DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
321 BULLFINCH ROAD
PANAMA CITY, FLORIDA 32407-7015

IN REPLY REFER TO:

NAVSEA TA 97-022

NAVY EXPERIMENTAL DIVING UNIT TECHNICAL REPORT NO. 5-99

EVALUATION OF EMERGENCY EVACUATION HYPERBARIC STRETCHERS (EEHS)

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SEPTEMBER 1999

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Distribution: As Applicable
Original to Technical Library

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT DISTRIBUTION STATEMENT A: Approved for public release; Distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING AUTHORITY	
4. PERFORMING ORGANIZATION REPORT NUMBER (S) NEDU TECHNICAL REPORT No. 5-99	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Navy Experimental Diving Unit 6b. OFFICE SYMBOL (If Applicable) 02	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) 321 Bullfinch Road, Panama City, FL 32407-7015	7b. ADDRESS (City, State, and Zip Code)
8a. NAME OF FUNDING SPONSORING ORGANIZATION NAVAL SEA SYSTEMS COMMAND 8b. OFFICE SYMBOL (If Applicable) OOC	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) 2531 Jefferson Davis Highway, Arlington, VA 22242-5160	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
		97-022	

11. TITLE (Include Security Classification)

EVALUATION OF EMERGENCY EVACUATION HYPERBARIC STRETCHER (EEHS) (U)

12. PERSONAL AUTHOR(S)

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13a. TYPE OF REPORT	13b. TIME COVERED FROM	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
TECHNICAL REPORT		September 1999	65

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	EEHS, Emergency Evacuation Hyperbaric Stretcher, Hyperbaric Chamber (transportable), Hyperlite, GSE Flexible Hyperbaric.

19. ABSTRACT: The U.S. Navy has identified a need for portable and collapsible one-man hyperbaric chambers, called Emergency Evacuation Hyperbaric Stretchers (EEHS), which could be used as a means of transporting divers or submarine rescuees suffering from Decompression Sickness (DCS) or Arterial Gas Embolism (AGE) to a recompression chamber for treatment. As part of a comprehensive evaluation of two candidate systems (SOS Hyperlite and GSE Flexible Hyperbaric), NAVSEA 00C tasked NEDU to conduct non-developmental operational evaluations of the two systems, including manned and unmanned operational tests of function and safety. This report contains results of these tests. It is concluded that the SOS Hyperlite was suitable for the mission outlined. The GSE Flexible Hyperbaric, of the size and configuration tested, is not suited to the mission described. The combination of size, weight, and lack of safety features raises significant concern for use as a system that might be moved with an occupant under pressure. The report also contains additional information on the medical considerations for use of the EEHS, recommended improvements and accessories, and a review of available information.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
| | UNCLASSIFIED/UNLIMITED |X| SAME AS RPT. | | DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
NEDU Librarian	(850) 230-3100	

DDFORM 1473, 84 MAR 83 APR edition may be used until exhausted.
All other editions are obsolete.

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INTRODUCTION

BACKGROUND

The U.S. Navy has identified a need for portable and collapsible one-man hyperbaric chambers, called Emergency Evacuation Hyperbaric Stretchers (EEHS), which could be used as a means of transporting divers or submarine rescuees suffering from Decompression Sickness (DCS) or Arterial Gas Embolism (AGE) to a recompression chamber for treatment. In addition to providing emergency recompression capability for diving operations in situations where conventional recompression chambers are not available, EEHS systems could potentially be integrated into the Submarine Rescue Diving and Recompression System (SRDRS) to support the submarine rescue mission. Additionally, the U.S. Coast Guard and Air Force have expressed interest in incorporating EEHS systems into their rescue operations.

TASK DESCRIPTION

This report describes the operational evaluation performed by the Navy Experimental Diving Unit (NEDU) of the candidate EEHS systems in accordance with NAVSEA Task Letter 97-022[1]. NAVSEA 00C is responsible for overall coordination of the comprehensive evaluation of the EEHS systems under a Foreign Comparative Test Program[2]. Destructive, environmental, material and hydrostatic pressure limit testing has been completed by Wyle Laboratories under NAVSEA direction[3]. Manufacturing quality assurance, certification and related issues are being addressed by the NAVSEA 00C program manager. The U.S. Air Force is addressing issues relating to approval for transport in fixed-wing and rotary aircraft[4]. The ultimate goal of the EEHS program is to determine the suitability of the EEHS prototypes of two manufacturers for the operational needs of the U.S. Navy. It should be noted that the EEHSs are being evaluated as emergency devices only, rather than being considered under the full criteria for recompression chambers. The American Society of Mechanical Engineers (ASME) committee on Pressure Vessels for Human Occupancy (PVHO) has issued certification guidance that restricts use to emergency situations[5]. A separate NEDU technical report[6] addresses the proposed role of EEHS systems in the medical support of the submarine rescue mission.

DESCRIPTION OF CANDIDATE EEHS SYSTEMS

The EEHS systems tested were 1) the "Hyperlite" manufactured by SOS Ltd. of Great Britain, and 2) the "GSE Flexible Hyperbaric" (30 inch (76 cm) diameter model) manufactured by GSE Trieste Ltd. of Italy. Each manufacturer supplied one unit to NEDU for evaluation, and conducted orientation training with the Task Leader and Principal Investigator.

The operational strategy outlined in the task letter included the ability to transport a patient under pressure to a fully capable recompression facility, and the ability to complete a U.S. Navy Treatment Table 6 during transport if necessary[1,2]. This implies pressurization to at least 60 fsw (18.3 msw, 2.8 ATA) with delivery of 100% oxygen to the patient. Minimal weight was also deemed a priority, with an aim of having a system that could be manually carried by as few as four people, and that could be approved for transport in fixed-wing or rotary aircraft. Other considerations include ease of set-up, safety features, compatibility with standard SCUBA cylinder air supply for pressurization, a medical (supply) lock, and a communication system.

Both of the systems under consideration meet most of these objectives, but there are significant conceptual and design differences. Most importantly, the British Hyperlite seems to have been designed from the outset with the mission of evacuation in mind, while the Italian GSE Flexible Hyperbaric seems to have been conceived as a portable treatment chamber to be used in a stationary mode in a remote location. The GSE originally advertised the capability of pressurization to 7.9 ATA (230 fsw, 70.1 msw), and has an option that allows the attachment of a second compartment, which would allow an attendant to be in the chamber with the patient. While these capabilities would offer a significant advantage in some circumstances, they add weight and complexity, which are disadvantageous for efficient evacuation.

Other features of note and illustrations are compared and summarized in Appendix A.

METHODS

OVERVIEW OF TESTS PERFORMED

Testing was performed in two phases, unmanned and manned. Separate test plans were submitted and approved for each phase[7,8].

The unmanned phase focused on general evaluation and feasibility of use in several operational scenarios. Multiple teams of qualified U.S. Navy divers were instructed in the use of the candidate systems. They inspected the systems for potential problems or hazards, evaluated the operational characteristics, and performed a variety of exercises simulating situations in which EEHS systems might possibly be used, including transport while pressurized and transfer into another recompression chamber while pressurized. These simulations used a weighted (175 lbs, 79.4 kg) mannequin inside the EEHS to avoid human risk. Equipment breakage or failure and design features that were felt to be potentially hazardous or otherwise problematic were identified and operational limitations were noted.

The manned phase focused on human factors and variables related to the human occupant, including oxygen consumption, carbon dioxide accumulation, temperature, noise levels, and performance of the built-in-breathing-system (BIBS). This included

multiple manned exposures in each EEHS. A full U.S. Navy Treatment Table 6 was performed in the British Hyperlite on three occasions. Manned testing in the Italian GSE Flexible Hyperbaric was restricted to 45 fsw (13.7 msw) because it was not possible to quickly change the BIBS to air and there was concern that there would be no way to stop oxygen delivery to a patient in the event of an oxygen toxicity seizure.

RESULTS

GENERAL OBSERVATIONS

Weight:

There was a notable difference in weight and bulk between the two systems. The Hyperlite is relatively small, light weight, and obviously designed to be carried, while the GSE is larger, heavier, and very difficult to carry. The weight of the pressure vessel, without accessories, hoses or gas supplies, which is the minimum that would have to be carried while pressurized and occupied, is 170 pounds (77.1 kg) for the Hyperlite, and 270 pounds (122.5 kg) for the GSE Flexible Hyperbaric. While this may not seem to be a tremendous difference, the size and shape of the GSE in combination with the extra 100 pounds of weight make it very awkward to lift and carry with the added weight of an occupant. There were instances when attempts to carry it, or load it to or from a vehicle, became hazardous for the personnel involved.

Pressure Vessel Design:

There were obvious differences in design of the pressure vessels. NAVSEA 00C has performed an engineering evaluation of the pressure vessels. Destructive, environmental, material, and hydrostatic pressure limit testing has been completed by Wyle Laboratories[3], under NAVSEA direction. NEDU was not asked to evaluate the strength of the pressure hulls, and a detailed engineering critique of the pressure vessel design is beyond the scope of this report, but design features that affect operation and use will be discussed.

The Hyperlite is comprised of a flexible, collapsible, tubular hull made from para-aramid fibers in a silicone-rubber matrix with totally separate clear acrylic end plates. Each component is lightweight and, when disassembled, can be easily carried by one person. The hull has an inherent tubular shape when removed from the container, and it maintains itself in a workable form during assembly. The end plates fit securely against molded ridges at the ends of the tubular hull. They seal with minimal pressurization against the ridges, and are held in place by internal pressure and thus do not require a latch. If they are incorrectly placed, pressurization cannot occur, and if placed correctly, they cannot be dislodged once the vessel is pressurized. This simple, error-proof method of securing the end plates is one of the major benefits of the Hyperlite design.

The GSE Flexible Hyperbaric is composed of a urethane-impregnated polyester cloth bag that provides an airtight envelope, surrounded by a net of woven nylon straps, which provide longitudinal and circumferential strength. The cloth bag and straps are attached to aluminum alloy end plates with clamps and bolts. There is a removable hatch in one end that is attached with 1/8 turn interrupted thread "bayonet" fittings. Operationally, this design has some drawbacks. Since the endplates are permanently attached, the entire hull and endplates must be carried as one piece. It cannot be broken down into manageable components. It is heavy and very difficult to move. The heavy endplates become hazardous during moving. The fabric hull has no inherent structural form, so it must be supported during assembly, making the process more difficult. The hatch attachment lacks a feature to prevent misalignment, and it is possible for the chamber to be pressurized with the hatch incorrectly positioned. This could result in catastrophic failure of the hatch under pressure. It is notable that, in response to our concerns, the manufacturer has improved the design of the latching mechanism and devised a safety interlock that prevents pressurization if the hatch is misaligned. These improvements are available in newer units, but not in the unit which is the subject of this report.

Piping:

There were notable differences in the design of supply hoses and electrical cables. All hoses and cables on the Hyperlite enter through the center of one endplate in a longitudinal fashion. They are easy to access and are not vulnerable to damage if the chamber is rolled. Quick-disconnect fittings are specific for air and oxygen supply and exhaust, and are color-coded for ease of connection.

Hoses protrude from the GSE Flexible Hyperbaric in a radial orientation around the rim of one end plate. They are unprotected, and seem vulnerable to damage or disconnection if the chamber is rolled. This design also creates a need for additional space around the chamber to provide clearance for the hoses. Hoses were not color coded, slowing assembly. The quick-disconnect fittings on the high-pressure hoses for both systems did not engage positively. A locking mechanism would improve safety. There were two instances of inadvertent disconnection during use of the GSE Flexible Hyperbaric. Also, the fittings are not specific for each connection, allowing hoses to be connected to the wrong fitting. On at least one occasion the high-pressure hose from the air supply tank was connected directly to the inlet to the chamber, bypassing the control box. This could have caused overpressurization of the chamber if the error had gone unnoticed.

Controls and Gauges:

The control box for the Hyperlite was made from durable plastic, and controls were intuitive and easy to operate. The chamber pressure gauge read true chamber pressure (referenced to outside atmospheric pressure) during pressurization and depressurization. There were some suggestions regarding improved labeling of

gauges and some suggestions for extra labeling regarding which direction turned valves open or closed.

The GSE Flexible Hyperbaric control box was made of sheet metal, and in the opinion of most evaluators, would not have lasted long in Navy use. The main chamber pressure gauge was connected to the chamber exhaust in such a way that it did not read true chamber pressure during venting or depressurization (it apparently read the exhaust line pressure). The labeling of valves and gauges is marginal as the evaluators felt that the valves could easily be inadvertently placed at intermediate positions.

Built in Breathing System (BIBS):

The BIBS for both chambers employed commonly available off-the-shelf masks with demand regulators and overboard exhaust. The Hyperlite was originally supplied with a Divex brand mask/regulator. The mask fit some subjects poorly and the regulator malfunctioned (persistent free flow). Fortunately, the system was compatible with a standard Scott brand mask/regulator, which was used for most of the manned exposures. We recommended to the manufacturer that the Scott brand mask/regulator be used due to its common use throughout the U.S. Navy, which simplifies repair or replacement. The GSE Flexible Hyperbaric was supplied with a Scott mask/regulator.

