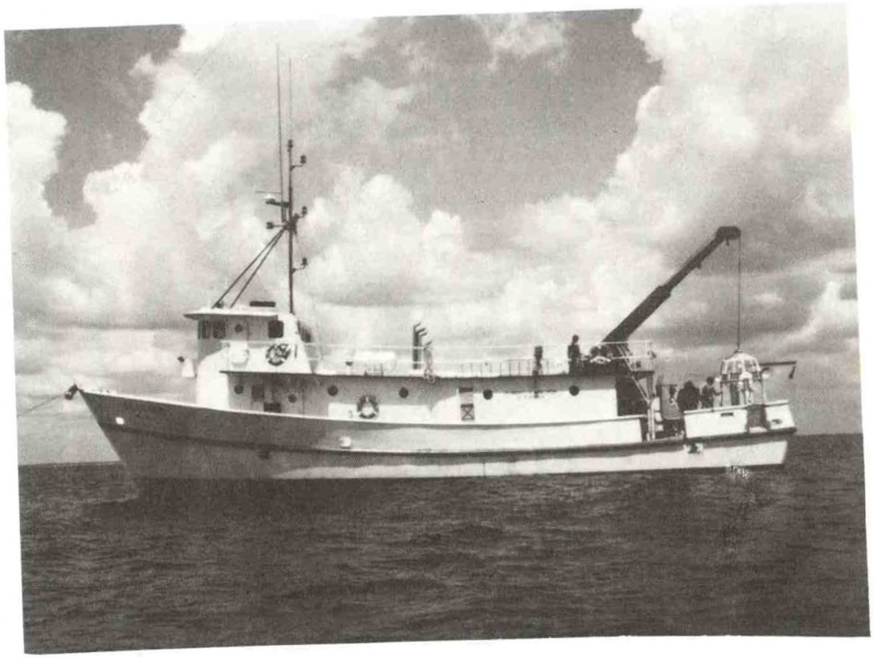


Figure 12.--University of North Carolina (Wilmington) surface support ship, R/V SEAHAWK, used for conducting mixed gas scientific diving operations to 250 ft depths

This cruise represents the first year of a planned 5-year program to increase our understanding of the physical, chemical, and biological dynamics of the Great Lakes. The University of Connecticut will combine its Great Lakes activities and New England coast projects into a well-integrated science program, using a competitively leased manned research vehicle as its primary undersea facility. Depending on the needs of researchers, a sophisticated remotely operated vehicle (ROV) system may be used to augment the submersible work.

University of North Carolina (Wilmington)

NOAA's undersea program at UNC-W became fully operational and conducted its first scientific mission in 1982. As the primary facility, the research ship R/V SEAHAWK, shown in figure 12, supports a surface-tethered mixed-gas diving system and an open or "wet" bell. The ship has an overall length of 76 ft and berthing arrangements for 12 persons (8 crew and 4 scientist/aquanauts), can support at-sea operations for a maximum of 7 days, has a refrigerated specimen storage area, and provides a laboratory complete with running water, working space, and electricity.

The onboard diving equipment includes a double lock recompression chamber, a fully equipped open bell, a diver in-water stage, tethered diving gear, and a highly trained and experienced diving support crew. Both the system and the crew are certified to use scuba (air) to 130 fsw, surface-supplied air without use of a bell to 130 fsw (with a bell to 190 fsw), and to 250 fsw using mixed gas (NITROX) with the bell. Prior to the mission, the scientific team is trained and checked out on the systems it will use. During scientific missions, a staff diver always accompanies the scientific diver, with a standby staff diver on the surface suited up and ready to enter the water in case of an emergency. Each member of the diving crew is trained and experienced as a Diver Emergency Medical Technician (DEMT) and hyperbaric chamber operator.

A few overall system difficulties have been identified in the course of 3 years of scientific operations. Specifically, the difficulty of maintaining a three-point moor during an appreciable sea state, with wave heights greater than 4 ft, has presented a major problem. Without a proper moor, the bell cannot be launched, and several scheduled missions have been aborted for this reason. The limited scientific space onboard the SEAHAWK has also been a concern. To enhance the program's capabilities to conduct more missions in higher sea states and to provide more onboard scientific space, a larger support ship is being considered to replace the R/V SEAHAWK. A modular approach to the development of the new ship's capabilities will be taken: the ship must support "wet" bell mixed-gas diving operations, permit operation of a one-ATA suit, a remotely operated vehicle (ROV), a small submersible, and a saturation bounce dive system, depending on the direction of scientific research and the needs of specific researchers. The general performance requirements being considered for a new research vessel for the UNC-W program are shown in table 3.

The geographical region encompassed by the program covers thousands of square miles stretching from the Gulf of Maine to the Gulf of Mexico. Fishery habitats, sandy bottoms, and hard-bottom faunal communities are characteristic of these areas. The principal research topics of interest are:

- Environmental impacts of marine pollution and waste disposal programs
- Fisheries management
- Hyperbaric physiology and diving medicine
- Marine archaeology
- Baseline data on undersea geology, plant and animal life, and seafloor processes.

The program plans to phase in additional capabilities and equipment as needed to expand the scope and range of its research activities.

Other Undersea Programs

Submersible vehicles have been one of the principal research tools used in NOAA's undersea research program. The program has made use of both deep- and shallow-water submersibles that are owned and operated by private companies, institutions, and the Navy. OUR's role is to obtain the use of these vehicles, to provide peer review of scientific proposals submitted by potential researchers, and then to implement the selected submersible cruises. This program has been extended to include not only NOAA scientists but also those in colleges and universities participating in the National Sea Grant Program.

OUR has found submersibles ideal for direct in-water observation of the underwater environment. They are particularly valuable in helping scientists to understand underwater phenomena that involve time-related or dynamic functions, such as sediment transport, current activity, or benthic reworking. In areas of rough bottom topography, studies of animal behavior and species distribution are nearly impossible to perform without the use of submersibles. Ocean dumping studies and many other types of undersea environmental assessments are also best performed via submersible vehicles. In addition, actual underwater photographs, core samples, and measurements often make interpretation of existing data easier by providing important "hands-on" clues to underwater events.

In addition to the undersea facilities discussed earlier, OUR supports a considerable number of undersea technology projects, activities in diving medicine and safety, and international projects.

Each year the office implements a series of workshops on timely topics of interest to the diving medicine and marine research community. These workshops are arranged by the Undersea Medical Society (UMS) under a NOAA-OUR grant and are attended by experts from military, other Federal, academic, industrial, and private sector circles. Past topics have included the use of hydrogen as a diving gas, advances in decompression procedures after saturation, findings of recent man-in-the-cold studies, post-accident treatment of divers, and the special needs and requirements of handicapped divers.

Since 1972, NOAA has continued to participate in joint U.S.-Japan diving research and undersea development programs through the UJNR. OUR is working closely with the Japan Marine Science and Technology Center (JAMSTEC) to develop and implement joint undersea programs that will:

1) Encourage, develop, and implement the exchange - between the United States and Japan - of undersea science and technology (including data, other information, facilities, state-of-the-art equipment, and personnel) in the areas of diving physiology and technology

2) Develop close and meaningful scientific, governmental, industrial, and personal ties among scientists, engineers, and administrators from the two countries

3) Conduct joint undersea and diving-related research and development missions and hyperbaric physiology projects using undersea technology. Resources to be used include such facilities and techniques as hyperbaric chamber complexes,

SCUBA and tethered diving (both air and mixed gas), manned submersibles, diving support vessels, habitats, and unmanned undersea vehicles

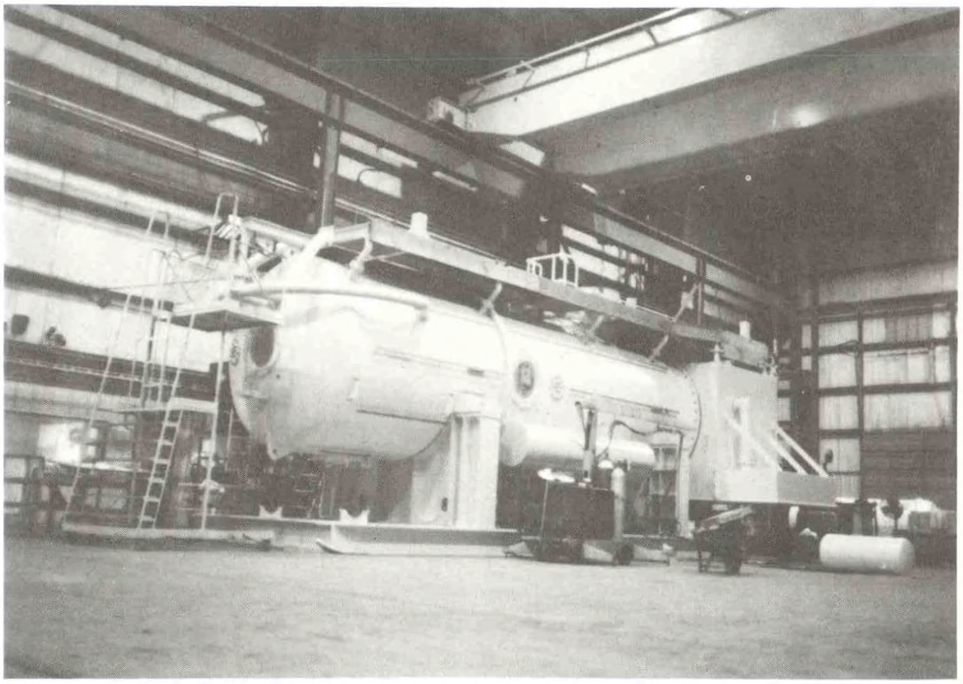
4) Implement administrative mechanisms, systems, and procedures to achieve the panel's joint objectives.

Topics and subject areas of special interest to the UJNR Panel are: Hyperbaric and diving medicine; hyperbaric, diving, and thermal physiology; diver performance; diving technology; and the application of diving technology (including the use of related undersea facilities).

Summary

The Office of Undersea Research will continue supporting its present undersea research programs and projects and expand into new areas and disciplines dictated by the needs of the science community. OUR intends to continue the development of the network of cooperative undersea programs established in 1980. Since its inception, the national program has grown from a single Caribbean facility to include five active programs located in diverse geographic regions: the Caribbean, North Carolina, Hawaii, California, and Connecticut. Plans call for continued expansion of the program to take maximum advantage of U.S. personnel and environmental marine resources.

Table 1.--Preliminary Specifications for the GEORGE F. BOND Habitat



General Data

Overall envelope & dimensions:

Length: 43'
Breadth: 20'
Height: 16.5'

Internal lengths & volume:

Main lock (ML)	21.5'	1400 ft^3
Entrance lock (EL)	8.5'	500 ft^3
Wet porch (WP)	8.0'	700 ft^3

Internal diameter: 9'

Wet porch

Length: 8'
Breadth: 12'
Height: 7'

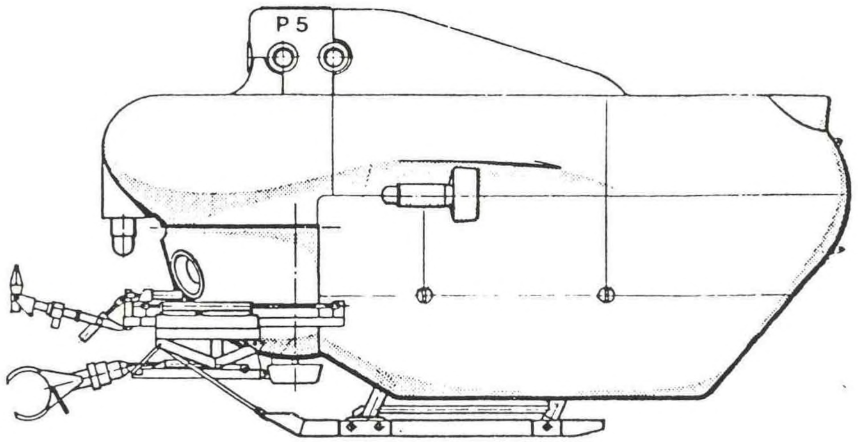
Table 1.--Continued

Weights	
Dry in air:	
Habitat:	130,661 lbs.
Ballast and trim:	14,725
	145,386
Displaced:	152,369
Buoyancy:	
WP blown dry:	44,000
WP flooded (with 6" bubble)	7,000
Surface buoyancy (ballast tanks blown)	11,410
Payload (mission weight including: personnel, provisions, and equipment)	5,000
Baseplate (on seafloor with cement ballast)	72,400
Surfaced freeboard	3 ft
Surfaced draft	12 to 13 ft
Personnel accommodations:	
6 scientists (aquanauts)	
Mission duration:	
Average: 10 days	
Maximum: 30 days	
Hyperbaric capability:	
Max. external depth:	120 fsw (54 psi)
Max. internal depth:	232 fsw (103 psi)
Emergency life support:	72 hr for 6 persons + 1 complete decompression from maximum depth
Environmental ranges:	
External water temperature:	4°-21°C (39°-70°F)

Table 1.--Concluded

External air temperature:	4°-38°C (39°-100°F)
Internal temperature:	20°-35°C (68°-95°F)
Internal humidity:	50°-60°C% of RH
Maximum surface conditions:	Sea State 3
<u>Electrical power</u>:	
Connected load: (1 phase, 220 V to habitat; 120 V ac, 24 V dc in habitat)	90 KVA
Normal system total operating load	62 KVA
Normal habitat (umbilical) load	16 KVA
External access to habitat:	
Manway size:	24" W x 60" H
Hatch size:	26" ID
Provisions/medical lock:	12" ID
Viewports:	23 1/2" (2 each)
	10" (6 each)
<u>Diving systems</u>:	
Scuba (air), tether (air), way station wet bell	

Table 2.--Specifications for the PISCES V Submersible



PISCES V submersible operated by the University of Hawaii

General Data

Length: 20' (6.10 m)

Breadth: 10.5' (3.18 m)

Height: 11' (3.35 m)

Weight: 12 tons

Payload: 600 lbs. (278 kg)

Crew: 1 pilot, 2 scientists

Life support: 3 men for 176 hours

Operating depth: 6,600' (2,012 m)

Max. speed: 2 knots

Normal speed: 8 hours at 1 knot

Duration: 6-8 hours

Power: 120 V dc

Main Propulsion: 2 side thrusters 5 HP

Table 2.--Continued

Construction

- Built by HYCO and classified by the American Bureau of Shipping
- Pressure hull is made up of three spheres of HY 100
- Viewports: 3 of 6" (15 cm) in pilot sphere
- Through-hull fittings all go through removable penetrator; several blanked spares for additional equipment functions.
- ABS classified: Design depth: 2,000 m
  Operating depth: 1,500 m

Jettison:

- 1 main dropweight 398 lbs (181 kgs)
- 2 fwd dropweights 220 lbs (100 kgs)
- 1 heavy duty claw 29 lbs (13 kgs)
- 1 arm claw 29 lbs (13 kgs)
- 2 thrusts 238 lbs (107 kgs)

Table 3.--UNC's New Support Ship -- Performance Specifications

1) ABS classified and USCG inspected;
2) Overall length: 165 to 200 ft;
3) Berthing: 30 persons (15 crew, 15 scientists);
4) Endurance (at sea): 30 days;
5) Speed: 12 knots;
6) Navigation: ability to locate and relocate specific research sites precisely; Loran C, satellite systems;
7) Communication: VHF, HF, and radio-telephone;
8) Four-point mooring capability for 300-ft depths and 12-ft seas;
9) Both fore and aft thrusters (preferably 360° directional units);
10) Constant tension/heave compensated bell launching system;
11) 300-fsw mixed-gas diving system;
12) Lifting capability of 20-ton hydraulic crane and 15-ton movable A-frame (both ABS and man-rated operations);
13) Wet-dry photo lab facilities, science storage space with freezer and refrigerator, climate control to maintain comfortable temperature in all inhabitable spaces; and
14) 400-kW electrical system;
15) Capable of supporting modular operations, e.g., ROV's, 1-ATA systems (JIM, WASP, MANTIS), manned submersibles, and mixed-gas open bell tethered diving systems.

