Navy Experimental Diving Unit (NEDU)
321 Bullfinch Rd.
Panama City, FL 32407-7015

TA 02-25
NEDU TR 04-10
March 2004

Evaluation of the Integrity of the MK 21 Contaminated Water Diving System and of the Efficacy of Decontamination Procedures

Author: F. F. Leyva, M.D.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

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. 04-10	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Navy Experimental Diving Unit 6b. OFFICE SYMBOL (If Applicable)	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 Bureau of Medicine and Surgery 8b. OFFICE SYMBOL (If Applicable) 6.4	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) 2300 E. Street N.W., Washington DC 20372-5300	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 0604771N PROJECT NO.: M0933 TASK NO.: WORK UNIT ACCESSION NO.: 03-07

11. TITLE (Include Security Classification)
(U) Qualitative Evaluation of the Integrity of MK 21 and Vulcanized Dry Suits for Diving in Contaminated Water and of the Efficacy of Decontamination Procedures

12. PERSONAL AUTHOR(S)
Fernando F. Leyva, M.D.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT	15. PAGE COUNT
Technical Report	Nov 03 TO Dec 03	March 2004	24

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Thermal stress, contamination, diver protection

19. ABSTRACT (Continue on reverse if necessary and identify by block number)
Current Navy recommendations for diving in contaminated water include wearing a vulcanized rubber dry suit mated to a MK 21 helmet with double exhaust valve to isolate the diver from the contaminated environment. No full-scale testing of this configuration or of the efficacy of recommended decontamination procedures has been performed. The purpose of this immersion testing therefore is to evaluate the integrity of the MK 21 contaminated water diving system and the efficacy of decontamination procedures. Using fluorescein as a contaminant analog, 14 dives followed by decontamination were performed in September 2003 and 22 in December 2003 at the Navy Experimental Diving Unit. Overall, the dry suits adequately protected divers, but the MK 21 with double exhaust valve failed to prevent intrusion of water when the diver's head moved from the upright position at any depth. Decontamination procedures were not thoroughly evaluated, but preliminary testing suggests that, because of the time restrictions, surface decompression diving should not be attempted if decontamination is needed. We recommend that the Navy consider alternative diving helmets for use when absolute isolation of the diver is necessary, and that the draft "Contaminated Water Diving Technical Manual" be updated to acknowledge these results.

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

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

DD Form 1473

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

ACKNOWLEDGMENTS

I would like to thank the NEDU Engineering Department for its hard work in setting up the ark and OSF so that this study could be performed. I must also thank the NEDU divers who volunteered to serve as diver-subjects. Finally, thanks to Petty Officer Second Class (HM) Allen Truhn for his exceptional work as task leader. He tirelessly coordinated each diving evolution not only with NEDU departments and personnel but also with Navy Diving and Salvage Training Center and Naval Support Activity Panama City personnel.

CONTENTS

INTRODUCTION

Whether in war or routine peacetime operations, U.S. Navy divers are frequently required to dive in contaminated waters, where hazards may range from relatively benign petroleum products to a worst-case exposure to chemical, biological, or radiological agents. Since the potential for encountering contaminated environments is increasing, the Navy Experimental Diving Unit (NEDU) was tasked with developing a technical manual that provides comprehensive recommendations for planning diving missions in contaminated water.

That manual (currently in draft form) includes guidance for conducting water tests, characterizing risks, choosing protective equipment, coordinating decontamination, and designing training guidelines. Current recommendations in the *U.S. Navy Diving Manual* and the draft technical manual sequester the diver from contaminated water environments via a MK 21 underwater breathing apparatus (UBA) mated to a vulcanized rubber dry suit.[1,2] However, no full-scale testing of the integrity of the recommended contaminated water diving system (CWDS), has been conducted. A manned evaluation of several vulcanized rubber dry suits was conducted at NEDU in 1993; however, that study tested the integrity of neither the suits nor the full CWDS.[3] Developing a qualitative testing method and performing full-immersion testing has therefore been needed to validate the effectiveness of current as well as any future candidate equipment.

For diving in contaminated water, protective gear on the Approved for Navy Use (ANU) list includes a MK 21 helmet with a double exhaust valve installed to prevent intrusion of water into the helmet, which is mated to a vulcanized rubber dry suit via a watertight seal. Rubber gloves and boots (if not already incorporated into the dry suit) are also mated to the dry suit. But this configuration presents several potential problems.

First and most important are anecdotal reports that the MK 21 helmet with a double exhaust valve is prone to leaking. Informal conversations with experienced Navy and civilian commercial divers reveal little trust in this UBA's ability to protect divers operating in a contaminated environment, particularly at depths greater than 30 feet of seawater (fsw). When unmanned evaluation of this MK 21 configuration was conducted at NEDU in 1993, results suggested that the system adequately prevents intrusion of water as long as the peak inhalation pressure is not less than –6 kPa and respiratory minute volume (RMV) does not exceed about 60 liters per minute (L/min).[3] However, the study did not include any manned testing, nor were the helmets tested in positions other than upright — whereas a working diver may experience a variety of attitudes during a dive. The disparity between actual diver experiences and unmanned testing results emphasizes the need for human divers to objectively test the MK 21 with double exhaust system.