The BIBS supply to the Hyperlite could be easily switched from oxygen to air with a valve on the control box that allows the operator to independently change the BIBS gas. This is an important feature because it allows the patient to continue to use the BIBS during air breaks. The overboard exhaust from the BIBS prevents carbon dioxide accumulation within the chamber. The GSE Flexible Hyperbaric did not have a means to easily change BIBS supply gas. Thus, during air breaks the patient would need to remove the mask and breathe chamber atmosphere, with resultant rise in carbon dioxide within the chamber. Additionally, if a patient were unable to remove the mask himself, it would be impossible to provide air breaks. There was concern that there would be no way to stop oxygen delivery to the patient in the event of an oxygen toxicity seizure. For this reason, manned exposure in the GSE Flexible Hyperbaric was limited to 45 fsw (13.7 msw) while breathing oxygen.

MISCELLANEOUS OBSERVATIONS

Hyperlite:

- It was not immediately clear from which end the patient should enter the chamber (a training issue).

- There were multiple problems with the litter (stretcher). The length interfered with placing the end plates. Sharp metal edges cut into the chamber inner surface, causing small leaks. It was awkward to use.

- The medical lock cover plate could be inadvertently mispositioned, or its valve could be left open during set-up. This will cause it to leak, or even become dislodged, during initial pressurization. This occurred several times during exercises with multiple dive teams. This could be a potential hazard, but could be addressed during training, and stressed in operating procedures.

- The handles used for lifting and carrying could be improved with regard to placement and grip surface.

- It was initially difficult to get a good seal between the endplates and the hull. This maneuver often required the operator to sit on the ground and brace himself with his feet against the rim of the chamber while pulling the endplate into position. Success with this maneuver improved with training and practice, but was frustrating on initial attempts.

- Packing and unpacking the system required some skill and training, particularly folding the hull to fit into the crate. The storage container for the collapsible hull is barely large enough to contain the hull. It must be carefully folded in a specific manner which requires some training and practice to do well.

GSE Flexible Hyperbaric:

- It was difficult to load or unload the patient through the small opening, and this was complicated by the fact that only one end was open. Loading of a disabled patient would require someone to crawl into the chamber to pull the patient in, then exit the chamber by crawling over the patient. While possible, this is a very awkward maneuver.

- The medical lock completely obscured the view from one end of the chamber, resulting in very limited ability to monitor the patient.

- The lifting handles were of poor quality, and caused considerable discomfort to the hands of personnel attempting to carry this heavy weight. During the course of the evaluation, two of the handles broke. Handle failure at a critical time during occupied, pressurized transport could be dangerous. As a result, it was decided not to perform any exercises requiring lifting or carrying the GSE Flexible Hyperbaric during manned testing.

UNMANNED OPERATIONAL TESTS

Trial Pressurizations:

Each EEHS was prepared per manufacturer's instructions. Air supply pressures were verified with calibrated gauges. The units were pressurized as rapidly as possible to determine maximum pressurization rate. Time for complete pressurization, and air supply used for pressurization, was recorded. The chamber pressure was maintained for two hours, during which time, temperature, and additional gas needed to maintain pressure was recorded. The units were then depressurized in emergency mode and the time for complete depressurization was recorded. The procedure was repeated three times for each unit. Any problems or notable observations were recorded.

Results for the Hyperlite were:

- Time to pressurize to 60 fsw (18.3 msw) at maximum pressurization rate - 80 seconds
- Time for emergency depressurization from 60 fsw (18.3 msw) - ranged from 3 to 4 minutes
- Temperature change with pressurization to 60 fsw (18.3 msw) at maximum rate (unoccupied) - start 82° F (27.78° C), end 106° F (41.11° C)
- Gas needed for pressurization to 60 fsw (18.3 msw) (unoccupied) - 38.95 Standard Cubic Feet (SCF) (Aluminum 80 cu. ft. SCUBA tank, starting pressure 2,755 psig, ending pressure 1,305 psig). In other words, about one-half of a standard SCUBA tank

Results for the GSE Flexible Hyperbaric were:

- Time to pressurize to 60 fsw (18.3 msw) at maximum pressurization rate - 3 minutes, 47 seconds
- Time for emergency depressurization - ranged from 3 to 4 minutes
- Temperature change with pressurization to 60 fsw (18.3 msw) at maximum rate (unoccupied) - start 84° F (28.89° C), end 96° F (35.56° C)
- Gas needed for pressurization to 60 fsw (18.3 msw) (unoccupied) - 81.03 SCF. A single 80 cu. ft. tank pressurized to 3,000 psig was drained to 0 psig. It was found to be necessary to use a set of double 80 cu. ft. tanks for efficient pressurization. When double 80 cu. ft. tanks were used, a starting pressure of 2,800 psig was drained to 1,300 psig.

Operational Scenarios:

Four separate scenarios were simulated.

1) Initial set-up of EEHS system and transfer of pressurized EEHS into a treatment chamber.

2) Evacuation of a diver from a remote shore based diving operation (pier) to a treatment chamber.

3) Transport of a diver on a boat ("NEDU-1", 36-foot length) not equipped with a deck decompression chamber to a treatment facility.

4) Transfer of a patient under pressure out of a pressurized chamber, simulating the removal of an injured diver from a deck decompression chamber for transfer to a treatment chamber or medical facility.

These scenarios are described in further detail in Annex C of the Unmanned Test Plan[7].

Pertinent findings were as follows for the Hyperlite:

- Initial set-up time ranged from 5 to 10 minutes. Occasional delays after initial set-up were encountered due to difficulty getting the endplates to seal.

- The pressurized chamber, with the mannequin inside, could be carried safely by four people. Clearing obstacles such as steps or doors was not a major problem.

- It was easy to load into the NEDU treatment chamber, which is slightly larger than recompression chambers commonly available in the fleet. Pressurization of the larger chamber allowed equalization of pressures with the Hyperlite, and it was then easy to remove the endplate and extricate the mannequin. It was possible, but not easy, to load the Hyperlite into a "Dixie Double Lock" recompression chamber, similar in size and configuration to recompression chambers commonly used in U.S. Navy diving operations. Rearrangement of the equipment and shelves inside the Dixie Double Lock chamber was necessary. It would have been difficult, but possible, to transfer a patient under pressure from the Hyperlite into the Dixie Double Lock. Extensive procedural training would be recommended if this were to be contemplated as an operational strategy by a group receiving a Hyperlite.

- Simulated evacuation from a remote shore-based site with the Hyperlite was relatively easy. The pressurized Hyperlite, with the weighted mannequin, was

loaded into a standard pickup truck with no difficulty and transported approximately one mile to the receiving facility (NEDU). Unloading and transfer presented no problems.

- Transport of the Hyperlite on a small boat ("NEDU-1", 36-foot length) presented no problems. Set-up and pressurization was easily accomplished in the limited space. The pressurized Hyperlite could be safely unloaded and carried along the narrow dock (approximately 48 inches wide (122 cm)) by four people. Additionally, at the request of an Explosive Ordinance Disposal representative, the Hyperlite was assembled and pressurized at sea on a smaller "utility boat" ("UB"), (22-foot length center console Boston Whaler). This was accomplished with no difficulty.

- Transfer under pressure out of a multiplace recompression chamber in the Hyperlite did not present any major problems, but did require some ingenuity with regard to loading the components of the Hyperlite into the small outer lock of the multiplace chamber to get them into the main lock for set-up. It is recommended that training in this procedure be undertaken in advance of using it for patients.

Pertinent findings for the GSE Flexible Hyperbaric were as follows:

- Set-up time ranged from 5 to 10 minutes. Pressurization was slow (approximately 5 minutes, 11 seconds), which delayed the time for the unit to reach 60 fsw (18.3 msw).

- The pressurized chamber with mannequin inside was very difficult to carry with four people. The weight, bulk, shape, and placement of the carrying handles made it awkward to handle. Carrying it over obstacles or through doorways was at times hazardous. The lifting handles were poorly designed, causing pain in the hands after a short time. Two of the handles broke with only moderate use. It would be very hazardous if the chamber end was dropped due to the exposed metal surface of the endplates.

- While it was possible to load the GSE Flexible Hyperbaric into the NEDU treatment chamber, it was awkward and difficult. The extra size created difficulty in clearing the space for the hatches to swing to the closed position. The extra weight was difficult to lift over the lip of the entrance, and to position in the chamber. It was hazardous to the personnel, with a significant risk for back strain due to the awkward lifting positions necessary. It is not possible to load the GSE Flexible Hyperbaric 30-inch models (76 cm) (the unit that was tested) into a Dixie Double Lock chamber. The diameter of this EEHS is larger than the diameter of the opening to the Dixie Double Lock. Thus, for use as an evacuation device, it is not compatible with the most common receiving

recompression chamber in U.S. Navy fleet use. Transfer of the patient into these common multiplace chambers would require decompression of the patient, negating one of the primary goals of the EEHS concept. It is also notable that the diameter of the end plates is too large to fit through a submarine hatch, thus making it impossible to easily load into a submarine.

- Simulated evacuation from a remote shore-based site with the GSE Flexible Hyperbaric presented some difficulties. The pressurized GSE Flexible Hyperbaric, with the weighted mannequin, was loaded into a pickup truck with great difficulty. The weight and placement of the lifting handles made it very difficult to lift into the truck with four people. It was transported in the truck approximately one mile to the receiving facility (NEDU). There was concern about its tendency to roll, endangering the protruding hose attachments. Unloading was begun, but was stopped by the safety observer due the obvious hazards to personnel from attempting to maneuver the heavy, awkward unit. The unit was depressurized and the weighted mannequin was removed prior to unloading the components.

- Transport of the GSE Flexible Hyperbaric on a small boat ("NEDU-1", 36-foot length) also presented problems. Set-up and pressurization was easily accomplished in the limited space, but the pressurized chamber could not be safely unloaded from the boat or carried along the narrow dock (approximately 48 inches wide (122 cm)) by four people. The extra width of the unit prevented men alongside from fitting on the narrow walkway. This exercise was aborted.

- Transfer under pressure out of a multiplace recompression chamber in the GSE Flexible Hyperbaric did not present any major problems, but did require some ingenuity to load the components into the small outer lock of the multiplace chamber to get them into the main lock for set-up. The extra size increased the difficulty of set-up within the chamber, and it was difficult to clear the hatch openings. It was difficult to remove the pressurized unit from the chamber. This exercise could not have been done from a standard Dixie Double Lock recompression chamber.

Compatibility with Transport Vehicles:

The EEHS systems were evaluated for feasibility of transport in several common vehicles. The Hyperlite was found compatible with all vehicles evaluated, including a pickup truck and a standard commercial van. The GSE Flexible Hyperbaric was found to be difficult and possibly unsafe to transport in a pickup truck. It was very difficult to load or unload, and the gas hose connections protruded from the rim in a way that made them vulnerable if the unit was rolled. It would be possible, but difficult, to fit into a van.

The Hyperlite was also evaluated for three different types of U.S. Navy helicopters. One Hyperlite unit could fit within the UH1N ("Huey"), but there was limited room to attend for the patient if it became necessary. The Hyperlite could not be placed within the H-60 ("Sea Hawk"). Securing it from a sling below the helicopter was considered as a possibility, but would not be recommended unless the necessity was very great. The H-53 ("Sea Stallion") class helicopter could potentially hold up to nine EEHS units.

The Hyperlite has also been taken aboard a U.S. Navy submarine. It was able to be loaded via the standard hatches, transported throughout the boat, and set up for operation in multiple sites[6].

MANNED TESTING

Exposures Performed in Hyperlite:

A total of 18 manned exposures were performed in the Hyperlite. Twelve of these exposures were short human factor evaluations (10 to 30 minutes). Three were complete U.S. Navy Treatment Table 6 profiles, one was a U.S. Navy Treatment Table 9 (45 fsw (13.7 msw) for 105 minutes), and two exposures involved transferring a patient under pressure into and out of a multiplace recompression chamber. Human factor observations are summarized as follows:

- Most subjects planning a short (~20 minute) exposure seemed to tolerate it well, but three subjects who initially volunteered for a full Treatment Table 6 became uncomfortable within the first few minutes, and asked to be removed. Complaints included heat, anxiety, and nausea while on oxygen. All subjects noted that they probably could have endured the full time if they had serious DCS. Three other subjects were able to complete Treatment Table 6 without difficulty.

- Initial attempts to use the litter (stretcher) supplied with the Hyperlite were problematic. It did not facilitate loading, actually reduced space for the subject, and resulted in cuts to the inner surface of the chamber. A technique of loading the patient on a fire retardant blanket and then pulling the blanket from the opposite end of the chamber was found to be simple and effective. Subjects were more comfortable on the blanket than the litter. Our recommendation is to reject the purchase and use of the litter (stretcher).

- Several subjects noted that turning in the lateral position rather than supine relieved a feeling of spatial disorientation caused by staring at the curved inner surface of the chamber. The clear endplates allowed adequate light for reading and helped to relieve confinement anxiety.

- Sound transmission through the chamber hull was quite good. Subjects inside the chamber could easily hear conversations from outside, but it was difficult for persons outside to understand the subject inside. This may have been partially due to muffling of the subject's voice from the BIBS mask. It was comforting to realize that communications were possible, if necessary, without the communication system.

- The communications system of the Hyperlite was quite good, and it enhanced communication between the subject and operator, particularly during noisy periods such as compression or venting. The only problems noted were that the microphone of the operator's headset had a tendency to fail due to the connection of the microphone boom to the earpiece, and the headsets did not seem very rugged. The system could have been enhanced with more durable components.

- The hose for the Divex brand BIBS was barely long enough to reach the patient's head. This presented a slight problem during entry into the chamber, as the patient could not place his headset until he was almost completely within the chamber, and it was difficult to assist the patient with straps or microphone, or troubleshoot the system if there were problems. Lengthening the hose by one to two feet would be helpful.

