The following article is a full reprint of the *Skin Diver* magazine article that Richard Walsby references in his article "Before The Electrolung." It was written by the *Skin Diver's* Publisher/ Editor Paul Tzimoulis, and published 45 years ago.

300

feet on computerized scuba

An exclusive SDM test report on the revolutionary closed circuit scuba

BY PAUL J. TZIMOULIS

I hung there, just floating effortlessly two feet from the vertical face of the Great Wall of Andros, enjoying the superb stillness of the deep reef. To my left, 80 feet above, I could see the silhouette of a large black coral tree with the distant sun creating a feather-like effect. A large, curious amberjack eyeballed our movements and executed a series of perfect figure eights between me and my two diving partners. Dr. Walter Starck pointed to his depth gauge and held up three fingers, indicating that we had leveled off at precisely 300 feet. We had penetrated the forbidden world of the deep reef.

There was time—a full five minutes—to observe the fish and be awed by the magnificence of this immense coral cliff. As I soaked up the pleasures of this spectacular sight, I marveled over the ingenious diving machine on my back—a space-age scuba that made such deep dives possible, practical, and safe. At that moment, my life was totally dependent on three small teflon membranes, each of them barely 1/1000th of an inch thick, and a miniaturized electronic computer which silently calculated the proper mixture of the gas I breathed.

Yet knowing all this, I still felt entirely at ease. For the first time in 14 years of scuba diving, I was not concerned about the normal anxieties of being befuddled by nitrogen narcosis or running low on air. I felt comfortable, lucid, and completely in concert with the rhythm of the reef. No noisy exhaust bubbles exploded around my head to send frightened fish scurrying off to the protection of their homes. There was no problem focusing my eyes on the delicate details of the deep water gorgonia, or later recalling exactly what I had observed at this extraordinary depth. I could enjoy everything that went on about me, because I was using an Electrolung—a computer-controlled, closed circuit, mixed gas scuba unit.

The Electrolung, manufactured by Beckman Instruments Company, is the first of a whole new generation of scuba diving devices which will undoubtedly revolutionize deep diving technique. General Electric and BioMarine are also producing closed circuit mixed gas units.

I chose to test dive the Electrolung because it was the first of its kind in the field and it has compiled an impressive record of more than 1,000 open water dives in the past two and a half years. The premise of the basic design is a closed circuit system which continually recirculates the breathing gas after properly filtering and rebalancing the mixture. Closed circuit design offers prolonged breathing gas supply, in which the precious exhaled gas is reclaimed and reused. With the Electrolung, this means six hours of diving on one fill—at any depth, from the surface to 1,200 feet! The limiting factors for duration are actually the effective lifespan of the CO_2 scrubber and batteries rather than the actual gas supply itself.

Another departure from what we as sport divers consider normal or open circuit scuba is the use of gas mixtures in place of compressed air. Until now, closed circuit scuba has been relegated to military or experimental use and is considered almost taboo in sport diving activity. Legends about diving accidents with World War II rebreathers still linger; most scuba instructors treat the subject of rebreathers as though it were a plague, or they ignore it altogether.

The new 1968-1970 generation of closed circuit scuba can utilize a variety of different gas mixtures, depending on the planned diving depth and mode of decompression selected. In the case of the Electrolung, a mixture called "tri-mix" is used for most dives ranging from 50 to 400 feet. Three ingredients are used for a tri-mix setup: pure oxygen, pure helium, and regular compressed air. Pure oxygen is stored in one cylinder, while the helium and compressed air are mixed together in the other so-called "inert gas" cylinder. Tri-mix offers many advantages over a straight heli-ox mix, including lower cost, shorter decompression, and better voice communication. Mixed gas diving enables man to push well beyond the red line depth (132 feet) for compressed air, since the nitrogen narcosis can be eliminated.

What sets the Electrolung and its contemporaries apart from those ancient rebreathers is the fact that this new closed-circuit concept utilizes mixed gas, not pure oxygen, and the diver can visually monitor his gas mixture while underwater. He knows exactly what's going on inside his scuba. The Electrolung is equipped with a unique electrochemical sensor device which can accurately tell the partial pressure of oxygen (signified as pO_2) at any depth or at any time. This information is then fed into a miniature computer which figures how much additional oxygen is required, or it can sound an alarm if something has gone wrong. In other words, the Electrolung automatically monitors, measures, and mixes the breathing gas while you're underwater, regardless of depth or rate of energy expended. Out of this marriage between space age electronics and the closed circuit scuba principle is born a new generation of diving devices, it's the age of computerized scuba.