Another concern for Navy diving is that use of the MK 21 for diving in contaminated water is rapidly declining among commercial diving companies. In fact, few commercial divers recommend its use. Rather, commercial divers are increasingly using positive pressure rigs for such dangerous diving operations. The MK 21 is a "negative pressure" UBA: its inspiratory demand regulator creates negative pressure on the inside of the helmet relative to ambient pressure and thus creates a natural tendency for water intrusion. A positive pressure rig does the opposite: the constant flow of air into such a helmet creates greater pressure inside the helmet than that outside it, and thus discourages water entry.

The advantage to a positive-pressure system is clear; however, the disadvantage is that it may require an unlimited gas supply. Because of this requirement, such a system may not be practical for the Navy's operational needs. One solution that has been suggested for the MK 21 UBA is to adjust the dial-a-breath knob to maintain a slight, constant flow. This procedure is thought to create a slight positive pressure and decrease the pressure differential across the exhaust valve, but it has not been validated.

A final concern is that currently recommended procedures for decontaminating divers, diving gear, and dive stations have not been rigorously tested for Navy operational needs. Derived from standard decontamination techniques found in general texts on chemical, biological, and radiological threats as well as from methods used by commercial diving specialists,[5–11] decontamination procedures recommended in the draft technical manual have not been evaluated. While the recommended techniques have been tested in field settings, they have not been tested on Navy dive stations. Since land-based settings and commercial diving operations are different milieux from naval field settings and operations, such testing is needed to ensure that currently recommended procedures can be implemented during Navy diving operations.

Of particular concern are possible situations in which surface decompression (SUR D) diving may be needed in a contaminated environment. Because of the five-minute time limit required to bring divers up from 40 fsw, undress them, and place them in the chamber for recompression,[9] present decontamination procedures may be impractical. Furthermore, the potential for secondary contamination and decontamination of dive station support equipment needs to be evaluated thoroughly: Navy dive stations tend to be much smaller than field spaces or civilian diving platforms.

The purpose of conducting immersion tests under this study was therefore to evaluate the integrity of the MK 21 CWDS and the efficacy of decontamination procedures. Although the decontamination procedures were considered to be important, we did not seek to thoroughly evaluate their effectiveness in relation to the tenders, dive station, and external diving equipment. The study also established a qualitative method for testing the efficacy of contaminated water diving equipment.

METHODS

GENERAL

Testing of the recommended protective gear was conducted in two phases at NEDU. In each phase, U.S. Navy divers were submerged in a 3,600-gallon, stand-alone tank ("ark") approximately 10 feet deep and large enough to accommodate three divers at a time. Performed in September 2003, Phase 1 was designed to test the general integrity of the system and the preliminary efficacy of decontamination procedures by conducting full immersion at the surface (depth <8 ft) followed by decontamination. To further evaluate the integrity of the MK 21 double-exhaust system, in December 2003 divers in Phase 2 were submerged and pressurized to depths >10 fsw in NEDU's Ocean Simulation Facility (OSF).

EQUIPMENT

In Phase 1, divers were dressed in the full CWDS, including gloves. The Naval Diving and Salvage Training Center (NDSTC), loaned six rarely-used Viking HD vulcanized rubber dry suits to NEDU. These suits were used in all diving. Three MK 21 UBAs, each with new double exhaust valves installed on them, were also used throughout the diving. The U.S. Navy MK 3 surface supply diving system provided air to the divers.

In Phase 2, divers were dressed in newly purchased Amron AHD1600™ vulcanized rubber dry suits, three of which were used for all diving. The same three MK 21 UBAs with double exhaust valves that had been used in Phase 1 were also used in Phase 2. Unlike Phase 1 divers, those in Phase 2 did not wear gloves mated to the dry suit. Divers used surface supplied air from the OSF air banks.

Phase 1

Tests of CWDS integrity and decontamination procedures were conducted on the same dives. For this phase, the ark was placed in the OSF high bay. Wearing only shorts underneath the dry suit, fully outfitted divers submerged themselves in the ark, which was initially filled only with water.

Once they were on the bottom of the ark (maximum depth, 5 fsw), they were instructed to simulate working conditions by performing a series of physical maneuvers that placed strain on potential leak points (e.g., neck and wrist seals) in the configuration. These maneuvers included abduction and adduction of the arms and legs, as well as flexion and extension of the neck, shoulders, elbows, wrists, hips, and knees. Finally, divers were asked to assume a modified inverted position (on hands and knees, with the top of the helmet on the bottom). While performing these maneuvers, divers were asked to report any sensation of water intruding into the gear.

After completing the maneuvers, divers surfaced and then exited the ark via an elevated platform with steps leading outside. Once outside, decontamination was conducted following procedures outlined in the draft technical manual.[2] The purpose of the initial dives was to allow divers to become accustomed to the dry suits and the decontamination teams to receive training and practice in decontamination. These initial dives also allowed decontamination to become standardized.