- One subject had difficulty equalizing ears in the supine position. The small diameter of the chamber made it difficult to assume a partially erect position to help with valsalva.

- Noise did not seem to be a major problem. Recordings of sound levels were made during pressurization and venting. The maximum level inside the Hyperlite was 95 decibels, for only five seconds. Noise levels were actually higher outside the chamber, near the control box, where noise levels up to 107 dBA were recorded during venting. Details are included in Appendix B.

- Temperature inside the Hyperlite ranged from 77° F (25° C) to a maximum of 93° F (33.89° C), while the temperature in the room where the chamber was located was approximately 75° F (23.89° C). The high temperature was reached within the first 30 minutes of pressurization, and was reduced to 83° F (28.34° C) with a single three minute venting of the chamber. Temperature then remained below 83° F (28.34° C) for the remainder of the treatment. In hot environments, inside temperature would be expected to be, at best, a few degrees above the temperature outside the chamber. A dependable means of measuring inside temperature would be a useful accessory, and is offered by the manufacturer. Measures to reduce internal chamber temperature would include frequent ventilation, shading from radiant heat, and possibly cooling the

outside of the chamber with water. In some circumstances, this could become an operational problem.

Exposures Performed in GSE Flexible Hyperbaric:

A total of 11 human exposures were performed in the GSE Flexible Hyperbaric. Nine of the exposures were short trials for human factor observations, and two exposures were for 105 minutes at 45 fsw (13.7 msw), according to U.S. Navy Treatment Table 9. Exposures in the GSE Flexible Hyperbaric were limited to 45 fsw (13.7 msw) due to the inability to easily change BIBS supply from oxygen to air. There was concern that there would be no way to quickly discontinue oxygen in the event of a seizure from oxygen toxicity, and the risk of a seizure was felt to be a concern at 60 fsw (18.3 msw). Human Factors observations for the GSE Flexible Hyperbaric are summarized as follows:

- Most subjects felt the inside space was generous. There was room to partially sit up on elbows, turn over, and even crawl and change direction within the chamber. In this regard, the GSE Flexible Hyperbaric was better than the Hyperlite.

- The inside chamber surface was not soft, and the thin cushion supplied was barely adequate padding for an extended stay. Extra padding in the form of fire retardant pillows and blankets were needed for comfort.

- Light entering the chamber through the translucent hull was adequate for most purposes, but there was very limited visibility of the outside from within the chamber due to the small size of the viewport.

- There was very limited ability to visually monitor the patient. If the medical lock is used, there is only one small viewport, located at the end opposite the medical lock. If the patient positions himself with access to the medical lock, the only view of the patient will be through a small window at the patient's feet.

- Sound transmission through the chamber hull was quite good. Subjects inside the chamber could easily hear conversations from outside, but it was difficult for persons outside to understand the subject inside. This may have been partially due to muffling of the subject's voice from the BIBS mask. It was comforting to realize that communications were possible, if necessary, without the communication system.

- The communications system of the GSE Flexible Hyperbaric was inadequate. It became non-functional during evaluation, and was not repaired. Fortunately, it was not vital to continued testing.

- Noise did not seem to be a major problem, but sound levels within the GSE Flexible Hyperbaric were higher than the Hyperlite. Recordings of sound levels were made during pressurization and venting. The maximum level inside the chamber was 108 dBA, for four minutes near the gas exchange end of the chamber. Noise levels were higher outside the chamber, near the control box, where noise levels up to 112 dBA were recorded during depressurization. Details are included in Appendix B.

Internal Chamber Atmosphere Oxygen and Carbon Dioxide Levels:

Continuous sampling of internal chamber atmosphere was performed by attaching a 1/8-inch (.32 cm) diameter Nylaflow tubing to the inside and outside of the emergency exhaust vent fitting. A flowmeter regulated sample flow at approximately 450 cc/minute. The sample gas was continuously analyzed using a Rosemont Model NGA 200 paramagnetic analyzer. Oxygen and carbon dioxide results were recorded manually. Detailed results are presented in Appendix C. The following observations deserve discussion.

- The Hyperlite, due to its small internal volume, was prone to rapidly rising oxygen levels if the BIBS mask was not properly fitted and sealed. Samples taken from near the patient's head or chest showed oxygen levels as high as 33.75% after as little as 15 minutes in one case using the Divex brand mask. However, when attention was focused on getting a good mask fit and seal, using the Scott brand mask, and samples were taken from the mid-point of the chamber, oxygen levels consistently measured below 27%, even for the duration of a U.S. Navy Treatment Table 6. These findings underscore the importance of proper use of the BIBS. Oxygen levels over 30% raise concern over fire hazards. Note that operators were able to discern when the BIBS was leaking because the chamber pressure rose as oxygen was drawn from the BIBS and expired into the chamber from a poorly fitted mask. This observation could be emphasized in training to prompt the operator to encourage the patient to check his mask fit, or vent the chamber. It would be desirable to have a monitor for oxygen levels within the chamber. There are some suitable oxygen monitors available. For more information on accessories, see Appendix G.

- Carbon dioxide (CO_2) also rose within the Hyperlite, particularly with poorly fitting BIBS masks, however it did not reach dangerous levels. The highest level recorded was 0.33%, at 60 fsw (18.3 msw) (0.924% SEV CO_2) during a 24 minute exposure using a subject with a poorly fitting mask. In another trial, in the final stages of a Treatment Table 6, the CO_2 level rose to 0.45% (0.855% SEV CO_2) at 30 fsw (9.1 msw). It is notable that the CO_2 level during this treatment had remained below 0.2% (0.361% SEV CO_2) until the patient removed his mask in order to eat and drink during an air break, resulting in a rise to 0.45% (0.855% SEV CO_2) in less than five minutes. This observation

again underscores the importance of proper use of the BIBS. It would be desirable to have a monitor for carbon dioxide, but current technology for a sensor that can be placed within the chamber is expensive. Candidate sensors are reviewed in Appendix G.

- Oxygen levels did not rise as quickly in the GSE Flexible Hyperbaric because it has a larger internal volume. The highest level recorded was 25.15%.

- Carbon dioxide levels in the GSE Flexible Hyperbaric did not rise quickly as long as the BIBS was in use, but as currently configured, the BIBS mask had to be removed to provide air breaks, which resulted in rise in carbon dioxide. The highest carbon dioxide level noted was 0.35% at 45 fsw (13.7 msw) (~.875% SEV CO_2).

Oxygen Consumption:

Oxygen usage was recorded during U.S. Navy Treatment Table 6 exposures using the Hyperlite. We found that approximately 185 SCF was consumed, based on pressure change of approximately 1500 psi (~102 Bar) in standard "T" size oxygen cylinders (floodable volume 1.8 cubic feet). This would be expected to be highly variable between subjects due to differences in size, respiratory rate, and breathing system efficiency. For planning purposes, we would recommend having a minimum of 200 SCF (approximately equal to a standard "K" cylinder) available for each U.S. Navy Treatment Table 6.

DISCUSSION

MEDICAL INDICATIONS FOR USE OF EEHS

Several conditions needing recompression therapy are likely to be encountered in diving and in the Submarine Rescue Mission. They are detailed as follows:

Decompression Sickness (DCS):

DCS is the condition which occurs when the body absorbs an inert gas (the nitrogen component of air) at an increased pressure and subsequently is brought to a lower pressure too rapidly to allow the dissolved gas to be eliminated from the body without the formation of bubbles in the bloodstream or tissues[9]. These bubbles may cause a wide variety of pathologic events, referred to as Decompression Sickness (DCS).

DCS is commonly discussed as two types; Type I DCS involves pain (usually in the joints) as the only symptom, whereas Type II DCS is more serious and involves neurologic, circulatory, or respiratory symptoms. In situations where an EEHS might be

used, the focus will be upon Type II DCS because it can lead to life threatening complications and permanent neurologic injury. Type II DCS may occur immediately upon surfacing or up to 24 hours later, and may cause neurologic symptoms ranging from mild numbness to severe paralysis, visual impairment, coma, or death.

The treatment of choice for Type II DCS is recompression and hyperbaric oxygen therapy. With prompt recompression, resolution of DCS occurs in over 90% of cases[10]. Delay in treatment reduces the chance of resolution. For this reason, early treatment using the EEHS system should yield improved results. Treatment should be based on the U.S. Navy Treatment Table 6, which has been the standard treatment for Type II DCS in the U.S. Navy for several decades. This protocol involves recompression to 60 fsw (18.3 msw) (2.8 ATA) pressure and breathing 100% oxygen. Variations from the standard regimen may be allowed at the discretion of the on-site Undersea Medical Officer. The protocol is detailed in Appendix D.

Arterial Gas Embolism (AGE):

AGE is the condition, which occurs when ascent or reduction in pressure occurs so rapidly that air trapped in the lungs expands and ruptures the air sacs in the lung. Bubbles of gas (gas emboli) enter the circulation, pass through the heart, and are transmitted via the arterial circulation throughout the body, where they can occlude the circulation to vital tissues causing damage similar to a stroke or heart attack.

Treatment for AGE follows the same basic principles of recompression and Hyperbaric oxygen therapy as for DCS, and may be accomplished using the EEHS. Some experts advocate a more aggressive application of pressure, up to 165 fsw (50.3 msw) (6 ATA), however; the necessity of this is controversial. The EEHS, as currently tested, will only allow recompression to 2.8 ATA with 100% oxygen, which many experts consider to be sufficient for AGE[11]. A proposed treatment protocol is detailed in Appendix B. AGE is more likely to present with severe neurologic symptoms, unconsciousness, and cardiovascular instability, and will thus be a high priority for recompression (see Appendix B). Pulmonary barotrauma and unconsciousness are also more likely, and these conditions may preclude or complicate the use of the EEHS (see contraindications, below).

Thermal Burns:

In a ship or submarine collision, attack, or malfunction, fire is a significant possibility, and due to the crowded conditions, severe burns would be likely. Hyperbaric oxygen therapy has been shown to be a helpful adjunctive therapy for burns[12]. There is evidence that it reduces tissue edema in the acute phase[13]. Thus, patients with significant thermal burns might be candidates for therapy in the EEHS, with or without co-existent DCS. Use of the EEHS for these indications would be strictly under the direction of a qualified Hyperbaric Medical Officer or Undersea Medical Officer. See Appendix D and E.

Carbon monoxide (CO) poisoning often coexists with burns, and would be highly likely in the confined atmosphere of a disabled submarine (DISSUB). Hyperbaric oxygen therapy has gained recognition as a valuable, and perhaps life-saving, treatment for CO poisoning, and could be accomplished in the EEHS[14]. See Appendix D for details.

Smoke inhalation including toxic products such as cyanide, phosgene, and chlorine gases is another possibility. Hyperbaric oxygen has also been proposed for therapy of smoke inhalation and cyanide poisoning but may be relatively contraindicated in chlorine gas exposure due to pulmonary injury[15].

Trauma and Crush Injury:

Traumatic injuries would be expected in most situations where a submarine becomes disabled. Crushed extremities with ischemic tissues and developing compartment syndromes may benefit from hyperbaric oxygen therapy, which could be provided in an EEHS. See Appendix D.

It becomes evident that the possible uses for the EEHS are numerous, and decisions regarding which patients will be considered for evacuation or treatment in an EEHS may be complex. As an aid in this process, we propose a triage algorithm based on the severity of DCS/AGE, co-existent medical problems, contraindications, and resources available. Please refer to Appendix B for more information.

CONTRAINDICATIONS FOR USE OF THE EEHS

While the EEHS system is a valuable tool, it has significant limitations, and may pose serious hazards if used inappropriately. It is basically a monoplace hyperbaric oxygen treatment chamber, similar in design and capability to the chambers (such as those made by Sechrist Industries) used in hundreds of hospitals and medical facilities throughout the world for thousands of treatments annually. We can draw from the extensive experience in this field for both capabilities and cautions.

The most serious limitation of any monoplace hyperbaric system is the loss of "hands on" access to the patient. While this presents many challenges to physicians not accustomed to this situation, physicians experienced in the use of monoplace chambers have learned that many of the problems can be overcome with careful preparation and vigilance. Recommendations for care of critically injured patients in the EEHS will be addressed in Appendix F.

The most important concern for use of the EEHS should be consideration of airway management. If the patient is not fully conscious and capable of maintaining his own airway, he should not be placed in the EEHS unless personnel skilled at airway management are continuously managing the patient. The risk of airway obstruction in

an unconscious patient is always present, and the EEHS offers only very limited ability to observe respirations. Anoxia from airway obstruction is worse than most cases of DCS or AGE, and the relative risks must be carefully weighed. The use of airway adjuncts, such as oral or nasopharyngeal airways, endotracheal intubation, laryngeal mask airway, esophageal obturator airway, or other devices may be helpful, but should only be used by skilled personnel. Their use will be further addressed in Appendix E.

Acute head injury, by itself, is not necessarily a contraindication, but if the patient were unconscious, the above discussion would apply. Vigilance would be necessary to follow changes in level of consciousness. Trauma to the face, particularly involving the airway, would require careful consideration.

Chest trauma or the presence of pneumothorax or pneumomediastinum should be considered a relative contraindication due to the possibility of development of tension pneumothorax. Unlike a multiplace hyperbaric chamber, a pneumothorax could not be vented at depth, and would thus be worsened on decompression with the possibility of development of tension pneumothorax. Immediate thoracostomy upon exit from the chamber could be performed, but this would be a very hazardous procedure. If the need for recompression was extreme and the EEHS was the only available asset, tube thoracostomy prior to recompression would be an option.