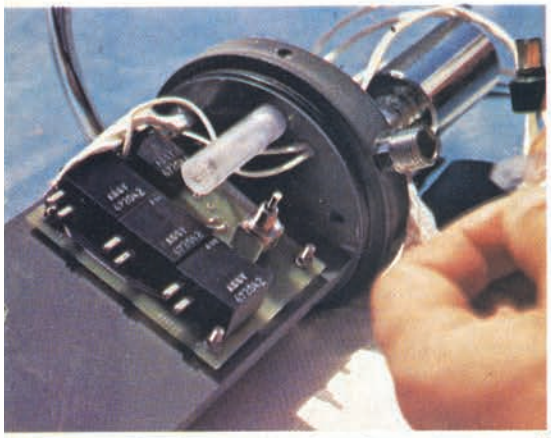
At first glance, the Electrolung appears three times more complicated than it really is. Its intricate network of tubes, wires, and valves tends to bedazzle the mind. Much of this complicated appearance is due to a series of safety back-ups and alternate manual controls which provide a fully integrated fail-safe system. The basic design is a relatively simple assembly.

There are two chrome cylinders which carry the breathing gas supply. These are standard high-pressure tanks capable of holding 11 cubic feet of gas in each cylinder. They are chromed plated because chrome seems to hold up better under the corrosive effects of seawater and because the chrome finish can be seen at maximum distance underwater. The cylinders are also available in a grey Kynar finish, but this is more expensive. Each cylinder is fitted with a standard K-valve. The cylinder on the diver's left is considered the "inert gas" tank and is generally filled with half helium and half compressed air when the tri-mix setup is employed. The resulting mixture in the left tank is 50% helium, 40% nitrogen, and 10% oxygen. A manual shutoff valve and low pressure line run directly from this tank to the breathing bag. This permits the diver to add "inert gas" to the bag as he descends, thus compensating for the increased pressure and reduced breathing gas volume.

The tank on the diver's right is filled with pure oxygen. The first stage of a single hose regulator and a sea vue gauge are connected to the valve of this tank. The diver can check his oxygen supply at any time by just looking at this gauge. The intermediate pressure line from the regulator carries the oxygen to a large chrome solenoid located in the sensor chamber, a cylindrical plexiglas compartment at the top of the unit. There is also a bypass valve and direct tube that leads from the O_2 tank to the breathing system. This is another of the Electrolung's fail-safe designs which is also used as a manual purge device for switching over to pure O_2 during decompression. By switching to pure O_2 for the last 40 feet of ascent, decompression is speeded up.

The large plexiglas cylinder between the two chrome tanks is the CO_2 scrubber canister. It is filled with baralyme, a pinkish (when fresh) granular substance that is a highly efficient carbon dioxide absorbent. The scrubber canister