TIMEKEEPING DEVICES IN DIVING

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INTRODUCTION

Diving into the sea requires sure control of time; divers should wear a diver's watch and an on-board timekeeper should measure the dive times, because the exposure of the human body to water pressure, which increases with depth, may cause decompression sickness. Human beings also wear an underwater breathing apparatus, a diving suit, and other equipment to minimize the dangers of the sea and to ensure their safety.

Today, divers' watches and stopwatches are electronic and have a combination of digital and analog indicators, an additional alarm, a bottom timer that actuates the button switch of a stop watch by means of water pressure and the measurement of bottom time, and a decompression computer that indicates decompression information. Their accuracy has also increased; thus, timekeeping devices for diving are entering a new era.

DEVELOPMENT OF WATERPROOF WATCHES AND DIVERS' WATCHES

An older type of portable timepiece was the pocket watch, which was sensitive to dust. A waterproof watch was patented in the late 19th century and the use of wrist watches started in the 20th century. Washing the hands while wearing a wrist watch frequently caused the watch to malfunction because of water pene-

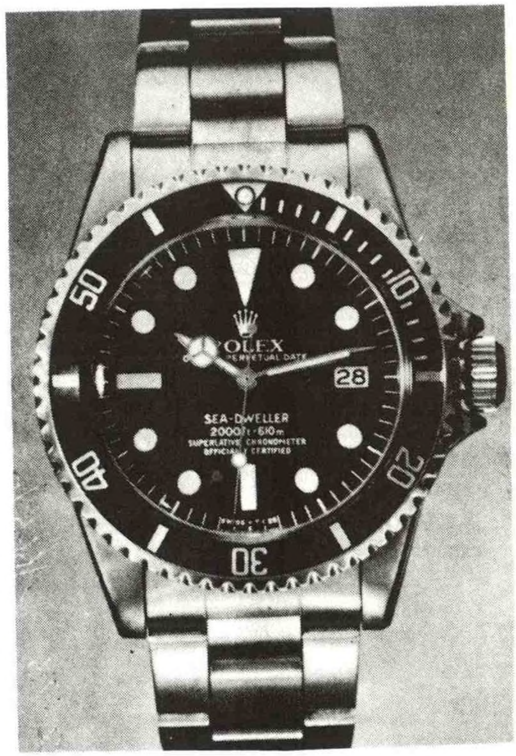


Figure 1.--ROLEX Sea-Dweller 4000

tration, so that making them waterproof has increased their usefulness. As for spring-driven wrist watches, the stem packing was easily worn down and frequently penetrated by water. The first type of diver's watch (ROLEX OYSTER: watertight at a depth of 50 m) emerged in 1926. In World War II, diver teams were organized by the navies of several countries, so that demand for a diver's watch increased. In 1953, a diver's watch capable of being used to a depth of 100 m was marketed. Not until 1971 was a watch that could be used at 610 m developed, but by the 1980's, the ROLEX SEA-DWELLER 4000 (1,220 m), CITIZEN PROFESSIONAL DIVER (1,300 m), and SEIKO PROFESSIONAL 600 (2,000 m) had been developed (Figures 1, 2, and 3).

Figure 2.--CITIZEN Professional Diver 1300

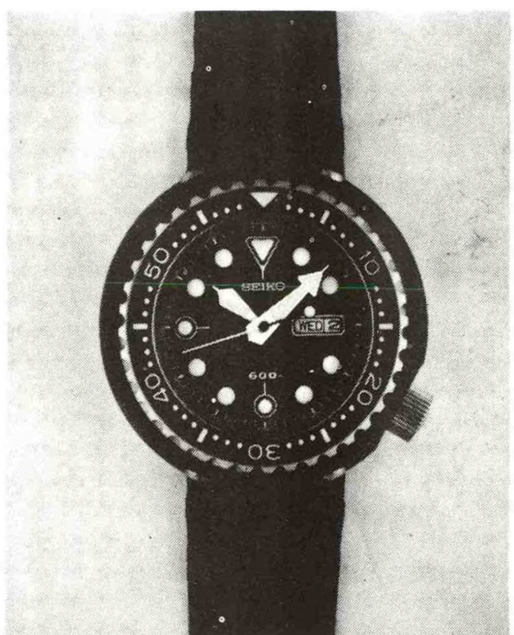


Figure 3.--SEIKO Professional 600

CURRENT REQUIREMENTS FOR DIVERS' WATCHES

The waterproof case, crown, bezel ring, and band of divers' watches are specifically designed to withstand severe environments and underwater work, in contrast to ordinary waterproof watches. The standard for diver's watches is described in International Standard ISO 6425, Diver's watches (1982-12-01).

General Purpose Divers' Watches

General purpose divers' watches are used for scuba diving and for helmet diving on air in shallow water.

Tightness

Any diver's watch should resist an overpressure in water of not less than 100 m in depth. Depths more than 100 m are marked, e.g., 200 m, 300 m, and so on, in intervals of 100 m.

The following reliability tests are conducted based on a marked depth (L m).

1. Tightness test at water overpressure; all tested watches shall be immersed in water. Then an overpressure of (L + 0.25L)/10 bar shall be applied within 1 min and maintained for 2 hr. The watches shall then be removed from the water and shall pass the condensation test.

2. Resistance test of crowns and other setting devices to an external force; the watches in this test shall be subjected to an overpressure in water of (L + 0.25L)/10 bar for 10 min and to an external force of 5 N, applied as shown in Figure 4.

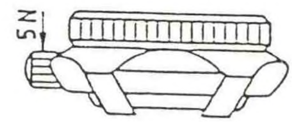


Figure 4.--Resistance tests on divers' watches

Waterproof case

The waterproof case of a diver's watch is generally and mainly made of stainless steel. The case consists of three parts: shell, back cover, and glass. A very pressure-resistant watch is provided with a thicker glass and back cover. Every connecting portion is sealed with an O-ring. Crowns are tested by the above external force combined with an overpressure and have a screw-type locking mechanism that increases the waterproof performance of the watch and an O-ring sealing the stem from water.

Accuracy

Modern divers' watches increasingly use a quartz and are generally of the automatic winding type. Divers' watches of this type usually have a daily loss/gain rate of 15-30 sec, so that their accuracy is sufficient to use to control dive times. "High beat" watches have a second pointer capable of moving 10 times within 1 sec, in contrast to ordinary automatic winding-type watches that have 5-6 motions of a second pointer within 1 sec. The high beat watches have an increased accuracy of several sec in terms of daily loss/gain. Quartz watches may lose or gain only 15 sec in a month; they lose in a month what earlier watches lost in a day.

Bezel ring

A diver's watch features a waterproof case and a bezel ring; the bezel ring is indispensable to the control of dive time (elapsed time) and is set to the minute hand at the start of diving and measures bottom time. Some bezel rings turn only counterclockwise and some can turn in both directions. If a bezel ring turns counterclockwise, the set bottom time indicates a longer time than the actual bottom time; that is, it will indicate a longer decompression time so that safety is increased. If a bezel ring turns clockwise, the set bottom time shows less time than the actual bottom time; as a result, the danger of omitting decompression may occur. Therefore, bezel rings that only turn counterclockwise are generally used, despite their slower setting.

The safety mechanisms on the bezel ring include designing the ring to require some rotating torque, which prevents a careless turn; a ratchet; an automatic lock allowing the bezel to be turned only by depressing and twisting the ring; and a lock to secure the bezel ring after setting. These mechanisms are produced by manufacturers with the intention of increasing the reliability of divers' watches.

Dial

Since the dials of divers' watches must be readable in the poor visibility conditions of the sea, the time, motion of the second hand, and elapsed time must be easily readable. A luminous paint is applied to the dial, hands, pointer, and bezel ring; ordinary luminous paints are of the spontaneous light emission type and the light storage type, which absorbs and accumulates light and emits it for 0.5 hr. In some cases, radioactive tritium, whose use is limited by some nations for safety reasons, is applied to the total dial to increase reading ease. Some watches have a digital indicator in parallel with an analog one and come equipped with a small light. The use of such watches may increase.

Analog and digital indicators

Conventional divers' watches have only an analog indicator, but hybrid watches having an additional digital indicator in parallel with the analog indicator have been developed.

An analog indicator allows the diver to read elapsed time at a glance. On the other hand, multifunctionalization of divers' watches may require digital indication systems because digital ones are convenient; because they show a date, day of the week, and local time; and because they act as a stop watch. Divers' watches furnished with a digital indication system alone are expected to be developed soon; some current digital divers' watches cannot meet the requirements of the present ISO standard, however.

Alarm function

An alarm is one of the functions built into a digital watch. An alarm used in the following ways is very useful during diving.

1. Actuation of an alarm at a preset time.

2. Determining elapsed time by using the alarm to indicate time to be subtracted. For example, an alarm is preset to 20 min and then indicates times such as 19, 18, and 17 min, etc.; so that the alarm can be used to indicate what time remains.

3. Actuation of an alarm to communicate a signal to other divers. Actuation of an alarm may involve any of the following four methods (see Figure 5):

a. Electromagnetic buzzer; this generates a good signal, but has the disadvantage of very low pressure in water;

b. Vibration of the cover glass by piezo-electric devices;

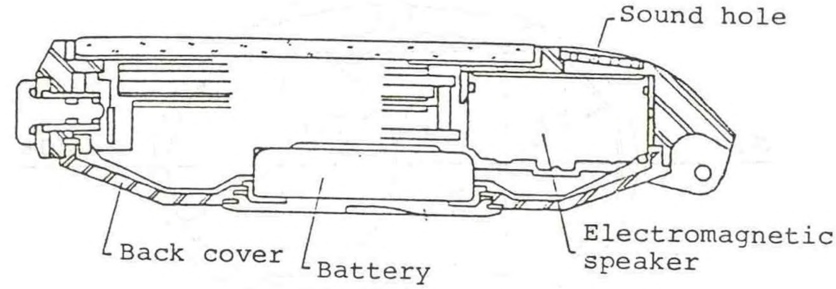
c. Vibration of the back cover by piezo-electric devices; or

d. Vibration of the double back cover by piezo-electric devices; the water pressure on the double back cover decreases the sound pressure.

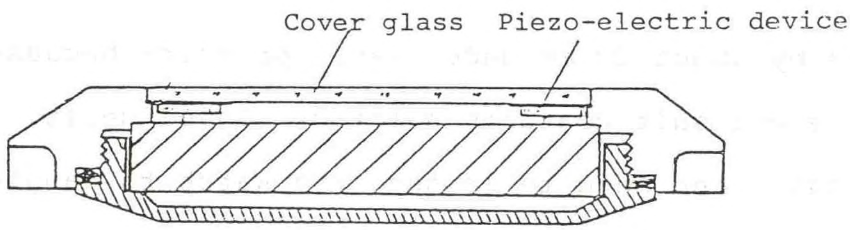
Tests have shown that methods a and b are recommended for underwater use.