In the next step of this phase, a water-soluble chemical marker, fluorescein, was added to the tank water to serve as a contaminant analog. Fluorescein is a harmless, fluorescent green dye agent used in medicine as a diagnostic tool where it is applied both topically (generally on the cornea to identify corneal abrasions) and intravascularly for radiologic imaging. Occupational Safety and Health Administration (OSHA) regulations do not consider it to be hazardous, nor does the Environmental Protection Agency (EPA) classify it as a hazardous waste.[12] The U.S. Navy also uses it as an emergency water marker for aviators downed at sea.[13] The primary advantages of using fluorescein are that it is safe for human contact and the environment; is water soluble and easily disposed of; and is easily visible to the naked eye. In fact, by using a black fluorescent light (Wood's lamp), researchers or diagnosticians can identify even minute quantities that may not be visible with ambient light.

For safety, before diving in water containing fluorescein, each diver was subjected to a simple skin test to be assessed for possible immune hypersensitivity reactions: a drop of fluorescein was simply placed on his skin during the week before the dives and he was then observed over a 72-hour period. During this time he was instructed to report any questionable reactions and return for formal evaluation after 72 hours. If no reaction was observed or detected, the diver was considered to be a nonreactant and therefore qualified to dive in this study. Any diver in whom a reaction occurred was not allowed to participate in dives involving fluorescein.

Divers performed the required maneuvers in the ark and were then instructed to surface and exit it. Upon surfacing, they were met by a decontamination team who completed their standard decontamination. Special attention was given to the amount of time required to complete the process. For the purpose of this study, only divers — not tenders or the rest of the dive station — were decontaminated.

After being decontaminated and having their gear removed, divers were taken to a dark room and examined, under both ambient light and a Wood's lamp, for any traces of fluorescein remaining on their bodies. The presence or absence of fluorescein on the diver and its location was noted, but the amount not quantified. If examination under a Wood's lamp and magnifying glass revealed no trace of fluorescein on the divers, the absence of a contaminant was presumed. The divers' gear (helmets, dry suits, gloves) was similarly examined for traces of fluorescein (both inside and outside of the gear). Any gear found to be "contaminated" with the chemical was washed thoroughly and reexamined. This procedure was repeated until no trace of fluorescein could be found on the gear, all of which was used multiple times throughout the study.

The decontamination site was divided into three zones to simulate proper sequestration of contamination throughout the procedures, and divers were moved from zones of the highest to the lowest level of contamination. Decontamination by zone consisted of the following steps:

1. Zone 1 (highest contamination) — high-pressure freshwater rinse.
2. Zone 2 (low contamination) — removal of ancillary gear (e.g., harness and weight belt) followed by scrubbing with a stiff-bristle synthetic brush and a cleaning solution (Simple Green®). After the thorough scrubbing, a low-pressure freshwater rinse followed, and finally the diver's remaining equipment (e.g., helmet, dry suit) was removed.
3. Zone 3 (clean) — showering by the diver, and postdive inspection and maintenance for the equipment.

Since Zone 3 is considered to be a "clean" one, divers were instructed to shower only after they had been evaluated for traces of fluorescein on their bodies and equipment.

Phase 2

The ark was placed in the OSF and filled with water and fluorescein, and divers were outfitted with the recommended CWDS. Unlike their dress for Phase 1, however, they did not wear gloves; they were allowed to wear t-shirts, sweatshirts, or sweatpants, as they desired.

Two to three divers entered the OSF and ark via a ladder, and the facility was then compressed to 60, 50, or 40 fsw (55, 45, and 35 fsw, respectively, on the OSF digigauge). Depth was deliberately varied to see whether any difference resulted in the performance of the helmet. For two dive sets, the OSF was not pressurized, and at the designated depth the divers were instructed to assume various positions that could simulate working postures. These included lying prone and supine and then assuming a modified inverted position, as described in the Phase 1 section. Furthermore, divers in each position (including upright) were instructed to take several deep breaths. At any time during dives, divers were instructed to report any sensation of water leakage into their helmets or into any other portions of their suits.

After all divers had completed the designated maneuvers, the OSF was decompressed to the surface. Before exiting the facility, divers were hosed down with water to remove exterior fluorescein while they stood on the ladder above the ark. Each diver then exited the OSF, and his gear was removed.

Immediately after the helmet was removed, a black fluorescent lamp was used to examine both the helmet's interior and the diver's head and neck for traces of fluorescein. Any traces of the chemical and its locations were noted but not quantified. Any helmet found to have fluorescein in it was washed thoroughly, until no signs of the chemical could be found. As in Phase 1, all dive gear was reused. Before being reused, each helmet was dried with cotton gauze to remove any remaining water.

Factors other than depth and position were also manipulated during this phase. We performed some dives with the MK 21 dial-a-breath open slightly (so that the diver could hear a quiet flow of air), some with the steady flow valve open to create a slight positive pressure inside the helmet, and some with both the dial-a-breath and steady flows open. These factors were adjusted both before and during selected dives. Results from specific manipulations of these factors are shown in Appendix A, Table 1. Furthermore, after the first three dive sets, divers were instructed to perform an initial prolonged ventilation and purge procedure to purge the helmet of any residual water that the cleaning conducted between dives may have left in it.