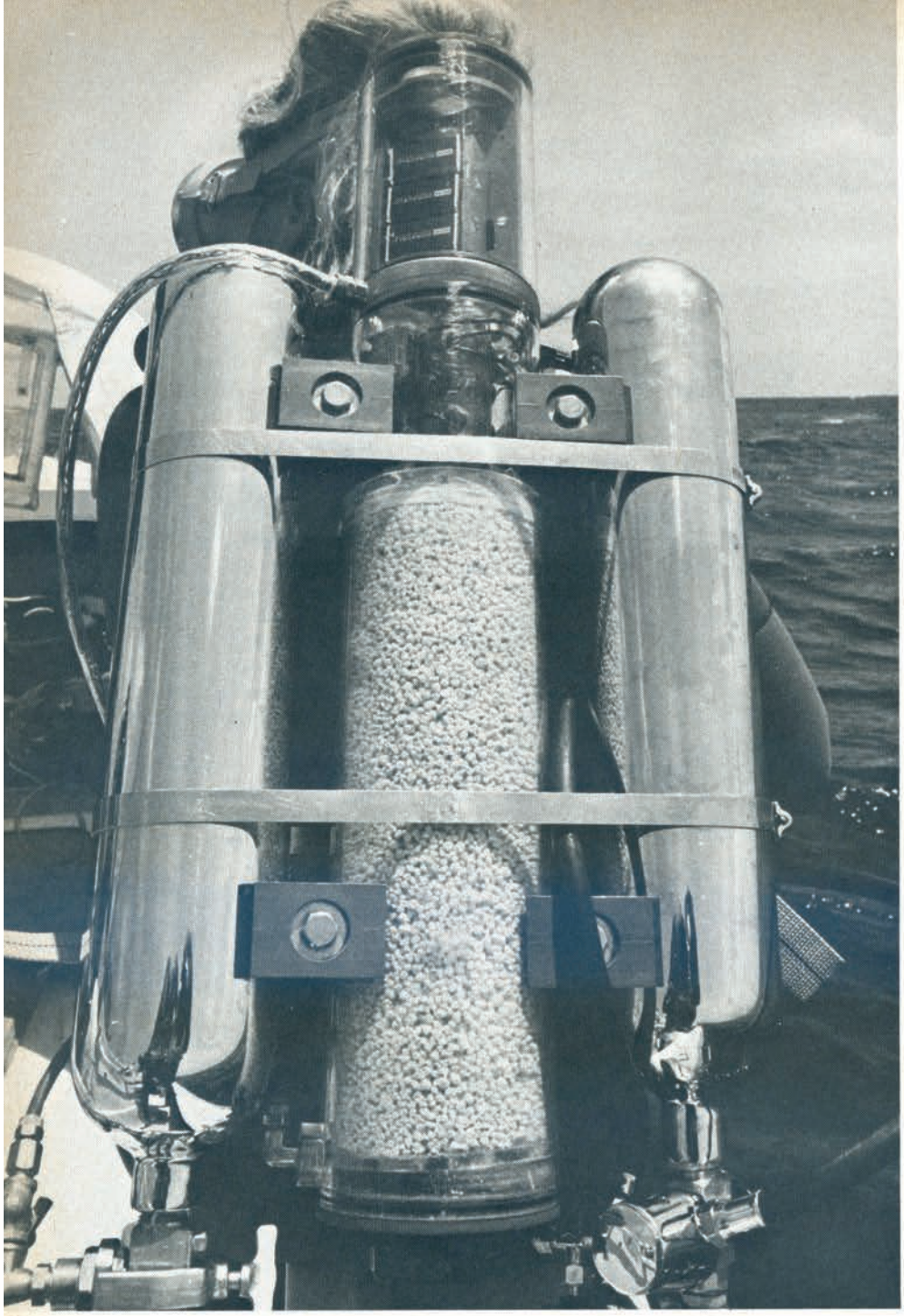
PHOTOS BY AUTHOR



The brain of Electrolung is a small computer the size of a cigarette pack.

Thimble-sized electro-chemical sensors monitor the partial pressure of oxygen.

Walter Starck II, co-inventor, has spent two years refining the design of the lung.



300

is constructed of plexiglas so that the diver can easily see if the canister is filled and if the baralyme is fresh. As the baralyme grows old and saturated with CO_2 it turns a purple-blue. The plexiglas cylinder is automatically pressurized to ambient working depth. Should there be a crack or O-ring leak, gas would bubble out instead of water leaking in. The exhaled breathing gas comes down a center tube in the baralyme canister and then filters upward through the surrounding baralyme granules. The canister holds two quarts of baralyme, enough absorbent for six hours of diving in warm water (78°) and three hours in cold water (56°).