Significant multisystem trauma with shock would require careful consideration for use of the EEHS. Interventions necessary for support of shock, including large volumes of fluids, vasopressors, respiratory support or CPR would be compromised by recompression in an EEHS. Some proposed modifications and accessories for the EEHS, including intravenous access system, enhanced monitoring, and a ventilator, could become available (see Appendix E), which could provide the ability to treat some patients in shock, but these capabilities are not currently available. The complexity of providing these capabilities is such that it is not likely to be viable in a mass casualty scenario.

Extremity trauma may present logistic difficulties due to positioning and the process of loading into the EEHS, and the management of the injury may be complicated, but this should not be a contraindication. In fact, as mentioned earlier, hyperbaric oxygen may be beneficial in many cases of extremity trauma.

SAFETY CONCERNS

Fire hazard is a major concern in any hyperbaric chamber, and appropriate precautions must be conscientiously followed in the use of the EEHS due to the use of oxygen and lack of any fire suppression system. With proper use of the BIBS, oxygen levels within the EEHS will remain under 25%, but leakage from a poorly fitting BIBS can raise the oxygen level within the EEHS to over 30%, which could increase the risk of fire. Careful attention to proper use of the EEHS is mandatory, and monitoring of the oxygen level would be desirable. Strict adherence to standard fire safety precautions,

including elimination of flammable materials from the chamber and use of 100% cotton materials is strongly advised. Clothing soiled with oil or grease should be removed and replaced with clean cotton garments. Any fire would likely be catastrophic not only to the chamber occupant, but to bystanders as well.

There are hazards associated with use of pressurized systems. The high-pressure air and oxygen sources, valves, hoses, and regulators are similar to those commonly used for SCUBA systems and medical oxygen supplementation systems. The chamber itself is pressurized to a maximum of 30 psig, equivalent to the pressurization of an automobile tire. The Hyperlite has been shown in destructive testing to have a failure pressure of approximately 200 psig and failure resulted in rapid leakage rather than catastrophic bursting[3].

Excessive environmental heat could compromise use of the EEHS in some situations. Testing at NEDU indicates that the internal temperature of the EEHS may range from 2°-15° F higher than the surrounding environment. Internal chamber temperatures over 85° F (29.45° C) for extended periods could lead to potentially dangerous heat stress in patients[16]. Means of reducing the temperature inside the chamber include venting and cooling the exterior of the chamber with cool air, water, or ice. Monitoring of internal temperature would be advisable if possible.

Personal hygiene, particularly management of urine and feces, must be attended to. This is particularly important due to the small volume of breathable atmosphere within the chamber, making atmospheric contamination with ammonia or hydrocarbons a concern, although it is mitigated somewhat by the fact that the patient should be breathing from the BIBS rather than chamber atmosphere. Patients capable of caring for themselves should be provided urinals, condom catheters, or bedpans. Condom catheters or foley catheters should be used for debilitated patients. Absorbent diapers are an option, but would not be optimal.

Transport of pressurized vessels raises significant safety concerns, but it should be noted that the high-pressure components, which include the air and oxygen tanks, are routinely transported in emergency vehicles for other uses. As noted earlier, the EEHS chamber is pressurized to only 2.8 ATA for treatment, which is roughly equivalent to 27 psig. For comparison, note that an automobile tire is commonly inflated to 30 psig. When taken into perspective, the risk to outside personnel does not seem excessive.

POLICY CHANGES

Current U.S. Navy policies do not cover the use of the EEHS. Guidelines for recompression therapy for diving injuries outlined in the U.S. Navy Diving Manual are directed at the use of multiplace hyperbaric chambers, and are primarily concerned with diving related injuries. Since the use of the EEHS in the Submarine Rescue Mission would be emergency medical management, and would be unrelated to diving per se, it

could be addressed in a manner similar to the use of other emergency medical devices, such as oxygen delivery systems, MAST suits, ACLS adjuncts, etc.

If an EEHS system is later evaluated and approved for other diving related purposes, which is quite possible, appropriate changes to the U.S. Navy Diving Manual, or other appropriate instruction, would be necessary covering those applications. Policy areas that would need to be addressed include:

- Personnel authorized to operate the EEHS. Due to the nature of the system, which precludes access to the patient, a higher standard of medical qualification, such as Diver Medical Technician or DMO, would be recommended for primary operators. Alternatively, training specifically directed towards the medical problems likely to be encountered in the use of the EEHS could be a part of the required training for use of the system. The mechanical operation of the system is relatively easy, but the appropriate care of the patient could be challenging.

- Minimum number of operators required. From experience gained during this evaluation, a minimum of two operators would be recommended, in order for adequate vigilance to be maintained towards the patient by one person, and the system by a second person.

- Training requirements. Qualified divers found the Hyperlite EEHS to be quite easy to learn to operate, but operators would need thorough training in the limitations and inherent risks of using the system. This could probably be accomplished in as little as one day, assuming an organized curriculum was developed. Periodic requalification, at least twice yearly, would be recommended.

- Maintenance requirements. The Hyperlite EEHS system itself has relatively low maintenance needs. It would, of course, need to be thoroughly cleaned with a non-toxic, non-corrosive, solution after each use. Small leaks may develop in the flexible hull under normal use, which may result in small blebs on the surface of the chamber, and are easily repairable with a silicone rubber repair kit provided by the manufacturer. Inflation of the chamber to working pressure and measurement of the leak rate over two hours would be recommended after each use and at least yearly to detect small leaks. One other major concern would be ensuring that compatible air and oxygen supplies were available at all times. There are a wide variety of oxygen supply cylinders, each with slightly different valves, regulators, or fittings. Periodic exercises involving pressurization and use of the system to ensure that all components are available would be recommended. Periodic maintenance should also include thorough inspection of all gauges, regulators, valves, hoses, and fittings. The manufacturer's manual[17] includes service directions.

- Storage requirements. Although the EEHS systems have proved to be quite durable in storage, it would be recommended that they be stored in sealed containers at normal environmental temperatures. The units at NEDU were stored outside, under a covered walkway, for over a year without any signs of significant problems.

TREATMENT PROTOCOLS

Protocols for treatment of DCS/AGE at the scene using the EEHS will generally follow the schedules outlined in U.S. Navy Diving Manual[9], Treatment Tables 5 and 6. It should be emphasized that if these schedules are followed with respect to depth and oxygen cycles, no additional decompression obligation will be incurred, and the patient should be able to be decompressed to the surface (ascent rate not to exceed 60 fpm) at any time during treatment for emergencies, medical interventions, or interruption of treatment if necessary. While this should only be considered in special circumstances, and by experienced physicians, proposed guidelines should leave sufficient flexibility for the DMO on site to adjust the schedules based on his assessment of priorities (see Appendix D for additional details).

Protocols for transfer under pressure and evacuation may vary slightly from treatment protocols, but should generally follow the same principles. In most situations, U.S. Navy Treatment Table 6 will serve as the recommended schedule. The patient would be pressurized to 60 fsw (18.3 msw) breathing oxygen while awaiting evacuation, and maintained at the pressures and times outlined for Treatment Table 6 during transport. Clear documentation of treatment schedule will be vitally important if care of the patient is transferred during treatment. Ending a recompression treatment while in transit, particularly if in an aircraft, would best be avoided (see Appendix E for details).

CONCLUSIONS/RECOMMENDATIONS

The EEHS represents a significant advance in acute management of DISSUB or diving casualties. The Hyperlite EEHS, with minor modifications recommended, meets the mission requirements outlined in the Foreign Comparative Testing Proposal[2] and NAVSEA Task Letter[1]. Many logistical issues will require careful consideration and planning. Procurement, staging, transport, and training of qualified personnel will be major issues that should be addressed as soon as decisions on the incorporation of the EEHS into the U.S. Navy Diving or Submarine Rescue Mission are made. With foresight, many disabling permanent injuries may be prevented.

A summary of recommendations is as follows:

- The Hyperlite EEHS is suitable for the mission outlined, which includes evacuation of a patient under pressure and capability to perform a U.S. Navy

Treatment Table 6. Procurement and integration into U.S. Navy operations is recommended.

- The GSE Flexible Hyperbaric, of the size and configuration tested, is not suited to the mission described. The combination of size, weight, and lack of safety features raises significant concern for use as a system that might be moved with an occupant under pressure. With modification, it could offer some advantages as a system to be used while stationary in a remote location.

Recommended improvements to the Hyperlite include:

- Provision of a penetrator for intravenous access. This could be modeled after the system used commonly for other monoplace hyperbaric chambers, which consists of a penetrator sized to match intravenous fluid administration tubing with a one way "backcheck" valve to prevent leakage of fluid or pressure. An infusion pump located outside the chamber pumps the fluid. The operator maintains control of the infusion.

- Provision of additional electrical connections to allow electrocardiographic (ECG) monitoring of patients. This could be accomplished by increasing the pins in the existing electrical penetrator.

- Improvement of the lifting handles to provide a better grip surface.

- Improvement of the components of the communications system for greater durability.

- Use of the Scott brand BIBS mask/regulator, and lengthening of the hose by 18 inches (46 cm).

- Improvement of labeling of valves and gauges.

- The stretcher (litter) is not recommended.

- The addition of an oxygen monitoring system.

- Other useful accessories would include a carbon dioxide monitor, electrocardiogram, pulse oximeter, and internal chamber pressure gauge which is independent of outside atmospheric pressure, to be used during air transport. Evaluations of potential accessories are found in Appendix G.

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APPENDIX A

COMPARISON OF AVAILABLE EEHS SYSTEMS - SUMMARY

Basic Materials:

- SOS Hyperlite - "Filament wound para-aramid fiber in flexible polymeric silicone matrix" (similar to "Kevlar"), with a cotton fabric cover.

- GSE Flexible Hyperbaric - Two layers; inner bag of composite polyester cloth impregnated with urethane for impermeability and an outer layer formed by a net of polyester cargo straps for circumferential and longitudinal strength.

Weight:

- Hyperlite – 170 lb (77.1 kg) complete (not including gas supply cylinders).

- GSE - Varies depending on depth capability and options, but most likely in excess of 270 lb (122.5 kg) (not including gas supply cylinders).

Dimensions:

- Hyperlite – 88.5 inches (225 cm) long by 23 inches (58 cm) diameter (2250 mm by 595 mm).

- GSE – Approximately 85 inches (216 cm) long by 30 inches (76 cm) diameter (2165 mm by 762 mm).

End Plates:

- Hyperlite - Transparent acrylic plastic which seal against the lip of the tube by pressure from the inside (no mechanical latch).

- GSE - Machined cast aluminum end plates attached to inner bag and cargo straps. One end has a removable aluminum hatch with window which locks into place with an interrupted thread bayonet type fitting. (Note: Engineers expressed concerns that the hatch could be incorrectly positioned and the unit could still be pressurized. This was considered potentially hazardous).

Medical (Supply) Locks:

- Hyperlite's medical lock is small, but functional. It is simple and easy to operate. It does not obstruct the view of the patient. The only problem noted was that it

could be inadvertently left open during assembly, causing a leak during pressurization. When this occurs, it is obvious and easy to correct quickly.

- The GSE medical lock is large and heavy, and must be installed at one end of the chamber in place of a viewport. It obstructs the view from the affected end.

Oxygen Administration (BIBBS) System:

- Both systems comparable, including a demand regulator supplying 100% oxygen to an oral-nasal mask with overboard dump of exhaled gas.

- Hyperlite includes a switch valve on control panel to easily change BIBS gas from oxygen to air. GSE does not.

- A semi-closed circuit rebreather system has been proposed in concept by Navy personnel to conserve oxygen. It would be equally applicable to either system.

Gas Supply and Control Systems:

- The Hyperlite could be pressurized to 60 fsw (18.3 msw) from a single 80 cu. ft. cylinder, with plenty of air remaining, but the GSE could barely be pressurized from the equivalent supply (it needed double 80 cu. ft. tanks to perform efficiently).

- On the Hyperlite, hoses enter at the center of the end plates in a long axis orientation. They are not subject to damage if the unit rolls or must pass through a narrow opening during transport.

- On the GSE, hoses enter the end plate rim in the cross sectional axis, as a spoke would enter a hub. They are subject to damage, even dislodgment, if the unit is rolled. They protrude in such a way that they would interfere with transport through a narrow opening.

- Hyperlite control module is intuitive and easy to understand. Controls for supply, exhaust, pressure, and BIBBS gas have positive positions. Gauge readings are not altered by control settings.

- GSE control module is somewhat difficult to understand at first look. Valves can be in intermediate positions without being noticed. When the exhaust valve is partially open, the pressure gauge may read erroneously.

Human Factors:

- Light - Hyperlite hull is opaque, but entire end domes are transparent. This allows in plenty of light for reading, and allows some view of the outside. This also allows the patient to be seen easily from either end of the chamber. GSE is semi-translucent, and end domes are metal with small windows. There is adequate light, but the view from the inside is limited. It is very difficult to monitor the patient well.

- Space - GSE is larger in diameter. The extra space allows the patient to partially sit, turn easily, and even reverse position within the chamber. The smaller size of the Hyperlite is a problem for some patients. Confinement anxiety is greater in the Hyperlite, but was generally not problematic.

- Noise - Noise levels were not a problem in either chamber. Both chambers allowed communication through the hull if necessary.