Before the first day of diving, all equipment was maintained and serviced per U.S. Navy regulations. However, after the first day's dives, all the MK 21 helmets were disassembled, and each demand regulator assembly was sealed with silicon, as the manufacturer advised. The current Navy U.S. Navy MK 21 maintenance manual does not specify that silicon sealant be used for this purpose.[14]

RESULTS

Phase 1

Fourteen diver-subjects performed a total of 14 dives followed by decontamination over 2 days. Two dives were performed without fluorescein in the water; 12, with the chemical. The water temperature for both diving days was 80 °F, and air temperatures ranged from 78 to 85 °F. Of note, no diver experienced an adverse reaction to fluorescein during in any part of the study (including both phases 1 and 2).

Bottom times ranged from 5 to 8 minutes, with an average of 5.8 minutes. The times divers needed to complete decontamination (from exiting the water to completely removing the protective gear) ranged from 2 to 10 minutes, with an average time of 7.1 minutes. (This average is based on 13 dives, as an error prevented one diver's decontamination time from being recorded.)

On the bottom, two divers reported that they believed their dry suits were leaking. After being decontaminated, however, neither of these divers had traces of fluorescein on his body — although one had a clear liquid on his left foot. No diver on the bottom reported a helmet leak.

Seven of the 14 divers were found to have residual traces of fluorescein on their bodies after decontamination was completed: three divers had the chemical only on the head; one had it on both his neck and upper extremities; one had it only on his upper and lower extremities; and one had it only on his lower extremities. During post-decontamination inspection of gear, there were three incidents of fluorescein located inside the helmet (faceplate, oral-nasal mask, and hood). None of the divers in these cases had reported any sensation of leakage into his helmet during his dive. Two of the divers who had residual fluorescein on either the head or neck also had traces of fluorescein in their helmets. Two dry suits were also noted to have leakage of several drops of fluorescein around the dump valve located on the left arm. Of the divers who wore these two suits on occasions when the leaks were found, one had fluorescein on his left upper arm, and the other had traces of the chemical on his left lower leg. The remaining two divers who had post-decontamination traces of fluorescein on their bodies had no visible leaks inside either their suits or helmets.

Phase 2

Twenty U.S. Navy divers performed 22 dives in eight manned sets in the OSF during two days in December 2003. Dive depths ranged from 5 to 60 fsw (0 to 55 fsw on the OSF digigauge), and bottom times ranged from 9 to 14 minutes, with an average of 11.7 minutes. Since two dive sets (two divers each) were performed in the ark with the OSF not pressurized, the maximum depth for those dives was 5 fsw. Only two divers were used for each of these sets, since one helmet was pulled from the study for the day to examine it for worn parts. The helmet was subsequently returned for use on Day 2. Water temperature for both diving days ranged from 66 to 67 °F.

Regardless of depth, all divers reported water leakage into the helmet via the oral-nasal mask when both the dial-a-breath and the steady flow valve were closed. These reports occurred both on the surface and at depth when diver head positions were changed from upright. Throughout the entire study, no diver reported leakage into the helmet while he was in the upright position. Divers described leaks varying from a slight "trickle" onto the face to a "spraying" of water during deep inspiration. Eight divers reported leakage only while they were in the supine position; 1, only in the prone position; 1, only in the inverted position. Twelve experienced leakage while they were in more than one position.

When dives were performed with the dial-a-breath slightly opened and the steady flow valve off, results were similar. Three divers (set 6) attempted this configuration. Initially on the surface, the divers kept the dial-a-breath off, and two of them reported leaks in the supine, inverted, and prone positions. After an exaggerated ventilation and purge, the divers were taken to 60 fsw, where they opened the dial-a-breath. All three divers reported leakage in at least two of the three positions tested. During postdive inspection, the helmets of all three divers in this set had fluorescein in the oral-nasal mask.

Two dive sets (six divers in sets 7 and 8) were performed with both the dial-a-breath and the steady flow open. The maximum depth of one set was 60 fsw; that of the other was 40 fsw. Only one of the six divers reported leakage into the helmet while he was on the surface in the inverted position. He also experienced leakage while he was on the bottom. One diver reported no leaking in any position while he was on the surface and at depth. Four divers in these two sets reported leaks only at depth (two divers at 40 fsw and two at 60 fsw): two had leaks while they were in the supine position, one while he was in the prone position, and one while he was inverted. After performing their maneuvers, five of the divers in these sets turned off their steady flows and repeated the positions. All subsequently experienced leakage in at least one position. Two of the divers turned off the dial-a-breath but left the steady flow open and repeated their maneuvers at depth. With this configuration, both of these divers reported leakage. All helmets for divers in sets 7 and 8 were found to have residual fluorescein in the oral-nasal masks.

One dive (set 5; two divers) was performed with only the steady flow valves open. Divers in this set performed the maneuvers only at the surface (5 fsw). Both divers reported leakage into the helmet when they were in the supine position. However, only one of these diver helmets contained fluorescein during postdive inspection.