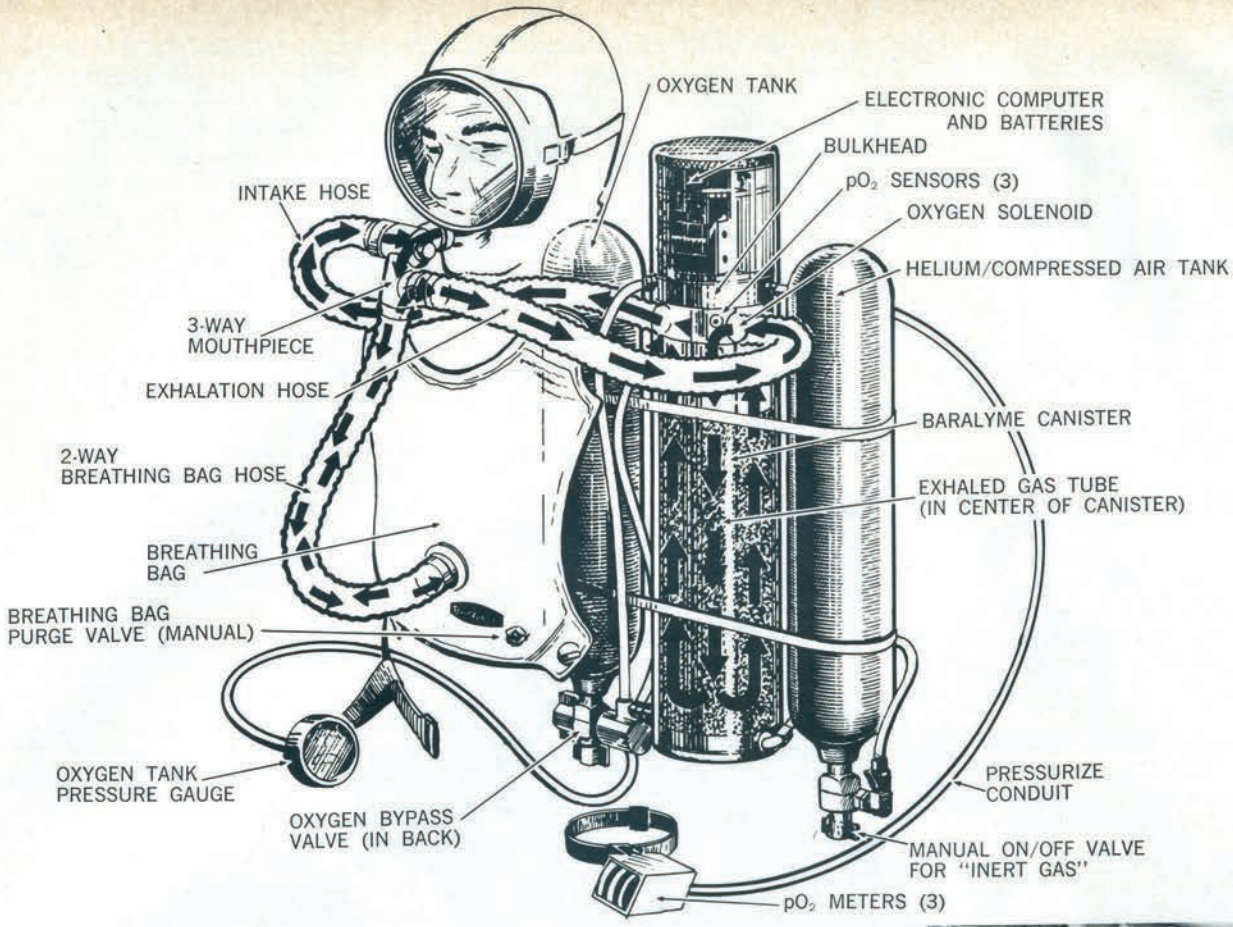
After filtering the CO_2, the freshly cleansed gas is monitored by three separate pO_2 sensors at the upper end of the baralyme canister. These unique sensors are the "nerves" of the Electrolung system. They are polarographic electrodes that operate electro-chemically. Each sensor is about the size of a small thimble constructed from a non-ferrous material. A disc-shaped piece of pure platinum is set in the center of the top end, functioning as the cathode. A deep narrow groove surrounds the platinum disc, and this is filled with electrolyte (potassium hydroxide). The outside edge of the groove is a thin concentric wall of pure silver, and this is the anode. The entire electrode is then covered with a teflon membrane which is less than paper-thin—only 1/1000 of an inch thick. An electrical potential of a little more than ½-volt is then supplied to the electrode. The amount of oxygen which diffuses through the teflon membrane then determines exactly what the partial pressure of the oxygen is at any given depth. It is this partial pressure (pO_2) which determines the correct balance in mixed-gas diving.

The Electrolung could operate well on one pO_2 sensor, but the combination of three electrodes is part of the unit's fail-safe design. The manufacturer describes it as "triple redundancy" design. According to the inventor, Dr. Starck, the estimated possibility of one sensor having an electro-chemical failure during a dive is one in a thousand. However, the chances of two sensors failing simultaneously is one in a million, and the odds against all three going bad are one in a billion.

The readings from all three sensors are fed into the Electrolung's brain—a miniature analogue computer. The computer takes an average of the three separate readings, and if one of the sensors is reading abnormally high or low, the computer automatically "freezes" or "clips" the input from the malfunctioning sensor. It then utilizes the input from the remaining two sensors and takes an average of that data.