Band

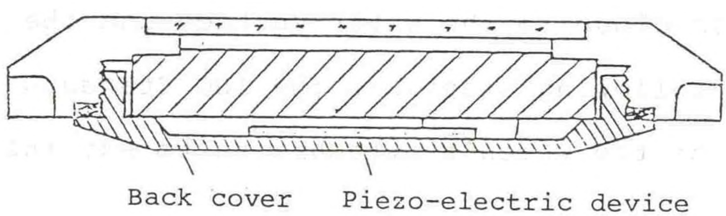
A diver's watch is worn during routine daily activities as well as during diving. The band of a diver's watch is required to fit both over a bare wrist and the sleeve of a wet suit, which increases the diameter of a wrist by about 40 mm; the length of a diver's watch band is therefore longer than that of ordinary watches. Some metallic bands are of the expandable type and are designed to fit the sleeve of a wet suit. The sleeve of a wet



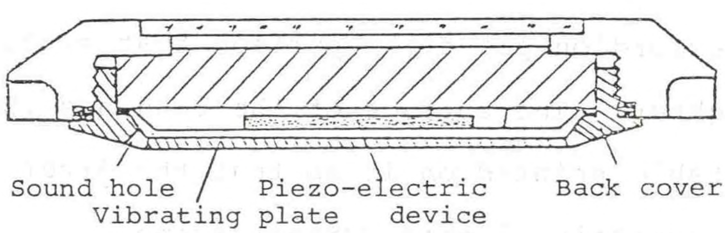
a. Electromagnetic buzzer



b. Vibration of the cover glass



c. Vibration of the back cover



d. Vibration of the double back cover

Figure 5.--Methods of actuating alarms

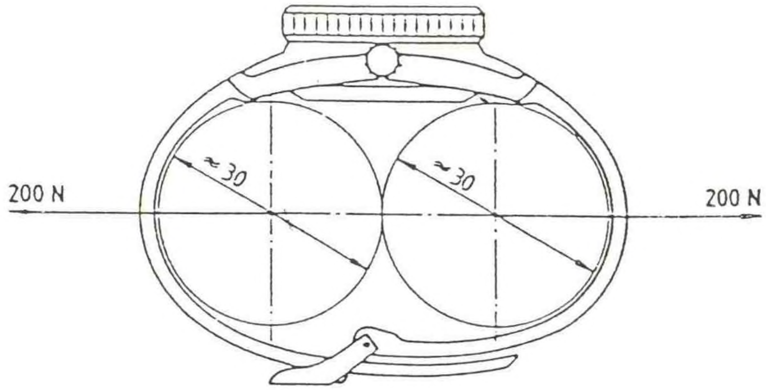


Figure 6.--External force test

suit shrinks by about 20 mm under water pressure because the material of a wet suit contains a lot of closed cells. This shrinking causes the band to loosen, the watch to dangle, and the dial of the watch to face downward, where it cannot be seen. If such a band is tightened, the band is subjected to extra force when the diver is close to the water surface and the suit again stretches. The following describes the ISO Standard for the resistance test of the watch's attachments to external force (see Figure 6).

The band, buckle, and fastening spring pin of a diver's watch are stronger than those of an ordinary watch. Some modern bands have an accordion-pleatlike portion that makes them more springy and tighter. The surface of the band has the no-decompression table printed on it so that the diver can easily see the no-decompression limits during diving.

Table 1.--Typical deep sea divers watches

Depth class	Kind	Depth
2000 m	I.W.C. OCEAN	2000 m
1000 m	CITIZEN PROFESSIONAL DIVER	1300 m
	ROLEX SEA-DWELLER 4000	1220 m
	BREITLING SUPER OCEAN	1000 m
	CHRONOSPORT HYPERBARIC	1000 m
	HEUER PROFESSIONAL	1000 m
	OMEGA SEAMASTER	1000 m
600 m	CITIZEN PROFESSIONAL	800 m
	ROLEX SEA-DWELLER 2000	610 m
	DOXA DIVING STAR	600 m
	SEIKO PROFESSIONAL	600 m
500 m	AQUAMSTER BENTHOS	500 m
	NAUTILUS PROFESSIONAL	500 m
	SCUALE PROFESSIONAL	500 m
	SCUBA-PRO	500 m
	SUBMAREX	500 m
300 m	YEMA	330 m
	DOXA SUB 300	300 m
	ROLEX SUBMARINER	300 m
	SEIKO PROFESSIONAL	300 m
	TAUCH-TEAM	300 m
200 m	CASIO DIGITAL DIVER	200 m
	CITIZEN SPORT DIVER	200 m
	ROLEX SUBMARINA DATE	200 m
	SEIKO PROFESSIONAL	200 m
	SQUALE DAMA DIPPY	250 m
	TECHNOS SKY DIVER	200 m

Divers' Watches for Saturation Diving

Diving into the sea at a depth of more than 50 m requires the use of mixed gas, primarily containing helium (He) instead of air. When a pressure vessel contains a high-pressure helium

Table 2.--Features of saturation diving watches

Diver's watch	Watch case	O-ring	Vent valve	Inside volume
A	3 piece	butyl rubber	-	4.0 cc
B	3 piece	butyl rubber	-	6.0 cc
C	2 piece	butyl rubber	-	6.2 cc
D	3 piece	neoprene rubber	0	6.2 cc

mixed gas, helium gas can penetrate into the parts through the packing (such as O-rings) and causes the pressure in the parts to increase gradually. The pressure vessel may thus be broken by the internal pressure of the parts during decompression.

The 300 m saturation diving experiment (SEADRAGON V 1982) conducted by the Japan Marine Science and Technology Center measured the increase and decrease in pressure in the waterproof case of four typical deep sea divers' watches and checked the influence of helium penetration. Table 1 shows deep sea divers' watches suitable for use at a depth of more than 200 m.

Four models used in the experiment have an anti-helium design, including such features as: (1) a glass tightened by a screw-type glass-fixing ring; (2) a waterproof case furnished with a vent valve; and (3) a packing designed to be anti-helium. Their features are shown in Table 2.

The inside part of the waterproof case of these watches is connected with a caisson gauge (made by 3D INST), which has proved to be useful in helium. The internal pressure was measured via a Bourdon tube.

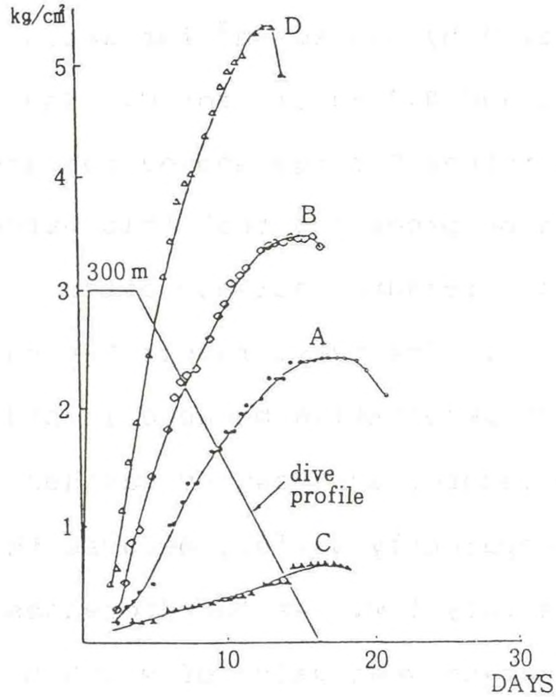


Figure 7.--Increase in pressure in divers' watches

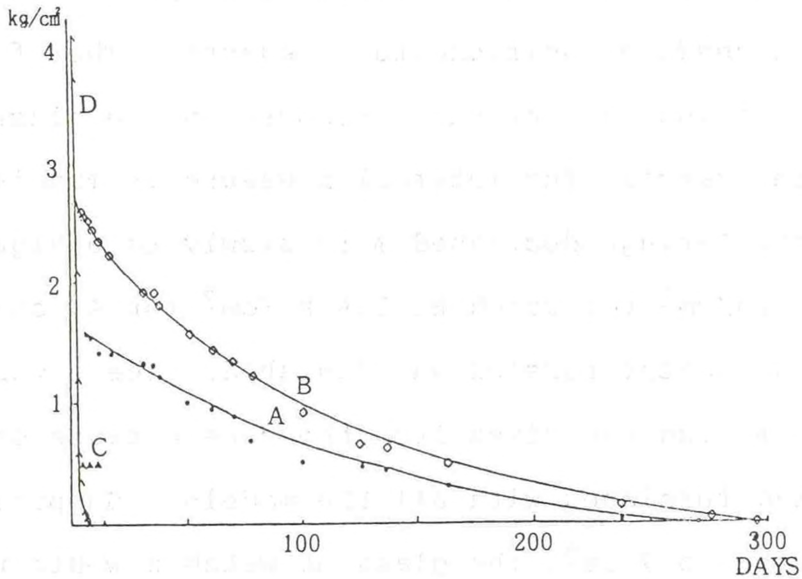


Figure 8.--Decrease in internal pressure in divers' watches

Test results show an increase in internal pressures, as shown in Figure 7, after saturation diving for a bottom time of 3 days only. A decrease in internal pressure is shown in Figure 8.

The pressure increased by 5.3 kg/cm^2 for watch D, 3.4 kg/cm^2 for B, 2.4 kg/cm^2 for A, and 0.7 kg/cm^2 for C. The D watch furnished with neoprene rubber O-rings showed the greatest increase, so that it can be predicted that this watch will show a nearly 15 kg/cm^2 internal pressure increase after a 300 m dive and 15 days of bottom time. The butyl rubber O-ring showed its usefulness against helium penetration because it had only moderate increases in internal pressure, as shown by watches A and B. A two-piece structure is apparently useful, because the pressure increase for watch C was very low. As for decreases in internal pressures, the nonreturn type vent valve of watch D effectively and gradually vented the internal gas and reduced the pressure to normal by keeping pace with the decompression speed of saturation diving and not exceeding environmental pressure. Therefore, the vent valve did not load an internal pressure on the glass and back cover of the watch. The internal pressure in models furnished with butyl rubber O-rings decreased more slowly to a high internal pressure of 2.6 kg/cm^2 for watch B, 1.6 kg/cm^2 for A, and 0.5 kg/cm^2 for C, when decompression was finished. There was no difficulty in removing the glass from the case because of the glass-fixing ring furnished with all the models. Suppose the glass surface area is 7 cm^2; the glass of watch B would then be subject to an 18.2 kg outside directional force. The glass of a diver's watch that was informally subjected to that experiment became dislodged during decompression. The watch was furnished with neoprene rubber O-rings and it might have had an internal

① Glass
② Shell
③ Crown
④ Back cover
⑤ Vent valve
⑥ Glass fixing ring
⑦ Helium gas penetrates
⑧ Glass dislodged
⑨ Discharge from vent valve

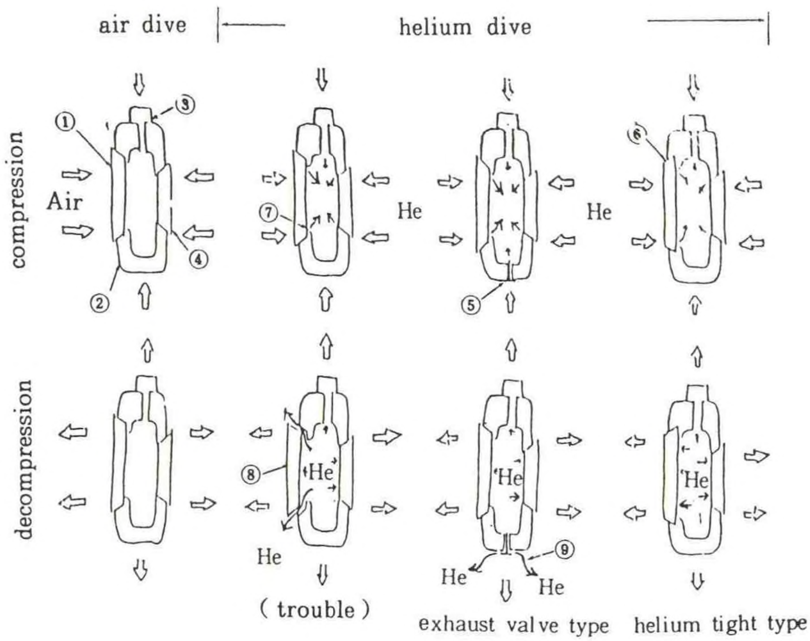


Figure 9.--Helium gas penetrates into a diver's watch

pressure of 5.3 kg/cm^2, equal to that of watch D. The theoretical force is 37.1 kg when the glass surface area is 7 cm^2, and the glass came off under this force. Some watches furnished with butyl rubber O-rings reduced the pressure very slowly and took about 300 days to reduce the internal pressure to normal. This slow rate of pressure reduction presents a new problem that will have to be solved.

All the watches tested formally in the SEADRAGON experiment were designed to resist helium penetration, but few modern divers' watches are appropriate for more than 300 m have an anti-helium design. Crowns cannot be pulled and operated to correct for time or day under a pressure of 300 m (see Figure 9).

Emergence of more reliable deep sea divers' watches is expected as a result of the inclusion of an anti-helium test in the requirements of the ISO standard.

Multifunctional divers' watches

Divers' watches generally have several functions, such as an analog indicator, bezel ring, and date and day of the week indicator. These functions are generally fewer than those on ordinary watches. Special functions on ordinary watches may include a stopwatch, alarm, counter, compass, thermometer, calculator, memory, and indicators of the cycle of the moon (moon face), local time, and heart pulsation. Some watches also have a recorder, radio, TV set, and computer. Divers' watches having some functions such as a stopwatch, alarm, and local time indicator will increasingly be used, because they are also useful for controlling diving time. One of the other desirable functions is a depth indicator, which is the most important factor in following dive time. Conventional capillary-type depth indicators are already in use and the emergence of more accurate indicators employing semiconductor technology is expected. A thermometer is also a desirable function; water, body, and suit temperature are also important parameters in diving. In particular, furnishing the temperature indicator with a sensor cord is a good idea, and building in a memory function can be useful, e.g., if the decompression table being used has been entered into the watch's memory.

Waterproof stopwatches

In diving operations, an on-board timekeeper uses a stopwatch

Figure 10.--Waterproof stopwatches

as a timekeeping device for measuring and recording compression and decompression by seconds. The degree of water resistance of the stopwatch is important because it is subjected to briny air, rain, spray, and handling by wet hands. A waterproof stopwatch is easily handled because it has passed a tightness test at 3-5 kg/cm^2, which means it can be washed with warm water, etc. (see Figure 10).

Diving stopwatches have the following functions for use in diving operations:

(1) Simple measurement of time; dive time measurement from the start of compression to the arrival at the water surface.

(2) Integrative measurement of time; measuring net time, simultaneous measurement of compression time during measurement of bottom time, etc.

(3) Measurement of time elapsed.

(4) Simultaneous measurement and tracking of time differences, e.g., ascent speed from bottom depth to an intermediate depth; ascent speed from the intermediate speed and first stop, etc.

Some of the above functions traditionally required the use of two stopwatches, and some stopwatches are able to perform these functions simultaneously by operating the start button and reset button alone.

Other functions that are sometimes available are as follows:

* A counter for counting the number of individual organisms in water.
* A timekeeping stopwatch furnished with an alarm; the watch is then started so that the remainder of the decompression time can easily be seen and the watch informs the diver of the end of the decompression time by actuating its alarm when only 4 sec are left.
* Elapsed time between wave crests, to measure wave frequency and swimming speed.
* A printout of the date (year, month, and day), start time, elapsed time, and finishing time.