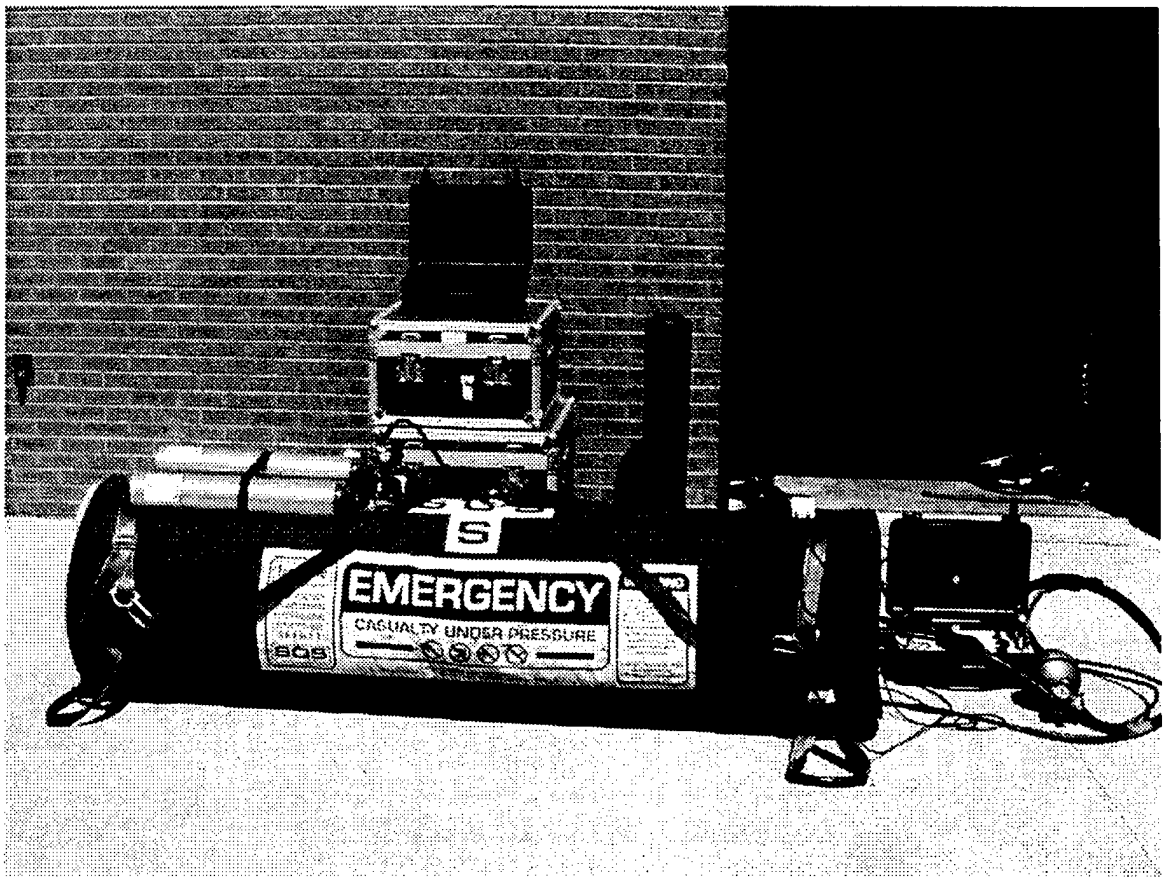


ILLUSTRATION A-1. SOS HYPERLITE EEHS SYSTEM.

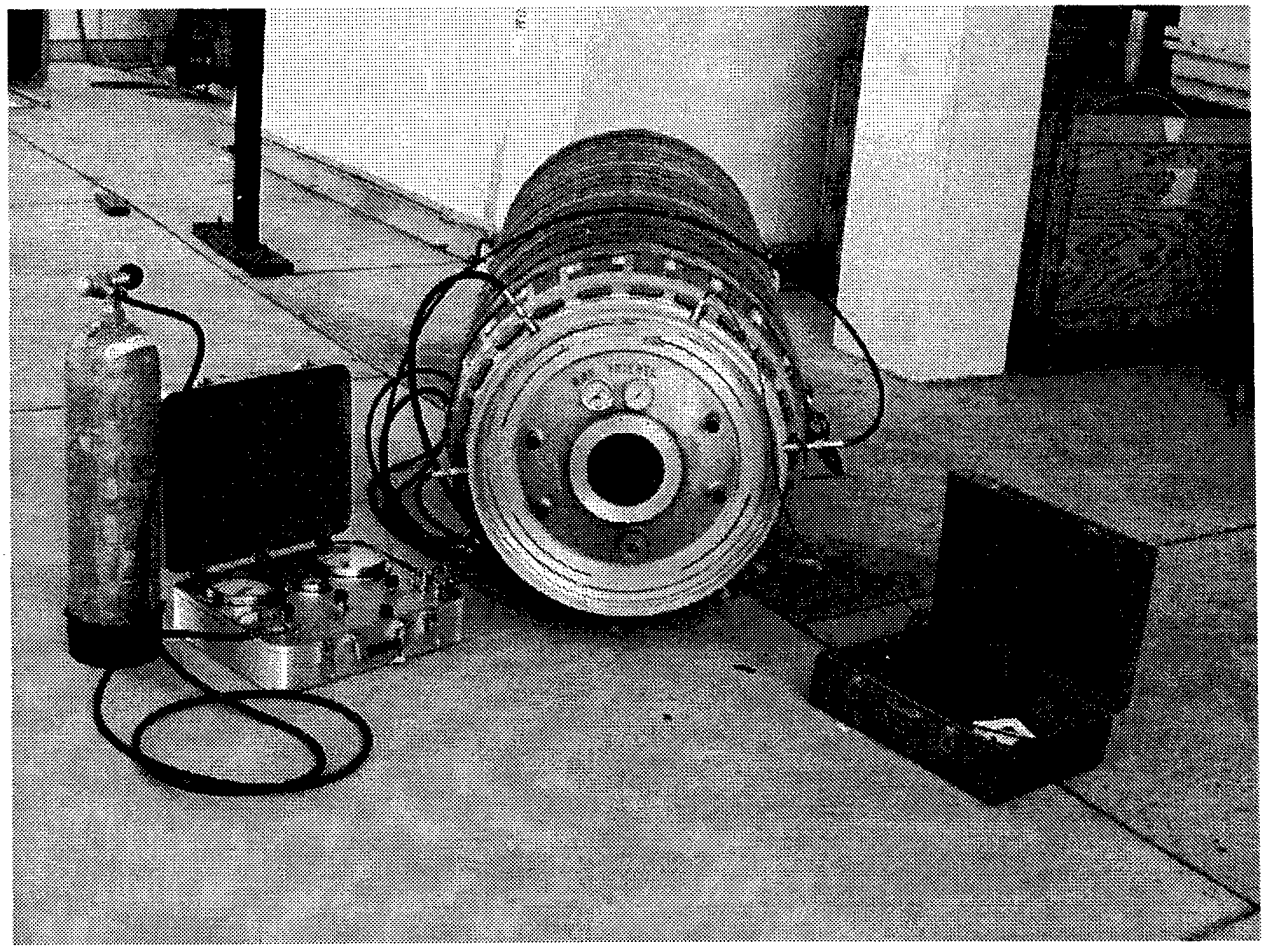


ILLUSTRATION A-2. GSE FLEXIBLE HYPERBARIC EEHS SYSTEM

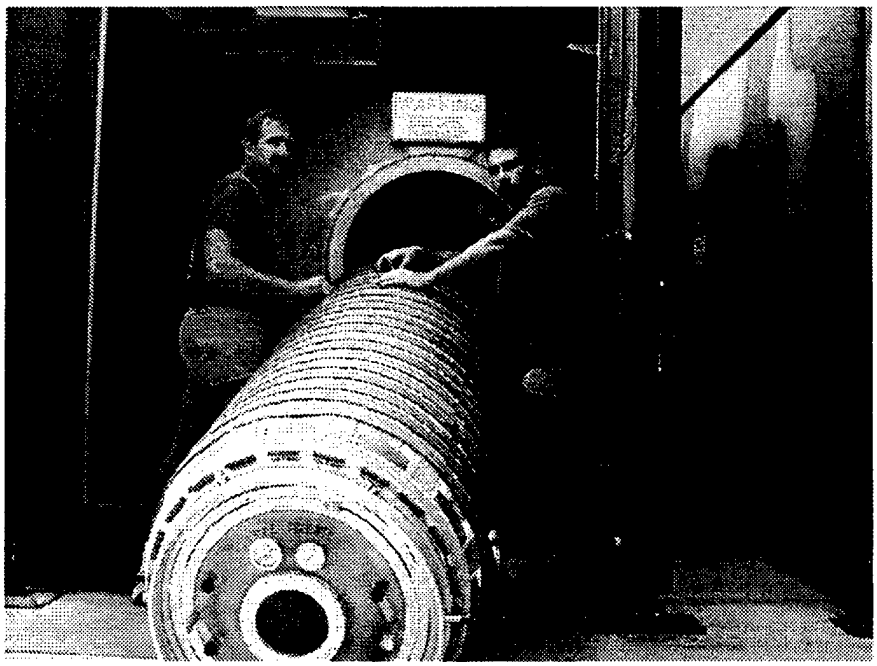


ILLUSTRATION A-3. GSE FLEXIBLE HYPERBARIC WILL NOT FIT INTO STANDARD U.S. NAVY DIXIE DOUBLE-LOCK CHAMBER.

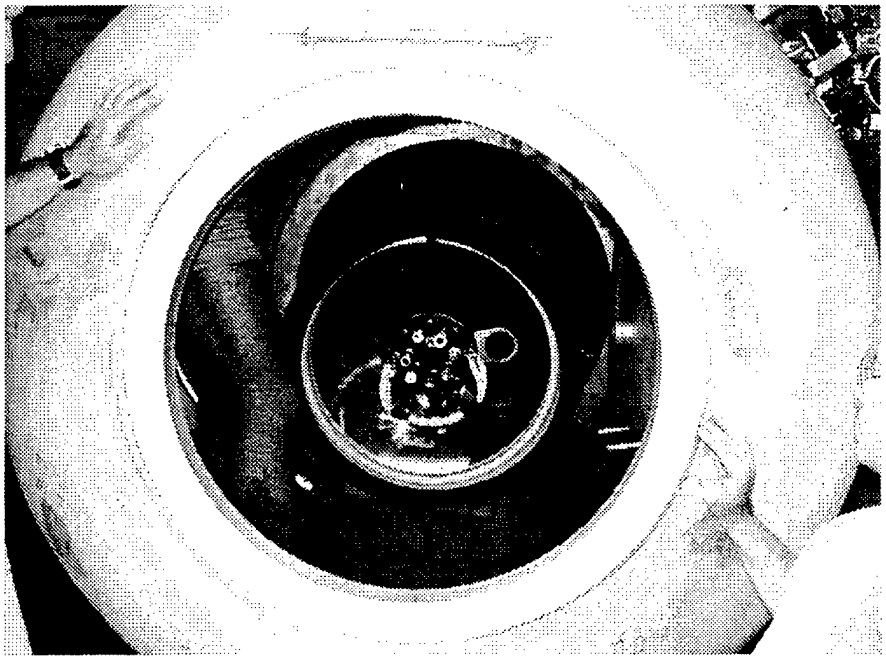


ILLUSTRATION A-4. HYPERLITE DOES FIT INTO U.S. NAVY DIXIE DOUBLE-LOCK.

APPENDIX B

EEHS NOISE STUDIES

22 March 1999

From: Torger Reppen
To: LCDR Latson
Subj: Emergency Evacuation Hyperbaric Stretchers (EEHS) Audio/Sound Testing

1. Objective:

   Determine sound levels for two different EEHS portable chambers. Sound levels were evaluated for diver as well as the chamber operator.

2. Devices under test:
   A. HYPERLITE- manufactured by SOS Ltd. of Great Britain.
   B. GSE Flexible Hyperbaric- manufactured by GSE Trieste Ltd. of Italy.

3. Test equipment:
   A. Analyzer and acquisition system: Brüel & Kjær (B & K), Nærum, Denmark PULSE Labshop 4.1.
   B. Diver microphone: EX-14 Microphone (SS# 97041403).
   C. Operator microphone: B&K Type 4192 (SS#1913832).

4. Test procedure:

   The Pulse System was setup in close proximity to the EEHS allowing the operator microphone to be placed within six inches (15 cm) above the gas control panel. The diver microphone was attached within six inches (15 cm) of the diver's ear. With the HYPERLITE EEHS, only one diver microphone configuration was necessary because the diver can only be situated one way (feet near the gas exchange fittings). In the GSE Flexible Hyperbaric EEHS, however, the diver could conceivably be placed with his head at either end of the chamber. Diver microphone measurements made with GSE Flexible Hyperbaric were acquired at both ends of the chamber.

5. Test results:

   All measurements are presented in overall A-weighted dB levels (dBA).

