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EVALUATION OF PROTOTYPE LITHIUM BATTERY FOR THE MK 16 UNDERWATER BREATHING APPARATUS (UBA)

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Naval Special Warfare (NSW) currently uses the MK 16 UBA for Seal Delivery Vehicle (SDV) diving operations. Originally developed for the Explosive Ordnance Disposal (EOD) community, the MK 16 UBA presently uses a Power-Sonic Model PS-60 rechargeable lead-acid dioxide battery. While it is adequate for EOD operations, this battery does not provide the operating life required for NSW SDV mission scenarios. Naval Special Warfare Command (COMNAVSPECWARCOM) tasked Naval Surface Warfare Center, Crane Division (NSWC) to develop a MK 16 UBA battery pack that could provide adequate voltage for a complete NSW SDV mission profile of 160 hours. NEDU was tasked to evaluate a prototype lithium battery for suitability and potential incorporation into the MK 16 MOD 0 UBA, and to determine if these batteries are satisfactory replacements for the existing battery pack in the MK 16 MOD 0 UBA.

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With an environmental chamber, NSWC evaluated battery performance using a test scenario emulating the MK 16's operational current draw during the NSW SDV 160 hr mission profile. Phase 1-at 24°C (75°F/100 hr), current draw was switched between 35.8 and 11.3 mA at 4 Hz, simulating MK 16 "dormant standby," where the red primary display LED flashes on and off. Phase 2-at 2°C (35°F/8.5 hr), current draw was continuously maintained 35.8 mA, simulating the MK 16 operation while the green primary display LED continuously remains on. Phase 3-at -29°C (-18°F/48 hr), current draw was switched between 35.8 and 11.3 mA at 4 Hz, simulating MK 16 "dormant standby," where the red primary display LED flashes on and off. Phase 4-at 2°C (35°F), current draw was continuously maintained 35.8 mA, simulating the MK 16 operation with the green primary display LED continuously illuminated. Testing at this phase continued until the battery voltage dropped below 5.2 volts.

The prototype lithium battery pack meets all criteria of the original Naval Special Warfare requirements specified by COMNAVSPECWARCOM except the requirement for minimum voltage during storage at -20°C.

Unfortunately, it is not known if the battery's failure to maintain the specified voltage during cold storage would have any impact on a mission. In other words, is the 5.2 v minimum battery voltage a realistic requirement? NEDU recommends testing of the MK 16's ability to function correctly during transition back to the water after cache at -20°C. NEDU further recommends that EOD Technology Center determine the minimum voltage level at which the MK 16 will function reliably. NEDU recommends that the MK 16 Operating Procedures be rewritten to direct the operators to secure the gas flask valves any time the UBA's have to be stored for any period of time at below-freezing temperatures. Opening the valves before deploying the diver should be written into the OP's as part of the MK 16 donning procedure. Valve closure should prevent the flasks from emptying during storage at cold temperatures.

Although the prototype lithium battery failed to meet one portion of the test plan, these new batteries do provide a significant improvement over the batteries currently used in the MK 16 MOD 0 UBA. Therefore, NEDU recommends that the present batteries be replaced by the prototype lithium batteries.

CONTENTS

INTRODUCTION

The MK 16 Underwater Breathing Apparatus (UBA) is an electronically controlled, mixed gas, battery powered rebreather. Naval Special Warfare (NSW) currently uses the MK 16 UBA for Seal Delivery Vehicle (SDV) diving operations. Originally developed for the Explosive Ordnance Disposal (EOD) community, the MK 16 UBA presently uses a Power-Sonic Model PS-60 rechargeable lead-acid dioxide battery. While it is adequate for EOD operations, this battery does not provide the operating life required for NSW SDV mission scenarios.

TEST HISTORY

First series

Naval Special Warfare Command (COMNAVSPECWARCOM) tasked Naval Surface Warfare Center, Crane Division (NSWC)[1] to develop a MK 16 UBA battery pack that could provide adequate voltage for a complete NSW SDV mission profile, of 160 hours[2]. NSWC tested eight prototype batteries[3] using an electronic load bank to impose a continuous 11 mA draw at the test temperatures shown in Table 1.

Table 1. First Series Test Scenario (NSWC)

Test Phase	Time (Hours:minutes)	Temperature °C (°F)
1	100:00	24 (75)
2	8:45	2 (35)
3	48:00	-29 (-20)
4	1:45	2 (35)

Unfortunately, this test scenario failed to emulate the average MK 16 UBA electrical load typically produced during normal operation.

Second series

Subsequently, Naval Sea Systems Command (NAVSEA) tasked NEDU[4] to characterize the NSWC prototype lithium battery performance. NEDU tested 24 prototype batteries[5], eight at three different temperatures (-29°, 2° and 21°C (-20 °, 36 ° and 70 °F)), using fixed resistors to impose the current draws shown in Table 2.