Other timekeeping devices

Bottom timer

The start button of a bottom timer is depressed by water pressure when diving begins. Some timers also measure a succeeding surface interval time; they may be considered a type of waterproof stopwatch.

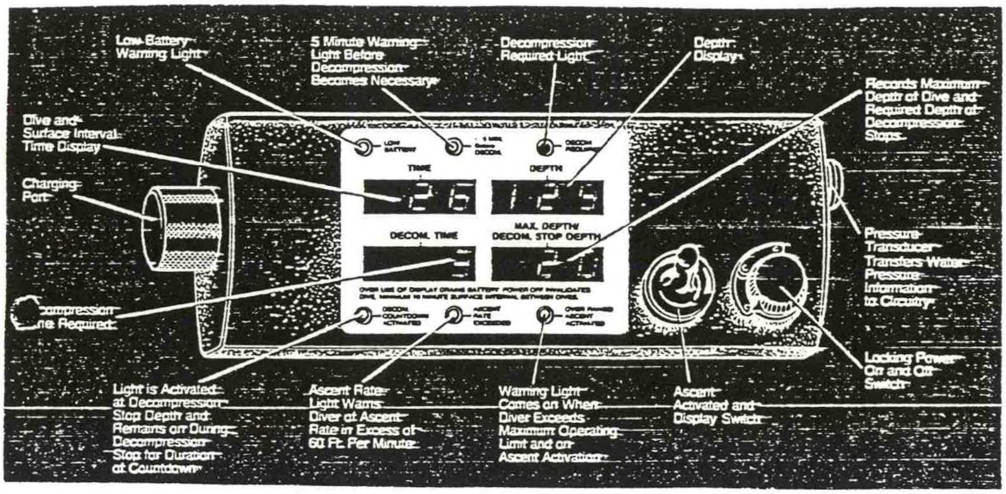


Figure 11.--DIVE COMPUTER

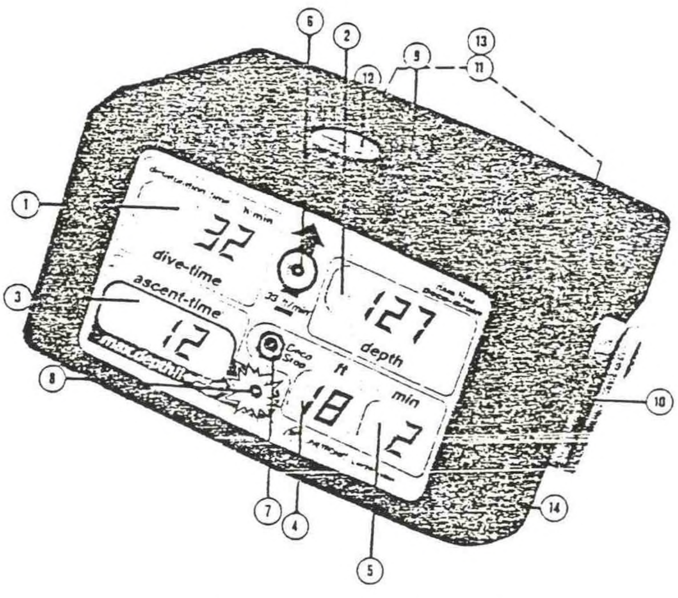


Figure 12.--DECO-BRAIN

Decompression computers

Timekeeping devices for scuba diving are now in a new era, because of the emergence of electronic decompression computers, such as the DIVE COMPUTER by DACOR (Figure 11) and the DECO-BRAIN by HANS HAS (Figure 12), etc. These devices calculate a decompression time by using both time and depth as parameters, or they indicate an applicable value from a stored decompression table. Therefore, accurate depth measuring is required.

Conventional depth gauges are mechanical, such as the diaphragm type, and no electronic depth gauge is now on the market. Electronic depth gauges use a strain gauge or semiconductor unit to measure depth; they will be on the market after accuracy problems at a depth of 30-50 m are solved. In addition, the rapid temperature changes at 3-6 m affect their accuracy.

It is natural that the commercial development of decompression computers tracks the reliability of electronic depth gauges.

Tidal meters

Tidal meters (SEIKO FISHING MASTER) developed in Japan in 1985 are useful not only for diving but also for all marine operations. These meters can calculate and indicate times of tidal rise and fall and the difference between high and low tide at about 70 points in Japan from 1980 to 2000, which would be useful for diving and marine operations.

CONCLUSIONS

This paper has discussed the improvements in accuracy, tightness, and handling reliability that have occurred in the development of modern timekeeping devices, especially of divers' watches. A problem that remains to be solved is the inability of most deep sea diving watches used at 300 m or more to withstand the penetration of helium from the mixed gas environment. Many watches used under such conditions end up with dislodged glasses.

Improvements in the numbers of special functions and features are expected to keep pace with developments in electronic equipment, and improved electronic depth gauges and decompression computers are also anticipated.

These devices all improve the safety of divers, and the further development of these useful tools is awaited by divers of all nations.

REFERENCES

International Standard ISO 6425 Diver's Watches 1982-12-01.

Yamada, M. 1984. "Problems with Diver's Watches." International Underwater Systems Design, Vol. 6, No. 3, May.

Yamada, M. 1984. "Rise in the Interpressure of Diver's Watches in Saturation Diving." Journal of the Horological Institute of Japan, No. 109.

OPPORTUNITIES FOR COOPERATION IN PACIFIC MARINE SCIENCES AND SERVICES

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My office, NOAA's Division of International Affairs, is housed in the Office of Policy and Planning, which is in turn part of the Office of the Administrator. The Division assists in coordinating NOAA's international activities. We also represent the agency at international negotiations and prepare long-range policy studies.

One of our current studies involves an examination of opportunities for expanded international cooperation in the Pacific. In particular, of course, we are interested in opportunities for NOAA and this means focusing on the oceans and the atmosphere.

There are several reasons for doing this study at this particular time. First, since the fall of 1984, Prime Minister Nakasone has made several references to the importance of Pacific Basin cooperation. His interest in the concept of a "Pacific Era" dates as far back as his book, Atarashii Hoshu no Ronri (The New Conservatism). Last November, the Prime Minister elaborated his concept in a NHK-TV broadcast. He emphasized cultural, technological, and economic ties and personal exchanges as the principal elements of cooperation. In a speech, to the National Press Club in Canberra, Australia, on January 16, 1985, Mr. Nakasone depicted the future of Pacific cooperation as a "...building up layer by layer co-operation in differing fields and developing the overall interdependence and mutual reliance which will underpin the prosperity of the whole."

Japanese enthusiasm for Pacific Basin cooperation is shared at the very highest levels of the U.S. Government as well. For example, in September 1984, the United States established a National Committee for Pacific Basin Economic Cooperation. The approximately 70 members of this Committee are influential individuals from government, academic, and business circles. President Reagan mentioned the importance of the Pacific region in his 1985 State of the Union Message. Secretary Shultz has asked Ambassador Fairbanks to head a U.S. Government review of the Pacific area.

Interest is not restricted to the United States and Japan. Last July, ASEAN foreign ministers met with their counterparts from Canada, Japan, Australia, New Zealand, and the United States at the so-called "6+5" meeting to discuss the prospects of Pacific cooperation. A Human Resources Development project was chosen as the initial focus and is now proceeding.

Although the Latin American countries have generally been less interested in the prospects of the Pacific Basin cooperation in the past, there is growing evidence that this is changing. A major symposium last December here at the East-West Center entitled Latin America and the Asia-Pacific Region elicited a considerable amount of interest.

There are several Pacific-wide organizations that promote cooperation. Most are academic or business oriented, with only informal government participation. For example, the Pacific

Trade and Development (PAFTAD) Conferences have been held annually since 1968. In 1981, PAFTAD explored renewable resource issues including energy and fisheries.

The Pacific Economic Cooperation Conference (PECC) has met four times since 1980. Fisheries received attention at the 1985 meeting. The Pacific Forum and the East-West Center symposium, mentioned above, also addressed living marine resources. Other organizations include: The Pacific Science Association, The Pacific Basin Economic Council (PBEC), and the Asia Pacific Economic Council. In the minerals area, a Pacific Marine Mineral Resources Training course is being conducted during June at the East-West Center. Representatives from at least 15 Pacific Basin nations are attending.

Examples of common marine areas of interest on which our study will focus include:

- the need to manage coastal and marine resources intelligently to provide for sustained prosperity and protection of the environment;
- the occurrence of a variety of marine mineral deposits of potential commercial interest;
- the need to find consensus on management of migrating fish stocks, notably tuna;
- common meteorological and climatological events, e.g., tsunamis and El Nino Southern Oscillations; and
- common energy production problems and potential solutions, such as Ocean Thermal Energy Conversion (OTEC).

In summary, then, NOAA's study will attempt to identify opportunities for Pacific Basin cooperation in marine and atmospheric areas and, taking current broader political discussions into account, explore ways in which this cooperation might be pursued.

MARINE FOULING ANIMALS OF THE JAPANESE COASTS

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INTRODUCTION

Marine structures that are immersed underwater for long periods are covered by a wide variety of marine organisms that attack their surfaces. When tolerance levels, dependent on the quantity of organisms, are surpassed, a situation that has been called "Marine Fouling" develops.

It has been necessary to take certain measures to protect the attaching surfaces against fouling organisms. However, the anti-fouling techniques are of limited value in those underwater fields in which many types of marine structures are immersed. Up to the present, the lack of sufficient technical information and in-water work experience in Japanese fields has inhibited the development of such techniques.

As a first step, the present fouling conditions were researched using SCUBA diving methods. This paper provides some field research and measuring techniques.

This study was performed through the Special Coordination Fund for Promoting S&T of the Science and Technology Agency of the Japanese Government.

METHODS

These studies were carried out underwater a total of 30 times at 7 structures, all of which were of the gravity type

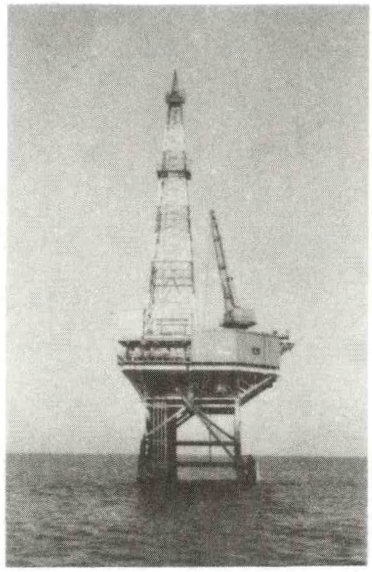

Photo 1.--Artificial platform off Ogata

Table 1.--Locations and other characteristics of marine structures

Name	Location	Depth	No. of times
1) Observation Tower	off Hiratsuka	21 m	13
2) Artificial Platform	off Ogata	7 m	1
3) Artificial Platform	off Ogata	22 m	1
4) Seaberth (for 200000t)	in the Port of Kashima	21 m	1
5) Seaberth (for 100000t)	in the Port of Kashima	16 m	1
6) Experimental exposure facility	off Oigawa	8 m	3
7) Pier	in the Port of Yokosuka	6 m	10

(e.g., a bridge post; see Photo 1). The locations and other details are shown in Table 1.

In each field we sampled, observed, and measured fouling communities, each in a 1-meter area, measured from surface to

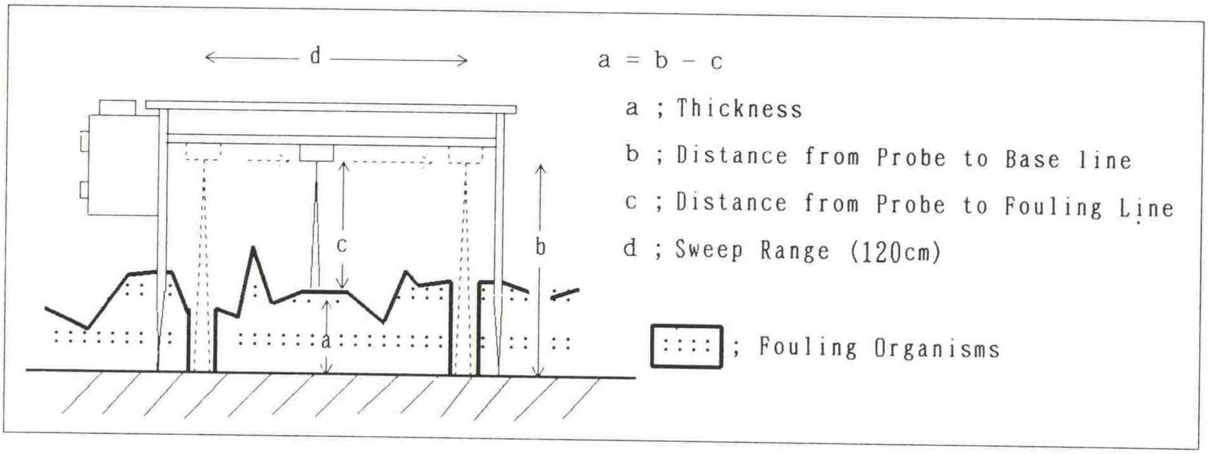

Figure 1.--Survey method of measuring fouling thickness

bottom. These samples were taken from areas 100 cm^2 (10 x 10 cm quadrate method).

We have memorized and taken many photographs underwater of the fouling conditions, while at the same time we have measured the thickness of the fouling assemblage at each sampling point by means of a steel measuring bar. In the case of research at the pier, we are also making experimental use of a thickness-measuring device (see Figure 1).

After detailed observation, we measured these samples' wet-weight in g, and classified each species at our laboratory. Thus, the biomass, zonation, species composition, and settling formation of the fouling animals at each sampling point were investigated.

Field observations were undertaken by means of SCUBA diving.

RESULTS AND DISCUSSION

Biomass (wet-weight in g/100 cm^2) and zonation

Within the 1800 g, the fouling biomass varied greatly. In these structures some vertical zonations were shown clearly by the change in biomass, and the consequent change of dominant species. In those cases taken from the observation tower, for example, the change in biomass at designated water depths and the average biomass of each zonation are shown in Figure 2 and Table 2, respectively.

These results suggest the possibility that there are some zonations, not only in the splash and littoral zones, but even in the immersed range.

Information on changes in biomass and zonation is essential for routine maintenance operations such as underwater cleaning and repair.