Results of postdive helmet inspections showed all but one helmet to have fluorescein in the oral-nasal mask (Appendix A, Table 2; this exception was from a dive performed at 5 fsw with the steady flow open throughout). Thirteen divers were found to have residual fluorescein on their faces. All of these divers had fluorescein in one or more of the following areas: chin, nose, cheeks, or perioral region. Two divers each had residual fluorescein on one ear.

DISCUSSION

Phase 1

Overall, the MK 21 CWDS performed well in this phase of testing. Despite using rather old and worn dry suits, only two divers reported feeling leakage into their suits during the dives, and these divers were found to have no residual fluorescein on their bodies or in the suits they used. Both of these divers also reported feeling very hot before and during diving, a feeling that is to be expected because of the relatively hot air temperatures during the study. Both divers are likely to have mistaken sweat for water intrusion. In fact, one of these divers (who had reported leakage around his right leg) was found to have a clear liquid (*not* fluorescein) on his right foot during postdive inspection.

Of the seven divers found to have residual fluorescein on their bodies during postdive inspection, none had reported feeling leakage during their dives. In only four of these cases, the location of the fluorescein discovered seemed consistent with the location of the leak: two with leaks around the suit's exhaust valve, and two with helmet leaks. For the remaining three "contaminated" divers, no visible signs of fluorescein were found in either the suit or the helmet. It is difficult to determine whether they were exposed to fluorescein by a breech into the suit or helmet or whether they were "contaminated" by some other event during the study (e.g., secondary contamination from the decontamination and undress procedure).

During diving it seemed unlikely that divers could have fluorescein inside their helmets, hoods, or suits without feeling an intrusion of the cooler (80 °F) water. Additional observation revealed that the dive station (where divers dressed) was located below the ark's access platform, and on several occasions divers caused sufficient splashing upon entering the water that the fluorescein-containing water might contaminate the dive station just before the next diver was dressed. This splashed water might have contaminated the helmets and divers before they entered the water. Fortunately, the splashing problem was observed early, and divers were instructed to make a more gentle entry.

However, even after this problem was corrected, at least one diver had residual fluorescein inside his helmet and on his body (head and hands). This diver and several others had served as dive tenders before making their dives, and so they might have been contaminated before making their dives. The inability to definitively determine when an exposure to fluorescein occurred may represent a flaw in the study design. It would have been useful to undress and examine some divers without having them undergo decontamination.

Two potentially significant problems were found with the suits. First, since the suits were old and had been poorly maintained, the rubber parts were stiff or cracking and easily torn. At least three of the suits were damaged during diver dressing or undressing: in two incidents the neck seals were torn when suits were removed during decontamination. This problem of equipment condition is a likely difficulty in the fleet, since dry suits are not frequently used. Therefore, if such suits are needed, the ones available for a particular operational unit may also be old, worn, and easily damaged — if they are not frequently and properly maintained.

The second problem discovered with the dry suits was that of leakage through the exhaust valve. Although only two of the suits leaked around this valve, both of them were used multiple times during the study, and each leaked only once. These two incidents, however, constituted 17 percent of the dives performed with fluorescein in the water. This exhaust-valve leakage is not surprising, since dry suit manufacturers report that any valve on a dry suit is a potential source of water intrusion and that the number of valves on dry suits should be minimized when maximal protection is to be used.[8]

The decontamination procedures seemed effective in removing the fluorescein. This is not surprising, since the dye is water-soluble. The greatest amount was washed away during the high-pressure rinse in the first zone of decontamination. However, this procedural step would not likely be as successful in removing more viscous or lipid-soluble chemicals (e.g., petroleum products) and additional testing using a lipid-soluble contaminant analog, some added solids, and some adhesive contaminants is needed to support increasingly definitive conclusions about the efficacy of the recommended decontamination procedures.

Nevertheless, fully performing these current procedures provided much useful information. One major problem identified was that divers might become contaminated by contact with tenders during removal of the suits. Removing a dry suit even in an uncontaminated setting is difficult and requires cooperation between the diver and tenders. In a contaminated environment, members of a decontamination team may have residual contamination on their protective suits, and these residuals can get on the diver while the neck seal and arms are being removed. Experienced divers also tend to try to remove the suits themselves, and this tendency increases their chances of becoming contaminated. During the study we had to continually remind divers to let the decontamination team do most of the work.

The average time needed for decontamination was more than 7 minutes. While this seems relatively fast, it is too slow to be used in SUR D diving, especially since this time does not include individual showering, the final step of decontamination. Furthermore, if a contaminant is more difficult to remove than the water-soluble fluorescein, the time required for decontamination is also likely to be longer than it was in this study.

Another potential concern is the high-pressure wash the diver receives immediately upon exiting the water. We found that the spray produced by this wash can easily spread to other areas of the dive and decontamination stations. Even if a diver is being rinsed on a boat ladder before he comes aboard, the potential for secondary contamination from the spray is great, especially in windy or rough conditions. This potential for secondary contamination is significant, because most diving vessels have a relatively small amount of space to set up a dive station and an area for decontamination. Droplets produced from the spray could also contaminate ventilation or gas intake structures.