HYPERLITE	**Diver**	**Operator**
Pressing to depth (4 minute exposure)	76 dBA	71 dBA
Venting (1 minute exposure, typical)	76 dBA	107 dBA
Surfacing (3 minute exposure)	77 dBA	105 dBA
Steady at depth	71 dBA	72 dBA
Shifting to O_2 (5 second exposure)	95 dBA	71 dBA

GSE Flexible Hyperbaric	Diver[1]	Diver[2]	Operator
Pressing to depth (4 minute exposure)	102 dBA	108 dBA	72 dBA
Venting (1 minute exposure, typical)	Omitted	88 dBA	104 dBA
Surfacing (3 minute exposure)	96 dBA	98 dBA	112 dBA
Steady at depth	81 dBA	83 dBA	85 dBA

1. Microphone placed away from gas exchange end of EEHS
2. Microphone placed near gas exchange end of EEHS

Torger Reppen, Test Engineer

APPENDIX C

HYPERLITE/GSE OXYGEN AND CARBON DIOXIDE LEVELS

(EEHS) HYPERLITE BRITISH

Hyperlite O_2/CO_2 Level Evaluation

Date 2/19/99

Subject #1

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
60'	:02	21.73	0.19	0.532
60'	:07	22.56	0.2	0.56
60'	:12	22.8	0.21	0.588

Date 2/19/99

Subject #2 TT-6

Depth	Plus Time	O_2%	CO_2%	CO_2 % sev	
60'	:00	20.78	0.08	0.224	
60'	:10	20.83	0.08	0.224	
60'	:20	20.9	0.08	0.224	
60'	:30	20.89	0.07	0.196	:04 vent
60'	:40	20.89	0.07	0.196	
60'	:50	20.89	0.08	0.224	
60'	01:00	21.02	0.08	0.224	
60'	01:10	21.15	0.09	0.252	Travel to 30'
54'	01:20	21.3	0.09	0.237	
44'	01:30	21.52	0.1	0.233	
35'	01:40	21.73	0.11	0.226	
30'	01:50	22.02	0.12	0.228	
30'	02:00	22.02	0.14	0.266	
30'	02:10	22.35	0.15	0.285	
30'	02:20	23.15	0.16	0.304	
30'	02:30	23.59	0.18	0.342	
30'	02:40	24.25	0.19	0.361	
30'	02:50	24.19	0.19	0.361	
30'	03:00	24.12	0.19	0.361	Off bib to eat
30'	03:10	23.71	0.45	0.855	
30'	03:20	23.66	0.44	0.836	

Hyperlite O_2/CO_2 Level Evaluation

30'	03:30	23.62	0.43	0.817
30'	03:40	23.57	0.43	0.817
30'	03:50	23.71	0.43	0.817
30'	04:00	23.85	0.43	0.817
30'	04:10	24	0.43	0.817
26'	04:20	23.97	0.43	0.768
16'	04:30	24.1	0.45	0.668
6'	04:40	24.49	0.47	0.555

Date 2/17/99

Subject #3

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev	
60'	:05	30.13	0.32	0.896	
60'	:10	28	0.26	0.728	vented stretcher
60'	:15	25.72	0.21	0.588	
60'	:20	25.68	0.21	0.588	

Date 2/17/99

Subject #4

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
60'	:05	21.75	0.06	0.168
60'	:10	26.8	0.2	0.56
60'	:15	25.46	0.15	0.42
60'	:20	29	0.21	0.588

Date 2/17/99

Subject #5

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
60'	:05	24.71	0.14	0.392
60'	:10	24.76	0.17	0.476
60'	:15	25.83	0.17	0.476
60'	:20	26	0.17	0.476

Hyperlite O_2/CO_2 Level Evaluation

Date 2/17/99

Subject #6

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
60'	:05	20.14	0.02	0.056
60'	:10	20.75	0.04	0.112
60'	:15	20.76	0.04	0.112
60'	:20	21.02	0.04	0.112

Date 2/18/99

Subject #7

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
60'	:05	21.3	0.07	0.196
60'	:10	25.15	0.2	0.56
60'	:15	25.14	0.2	0.56
60'	:20	26.44	0.21	0.588
60'	:25	26.39	0.22	0.616

Date 2/18/99

Subject #8

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
60'	:05	23.3	0.14	0.392
60'	:10	26.3	0.2	0.56
60'	:15	26.9	0.21	0.588
60'	:20	27.5	0.2	0.56
60'	:25	29	0.22	0.616

Date 2/18/99

Subject #9

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev	
60'	:05	21.07	0.04	0.112	
60'	:07	23.37	0.13	0.364	aborted TT-6

Hyperlite O_2/CO_2 Level Evaluation

Date 2/18/99

Subject #10

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev	
60'	:03	23.2	0.18	0.504	
60'	:10	29.12	0.28	0.784	
60'	:15	33.36	0.32	0.896	
60'	:17	32.75	0.33	0.924	vented stretcher
60'	:20	31.5	0.29	0.812	
60'	:24	32.27	0.28	0.784	

Date 2/18/99

Subject #11

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
60'	:03	22.15	0.07	0.196
60'	:05	21.57	0.06	0.168
60'	:09	21.93	0.07	0.196
60'	:12	24.07	0.13	0.364
60'	:16	24.78	0.13	0.364
60'	:20	25.4	0.13	0.364

Date 2/18/99

Subject #12

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
60'	:00	21.97	0.12	0.336
60'	:05	21.31	0.1	0.28
60'	:09	24.15	0.15	0.42
60'	:12	23.17	0.14	0.392

Hyperlite O_2/CO_2 Level Evaluation

Date 2/19/99

Subject #13

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev	
30'	:05	24.79	0.17	0.323	
30'	:20	24.48	0.19	0.361	TT-6 started sampling at 30'
30'	:35	25.18	0.22	0.418	
30'	:50	25.58	0.23	0.437	
30'	01:05	25.76	0.24	0.456	
30'	01:20	25.75	0.25	0.475	
30'	01:35	26.21	0.27	0.513	

Date 3/10/99

Subject #14 TT-6

Depth	Plus Time	O_2%	CO_2%	CO_2 % sev
60'	:15	21.16	0.07	0.196
60'	:30	21.22	0.07	0.196
60'	:45	21.26	0.07	0.196
60'	01:00	21.32	0.08	0.224
60'	01:15	21.36	0.08	0.224
60'	01:30	21.44	0.08	0.224
46'	01:45	21.49	0.08	0.191
30'	02:00	21.55	0.09	0.171
30'	02:15	21.55	0.09	0.171
30'	02:30	21.58	0.1	0.19
30'	02:45	21.66	0.1	0.19
30'	03:00	21.77	0.1	0.19
30'	03:15	21.9	0.11	0.209
30'	03:30	21.91	0.11	0.209
30'	03:45	21.48	0.07	0.133
30'	04:00	21.64	0.08	0.152
30'	04:15	21.98	0.09	0.171
30	04:30	22.11	0.1	0.19

(EEHS) GSE ITALIAN

GSE O_2/CO_2 Level Evaluation

Date 3/16/99

Subject #1

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
0'	:00	22.40	0.10	0.10
45'	:05	21.90	0.09	.212
45'	:10	21.20	0.08	.188
45'	:15	21.37	0.08	.188
45'	:20	21.48	0.08	.188
45'	:23	21.59	0.08	.188

Date 3/16/99

Subject #2

Depth	Plus Time	O_2%	CO_2%	CO_2 % sev
0'	:00	21.32	.05	.05
45'	:05	21.54	.05	.118
45'	:10	21.57	.05	.118

Date 3/17/99

Subject #3

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev	
0'	:00	24.28	.20	.20	
45'	:10	22.01	.09	.21	
45'	:20	21.75	.09	.21	AIR BREAK
45'	:30	22.36	.18	.42	
45'	:40	22.50	.18	.42	

GSE O_2/CO_2 Level Evaluation

Date 3/17/99

Subject #4

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev	
0'	:00	22.30	.20	.20	
45'	:06	21.75	.09	.21	
45'	:08	22.00	.10	.23	AIR BREAK
45'	:13	22.24	.10	.23	AIR BREAK
45'	:28	22.83	.21	.49	
45'	:38	22.95	.21	.49	AIR BREAK
45'	:43	23.02	.21	.49	AIR BREAK
45'	:48	23.38	.30	.70	
45'	:58	23.54	.30	.70	AIR BREAK
45'	1:03	23.64	.30	.70	AIR BREAK
45'	1:18	23.92	.39	.92	

Date 3/18/99

Subject #5

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
0'	:00	21.22	.09	.09
45'	:09	22.60	.21	.49
45'	:14	22.73	.21	.49
45'	:19	24.15	.24	.56
45'	:21	25.15	.24	.56

Date 3/18/99

Subject #6

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev	
0	:00	21.9	.09	.09	
45'	:18	21.88	.08	.18	
45'	:27	22.05	.08	.18	AIR BREAK
45'	:32	22.30	.15	.35	AIR BREAK
45'	:47	22.47	.17	.40	
45'	:57	22.61	.17	.40	AIR BREAK
45'	1:02	23.21	.24	.56	AIR BREAK
45'	1:17	23.67	.26	.61	

GSE O_2/CO_2 Level Evaluation

45'	1:27	23.68	.26	.61	AIR BREAK
45'	1:32	24.24	.33	.77	AIR BREAK
45'	1:47	24.56	.35	.77	

Date 3/18/99

Subject #7

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
0'	:00	24.09	.09	.09
45'	:09	21.26	.06	.14
45'	:14	21.32	.06	.14
45'	:19	21.44	.06	.14
45'	:24	21.50	.06	.14

Date 3/18/99

Subject #8

Depth	Plus Time	O_2 %	CO_2 %	CO_2 % sev
0'	:00	21.51	.06	.06
45'	:12	21.53	.16	.37
45'	:17	21.64	.16	.37
45'	:22	21.72	.16	.37

APPENDIX D

TRIAGE ALGORITHM FOR THE USE OF EEHS IN THE MANAGEMENT OF DIVING OR SUBMARINE RESCUE CASUALTIES

The possible uses for the EEHS are numerous, and decisions regarding which patients will receive priority in treatment may be complex. As an aid in this process, we propose a triage algorithm based on the severity of DCS/AGE, co-existent medical problems, contraindications, and resources available.

There are many possible scenarios, depending on the nature of the casualty, the assets available, and the number and type of other casualties. The major factors to consider include:

- The presence and severity of other injuries besides DCS/AGE. The treatment of life threatening trauma will obviously supercede recompression, particularly if recompression compromises access to the patient.

- The severity of DCS/AGE. Neurologic involvement obviously is a higher priority than pain-only symptoms. Furthermore, paralysis of major muscle groups, or gross cerebral deficits are more significant than sensory findings (i.e. numbness or paresthesia). Rapidity of onset is a consideration; DCS presenting early and changing rapidly should probably be treated more aggressively than slowly evolving symptoms. Milder pain-only symptoms may not warrant use of the EEHS if multiplace recompression assets are available within two hours.

- The presence of contraindications to recompression therapy.

- The assets available. If there are multiple casualties, are there enough recompression chamber spaces or EEHS units to accommodate all of the serious cases? Is evacuation to another facility possible within a reasonable time?

- Complicating conditions. Does the patient have problems that, although not contraindications, would make recompression in an EEHS difficult? Will the patient accept confinement and treatment in the EEHS.

- Likelihood of success. This is frequently the most difficult issue. In a multiple casualty situation, should a recompression asset be tied up with a case unlikely to recover while other patients, while less severely injured, may have a better chance of recovery? It is possible that EEHS units may be the only recompression assets available, and there may not be enough to treat all patients.

STEP ONE:

Assess for life threatening injuries other than DCS/AGE, particularly hypothermia, near drowning, and barotrauma to ears, sinuses, or lungs. If present, address injury. If use of EEHS would compromise care of other conditions, defer recompression until immediate threat stabilized. Supplemental oxygen, if available, is strongly recommended.

- If no other immediately life threatening injuries present, go to step two.

STEP TWO:

Assess for DCS/AGE. This should be a rapid screening exam.

- Does the subject complain of any weakness, paralysis, visual disturbance, or cognitive defect?
- Can the subject answer simple questions, recognize a visual object, stand, walk, reach above his head with both arms, and grip?
- If gross deficit found, go to step three.
- If no gross deficit, observe expectantly, treat other injuries when feasible, and provide fluids and surface oxygen if available. Re-assess periodically, and in more detail as time and resources allow. If symptoms of DCS of a milder nature are discovered, go to step three as resources allow.

STEP THREE:

Rule out possible contraindications to recompression in the EEHS.

- Unconsciousness (unless skilled personnel available).
- Any airway compromise
- Chest Trauma
- Pneumothorax (particular attention to this should be paid if patient has rapidly developing neurologic symptoms which could be AGE from pulmonary overinflation)
- Traumatic injury
- Shock

- Head injury

If contraindications exist, defer recompression until problems addressed (i.e., chest tube placed for pneumothorax, shock stabilized, or airway secured by skilled personnel).

If no contraindications, go to step four.

STEP FOUR:

Assess the likelihood of recovery compared to other candidates for recompression therapy if resources limited. Avoid dedicating scarce resource for indeterminate time period if patient is unlikely to recover.

Also consider co-existent conditions other than DCS/AGE which would benefit from hyperbaric oxygen therapy, such as carbon monoxide poisoning or burns. While these conditions will probably not be the primary concern for decisions regarding allocation of EEHS, they may be a factor. If resources are available, go to step five.

STEP FIVE:

Special considerations requiring preparation. If patient needs extensive preparation (i.e., chest tube, wound care, etc), it may be more efficient to treat another patient in the EEHS while this patient is being readied. If resources are not limited, prepare patient and go to step six.

STEP SIX:

At earliest opportunity, place patient in EEHS, using criteria discussed above to prioritize which patients will be treated first. Teach use of BIBS and equalization techniques, and compress (patients unable to equalize the pressure in the middle ear space may require decongestants, slow compression or myringotomy). Give 100% oxygen via BIBS system. Assess for response to treatment.