Thickness

Data on thickness also provide useful information for understanding the phenomena of fouling organisms. Many of these findings were provided by divers using a measuring bar, so the results could be reported only at 0.5 cm intervals.

The vertical distribution of thickness is shown in Figure 3, taken at the sea berth (for 200,000 t).

In any case, changing situations were paralleled in each case by similar changes in biomass. The average value from the surface was 12.2 cm at the sea berth.

Additionally, by using our thickness-measuring device, it was possible to obtain several cm of continuous data (see Figure 4). The repeating of this method allowed us to accumulate a large quantity of thickness data, which was far more objective

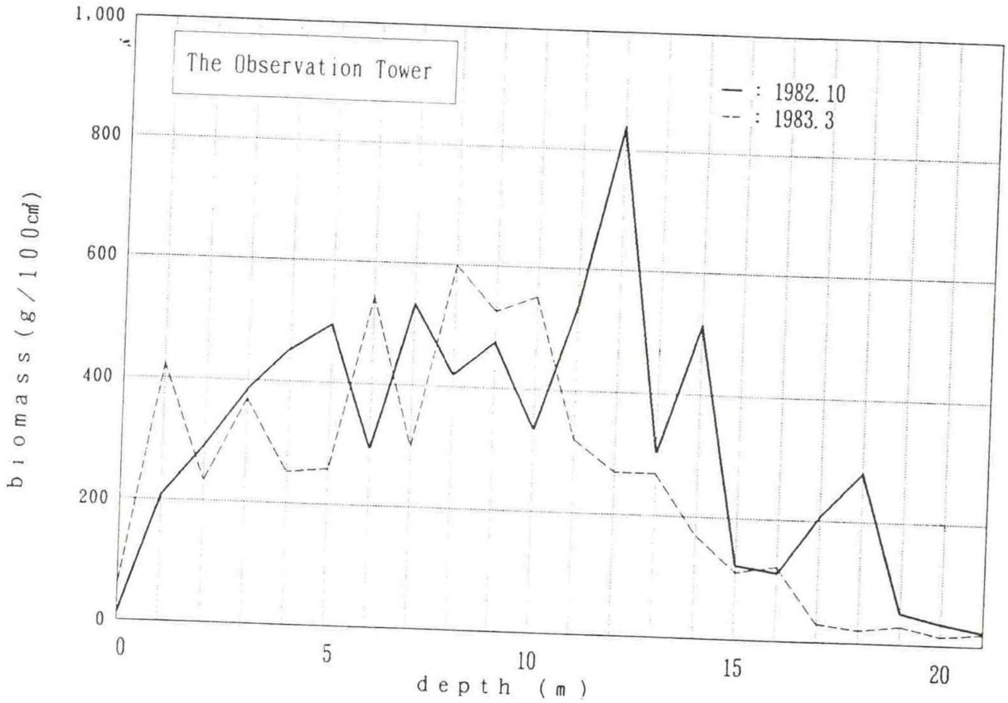

Figure 2.--Change of biomass at designated water depths

Table 2.--Average biomass of each zonation (the Observation Tower off Hiratsuka)

zone name	(1982.10)		(1983.3)	
	depth (m)	average biomass (g /100 cm²)	depth (m)	average biomass (g /100 cm²)
splash zone (animals rare)	0≦	0	0≦	0
littoral zone (red barnacle dominant)	0	62	0	14
first zone (red barnacle dominant)	1~13	379	1~14	436
second zone (oyster dominant)	14~16	134	15~18	181
near bottom zone (hydroid dominant)	17~21	24	19~21	36

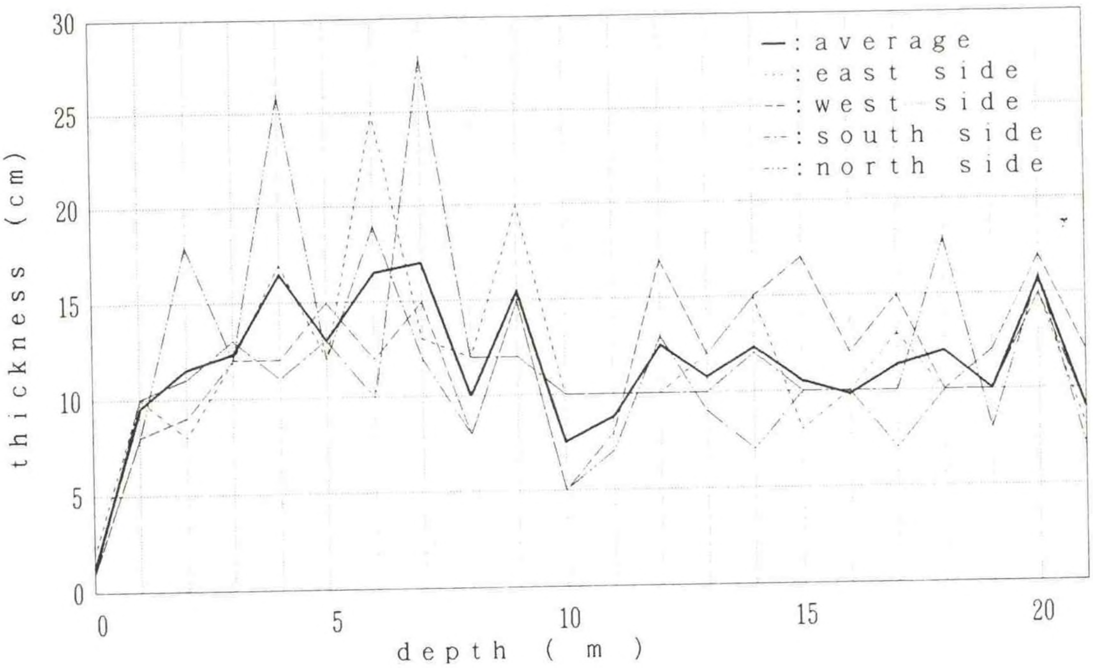

Figure 3.--Changes of thickness at the sea berth (for 200,000t) using measuring bar

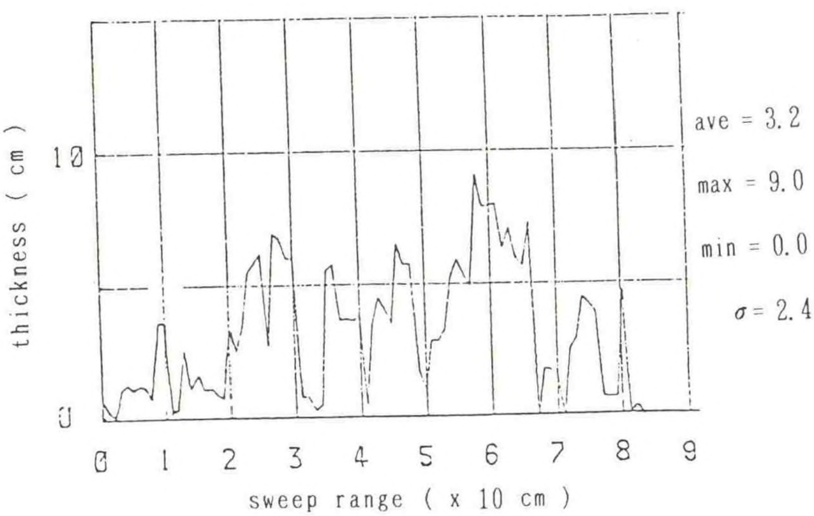

Figure 4.--Change of thickness at the pier, using thickness-measuring device

than that obtained by the methods using the thickness-measuring bar.

Table 3.--Species composition at observation tower

(barnacles)	(others)
Megabalanus rosa	Haliclona permollis
Balanus trigonus	Halichondria japonica
Balanus amphitrite	DEMOSPONGIAE sp
Chathamalus challengeri	ACTINIARIA sp
(bivalvia)	Gaetice depressue
Crassostrea gigas	Xantho reynaudii
Mytilus edulis galloprovincialis	Pugettia nipponensis
Crenomytilus grayanus	Talitridae sp
(hydroids)	Pleustidae sp
Salmacina dysteri	Janiropsis longiantennta
Loimai medusa	Caprella scaura
Hydroides elegans	Paracaprella crassa
Serpulidae sp1	Nereis pelagica
Serpulidae sp2	Aphroditidae sp
(ascidians)	Muricidae sp
Halocynthia roretzi	Cleantis planicauda
Pyura vittata	Ascorhynchus sp
Leptoclinum mitsukurii	Ophiocomidae sp
(bryozoans)	
Bugula neritina	
Dakaria subovoidea	
BRYOZOA sp	

Species composition and dominant species

After classification, a total number of around 70 species were found. The number of species at each field varied from 10 to 40; about 20 species were found to predominate.

Judging from a view of the biomass, the major groups in a species classification consisted of barnacles, marine mussels, ascidians, tube worms, hydroids, bryozoans, and sponges. An example of species composition found at the observation tower is provided in Table 3.

Four species were found to dominate: the large red barnacle (Megabalanus rosa), marine mussel (Mytilus edulis galloprovincialis), large oyster (Crassostrea gigas), and large monozoic ascidian (Halocynthia roretizi).

At the same time, many species were able to be separated into two groups: those of soft and hardshell animals. The hardshell animals usually have, naturally, a hardshell, whereas the soft animals normally do not; the presence or absence of these shells greatly affects both the attaching strength and the fouling weight in the water, and hence figures significantly in calculating buoyancy in floating structures and in the problems of underwater cleaning.

Settling formation

At the main settling formation, a triple fouling layer was observed. These layers have been tentatively named as follows: Basic Layer, Cored Layer, and Covering Layer.

The Basic Layer was present directly on the coating surface and consisted of tube worms and small barnacles, along with other small hard animals. This layer supplied a good, rough attaching base for the Cored Layer species.

The Cored Layer ran from the Basic Layer to the Covering Layer and was comprised of large barnacles and/or mussels and oysters et al. as the dominant species. Usually these animals were able to attach to the hard surface between the organisms of the Basic Layer. At the same time, the Cored Layer's organisms were able to pile upon one another in tree-like formations. So far, the maximum piling number observed is seven. Additionally, these Cored Layer's animals, all with large, monozoic shell formation, provided a main pillar with their strong clusters.

The Covering Layer formed above the Cored Layer and is comprised of soft organisms (hydroids, bryozoans, and sponges) and small, hard animals (small barnacles, tube worms and some hard bryozoans). The species composition of hard organisms in the Basic and Covering Layer was found to be similar.

REFERENCES

Ito, Nobuo, et al. 1982. "Ecological Studies of Marine Fouling Organisms on Artificial Construction: Report-1: Fouling Animals on the Floating Breakwater." JAMSTECTR 8. Japan Marine Science and Technology Center, Yokosuka, Japan.

Ito, Nobuo, et al. 1984. "Ecological Studies of Marine Fouling Organisms on Artificial Construction: Report-2: Fouling Animals on the Light Buoy Off Yura." JAMSTECTR 12. Japan Marine Science and Technology Center, Yokosuka, Japan.

Ito, Nobuo, et al. 1985. "Ecological Studies of Marine Fouling Organisms on Artificial Construction: Report-3: Fouling Animals on the Observation Tower Off Hiratsuka." JAMSTECTR 14. Japan Marine Science and Technology Center, Yokosuka, Japan.

Ito, Nobuo, et al. 1985. "Ecological Studies of Marine Fouling Organisms on Artificial Construction: Report-4: Fouling Animals on the Seaberth in the Port of Kashima." JAMSTECTR 14. Japan Marine Science and Technology Center, Yokosuka, Japan.

Kajihara, Takesi. 1964. "Ecological Studies on Marine Fouling Animals." Bulletin of Faculty of Fisheries, No. 16. Nagasaki University, Nagasaki, Japan.

DIVING AND DECOMPRESSION SICKNESS TREATMENT PRACTICES AMONG HAWAII'S DIVING FISHERMEN

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ABSTRACT

In 1981-1982, a survey was conducted of Hawaii's diving fishermen, 24 of whom were selected for this study. Up to the date of interview, these divers had collectively made over 250,000 dives. Each of the divers had been active diving fishermen and during this period of their diving experience had averaged over 500 dives per year. The dives ranged in depth from 140 to 350 feet. On an average day they made from five to eight dives. Many of these divers made a last dive at depths from 10 fsw to 60 fsw to catch whatever fish they could while decompressing from deeper dives made previously that day. All of those interviewed had had one or more incidents of decompression sickness (DCS), which they had treated by immediate in-water recompression. Some of the divers reported experiencing DCS symptoms on as many as one out of three diving days. Immediate in-water recompression was utilized 527 times for the treatment of early signs of DCS or of overt symptoms of the disease. The divers reported that when in-water recompression was utilized, it relieved or cured the disease in all but 65 incidents. Of this number, follow-up treatment in a recompression chamber had been sought 14 times. In the remaining 51 incidents, the divers had had improvement to the point that they elected to endure the remaining pain until it disappeared, usually in a day or two. The authors recommend refinements of the practice of in-water recompression to Hawaii's diving fisherman, i.e., the use of the Australian in-water oxygen treatment or the Hawaiian combination air-and-oxygen in-water recompression chamber.

INTRODUCTION

A spear was probably the only equipment used by Hawaii's early diving fishermen. Around the early 1900's, divers learned to make and use goggles (K. Masaki, 1979, personal interview) and then to use rubber fins in the 1940's. The "Aqua-Lung" (U.S. Divers Co., Cousteau-Gagnan process) or scuba was first commercially available in Hawaii around 1948. The diving regulators were of the twin hose style, one hose for inhaling and the other for exhaling. Each regulator came with an air tank and nylon strap harness. There were no instructions for its use, nor was any literature relating to dive tables issued with the equipment. The early purchasers of scuba in these islands had to rely on hearsay to gain knowledge pertinent to diving with this equipment, inasmuch as it was not until February 1957 that the U.S. Navy opened a school to train scuba divers at Pearl Harbor.

The introduction of the "aqua-lung" brought a dramatic change to the diving methods of Hawaii's fishermen. For some of the more experienced skin or free divers, use of scuba included changes to some basic equipment, i.e., from bamboo or hau wood eyefitting goggles to a full face mask and from bare feet or "tabi-style" shoes to rubberized fins.