Other questions about the efficacy of decontamination procedures include what protective gear is best for tenders and members of a decontamination team and how might the dive station, umbilical hoses, and decontamination teams be best cleaned. In this study we did not attempt to thoroughly evaluate such decontamination questions. More work is needed to ensure that the recommended procedures fit into Navy operational scenarios.

Phase 2

The MK 21 helmet with double exhaust valve fails to prevent intrusion of water, unless the helmet is in the upright position. We are confident in concluding that this helmet configuration fails: all divers reported leakage from spraying or trickling of water on their faces, and fluorescein was found in the oral-nasal masks inside all but one helmet after they were removed. This conclusion is particularly concerning, since the greatest amount of leakage (from spraying of water) occurred when divers took deep breaths, as they are likely to do during working dives.

The only configuration that excluded water from the rig was with the steady flow valve open in less than 10 fsw. At all depths tested below 10 fsw, no manipulation of the helmet (e.g., via the steady flow valve or the dial-a-breath) consistently prevented water intrusion if the helmet position was changed from upright. Although most commercial diving experts have recommended full positive pressure rigs for any contaminated water diving and opening the steady flow valve created additional positive pressure in the helmet, our finding is contrary to conclusions drawn from NEDU unmanned testing — test conclusions suggesting that simply opening the demand regulator's dial-a-breath to a slight free-flow could sufficiently reduce the pressure differential across the regulator and prevent leakage. In this study, adjusting the dial-a-breath did not prevent water intrusion.

Despite anecdotal reports that the MK 21 with double exhaust valve leaks, we were somewhat surprised in that all of the helmets leaked on the first day of diving. The technician responsible for helmet maintenance thought, during inspection after the first three dive sets, that one of the helmets had a worn regulator seal, so that helmet was removed for possible maintenance. Neither of the other two helmets was believed to have similar problems.

After the first day's diving, all of the helmets were taken apart and inspected, but none showed definitive signs of wear or malfunction. A representative from Kirby Morgan, Inc., the manufacturer of the helmet, suggested using a silicon seal for the regulator assembly. This adaptation was added, although the Navy's current maintenance manual for the MK 21 does not include this procedure. Despite such extra maintenance, however, on the following day the helmets did not perform better than they had performed the day before. Since the manufacturer's representative indicated that the Kirby Morgan testing of the helmet assembly had not included changing the helmet’s position, his information suggests that the manufacturer may not have been aware of the leakage problem.

The results are alarming for several reasons. Most important is a concern that the currently recommended CWDS cannot fully protect divers. Although we were unable to exclude water from the helmet, we may have found a way to reduce the amount of leakage. Divers who had the steady flow valve open to create a slight positive pressure tended to report feeling “drops,” rather than a spray, on their faces, while divers without the steady flow valve open almost always reported feeling significant spraying. The disadvantages to leaving the steady flow open throughout a dive are that it may interfere with diver communications, may create a noise hazard, and, by using additional gas, may create a problem if the diver’s gas supply is limited.

Since we did not quantify the amount of leakage into the helmet during dives or the amount of residual fluorescein in the oral nasal mask, we cannot offer conclusions about how leaving the steady flow open may decrease the intrusion of water. It may have been useful to somehow configure the MK 21 to quantitatively measure water backflow across the double exhaust valve, but such a method and such materials were unavailable for the purposes of this study. Furthermore, knowledge of exact amounts of water intrusion may not be useful if the purpose of protective gear is to completely sequester a diver from the environment and we have effectively demonstrated that such gear does not. One might argue that for some contaminated water scenarios, a small amount of leakage (e.g., minor oil spills) may be acceptable. However, in other scenarios (e.g., those involving chemical, biological, or radiological warfare agents), any amount of leakage is unacceptable.

Since both unmanned testing and the present study find no leakage into the rig when the head is kept in the upright position, a possible solution is to restrict diver movement while wearing the CWDS. This may be unreasonable depending on operational needs, but this resolution could be employed short term until more feasible solutions (involving equipment or procedures) are identified.

It should be noted that this study used only three MK 21 helmets with double exhaust valves installed. The double exhaust valves were new, but the helmets were not. (The helmets, however, had been maintained properly per U.S. Navy standards and were in excellent working condition.) Despite the small sample of equipment tested, this sample is likely to accurately represent what might be found in the fleet, where the supply of this expensive, cumbersome gear is very limited.

CONCLUSIONS

MK 21 CWDS

We found some aspects of the MK 21 to perform well, while others had shortcomings. Most important, this study validates anecdotal reports and commercial industry recommendations by revealing that the double exhaust configuration on the MK 21 helmet fails to exclude water. While it may be possible to minimize water entry by opening the steady flow valve, we were unable to consistently prevent leakage. And in many diving scenarios, any amount of exposure of contaminants to a diver is unacceptable.