Table 2. Second Series Test Scenario (NEDU)

Test Phase Number	Time of Phase (Hours:minutes)	Current Draw (mA) ::seconds / ::seconds (Light on / light off)
1	8:00	23.1 / 30.7 (::45 / ::15)
2	142:00	23.1 continuous
3	8:00	23.1 / 30.7 (::45 / ::15)
4	Until termination	23.1 continuous

However, we lacked the empirical data needed to determine whether our regimen accurately reflected the MK 16's current draw, precluding us from knowing whether the batteries would be adequate for NSW SDV mission use.

Third series

Simulated current draw. NSWC conducted a subsequent study that employed current loads believed to more closely reflect MK 16 levels[6]. Following a subsequent NEDU test plan[7], NSWC tested lithium batteries using their electronic load bank to impose the current draw levels at the test temperatures shown in Table 3.

Table 3. Third Series Test Scenario (NSWC)

Test Phase Number	Test Time (Hours:minutes)	Test Temperature °C (°F)	Current Draw (mA) ::seconds / ::seconds (Light on / light off)
1	100:00	24 (75)	23.1 continuous
2	8:45	2 (35)	23.1 / 29.3 (::45 / ::15)
3	48:00	-29 (-20)	23.1 continuous
4	Until termination	2 (35)	23.1 / 29.3 (::45 / ::15)

They encountered two major problems during this series. First a power failure allowed the temperature in the test chamber to rise from -28° C (-18° F) to 29° C (85° F) during the last three hours of Phase 3. This precluded evaluating battery performance during the most challenging conditions, namely in a cold environment at the point of diminishing battery voltage.

MK 16 current draw characterized. The same NEDU test plan[7] tasked NSWC to empirically characterize MK 16 current draw. They determined that, while in the "ready standby" mode (i.e., DIVE/SURFACE valve in the SURFACE position, UBA breathing medium at 0.75 PO_2, and the UBA primary display showing a steady green), the MK 16 consistently consumes 35.8 mA, although it can draw up to 43 mA for a few minutes at the beginning of a run using fully-charged batteries. Using operational MK 16 UBA's, the continuous 35.8 mA load depleted the prototype batteries in less than 110 hours.

Additionally, during Phase 3 all four flasks in both UBA's lost pressure, and the secondary displays showed erroneous oxygen sensor readings until the UBA's had warmed up during Phase 4.

After the need for conserving battery use became obvious, we suggested an alternate storage mode for the MK 16 UBA that might conserve battery life. The standard operating procedure[8] has been to conduct the bench setup, then store the MK 16 in the "ready standby" mode, again where the green primary light is continuously illuminated, inducing a steady 35.8 mA current draw. We proposed reducing current draw by conducting a modified set up. Instead of allowing the UBA to adjust the breathing medium to .75 PO_2, we advocated flushing the MK 16 with air by inhaling through the mouthpiece after removing the exhalation hose, reattaching the exhalation hose, then setting the DIVE/SURFACE valve in the SURFACE position.

While the MK 16 remains in this mode, hereafter referred to as "dormant standby," the average current draw is 23.6 mA (11.3 to 35.8) as the red primary display LED flashes on and off at 4 Hz, indicating low PO_2. NSWC Crane adopted this procedure during Phase 1 of the follow-on series[7] in an attempt to maximize battery life while still allowing for rapid UBA donning and deployment.

METHODS

NSWC evaluated battery performance using a test scenario emulating the MK 16's operational current draw during a mission that included two phases in the "dormant standby" mode. Using a computer-driven test setup equipped with a transistorized simulator that adjusted the electronic load and constantly monitored current draw, NSWC collected data using National Instruments' VXI automated test system. The current draws employed are shown in Table 4. A total of 24 batteries were tested.

Table 4. Fourth Series Test Scenario (NSWC)

Test Phase Number	Elapsed Time of Phase (Hours:minutes)	Test Temperature °C (°F)	Current Draw (mA) (Light on / light off)
1	100:00	24 (75)	35.8 / 11.3 @ 4 Hertz
2	8:45	2 (35)	35.8 continuous
3	48:00	-29 (-20)	35.8 / 11.3 @ 4 Hertz
4	Until termination	2 (35)	35.8 continuous

Phase 1

With the environmental chamber maintained at 24 °C (75° F), current draw was switched between 35.8 and 11.3 mA at 4 Hz, simulating MK 16 "dormant standby," where the red primary display LED flashes on and off.

Phase 2

With the environmental chamber maintained at 2 °C (35° F), current draw was continuously maintained 35.8 mA, simulating the MK 16 operation while the green primary display LED continuously remains on.