Typically, the early Hawaiian scuba diver made his first tank dive in about 40 feet of water and with a buddy acting as a safety person on the surface. The diver was rigged with tank and regulator and swam on the surface to the anchor rope. The safety diver could free dive to the scuba diver if required. The diver with the scuba would then slowly pull himself down the anchor rope. Usually before reaching the bottom, the diver would break away and be "free swimming" with the fish and other marine life. The scuba diver returned to the anchor rope on the ocean bottom and slowly pulled himself to the surface, being careful not to pass any exhaled bubbles. Most early diving fishermen believed that this was the only requirement for proper decompression. Because of the high cost and limited supply, only one tank and regulator were usually purchased.

Hawaii's warm, clear waters provide a natural setting for the extensive use of scuba, both recreationally and commercially. The introduction of scuba enabled Hawaii's diving fishermen to increase their daily catch so as to make fishing a rewarding occupation, and an enterprising group of divers established fishing as their profession. They operated with small trailerable boats that offered a number of advantages, i.e., reduced operating cost, speed, and the ability to carry a relatively large load of air tanks, nets, fish, ice, fuel, and other gear for a dive crew of two to four people. In addition to fishing, some divers harvested black coral, a precious coral that is found in very deep water and is sometimes sold by the ounce. The time-depth profiles used by some of Hawaii's diving fishermen have been measured and reported by Kanwisher, Lawson, and Strauss (1974) and Spencer, Hong, and Strauss (1974).

Large numbers of fish were caught with a minimum of equipment, but this required repeated dives throughout the day. The profit incentive made divers take risks relative to bottom times. It took about three repetitive dives for each of several divers to net a school of fish. These dives were often made with little or no interval between dives other than that required to change air tanks. Since these dive profiles were likely to produce decompression sickness (DCS), the dive profiles were modified by trial and error to lessen the frequency of DCS. The profiles were also designed so that the divers could get the maximum amount of fishing time out of the diving workday. They would make one or more deep dives for fish or black coral and then follow these with several shallower decompression dives involving a netting operation, or, if the netting was done in the deeper water, they would follow it with one or more shallow fish-spearing dives (very deep dives = + 170 fsw; deep dives = 90-170 fsw; shallow dives = 10-90 fsw).

The purposes of the survey reported in the present paper were: (1) to chronicle the diving habits of Hawaii's diving fishermen and coral collectors from the introduction of the aqua-lung to the present day; (2) to investigate the dive profiles that were developed by these divers; and (3) to study the methods of treating decompression sickness that evolved empirically.

METHODS

Diving fishermen who dove commercially on a full- or part-time basis in the state of Hawaii were surveyed. The total number interviewed was more than 40 divers; these fishermen were the hard-core scuba users who dove either for a primary or secondary source of income and were exposed to the most severe decompression stress.

On the basis of the data obtained from the interviews, it soon became apparent that the divers represented two different generations, i.e., an older group who were self-taught, had been diving for more than 10 years, and had made over 5,000 dives in their lifetimes; and a younger group who had not had such extensive experience, had been taught to dive through conventional NAUI or PADI courses, and had made far fewer dives. For the most part, these younger divers were not full-time commercial divers and did not rely on fishing for their primary source of income because the continued depletion of the fish population had made fishing less profitable. On the basis of this dichotomy in diving practice and experience, we chose to limit this analysis to results obtained from the older group of "self-taught" divers.

This survey was started in late 1981 and completed in December 1982, and included divers from each of the major islands of the state.

RESULTS

The oldest diver in the group was 61 and the youngest was 31. The average age at the time of the interview was 42.5 years. The average number of dives that had been made by each diver at the time of the interview was 11,475 and ranged from a low of 5,200 to a high estimated to be in excess of 23,000 for the most experienced diver, who had been diving since the late 1940's; prior to this survey, this diver had been treated 11 times at the U.S. Navy's recompression facility at Pearl Harbor.

These divers harvested the ocean's resources for food and profit--spearing, trapping, and netting. The average number of scuba tanks (72 cu ft) used in a day of fishing varied from a high of eight tanks to a minimum of two tanks per day, with a mean value of five tanks per day. The maximum number of scuba tanks used by a single diver in a day was 12, which equated to 12 dives.

Of the group studied, the deepest air dive reported was one to 350 fsw reported by one individual. However, one group of black coral divers had worked a coral bed at depths deeper than 300 fsw for a month. The mean value for deepest dive depth was 228 fsw; for one diver, 150 fsw was the deepest depth.

The maximum number of years of scuba experience reported was 32, and the minimum was 10 years, with an average number of years of experience at the time of the survey of 23 years.

Because underwater treatment of decompression sickness was frequently mentioned, the questionnaire was modified to include specific questions about in-water recompression and these divers' experiences with in-water recompression. The divers reported more than 527 incidents of underwater DCS treatment, for an average of 22 per diver. The most remarkable fact was that 462 (87.7%) of the in-water treatments were successful. Several cases of decompression sickness affecting the brain or spinal cord (CNS disease) were treated with in-water recompression, and the paralysis was reversed and sensation restored by this form of treatment. In-water treatment provided incomplete recovery and was deemed unsatisfactory in 14 incidents (2.7%); the divers in these incidents sought relief at the Navy chamber at Pearl Harbor. In 51 incidents (9.7%), the diver experienced improvement but still suffered some form of residual aftereffect, usually a mild pain or ache that lasted anywhere from hours to several days. These divers reported that they chose to wait it out--"bite the bullet"--and used home remedies such as beer and aspirin or took hot or cold showers. In some cases, tenderness or fatigue persisted but relief from pain was satisfactory.

In-water recompression depths that proved successful ranged from the deepest of 85 fsw to the shallowest of 25 fsw, with an average treatment depth of 41.3 fsw. In-water recompression times showed a high of 200 minutes and a low of 20 minutes, with an average time of 63.7 minutes.

The signs and symptoms that were relieved by in-water recompression varied from mild or suspected DCS (primarily pain and aches around the shoulders and arms) to more serious CNS conditions that included paralysis, loss of vision, loss of movement, and loss of sensation. However, this type of DCS treatment did not necessarily protect these divers against dysbaric osteonecrosis, since many of Hawaii's diving fishermen have developed this disease (Wade et al. 1978).

CASE HISTORIES

One of the authors (FF) has personally treated other divers several times, and has been treated twice himself, by in-water recompression. His personal treatments were for pain in the shoulder and arms. On one occasion after the onset of symptoms, he was rapidly taken to a shallower location and made two dives to spear fish in water depths of 45 to 55 fsw. Most of the pain disappeared immediately on reaching depth, and relief continued while diving. He was very comfortable after the "treatment" dives.

In another incident, he initiated the in-water recompression of another diver who had made three dives ranging from 120 to 160 fsw with approximately 45 minute rest periods between dives. Shortly after the third dive, the diver developed uncontrollable movements of the muscles of his legs. The boat was already underway, so the author piloted it towards shallower water. Within a few minutes the diver was paralyzed and had no feeling from the nipple line down. He could not stand or move his lower extremities. A full tank of air was strapped to the stricken diver, who was able to breathe through the mouthpiece of the regulator, and he was lifted over the side of the boat and rolled into the water. The author was waiting in the water and, after checking the diver's breathing, commenced pulling the disabled diver toward the bottom. No immediate benefit occurred in the 35 to 40 fsw depth, so the attendant diver towed the stricken diver toward deeper water. At approximately the 50-fsw depth, the stricken diver started tugging and made noises and gave an "OK" hand signal. He also demonstrated that he could again move his legs and feet.

The diver being treated was instructed by hand signals to remain at the bottom holding on to or swimming around a large boulder. The boat was anchored in close proximity and a safety diver hung from a rope attached to the boat and watched from the surface as the diver being treated on the bottom recompressed. When the recompressing diver engaged his reserve valve (indicating low air pressure in his tank), the observing diver went to the bottom and exchanged tanks, allowing the recompressing diver to have another full tank. The recompressing diver later ascended to 25 fsw and then to the 15-fsw level, where he stayed until the air supply was almost gone, at which time he surfaced. He felt a little tired that evening, but he appeared to be walking normally and had good return of strength in his legs and arms as well as good sensation throughout his body.

Another incident that was reported by one of the divers interviewed may explain why he and others in Hawaii practice immediate in-water recompression for the treatment of decompression sickness. This incident was subsequently verified by other divers involved and by the county Coroner's office. On this day of fishing, four divers were working in pairs diving at a site about 165 to 180 fsw deep. Each pair of divers alternated diving and each made two dives.

Upon surfacing from the second dive, both divers of the second pair rapidly developed signs and symptoms of severe CNS decompression sickness. The driver of the boat decided to take both stricken divers to the U.S. Navy recompression chamber, so they headed for the dock some 30 minutes away. However, one diver refused to go and elected to take in-water recompression. He took two full scuba tanks, told the boat driver to come back and pick him up after they got the other diver to the chamber, and rolled over the side of the boat. The boat crew returned after 2 hours and picked up the stricken diver where they had dropped him off in the ocean. He was asymptomatic and apparently cured of his disease. The other diver died of severe decompression sickness in the Med-Evac helicopter on the way to the recompression chamber.

DISCUSSION

Recent research has provided a scientific basis that explains the empirical practices of Hawaii's diving fishermen not only in diving but also in the treatment of decompression sickness.

On the basis of the personal interviews with the diving fishermen included in this survey, it can be inferred that they have empirically learned a very efficient and relatively safe diving method. The number of dives made by these fishermen greatly exceeds the number made by most commercial or military divers. For the most part, these divers have learned to dive by trial and error, and they have planned their underwater work to be as efficient as possible because the quantity of their harvest depended upon how efficiently they worked. In the beginning of their scuba diving careers, they had no guidelines in the way of dive tables, so they used their subjective feelings as an endpoint. They all have had decompression sickness of varying degrees of severity and by experience have learned to recognize their subjective DCS endpoints. When they recognized these early signs or symptoms, they usually terminated their diving "work" for the day and took a shallower (less than 60 fsw) dive to decompress and relieve the signs or symptoms that they used to signal their individual diving "limit." This "treatment" dive was used to spear fish or octopus in addition to recompression.

In addition to learning their subjective "bends" endpoint, these divers have empirically developed diving procedures that we now recognize as being based on sound scientific principles. The frequently quoted but previously undocumented statement that Hawaii's diving fishermen make more and deeper dives per day than would be permitted by U.S. Navy air diving tables has been established by this survey. The scientific explanation as to why these fishermen can make such deep dives and so many dives per day with relative safety can be explained on the basis of the micronuclei theory of gas bubble formation expounded by Yount and Strauss (1976) and by Kunkle (1979). According to the gas micronuclei theory, a diver could significantly increase his tolerance against bubble formation (and therefore against incurring decompression sickness) by following three simple diving practices, as follows:

(1) Make the first dive of the day a deep, short (crush) dive. This "crushes" the micronuclei down to a smaller, safer size;

(2) Make succeeding dives of the day progressively more shallow, thus diving within the crush limit of the first dive; and

(3) Make frequent dives, i.e., at least every other day, which depletes the gas micronuclei pool of the body,

thus depleting the number of micronuclei available to form bubbles.

The effectiveness of these practices has been substantiated by in-vivo testing (Beckman et al. 1984). Hawaii's diving fishermen have empirically learned to utilize these physical principles to their own advantage, as the results of this survey demonstrate.

Not only have Hawaii's diving fishermen empirically developed more efficient diving techniques, but they have also empirically learned more efficient techniques for treating DCS if it does occur. They have learned the advantage of immediate treatment and therefore practice immediate in-water recompression.

The U.S. Navy early recognized the advantage of immediate in-water recompression for hard-hat divers but pointed out the difficulties that would have to be overcome, i.e., cold, prolonged immersion, and difficulties in communication, if this treatment were to be used by scuba divers (U.S. Navy 1963).

Hawaii's diving fishermen also recognized these problems. They usually took extra scuba tanks against the possibility that treatment of a stricken diver would be required. They knew from experience that the waters around Hawaii are warm enough to permit long in-water recompressions, and that communication can be maintained both visually from the surface through the clear water and by the attendant diver swimming down, at regular intervals, to check the diver who is being treated.

In the early stages of the disease, the treatment of decompression sickness is basically the treatment of gas bubbles.

Beckman (1980) and Kunkle and Beckman (1983) demonstrated that the rapid dissolution of bubbles in gelatin, as in the body, requires immediate adequate repressurization. As shown in figure 1, the length of time required to dissolve bubbles with a given overpressure is directly proportional to the size of the bubble. Therefore, the smaller the bubble, the shorter the time it takes to dissolve that bubble at any given overpressure.

The bubbles studied by Kunkle and Beckman (1983) in both agarose gel and body fluids grew to approximately 1 mm in diameter in 5 hours (fig. 2). Hills and Butler (1981) measured the size of bubbles that were collected from the right heart of dogs that had been exposed to a simulated air dive. The bubbles increased in size from 30 micrometers 5 minutes after the dive to greater than 100 micrometers in 30 minutes and to a maximum diameter of 700 micrometers, a bubble growth rate comparable to that observed in gelatin. Figure 1 shows that with any given overpressure, the length of time that would be required to dissolve bubbles of 250 micrometers in diameter would be significantly shorter (i.e., more than 10 times shorter) than that required to dissolve the large bubbles (1 mm in diameter) that would occur if they were allowed to grow for 5 hours.