The industry standard is a positive pressure rig such as the Air Hat™ (DESCO Corporation; Milwaukee, WI). However, these rigs are expensive and require free-flow capabilities that may not be available on dive stations with limited gas supplies. Another possibility is to use a "return-line exhaust" configuration such as the Ultrajewel II "Dirty Harry" system (Divex Ltd.; Aberdeen, Scotland, U.K.) with the MK 21. The Divex is a closed-circuit breathing system that returns a diver's exhausted gas to the surface via a separate exhaust hose. Since this system uses the MK 21 helmet, it might be easily incorporated into Navy diving.

Ultimately, despite the shortcomings revealed in this study, I believe the MK 21 with double exhaust valve is the Navy's most protective gear configuration for diving in contaminated water. Although the MK 20 full face mask and basic scuba rigs were not tested, it is unlikely that they can protect the diver against contaminant exposure as effectively as the MK 21 can. Therefore, this helmet should remain the protective gear of choice for Navy diving until solutions to its leakage problems can be identified and implemented.

Despite their age and wear, the dry suits provide good protection, although their exhaust valves are prone to leak. The amount of leakage (2–3 drops) that this study found with these valves, however, was relatively small, and properly maintaining and testing them before diving may minimize if not eliminate contamination exposure problems. Furthermore it is ideal to use dry suits with the smallest possible number of valves or entry points in planning for dive operations in a contaminated environment. Old suits, even if maintained properly, may still suffer problems involving rubber parts: particularly when stretched, e.g., the neck seal will naturally age and crack. Special attention should be given to inspecting these rubber parts before, during, and between uses.

Decontamination Procedures

In making a limited evaluation of the currently recommended decontamination procedures, this study found them to be effective, overall, at removing a water-soluble contaminant. No conclusions can be drawn on their effectiveness in removing lipid-soluble substances, adhesive materials, or solids. Despite these positive results, certain aspects of decontamination may be potentially incompatible with Navy operational diving platforms. In particular, the high-pressure rinse may not be desirable, since it may exacerbate secondary contamination. Also, the potential for contaminating a diver during undress is great, and care should be taken to prevent the decontamination team from touching the diver's body. Additional work is needed to thoroughly evaluate decontamination procedures.

RECOMMENDATIONS

1. The MK 21 with double-exhaust valve should remain the protective gear of choice for Navy diving until a suitable solution to the leakage problem is identified and implemented.

2. Testing of other helmets or helmet configurations such as the DESCO Air Hat™ or the Divex "Dirty Harry" systems should be considered for contaminated water situations in which any contact of a contaminant (e.g., high levels of chemical, biological, or radiological warfare hazards) with a diver's face is unacceptable because its ingestion or inhalation exposes the diver to extreme risk.

3. Further research and testing is warranted to
    - determine definitive guidelines for what types of contamination qualify as "acceptable" for some exposure,
    - further test decontamination procedures with a lipid-soluble or adhesive contaminant analog on actual Navy dive stations, and
    - determine the quantity of water that enters the MK 21 helmet.

4. The draft contaminated water diving technical manual should be updated with the following changes:
    - The MK 21 CWDS should not be used in any setting when contact of a contaminant (e.g., high levels of chemical, biological, or radiological warfare hazards) with a diver's face is absolutely unacceptable because its ingestion or inhalation presents an extreme risk to the diver.
    - In situations where exposure to a small amount of contamination may be acceptable, the MK 21 CWDS should be used with the steady flow valve open to create a slight positive pressure inside the helmet. Divers should take special care to avoid assuming a supine, prone, or inverted position.
    - Wording that helmet leakage is minimal if a diver stays upright should be added.
    - Leakage in the MK 21 has been demonstrated objectively, although divers might not sense that such leakage is happening, and this information should be added in the section on the MK 21.

- Any wording stating that leakage of water into the MK 21 can be mitigated by adjusting the dial-a-breath to a slight free-flow once the diver reaches the bottom should be removed.
- The high-pressure rinse should be removed from the recommended decontamination procedures, and it should be replaced with a high volume, low-pressure rinse when contaminants are non-adhesive or water soluble.
- To detect signs of wear and tear before, during, and after diving, dry suits should be inspected before, during, and between dives. This inspection must include all valves and seals.
- No SUR D diving should be attempted in contaminated water operations.

REFERENCES

1. Commander, Naval Sea Systems Command, *U.S. Navy Diving Manual, Revision 4*, SS521-AG-PRO-101 (Arlington, VA: NAVSEA, 1999).

2. NAVSEA draft, "Contaminated Water Diving Technical Manual" (under review).

3. L. J. Crepeau, *Contaminated Water Diving System Evaluation*, NEDU TR 12-93, Navy Experimental Diving Unit, Dec 1993.

4. L. J. Crepeau, *Re-evaluating the DSI Contaminated Water Diving Kit's Ability to Prevent Water Aspiration in the MK 21 MOD 1 UBA*, NEDU TR 7-94, Navy Experimental Diving Unit, Apr 1994.

5. F. Perna, CWO3, OIC, MDSU-2, *Contaminated Water – USS Cole Recovery and Salvage Operations Lessons Learned*, memorandum to Commanding Officer, Navy Experimental Diving Unit, Jan 2001.