TREATMENT SCHEDULES

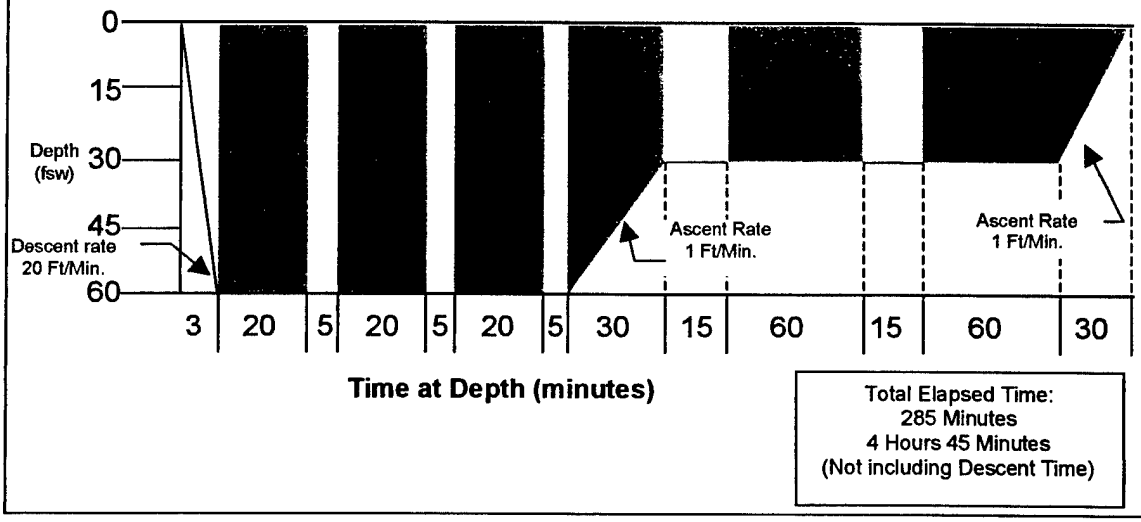
Treatment of Non-Saturation DCS:

Patients with DCS not due to prior saturation should be treated using U.S. Navy Treatment Table 6 (TT6) under most circumstances. The following excerpt from the U.S. Navy Diving Manual[1] provides the details. Treatment of omitted decompression from non-saturation diving could be provided in an EEHS and should follow procedures outlined in the U.S. Navy Diving Manual.

Treatment Table 6

1. Descent rate – 20 ft/min.
2. Ascent rate – Not to exceed 1 ft/min. Do not compensate for slower ascent rates. Compensate for faster rates by halting the ascent.
3. Time on oxygen begins on arrival at 60 feet.
4. If oxygen breathing must be interrupted because of CNS Oxygen Toxicity, allow 15 minutes after the reaction has entirely subsided and resume schedule at point of interruption (see paragraph 21-5.5.6.1.1).
5. Table 6 can be lengthened up to 2 additional 25-minute periods at 60 feet (20 minutes on oxygen and 5 minutes on air), or up to 2 additional 75-minute periods at 30 feet (15 minutes on air and 60 minutes on oxygen), or both.
6. Tender breathes 100 percent O_2 during the last 30 min. at 30 fsw and during ascent to the surface for an unmodified table or where there has been only a single extension at 30 or 60 feet. If there has been more than one extension, the O_2 breathing at 30 feet is increased to 60 minutes. If the tender had a hyperbaric exposure within the past 12 hours an additional 60-minute O_2 period is taken at 30 feet.

Treatment Table 6 Depth/Time Profile



It should be noted that if TT6 is followed, particularly with respect to oxygen breathing cycles, the patient should not incur extra decompression obligation. If a situation develops where access to the patient is needed, he can be depressurized to surface pressure and removed from the EEHS for short periods, or his treatment can be terminated early. The possibility of this need arising is greater with the EEHS than with the multiplace chamber because of the lack of access to the patient. Interruption in treatment may reduce treatment effectiveness and lead to incomplete resolution, worsening, or recurrence of symptoms, but would not be expected to be more dangerous than withholding treatment.

Treatment of AGE:

Standard treatment of AGE in a fully capable multiplace hyperbaric chamber would include, under some circumstances, compression to 165 fsw (50.3 msw) (6 ATA) per U.S. NAVY TT6A. The SOS Hyperlite, as currently supplied, does not allow

compression over 60 fsw (18.3 msw) (2.8 ATA), and for this reason treatment of AGE in the EEHS would follow TT6, with the considerations mentioned above.

Special precautions regarding pulmonary barotrauma should be taken in cases of suspected AGE. The patient should be carefully examined for signs of pneumothorax, and if present, a chest tube with one-way valve (i.e., Heimlich valve) should be considered. If pneumothorax is suspected while under pressure in an EEHS, preparations for emergency placement of chest tubes upon decompression should be made, because decompression may produce a tension pneumothorax.

Treatment of DCS From Saturation Exposure:

If subjects have a history of saturation exposure (defined here as over 12 hours at a depth greater than 20 fsw) (6.1 msw) and have had little or no decompression, TT6 may not provide adequate decompression time. Decompression may have to be customized according to saturation decompression procedures or according to accelerated decompression procedures using oxygen (currently under development at NEDU).

If an accelerated decompression procedure has been completed prior to onset of DCS, TT6 has been shown to be effective and well tolerated after decompression from saturation depths of up to approximately 50 fsw (15.2 msw). There is no experience at deeper saturation depths.

Use of EEHS for Omitted Decompression:

In the event of relatively rapid ascent from saturation depths greater than 35 feet, such as might occur with escape or rescue using a SRS (McCann Bell), it can be predicted that DCS will likely occur, and the EEHS could be used for decompression before the onset of DCS. Decompression times could exceed four hours (possibly up to twelve hours), and thus could be very difficult to tolerate in the confinement of the EEHS. Accelerated decompression schedules using oxygen are currently under development[2], and they may reduce decompression times significantly.

Decompression could be started in the EEHS with the expectation of the arrival of other assets. As other assets became available, patients could be transferred to larger chambers.

Treatment of Other Conditions with Hyperbaric Oxygen:

Several conditions likely to be encountered in a DISSUB situation could benefit from hyperbaric oxygen therapy, independent of whether DCS or AGE is present. Treatment should take into account any other recompression needs, but in general the following guidelines may be followed:

- Smoke Inhalation/Carbon monoxide poisoning - For mild to moderate cases, U.S. Navy Treatment Table 5 may be used. For severe cases, U.S. Navy Treatment Table 6 is recommended.

- Burns - 2.4 ATA (~45 fsw) (13.7 msw) for 90 minutes on 100% oxygen, as described in U.S. Navy Treatment Table 9[3].

- Crush injury or compartment syndrome - 2.4 ATA on 100% oxygen for 90 minutes (TT9).

All patients should be continuously evaluated. If a patient not under recompression deteriorates to the point that his symptoms exceed those of patients in the EEHS, consider decompressing the least serious patient from the EEHS to recompress more seriously injured patients. Weigh this decision very carefully.

If evacuation is possible, consider transfer under pressure using EEHS (see Appendix E).

APPENDIX D REFERENCES

1. Naval Sea Systems, U.S. Navy Diving Manual, Vol. #5, Rev. 4. NAVSEA SS521-AG-PRO-010, Page 21-41.

2. P. I. Raffaelli, M. R. Dean, *Subsunk for Medical Officers,* INM Report #R94042, Institute of Naval Medicine, Alverstoke, England, October 1994, Page 12.

3. Naval Sea Systems, U.S. Navy Diving Manual, Vol. #5, Rev. 4. NAVSEA SS521-AG-PRO-010, Page 21-46.

APPENDIX E

TRIAGE ALGORITHM FOR EVACUATION USING EEHS

The decision for evacuation in an EEHS requires careful consideration of multiple factors. Transport in the EEHS involves some degree of risk, so the benefits of both recompression and transport should exceed the risks. Alternatives include recompression treatment on-site without transport or transport without recompression.

STEP ONE:

- Are the injuries for which evacuation is being considered truly life or limb threatening?

- Will the treatment capabilities of the receiving facility really make a significant difference in the patient's ultimate outcome?

If not, consider treatment on site, with the EEHS or other recompression asset.

STEP TWO:

- Does the patient have a compelling need for transport under pressure, such as a saturation exposure without adequate decompression or neurological involvement of DCS or AGE (See Appendix B-1)? If not, consider transport with standard support, with surface oxygen supplementation if possible.

- What is the evacuation time/distance? For short transports, the lack of pressure during transport may be insignificant when weighed against the extra time and complexity of using the EEHS. For example, if recompression facilities are on shore or on another vessel less than one hour away, it may make more sense to transport without the EEHS.

- Are the operational factors, such as weather, sea state, and vessel characteristics favorable for evacuation? Often, the hazards involved in evacuation may exceed the benefit.

STEP THREE:

Is the patient a suitable candidate for use of the EEHS? Are there contraindications or special needs (see Appendix B-1)? Will the patient tolerate the confinement of the EEHS?

STEP FOUR:

Are there sufficient recompression assets on scene to treat other patients? Will the loss of the EEHS used for evacuation, and the trained personnel required for its use, compromise the care of other patients?

STEP FIVE:

If all of above factors have been considered, and evacuation using EEHS is elected, prepare patient for entry into EEHS and evacuation using transfer under pressure procedures.

STEP SIX: TRANSFER UNDER PRESSURE

Transfer under pressure may involve one or more of several different steps. The patient may enter and exit the EEHS at surface pressure, or he may be transferred into or out of, another recompression chamber while inside the EEHS. The latter involves equalizing the pressure of the larger chamber to the same pressure as the EEHS. Details are presented below.

Transport Under Pressure (not involving entry or exit in another chamber):

- Patient enters EEHS and breathes oxygen from BIBBS per selected treatment protocol. In most cases, the schedule for U.S. Navy Treatment Table 6 (TT6) should be followed as closely as possible.

- The schedule for TT6 can be followed enroute as long as adequate gas supplies are available.

- Control panel can be secured to top of EEHS.

- Gas supplies can be either secured to EEHS or carried alongside.

- Gas supplies may be disconnected for up to 15 minutes to load or unload EEHS into transport vehicle or carry over difficult terrain. When gas supplies are disconnected, the patient must remove the BIBS mask and breathe chamber atmosphere.

- Upon completion of treatment or arrival at receiving facility, depressurize EEHS per protocol and remove patient. If at altitude at the time of completion of treatment schedule, it would be advisable to keep patient in the EEHS at low pressure (i.e.,10 fsw) (3 msw) breathing air, or oxygen as tolerated, until return to ground level.

- Note that the EEHS can be depressurized for short periods to facilitate transport if necessary. While this is undesirable from a treatment standpoint, it should not be viewed as something that cannot be done if necessary.

Transport in Aircraft:

- Currently under review by both the U.S. Air Force and NAVAIR[1] (this has been done in other countries, and approval is anticipated).

- Consider that gauges may need to be corrected for altitude. The gauge on the control panel of the EEHS measures the differential between the pressure outside the EEHS and inside the EEHS. If taken to altitude, this gauge will read progressively higher as altitude increases. Since the goal is to maintain the EEHS at a constant pressure, a correction factor must be applied to the gauge reading. A table of correction factors is included in the Hyperlite manufacturer's manual[2]. Alternately, a pressure gauge not referenced to the pressure outside the chamber, such as a digital gauge placed entirely within the chamber, could be used to determine chamber pressure.

- Securing of EEHS during flight is imperative in order to prevent the EEHS from rolling or having gas supply hoses dislodged.

- Communications may be difficult in the noisy environment of some transport aircraft. Extra vigilance must be maintained on the part of the operators.

- Gas supply containers (air and oxygen cylinders) will need special approval/precautions. Ensure that adequate supplies of oxygen and compressed air are available.

- It is not advisable to depressurize the EEHS while at altitude. If at altitude at the time of completion of treatment schedule, it would be advisable to keep patient in the EEHS at low pressure (i.e., 10 fsw) (3 msw) breathing air or oxygen as tolerated until return to ground level.

Transfer of Patient Into Multiplace Recompression Chamber:

Upon arrival at receiving facility, it may be desirable to transfer patient into a larger multiplace hyperbaric chamber for continued treatment. If the multiplace chamber is at surface pressure, open its hatches to inner and outer locks. Inspect for compatibility in terms of size, obstacles, etc. (If larger chamber cannot accommodate EEHS, make all necessary preparations, depressurize EEHS at standard rate, remove patient and transfer into multiplace chamber as quickly as possible and recompress to treatment depth as appropriate.)

- Prepare EEHS. Arrange control panel and gas supplies for easiest loading. All hoses may be disconnected for up to 15 minutes to facilitate transfer if necessary (patient must remove BIBS mask and breathe chamber atmosphere while hoses are disconnected).

- Transfer EEHS into multiplace chamber. EEHS can extend into both inner and outer lock if needed. One or more tenders remain with EEHS. Seal hatches.

- Secure gas supply to EEHS. Pressurize multiplace chamber to same pressure as EEHS. When pressures equalize, the end plates of the EEHS will loose their seal and can be removed. Remove patient from EEHS to the degree needed for care. If possible, fold EEHS and place into outer lock for removal from the chamber.

Transfer of Patient Out of Multiplace Recompression Chamber:

- If patient is in the inner lock, and the empty EEHS is outside, clear the outer lock of all unnecessary articles. Remove the EEHS from storage containers and arrange components in the outer lock in a manner that allows movement of hatches. If all components cannot be fitted well, two or more cycles of outer lock may be necessary.