Immediate recompression within fewer than 5 minutes (i.e., when the bubbles are less than 100 micrometers in diameter) is therefore essential if rapid bubble dissolution is to be achieved. Hawaii's diving fishermen have recognized the urgency of immediate recompression if treatment is to be successful and have opted to

Curves to Show Time (L) Required to Dissolve
Bubbles of Graded Size After Application of Different Overpressures

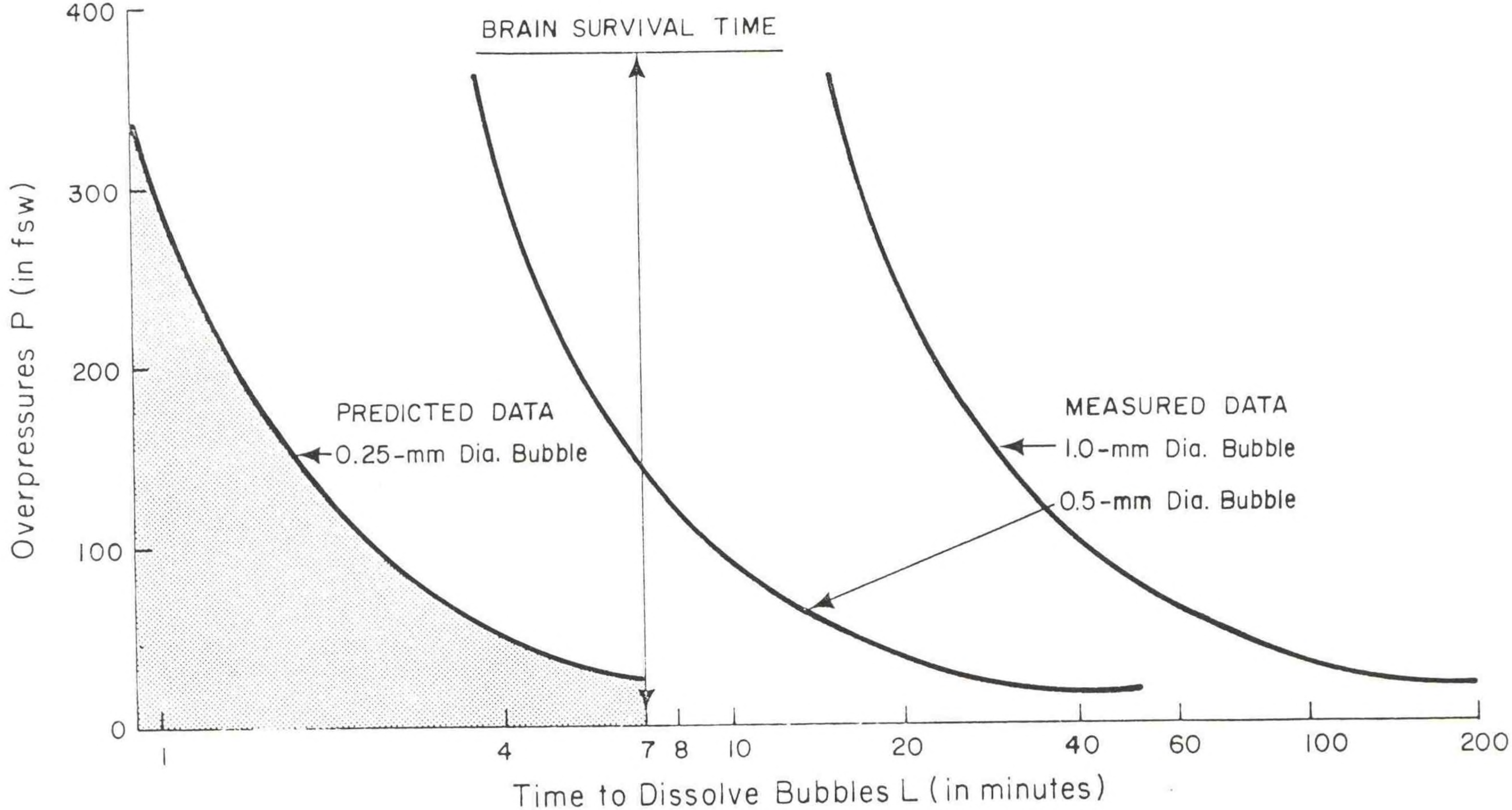

Figure 1.

Rate of Bubble Growth in Agarose Gel
At 1.0 ATA Ambient Pressure

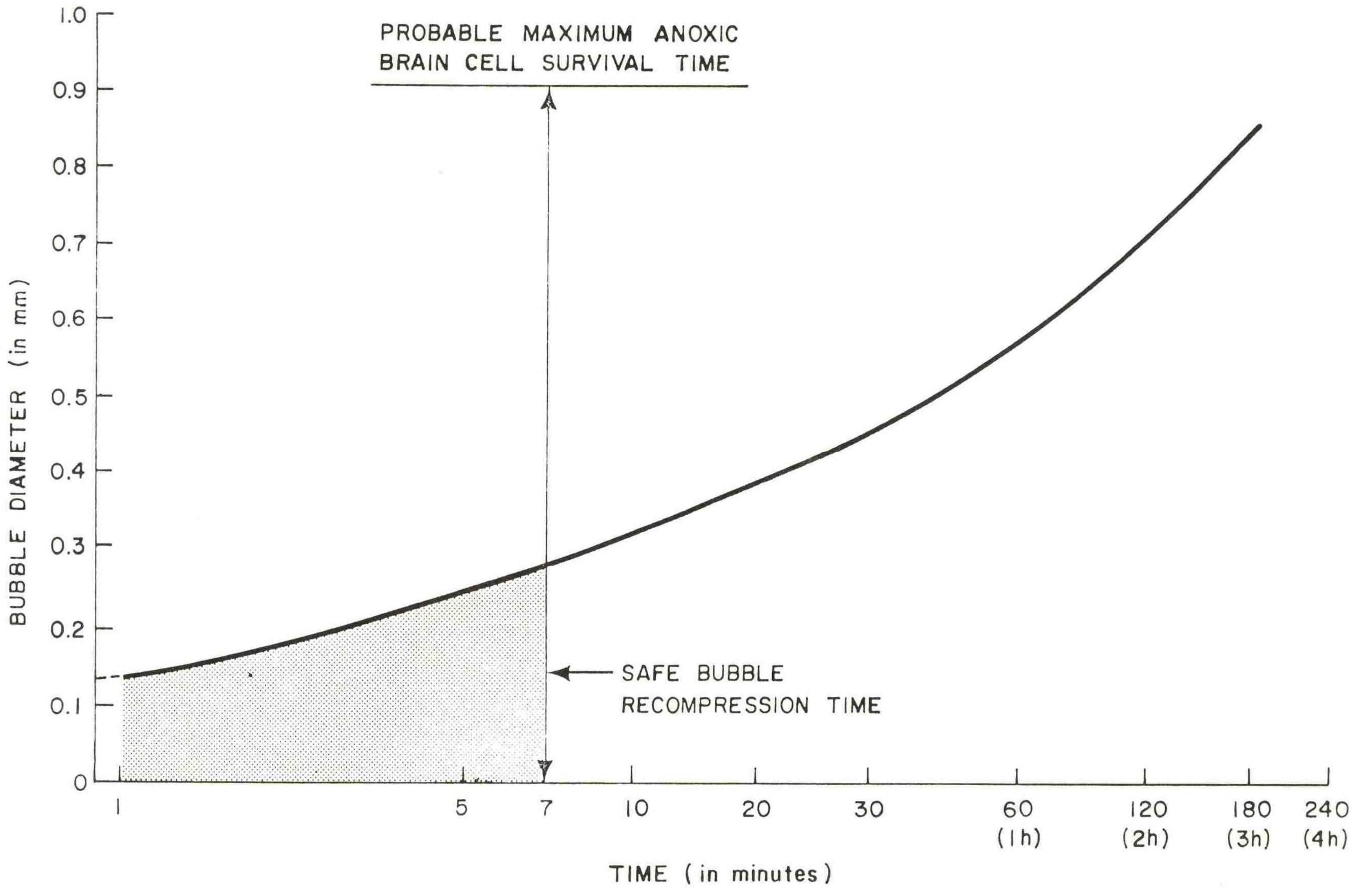

Figure 2.

return to the depths immediately. The statistics shown above bear out the wisdom of their decision. Only when in-water treatment has been unsuccessful do they seek help from the recompression treatment facilities on the islands.

More recently Hawaii's diving fishermen have been encouraged to carry a tank of oxygen (of 120 cubic feet or more capacity) in their boat for use in treating decompression sickness in the water. They have been instructed in the use of the Edmonds Australian emergency underwater oxygen treatment (Hills and Butler 1981) (see Appendix A) and the Hawaiian emergency in-water air-oxygen recompression treatment (Edmonds et al. 1976) (Appendix B). They have been encouraged to carry the necessary equipment (tank of oxygen and regulator with 30-foot tether) with them on their boat and to initiate treatment by either method immediately if any crew member develops signs or symptoms that could be related to decompression sickness. The recompression profiles to be used for these treatments are shown in figures 3 and 4.

CONCLUSIONS

The results of this survey establish that many of Hawaii's diving fishermen:

a) Make more dives during their diving career than most commercial or military divers;

b) Make more dives and deeper dives in a day than would be permitted by the U.S. Navy Standard Air Decompression Tables;

Australian Emergency In-Water Recompression Treatment Tables Using Oxygen

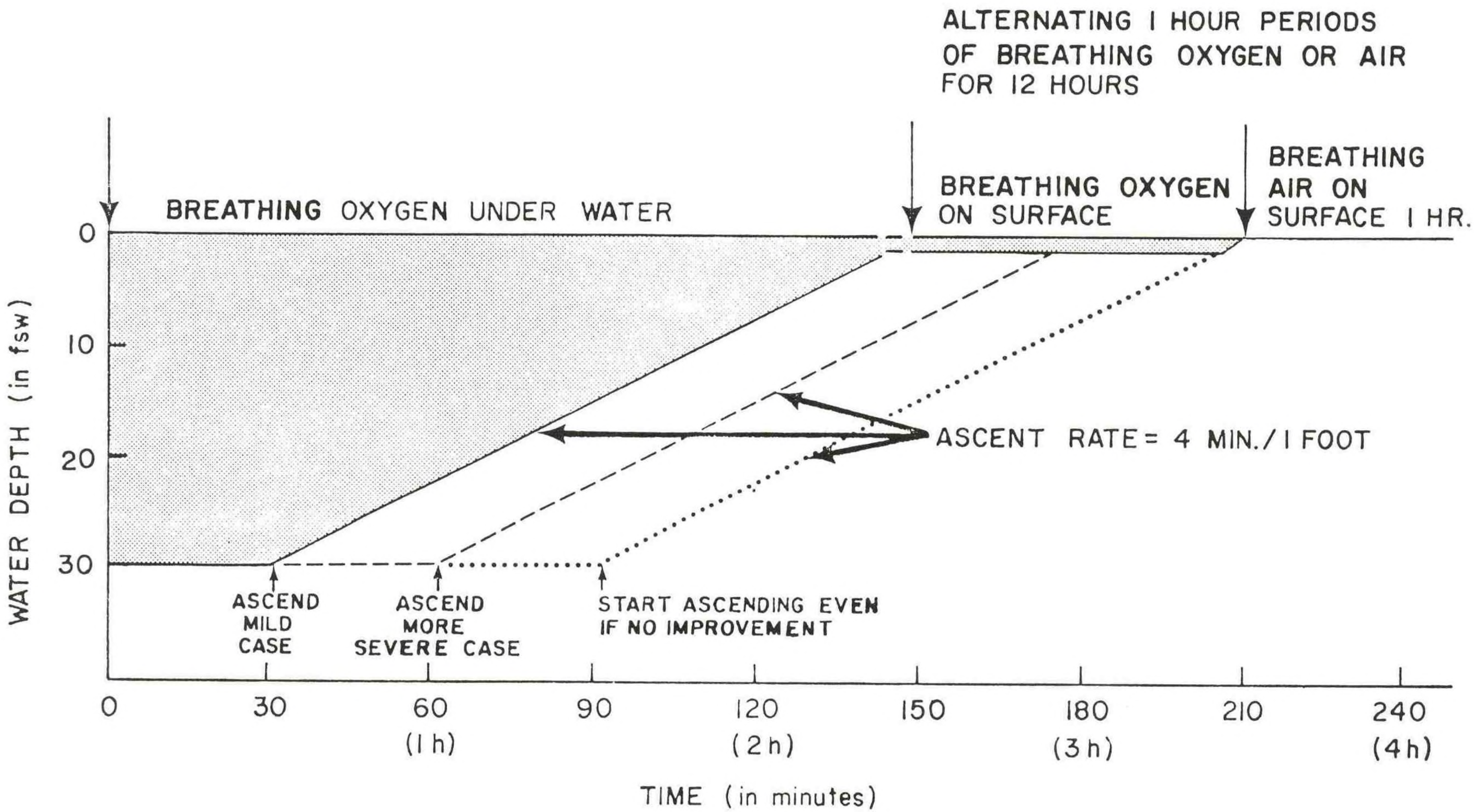

Figure 3.