6. W. A. Steigleman, *Survey of Current Best Practices for Diving in Contaminated Water*, Navy Experimental Diving Unit, NEDU TR 02-07, July 2002.

7. S. M. Barsky, *Diving in High-Risk Environments*, 3rd ed. (Santa Barbara, CA: Hammerhead Press, 1999).

8. *Diving in Contaminated Water*, 3rd ed. (Portsmouth, NH: Trelleborg Viking, Inc., 2000).

9. *Medical Management of Chemical Casualties Handbook* (Aberdeen Proving Ground, MD: Medical Research Institute of Chemical Defense, 1995).

10. *Medical Management of Biological Casualties Handbook* (Fort Detrick, MD: U.S. Army Medical Institute of Infectious Diseases, 1998).

11. *Medical Management of Radiological Casualties Handbook* (Bethesda, MD: Military Medical Operations Office, Armed Forces Radiobiology Research Institute, 1999).

12. *Material Safety Data Sheet — Fluorescein* (Piqua, OH: Kingscote Chemicals, 1999).

13. *Aviation-Crew Systems Rescue and Survival Equipment*, NAVAIR 13-1-6.5

14. Commander, Naval Sea Systems Command, *Technical Manual, Operation and Maintenance Manual, Organizational Level, Underwater Breathing Apparatus (UBA) MK 21 Mod 1, Revision 4*, S6560-AG-OMP-010 (Washington, DC: NAVSEA, 2002).

APPENDIX A

Table 1.

Dive set	Diver no.	Depth (fsw)	BT (min)	Dial-a-breath open (Y/N)?	Steady Flow On (Y/N)?	Leak (Y/N)?	If leak, what position/s?	Comments
1	1	60	13	N	N	Y	Supine	Diver had R ear squeeze during descent
1	2	60	13	N	N	Y	Supine	Possible moisture detected in prone position
1	3	60	13	N	N	Y	Prone, supine, inverted	Diver notes significant “spray” around oral-nasal mask.
2	4	60	10	N	N	Y	Prone, supine	Spray in inverted position
2	5	60	10	N	N	Y	Prone, supine	
2	6	60	10	N	N	Y	Prone, supine	
3	7	50	9	N	N	Y	Prone, supine, inverted	Diver reports possible leakage on surface
3	8	50	9	N	N	Y	Supine	Helmet examined and thought to have a worn seal — pulled out for maintenance
3	9	50	9	N	N	Y	Supine, Inverted	
4	10	5		N	N	Y	Supine, prone	Prior to dive, divers performed exaggerated ventilation and purge

Dive set	Diver no.	Depth (fsw)	BT (min)	Dial-a-breath open (Y/N)?	Steady Flow On (Y/N)?	Leak (Y/N)?	If leak, what position/s?	Comments
4	11	5		N	N	N	Supine, prone	
5	12	5		N	Y	Y	Supine	
5	13	5		N	Y	Y	Supine	No leak in helmet found post dive
6	14	60	12	N (s) Y (d)	N	N (s) Y (d)	Prone	
6	15	60	12	N (s) Y (d)	N	Y	Supine (s and d)	
6	16	60	12	Y (s and d)	N	Y	All	
7	17	60	14	Y	Y	N (s) Y (d)	Supine	On bottom, turned off steady flow and repeated maneuvers — significant leak
7	18	60	14	Y	Y	Y (s and d)	Supine and inverted	
7	19	60	14	Y	Y	N (s and d)		Secured dial-a-breath with steady flow on and repeated positions, + leak inverted
8	20	40	12	Y	Y	N (s) Y (d)	Supine	Secured steady flow on bottom and repeated positions, + leak prone
8	21	40	12	Y	Y	N (s) Y (d)	All	
8	22	40	12	Y	Y	N		Steady flow secured and positions repeated, + leak prone and inverted.

S = surface; D = depth

Table 2.

Dive Set	Diver Number	Fluorescein in Helmet post dive (Y or N)?	If Fluorescein Present, Location?	Fluorescein on Diver?	If on Diver, area?
1	1	Y	ONM	Y	Bilateral cheeks, chin
1	2	Y	ONM	N	
1	3	Y	ONM	Y	Chin, Right cheek
2	4	Y	ONM	Y	Chin
2	5	Y	ONM	N	
2	6	Y	ONM	Y	Chin
3	7	Y	ONM	Y	Chin, perioral
3	8	Y	ONM	N	
3	9	Y	ONM	Y	Left cheek
4	10	Y	ONM	N	
4	11	Y	ONM	Y	Left ear and chin
5	12	N		N	
5	13	Y	ONM	Y	Chin
6	14	Y	ONM	N	
6	15	Y	ONM	Y	Chin, perioral
6	16	Y	ONM	Y	Perioral
7	17	Y	ONM	N	
7	18	Y	ONM	Y	Nose
7	19	Y	ONM	N	
8	20	Y	ONM	Y	Perioral, chin, ear, neck
8	21	Y	ONM	Y	Perioral, chin, nose
8	22	Y	ONM	Y	Perioral