While Electrolung's brain is silently analyzing the input data from the sensor, the diver is also able to observe the behavior of the sensors. Three separate readout meters are strapped to the diver's left forearm, indicating the readings of each meter. The meter scale goes from 0 to 100. A reading of 20 means the partial pressure of the oxygen in the system is equal to air at normal atmospheric pressure (sea level). A reading of 100 means the pO_2 is equal to one atmosphere of water (33 feet). Under normal Electrolung operation, the meter needles are in the 50 to 55 range, which means the diver is breathing a pO_2 inert gas mixture equal to pure oxygen at a depth of 16 feet. This is considered the optimum gas mixture for the Electrolung, since the diver enjoys a wide safety margin on both the high and low sides of prescribed pO_2 setting.

The Electrolung's brain is probably the most fascinating aspect of the entire-



An Electrolung diver adjusts the pO_2 readout on an early prototype model of the computer, now condensed into miniaturized solid-state modular components. At far right, Jo Starck goes through a pre-dive checkout and assembly of the unit. Fresh electrolyte is added to the oxygen sensors to insure accurate meter readout. The components of the Electrolung (opposite page) consist of the baralyme CO_2 absorbent, flanked by two chromed tanks of compressed gas, with electronic computer behind the head.

system. The whole computer is hardly bigger than a pack of cigarettes, but crammed into this space is a highly sophisticated electronic machine that can monitor, average, signal, and operate the system. Most of the computer's components are miniature, solid state transistor circuits—one of those beneficial spin-offs from the U.S. space program. Five years ago, this kind of electronic circuitry didn't exist. The computer is powered by two nine-volt manganese alkaline batteries, and parallel to it is an extra set which is wired in as standby power (still another fail-safe feature). The diver can switch over to the spare batteries at any time during the dive. The computer and batteries are housed in a separate plexiglas compartment on top of the baralyme canister. It is also watertight and pressurized to ambient operating depth.

The computer performs three individual functions during an Electrolung dive. First, it reads, analyzes and averages the input of the pO_2 sensors, and it automatically compensates for temperature changes that might ordinarily effect the readings. Second, it activates an audio warning signal if the pO_2 in the system is higher or lower than normal. An audio-beeper alerts the diver the minute the pO_2 meters drop below 35 or rise above 70. The unit is still well within the safe operating range when the alarm goes off, but it does inform the diver that the gas mixture has changed in the Electrolung.

Once the alarm has sounded, and the gauges indicate low pO_2, the computer automatically compensates for the decrease in oxygen by activating the oxygen solenoid valve. A shot of pure oxygen is injected into the breathing system right at the upper end of the baralyme compartment. This brings the pO_2 back up to the prescribed balance in a matter of a few seconds—the time it takes to mix the fresh oxygen throughout the breathing system.

During a normal Electrolung dive, the audio-beeper goes off every two minutes, indicating a drop in pO_2. The alarm is immediately followed by the

300

hissing sound of the solenoid as it injects oxygen. The beeper momentarily sounds off again because of the now oxygen-rich mixture in the sensor compartment, but this alarm ceases as the O_2 is circulated throughout the system. The beeper is then silent for another two to four minutes before the cycle is repeated. The frequency of O_2 injections is relative to the operating depth . . . less often as you go deeper.

Because the Electrolung is a closed circuit unit, it is equipped with a breathing bag. The bag provides a place for the exhaled gas to go before the diver makes his next inhalation. It's a sort of seesaw balance: When the diver's lungs are empty (exhalation), the bag is full; when the diver's lungs are full (inhalation), the bag is empty. The Electrolung bag is different from other breathing bags in that it is made of a translucent plastic fabric. The semi-clear plastic permits sunlight to kill or prevent fungus growth from accumulating on the bag interior walls. The bag is attached to the diver's chest harness because this is the point closest to his lung and it provides the easiest breathing in a swimming position. A drain plug in the lower left front of the bag permits the purge of any water accumulation. It can be purged underwater in the same manner as clearing a face mask.

The Electrolung mouthpiece is fitted with a three-way valve. Fresh gas is inhaled from the diver's right-hand breathing tube. Meanwhile the exhaled gas in the bag passes up the middle tube and out the left-hand exhaust tube. Upon exhalation, both the left and right-hand tubes are shut and the exhausted gas passes down the center tube and into the breathing bag. It is only a little more complicated than two-hose regulators.