Hawaiian Emergency In-Water Decompression Treatment Schedule Using Air and Oxygen

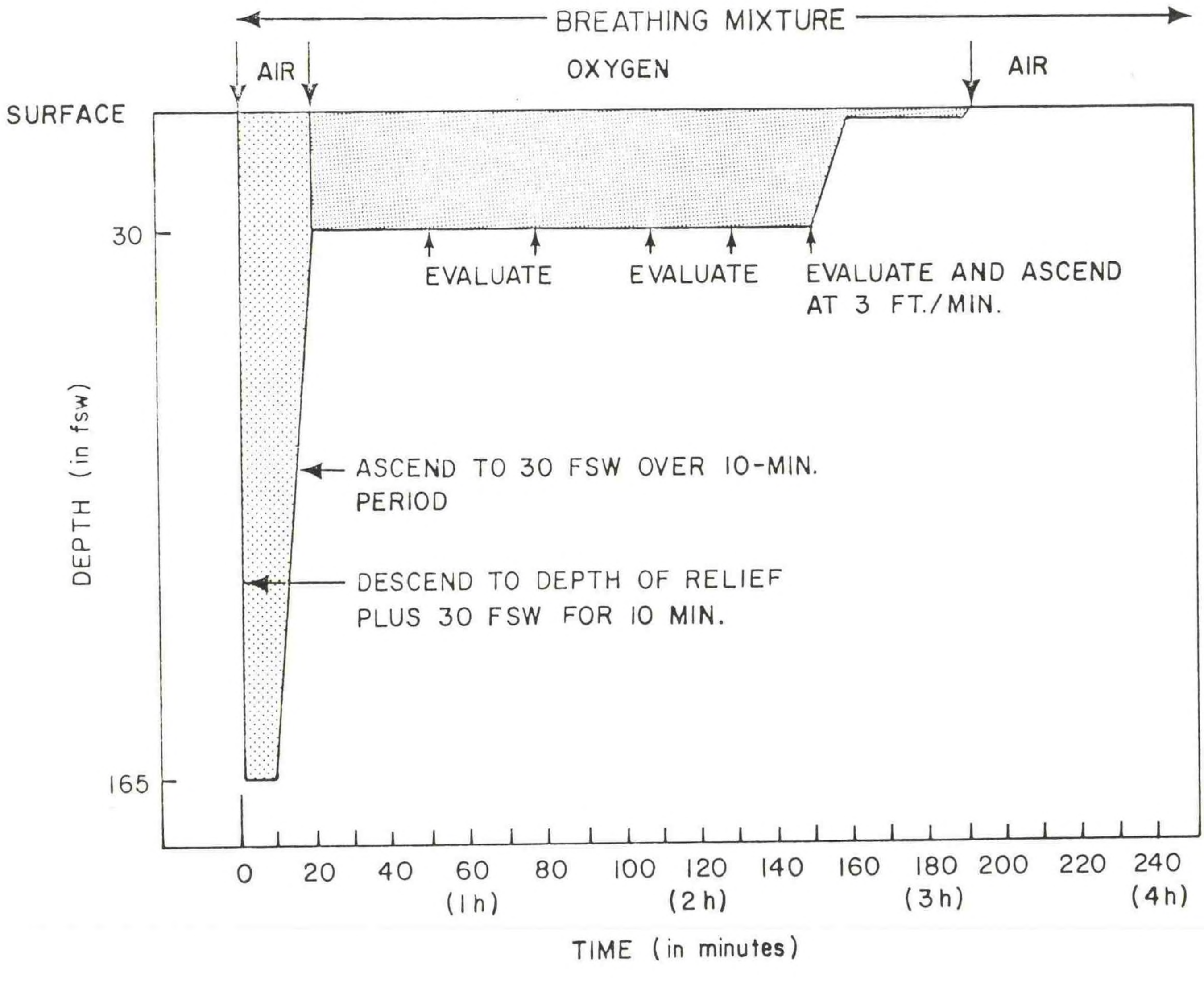

Figure 4.

c) Have experienced the onset of decompression sickness while diving from a boat;

d) Have learned to initiate immediate treatment for their decompression sickness by in-water recompression using scuba;

e) Have treated DCS of all types (i.e., bone pain, vertigo, loss of sensation and/or loss of ability to move limbs) by immediate in-water recompression;

f) Have established that the efficacy of immediate in-water recompression using air as a breathing gas is equal to or better than results from later treatment by recompression and oxygen in recompression chambers using standard treatment procedures (i.e., 87.7% had complete recovery; 9.7% had moderate residuals for which further treatment was refused; and 2.7% failed to obtain satisfactory relief and sought further treatment).

Several factors should be considered before making a decision to use in-water recompression. Such factors include: 1) availability of on-board supply of air and other breathing gases; 2) ability of the patient to accept treatment; 3) availability of personnel to help; 4) severity of the signs and symptoms and the urgency of treatment; 5) time, usually measured as distance from the dive site to land support; 6) ocean conditions; and 7) availability of transportation to get the patient to the treatment facility. If an evaluation of these factors indicates the need for and the support to undertake in-water recompression, this survey indicates that stricken divers would generally benefit from such treatment.

RECOMMENDATIONS

If Hawaii's diving fishermen were to add the use of oxygen-breathing to their in-water recompression treatment, the effectiveness of the treatment would be increased. We therefore recommend that Hawaii's diving fishermen utilize either the Australian emergency in-water recompression table using oxygen or the Hawaiian emergency in-water decompression sickness treatment schedule using air and oxygen when they are afflicted with signs or symptoms of decompression sickness while diving.

ACKNOWLEDGMENT

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REFERENCES

Beckman, E. L. 1980. "Treatment of Decompression Sickness Based Upon Bubble Dissolution Physics." In: Proceedings of the Second Japanese Commercial Diving Symposium, Tokyo, Japan.

Beckman, E. L. 1981. "An Emergency Method for Immediate In-Water Treatment of Decompression Sickness." Paper presented at Alii Holo Kai Dive Club, June 30.

Beckman, E. L., T. D. Kunkle, B. Porter, and A. Morita. 1984. "Gas Bubble Disease in Dogs. II. Effect of Rapid Compression." Paper presented at Undersea Medical Society Annual Meeting, San Antonio, TX, May 30.

Edmonds, C., C. F. Lowry, and J. Pennefather. 1976. "Diving and Subaquatic Medicine." 1st ed. Mosman, New South Wales: Diving Medical Centre.

Hills, B. A., and B. D. Butler. 1981. "Size Distribution of Air Emboli Produced by Decompression." Undersea Biomedical Research 8:163-170.

Kanwisher, J., K. Lawson, and R. H. Strauss. 1974. "Acoustic Telemetry From Human Divers." Undersea Biomedical Research 1:99-109.

Kunkle. T. 1979. "Bubble Nucleation in Supersaturated Fluids." Sea Grant Technical Report UNIHI SEAGRANT TR 80-01.

Kunkle, T. D., and E. L. Beckman. 1983. "Bubble Dissolution Physics and the Treatment of Decompression Sickness." Medical Physics 10:184-190.

Spencer, M. P., S. K. Hong, and R. H. Strauss. 1974. "Venous Gas Emboli in Hawaiian Divers." Undersea Biomedical Research 1-A-18.

U.S. Navy. 1963. U.S. Navy Diving Manual, Section 3. NAVSHIPS 250-538, Washington, D.C.: U.S. Government Printing Office, July.

Wade, C. E., E. M. Hayashi, T. M. Cashman, and E. L. Beckman. 1978. "Incidence of Dysbaric Osteonecrosis in Hawaii's Diving Fishermen." Undersea Biomedical Research 5:2.

Yount, D. E., and R. H. Strauss. 1976. "Bubble Formation in Gelatin: A Model for Decompression Sickness." J. Appl. Physiol. 47:5081-5089.

APPENDIX A

Australian Tables

Emergency Recompression Treatment in the Water, Using Oxygen

Notes

1. This technique may be useful in treating cases of decompression sickness in localities remote from recompression facilities. It may also be of use while suitable transport to such a centre is being arranged.
2. In planning, it should be realized that the therapy may take up to 3 hours. The risks of cold, immersion, and other environmental factors should be balanced against the beneficial effects. The diver must be accompanied by an attendant.

Equipment

The following equipment is essential before attempting this form of treatment.

1. Full face mask with demand valve and surface supply system OR helmet with free flow.
2. Adequate supply of 100% oxygen for patient, and air for attendant.
3. Wet suit for thermal protection.
4. Shot with at least 10 metres of rope (a seat or harness may be rigged to the shot).
5. Some form of communication system between patient, attendant, and surface.

Method

1. The patient is lowered on the shot rope to 9 metres, breathing 100% oxygen.
2. Ascent is commenced after 30 minutes in mild cases, or 60 minutes in severe cases, if improvement has occurred. These times may be extended to 60 minutes and 90 minutes respectively if there is no improvement.
3. Ascent is at the rate of 1 metre every 12 minutes.
4. If symptoms recur remain at depth a further 30 minutes before continuing ascent.
5. If oxygen supply is exhausted, return to the surface, rather than breathe air.
6. After surfacing the patient should be given one hour on oxygen, one hour off, for a further 12 hours.

Table Aust 9 (RAN 82), Short Oxygen Table

Depth (metres)	Elapsed Time		Rate of Ascent
	Mild	Serious	
9	0030-0100	0100-0130	
8	0042-0112	0112-0142	
7	0054-0124	0124-0154	12 Minutes
6	0106-0136	0136-0206	per metre
5	0118-0148	0148-0218	(4 min/ft)
4	0130-0200	0200-0230	
3	0142-0212	0212-0242	
2	0154-0224	0224-0254	
1	0206-0236	0236-0306	

Total table time 2 hours 6 min - 2 hours 36 min for mild cases
2 hours 36 min - 3 hours 6 min for serious cases

(Source: Edmonds, Lowry, and Pennefather 1981.)

APPENDIX B

Hawaiian Emergency Air/Oxygen Treatment for Decompression Sickness

This decompression sickness treatment table is designed for use by Hawaii's diving fishermen when a diver is afflicted with decompression sickness while fishing and is more than 30 minutes away from a regular recompression treatment facility.

In such an event, treatment must be initiated immediately, i.e., as soon as the signs or symptoms of decompression sickness are recognized. The urgent nature of this occurrence must be recognized and acted upon immediately inasmuch as nervous tissue of the brain or spinal cord can only be completely revived within the first 7-8 minutes after its oxygen supply has been stopped by the intravascular bubble emboli of decompression sickness.

Because of the urgency to initiate adequate recompression therapy, this treatment regime is designed to utilize: (1) immediate recompression in the water, breathing air and using standard scuba gear to a depth greater than that required to relieve the signs and symptoms of the disease; (2) oxygen breathing at 30 fsw to wash out the excess nitrogen and permit a safe ascent to the surface. An oxygen supply bottle is provided in the boat connected with a 40 ft length of diving hose and a scuba regulator. The stricken diver and his attendant diver, both using scuba, should descend to 30 feet past the depth of relief of the signs and symptoms of the disease, but not to exceed 165 fsw. The patient should stay at that depth for 10 minutes, and then start a gradual ascent with stops every minute to check to see that signs and symptoms of the disease have not returned. The rate of ascent should be no faster than 30 ft/min for the first 2 minutes with decreasing rates thereafter so that at 40 feet the rate is 5 ft/min. If no return of symptoms is noted, then slow ascent should be continued with total ascent time to 30 feet being not less than 10 minutes.

Upon reaching 30 feet the patient should switch to 100 percent oxygen breathing, using the regulator and hose supplied from an oxygen bottle (120 cubic feet) in the boat. Oxygen breathing must be continued at 30 fsw for a minimum of 1 hour, so as to wash out the excess nitrogen that caused the disease plus the additional nitrogen excess accumulated during the deep descent required to crush the bubbles producing the disease. The patient should be evaluated regularly (i.e., every 15 minutes) by an attendant diver who can descend from the surface. After 1 hour of oxygen breathing at 30 feet, consideration can be given to starting ascent if the disease was "pain only." However, if the disease had brain or spinal cord manifestations the patient should stay at 30 feet for another hour and carry out a "scrape" dive at 30 feet if desired. Regardless of the length of time spent breathing oxygen at 30 feet, the ascent to the surface should be slow (i.e., 10 minutes to surface), and the patient should continue to breathe oxygen on the surface in the boat for another hour, or until the supply of oxygen is exhausted.

The safety of the diver attending the patient must be taken into account at all times inasmuch as the attendant diver most probably will also have been fishing and exposed to increased air pressure. Therefore, the attendant diver may also need to decompress while breathing oxygen after taking the patient to depth, particularly if it was necessary to descend to 100 feet or greater. In this event the attendant diver should transfer responsibility for the patient to another diver as soon as the patient has relief of symptoms at depth and should himself ascend to 30 feet and breathe oxygen for 10 minutes before returning to the surface.

These emergency air/oxygen treatment tables, like all decompression sickness treatment tables, must be used with judgment based upon diving experience. Most experienced divers have learned that the disappearance of the signs and symptoms of the disease at depth does not mean that the disease is cured and that the diver can ascend and go home. After relief of symptoms, the tedium of preventing the disease from returning upon surfacing begins. This is the purpose of the oxygen breathing.

Even after a safe, symptom-free ascent to the surface has been accomplished, a diving medical officer should be consulted upon return to shore, and the possibility that the symptoms might return should be considered and planned for.

Although oxygen breathing is used in the treatment of DCS at depths to 60 fsw in a dry chamber, the possible occurrence of oxygen toxicity makes the use of oxygen breathing in water below a depth of 30 fsw unwise.

Equipment Required

1. An adequate supply of oxygen onboard the boat, i.e., a 120-cubic foot bottle or greater, length of oxygen-clean hose of at least 40-foot plus fittings, and an oxygen-clean scuba regulator and mouthpiece.
2. A length of line marked to 30 feet from the waterline with seat attached upon which the patient can sit during decompression. The seat should be weighted so as to make patient and seat negatively buoyant.
3. Extra air tanks for patient and attendant (minimum of two).
4. Anchor rope or sounding float line marked to 165 foot depth.
5. Depth gauge and watch for use by attendant.
6. Wet suit jacket for use by patient with appropriate weights.

Methods

1. Upon recognizing symptoms or signs of decompression sickness, immediately:
   a. Stop the engines;
   b. Throw over an anchor line and let out to 165 fsw or to bottom;
   c. Rig one full air tank for patient and another for attendant diver;
   d. Put patient in water with one attendant diver (or two if required) to take patient down anchor line;

e. Descend to depth of relief plus 30 feet;

f. Keep patient at that depth for 10 minutes;

g. Attendant and patient start slow ascent with initial rate of 30 feet per minute with stops every minute for assessment of patient;

h. Ascent from maximum depth to oxygen breathing depth of 30 feet should not take less than 10 minutes. Suggested rates of ascents from 165 feet are: 30 ft/min x 2 min; 15 ft/min x 2 min; 10 ft/min x 3 min; 5 ft/min x 3 min;

i. If patient starts to experience recurrence of any signs or symptoms, return to 10-foot deeper stop for 5 minutes, then resume ascent;

j. During deep air breathing period, crew in boat rigs oxygen breathing equipment with regulator attached to hose and line with seat at 30 foot depth;

k. Upon reaching 30 foot depth, patient switches to oxygen breathing;

l. Patient breathes oxygen at 30 feet for a minimum of 1 hour.

m. After 1 hour of oxygen breathing, if patient had symptoms of pain only and signs and symptoms are relieved, start slow ascent. If patient had signs and symptoms of CNS disease, keep patient at 30 fsw on oxygen for one or two additional 30-minute periods. When patient is completely relieved, start slow ascent to surface while breathing oxygen.

n. If the in-water recompression is not effective and the supply of oxygen is apparently inadequate, emergency helicopter transport to the on-shore recompression chamber should be arranged. Recompression on oxygen at 30 fsw should be continued until the oxygen supply is exhausted or transport arrives.

o. Even if patient is asymptomatic when he reaches surface, have him breathe oxygen in boat on surface until supply is exhausted, and consult with diving medical officer upon return to shore.