- Pressurize the outer lock to equalize with the inner lock. Transfer the EEHS into inner chamber and assemble. It may be necessary for the EEHS to extend into both locks.

- Place patient into the EEHS and place the end plates into position. Perform system checks. Pressurize the EEHS to a pressure slightly over the chamber pressure to create a seal.

- Note that the gauge on the EEHS control panel will read the amount that the internal EEHS pressure is over the multiplace chamber pressure. For example, if the exercise is performed at 60 fsw (18.3 msw), when the EEHS is sealed and minimally pressurized, it will read about 5 fsw (1.5 msw), but the true pressure inside the EEHS chamber is 65 fsw (19.8 msw). If the EEHS pressure is kept stable, as the multiplace chamber is depressurized, the EEHS gauge reading will rise until it finally reads true pressure when the multiplace chamber reaches surface pressure.

- Slowly depressurize multiplace chamber to surface (Don't forget tender's possible decompression obligations). Adjust EEHS pressure as appropriate, taking into account the differential in the gauge reading.

- Remove the EEHS from the chamber and transport.

APPENDIX E REFERENCES

1. *Aeromedical Evacuation Test and Evaluation of the Emergency Hyperbaric Treatment/Evacuation System*, United States Air Force School of Aerospace Medicine, Davis Hyperbaric Medicine Division, Project Number 9974-XXX2, In progress.

2. SOS Limited, Hyperlite Hyperbaric Stretcher; Model 585/3.1/3, London, England, 24 December 1997.

APPENDIX F

CRITICAL CARE IN THE EEHS

There may be situations where severely injured patients will need to be treated in the EEHS. In general, the EEHS is not designed for such use, but with certain modifications and experienced medical personnel, many patients can be safely treated. Recommendations are divided into two levels of advanced care.

Level I: Monitoring and IV Access:

This would include patients with painful injuries requiring narcotic analgesia or sedation, antibiotics, vasopressors, anti-hypertensives, or other medications, but not unconscious, and with no airway compromise. Modification to the EEHS would be relatively simple, including a penetrator for intravenous line (and an infusion pump capable of overcoming EEHS pressure) and electrical connections for ECG monitoring. The manufacturer has indicated that this would be quite easy to provide. Further enhancements might include pulse oximetry and non-invasive blood pressure monitor, both of which have been used in monoplace treatment chambers. A trained independent duty corpsmen or other paramedic could attend the patient with physician back up.

Level II: Intensive Supportive Care or Ventilatory Assistance:

This would include unconscious patients, patients with airway compromise, or patients with cardiovascular instability. Modifications to the EEHS would include all of the above, plus options for providing ventilatory support for patients with an endotracheal tube in place. This adds a measure of complexity, but is not entirely impractical. Monoplace chambers in wide use (i.e., Sechrist) have a variety of ventilatory support systems that could be adapted to the EEHS.

A physician trained in both critical care and use of the EEHS with these accessories would be required. Many options exist for airway management in skilled hands, including oral or nasopharyngeal airways, and endotracheal intubation. Accessories for use of these devices, such as adapters for connection to the BIBS, should be available. With these accessories and the requisite training and experience, even very seriously injured patients could be effectively treated. For a review of equipment and procedures for critical care in the monoplace hyperbaric chamber, refer to the textbook, Hyperbaric Medicine Practice, by Eric Kindwall et.al., Chapter 10[1].

This author would recommend that some EEHS units, if not all, be equipped for Level I care. This would be relatively simple and inexpensive and cover the needs of many patients. A few EEHS units, assigned to specialized groups such as Search and Rescue units or the Submarine Rescue Team, might be equipped for Level II care. Only specially trained physicians would use the advanced accessories as they arrive on scene.

APPENDIX F REFERENCE

1. E. Kindwall, *Hyperbaric Medicine Practice*, Best Publishing Co. Flagstaff, Arizona, 1995, Chapter 10.

APPENDIX G

ACCESSORIES TO THE EEHS

OXYGEN AND CARBON DIOXIDE MONITOR

The ability to monitor oxygen levels within the EEHS is highly desirable due to concerns for fire hazard if the patient is breathing oxygen. Measurement of carbon dioxide is not as crucial from a safety perspective, but is desirable to ensure that excess levels do not accumulate. Two systems for measurement of oxygen and carbon dioxide were evaluated during testing of the EEHS.

S.A.T. Systems Model CO200[1] was offered by SOS Hyperlite Ltd. as an accessory. This unit draws a gas sample from the EEHS by connecting to either the emergency exhaust valve (to measure chamber atmosphere, which would be the primary goal) or the BIBS exhaust valve (to measure patient's expired gas to confirm oxygen delivery). The unit remains outside the chamber and displays oxygen and carbon dioxide values. It has not been formally evaluated by the U.S. Navy, but NEDU has performed initial function and calibration checks and it appears to be accurate. Other analyzers currently approved for navy use could be adapted in a similar manner to analyze a sample drawn from the chamber. Placement outside the chamber requires additional connections, but these are relatively simple. The sample will be taken from the end of the chamber at the patient's feet, and this could result in readings much lower than those found near the patient's head, unless a sample tube is connected to the exhaust valve inside of the chamber and placed near the center of the chamber.

Geotechnical Instruments Model HB 1.2[2]. This device was developed in conjunction with the U.S. Navy for use in submarine dry deck shelters. The self contained, battery-powered unit is placed entirely within the pressurized chamber and measures pressure and temperature as well as oxygen and carbon dioxide. It has been evaluated by Naval Medical Research Institute (NMRI) and approved for Navy use by NAVSEA[3]. Placement inside the chamber offers an advantage in terms of simplicity, but does limit the operator's ability to change settings once treatment has begun, unless the patient is capable of following commands. The capability of measuring pressure and temperature adds value as an all-in-one-package monitor.

TEMPERATURE

Monitoring internal chamber temperature would be desirable for patient comfort, and for patient safety in warm environments where the temperature inside the EEHS could potentially reach dangerous levels. Thermometers that can be placed inside a hyperbaric chamber are obtainable, but not always immediately available. The manufacturer offers a digital thermometer/hygrometer as an accessory. We found this device to be cheaply made (it is marketed for homes, gardens and greenhouses) and to

have no documentation of pressure suitability[4]. Identification of a more suitable thermometer is recommended.

PRESSURE

The pressure gauge in the control box measures the pressure of the chamber relative to the atmospheric pressure surrounding it. While this is adequate for routine use at sea level, confusion could occur if the EEHS is transported to altitude, because the control panel gauge will begin to read progressively higher as the pressure outside the EEHS declines. To avoid confusion and the need to mathematically correct the control panel gauge, a self-contained pressure gauge (such as a diver's depth gauge) placed inside the EEHS chamber will continue to read true pressure relative to sea level. The manufacturer of the Hyperlite supplied a small digital gauge for this purpose, but it was not of high quality, the displayed values differed from the calibrated gauge, and is not recommended for purchase. Selection of a higher quality gauge is recommended.

PULSE OXIMETRY

Measurement of arterial oxygen saturation by pulse oximetry has become a valuable clinical tool. The real-time monitoring of arterial oxygenation provides valuable assurance of this critical physiologic parameter and a decrease in arterial oxygen saturation provides warning of impaired respiration or circulation. When treating a patient in the EEHS, the operator has no direct contact with the patient, and very limited ability to monitor respirations or vital signs, and thus the information provided by pulse oximetry would be particularly valuable. A pulse oximetry unit, the Ohmeda Model 3775[5], has been identified which is suitable for use inside the EEHS. It is compact, powered by alkaline batteries, does not emit toxic fumes, does not present a fire hazard, and has been tested for operation under pressure to 165 fsw (50.3 msw)[6]. Its use is recommended, particularly in any situation where the patient is suffering from any impairment in consciousness or respiration, such as could occur with an arterial gas embolus or near drowning.

ELECTROCARDIOGRAM

Addition of electrocardiogram monitoring to the EEHS system would only require additional pins in the electrical penetrator currently used for the communication system. Suitable adapters would then be made to connect patient leads to the penetrator inside the chamber, and from the penetrator to any suitable monitor placed outside the chamber. Any monitor could be used, provided the appropriate connections were made. This is recommended.

INTRAVENOUS ACCESS PENETRATOR

Monoplace hyperbaric units used in hospitals throughout the world are commonly equipped with a penetrator for administration of intravenous fluids. A pump capable of overcoming the pressure gradient from outside the EEHS to inside, approximately 30 psi (1500 mmHg) is also required. Several suitable pumps are available. The reader is referred to the text by Kindwall for details[7]. Selection and testing of at least one model is recommended.

APPENDIX G REFERENCES

1. Stokes, F., *CO2000 Operator's Manual*, Sub Aquatic Technical Systems Limited, Isle of Man, British Isles, ND.

2. Geotechnical Instruments, *Anagas™ Hyperbaric Monitor Operating Manual, Software Version Ana 4.07 28/3/96*. Environmental Instruments, Sovereign House, Queensway, Leamington Spa, CV31 3JR, U.K., C1995

3. R. S. Lillo, W. R. Porter, A. Ruby, W. H. Mints, J. M. Caldwell, J. F. Himm, *Development and Evaluation of Hyperbaric Carbon Dioxide Analyzer for Dry Deck Shelter Operations*, Naval Medical Research Institute, Technical Report, NMRI 98-01, February 1998.

4. Instruction manual for thermometer/hygrometer provided, ND.

5. Ohmeda, *3770/3775 Oximeter Operator's Manual*, Ohmeda, Inc., Madison, WI, 6050-0003-960, C1995.

6. NEDU Medical Department Technical note on Ohmeda Pulse Oximeter, (in preparation), Navy Experimental Diving Unit.

7. Kindwall, *Hyperbaric Medicine Practice*, Best Publishing Co. Flagstaff, Arizona, 1995.

APPENDIX H

REVIEW OF OTHER INFORMATION AVAILABLE

A search for other available information was conducted. Several technical reports and articles were reviewed. The most pertinent information is summarized below. The bibliography and references in this report contain additional information.

Qualification Testing on Four Emergency Evacuation Hyperbaric Stretchers (EEHS), Test Report #46769-01, Wyle Laboratories, Huntsville, Ala., 13 May 1998.

Technical report on the destructive and environmental testing of the chambers. This includes burst pressure testing on both units and results of exposure to heat, cold, ultraviolet radiation, and physical impact. The most notable result was hydrostatic testing to failure. The Hyperlite failed with non-catastrophic leakage at 215 psig, while the GSE Flexible Hyperbaric, despite being advertised as having greater strength, failed at a lower pressure, 200 psig, in a very dangerous, explosive loosening of the outer hatch. Subsequent to this result, the approved working pressure of the GSE Flexible Hyperbaric was lowered to 30.5 psig.

J. T. Florio, D. A. Elner, M. S. English, R. S. McKenzie, *Assessment of the Potential of a One Man Portable Recompression Chamber to Treat Submariners Suffering Decompression Illness Following Escape or Rescue,* Defence Research Agency, Alverstoke, England, DRA (AWL) Technical Memorandum 93711, June 1993.

A report on the possible uses of an EEHS system in the Royal Navy submarine rescue plans, and an overview of the Hyperlite system. It contains some useful historical information and calculations on gas supply requirements, as well as a review of testing done for the Lloyds Register for the Construction and Classification of Submersible and Diving Systems.

J. T. Florio, M. S. English, F. J. Stanley, *Evaluation of a One Man Compression Chamber for Submarine Rescue,* Defense Evaluation and Research Agency, DERA/SS/ES/CR971011/1.1, February 1998.

Specific testing completed by the Royal Navy Defence Evaluation and Research Agency (DERA) on the SOS Hyperlite EEHS. Includes results of manned and unmanned trials and useful calculations and data on the rise in carbon dioxide and fall of oxygen levels with the gas supplies disconnected. They found that the chamber was suitable for performing RN table 62, which is very similar to U.S. Navy Treatment Table 6, and that transfer under pressure into another chamber was not problematic. They did note some deficiencies with the BIBS regulator performance, which have since been resolved. Durability testing included over one hundred cycles of packing and unpacking with over ten cycles of pressurization, with acceptable levels of wear. Noise levels were found to be within acceptable limits.

HUNTING Engineering, *Manufacturing Procedure for Hyperlite Hyperbaric Stretcher Bodies*, HUNTING Engineering, Ampthill, Bedford, England, 29 March 1999.

A detailed, step by step description of the manufacturing process of the Hyperlite flexible pressure hull.

SOS Limited, *Hyperlite Hyperbaric Stretcher; Model 585/3.1/3*, London, England, 24 December 1997.

Contains assembly and operating procedures, and details of parts including schematics, weights, and dimensions. In general, it is well written and easily understandable. It includes useful ancillary information such as a table for correcting pressure gauge readings for altitude. It also contains information on accessories and maintenance procedures.

GSE Trieste, *30" FlexiDec serial number 007; Operating & Maintenance Manual*, Italy, December 1997.

Contains very little useful information. There are some schematics, but explanations are not easily understandable. Operating procedures are somewhat confusing. Overall, it was inadequate for operation without other training.

Kindwall, *Hyperbaric Medicine Practice*, Best Publishing Co. Flagstaff, Arizona, 1995.

This textbook on hyperbaric medicine, particularly the chapter on use of monoplace hyperbaric chambers, is highly recommended for any medical personnel planning to use the EEHS. Nationwide, there are hundreds of monoplace chambers in use in hospitals, and the experience gained is well presented in this text. A new edition has been published in 1999, but is not available at the time of this report.