Phase 3

With the environmental chamber maintained at -29 °C (-18° F), current draw was switched between 35.8 and 11.3 mA at 4 Hz, simulating MK 16 "dormant standby," where the red primary display LED flashes on and off.

Phase 4

With the environmental chamber maintained at 2 °C (35° F), current draw was continuously maintained 35.8 mA, simulating the MK 16 operation with the green primary display LED continuously illuminated. Testing at this phase continued until the battery voltage dropped below 5.2 volts.

RESULTS

Of the 24 batteries tested, one failed after about 100 hours[9]. The other batteries remained functional for about 175 hours.

During Phase 3 testing, battery voltages dropped below the failure criterion[2] of 5.2 volts[9]. However, after increasing test chamber temperature during Phase 4, voltages rose to operational levels, i.e., about seven volts, and all surviving batteries continued to provide at least seven volts through the 160 hour mark[9].

DISCUSSION

Twenty-three out of 24 batteries met or exceeded the goal of a 160 hour duration. The single battery that failed, did so precipitously, suggesting a manufacturer defect. Based on one failure out of 24 single shot devices, we estimate with 90% confidence a battery reliability of 0.84.

The primary display LEDs account for a substantial portion of the MK 16 primary current draw. When flashing in the "dormant standby" mode, the load is more than double the basal current draw of 11.3 ma[10]. When primary lights are steady green, the current draw is triple the basal load.

Subjecting activated MK 16's to extreme cold during Phase 3 incapacitated them. The cold caused the secondary display battery voltage to drop below operational levels. However, this condition proved temporary, disappearing after rewarming the batteries to just above freezing. What was more alarming was that all the gas in both flasks managed to completely bleed off during Phase 3. Due to the extreme cold temperatures of this phase, it appears that the gas leaked by the o-rings where the flasks mate with the MK 16 yokes.

In the present study, we used 5.2 volts as our termination criterion per NAVSEA tasking[2]. This was based on the rationale that discharging the rechargeable lead-acid type below 5.2 volts markedly reduces the number of recharge cycles they will subsequently provide. This criterion becomes irrelevant when using disposable lithium batteries; all that really matters is that the batteries continue to provide the UBA with sufficient voltage to keep it operational. We have seen MK 16s operate reliably after discharging the batteries below 4 volts. During NSWC testing (NEDU test plan[7]), one of the MK-16 rigs was still operating at -20^0 F and at 3.5 volts on the battery[9]. Consequently, the 5.2 V requirement may be unnecessarily conservative.

During the final few hours of Phase 3 testing, most of the battery pack voltages dropped to between four and five volts. It should be pointed out that this phase of testing is simulating the MK 16 in a "cache" period where the UBA is not in the operational mode. The lithium battery pack did demonstrate the ability to provide sufficient voltage after being restored to above-freezing temperatures.

CONCLUSIONS

NEDU was tasked to evaluate a prototype lithium battery for suitability and potential incorporation into the UBA MK 16 MOD 0, and to determine if these batteries are satisfactory replacements for the existing battery pack in the UBA MK 16 MOD 0. The prototype lithium battery pack met all the test criteria specified by COMNAVSPECWARCOM[2] with the exception of storage at -20° C.

The lithium battery pack holds great promise for markedly increasing MK 16 operational capability. The rechargeable battery currently used in the MK 16 UBA has a cycle life of 10 hours. Incorporating the lithium battery pack will provide operational durations at least ten times longer.

The advantages of the prototype lithium battery pack are multiple, as it: (1) possesses the greatest capacity for a battery of its size; (2) already is the correct size to fit inside the MK 16 UBA electronics housing; and (3) shows promise in other U. S. Navy applications, as it is currently being evaluated for use in submarines. The disadvantage of using a lithium battery is that the battery life cannot be determined from the battery voltage under load[11].

RECOMMENDATIONS

The prototype lithium battery is a suitable replacement for the MK 16 lead-acid battery. However, it does not meet all SPECWARCOM requirements for use in the MK 16 UBA during SEAL missions. Specifically, it does not meet the requirements for minimum voltage during storage at -20°C.

Unfortunately, it is not known if the battery's failure to maintain the specified voltage during cold storage would have any impact on a mission. In other words, is the 5.2 v minimum battery voltage a realistic requirement? NEDU recommends testing of the MK 16's ability to function correctly during transition back to the water after cache at -20°C.

NEDU further recommends that EOD Technology Center determine the minimum voltage level at which the MK 16 will function reliably.

NEDU recommends that the MK 16 Operating Procedures be rewritten to direct the operators to secure the gas flask valves any time the UBA's have to be stored for any period of time at below-freezing temperatures. Opening the valves before deploying the diver should be written in to the OP's as part of the MK 16 donning procedure. Valve closure should prevent the flasks from emptying during storage.

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