In order to fully understand the circuitry and function of the Electrolung, a novice needs only to read the operating manual twice and work with the unit for approximately one day. Learning to actually dive with an Electrolung is not difficult, but a formal course of instruction is definitely required. Closed circuit, mixed gas scuba is an entirely different mode of diving and there's a good deal of reorientation in diving physics and decompression technique required in order to make the transition. In the field of sport diving, closed circuit scuba would probably be limited to certified advance divers, scuba instructors, and semi-professional divers. The Electrolung is not a toy, nor can its usage and maintenance be treated as casually as regular open circuit scuba.

The process of learning to dive the Electrolung and mastering the basic predive and maintenance procedures take approximately the same amount of time as learning to solo in a private aircraft—from nine to twelve hours, depending upon the student. Three or four dives, one in the pool and the rest in open water, are sufficient for gaining the necessary coordination and self-confidence to dive the unit.

However, there is another six to twelve hours of classroom lecture and study necessary for learning the theory of mixed gas diving. All of the physics and theory related to open circuit scuba decompression and gas consumption no

U/W photographer Bob Hollis checks out the Electrolung for cold water diving. At lower temperatures, the effective absorption time for baralyme is reduced.

longer apply. Even though you may be an experienced and knowledgeable compressed air diver, you must begin all over again, relearning the principles of partial pressures, mixed gas diving tables, CO_2 absorption rates as related to temperatures, etc. It would be reasonable to assume that an experienced sport diver would require 20 to 24 hours of instruction to become qualified as an Electrolung diver.

To give you some insight into the skills required, let me relate my own learning experiences leading up to my 300-foot check-out dive. I flew to Andros Island in the Bahamas to spend a week aboard the research vessel TORITO, where I was to study and dive with the unit. My tutors were Dr. Walter Starck, II, co-inventor of the Electrolung, and his very capable diving assistant and wife, Jo Starck.

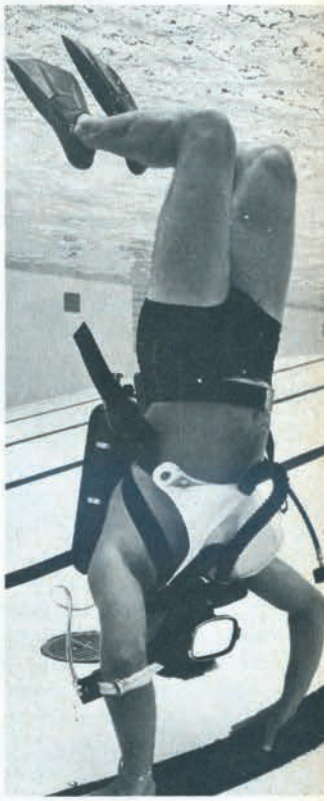
I spent the first day going over the basic features of the Electrolung with Dr. Starck and observing his diving team make a 280-foot dive on the Wall. I watched each diver make a pre-dive check of their unit, which included a check of the battery voltage, application of fresh electrolyte to the pO_2 sensors, and recalibration of the pO_2 meters. This procedure generally took 15 to 20 minutes. We were to make our dive from a 22-foot open boat and I was happy to see that no specially delicate care was needed for topside handling. The Electrolungs were placed in the bottom of the boat, right beside the standard compressed air tanks, with no apparent concern about the sun or salt spray. Since the Electrolung only weighs 35 pounds, it can be easily strapped on by the diver alone, but assistance from a buddy is much more convenient. Dr. Starck pointed out the need for additional four to six pounds of lead weight for Electrolung diving to compensate for the extra buoyancy of the breathing bag and closed circuit system. While I was observing the Electrolung divers underwater, I found that they dived in very much the same way as compressed air divers except that the fish were not frightened by their approach. The absence of exhaust bubbles seemed to be a great advantage.

I made my first Electrolung dive the very next day, in approximately 60 feet of water. We chose the site of the LCR wreck off Small Hope Bay Lodge for this familiarization session, since I had previously made many dives in this area. Starck explained that it was easier to start with an Electrolung in open water rather than in a shallow pool with little pressure changes and in at least 30-60 feet of water because there was less pressure differential at this depth zone and therefore less need to compensate the breathing bag volume for slight changes in depth. The breathing bag is the thing that is most likely to confound a sport diver on his first Electrolung dive. The trick is to compensate for changes in depth by decreasing or increasing the gas in the bag as you go up or down.

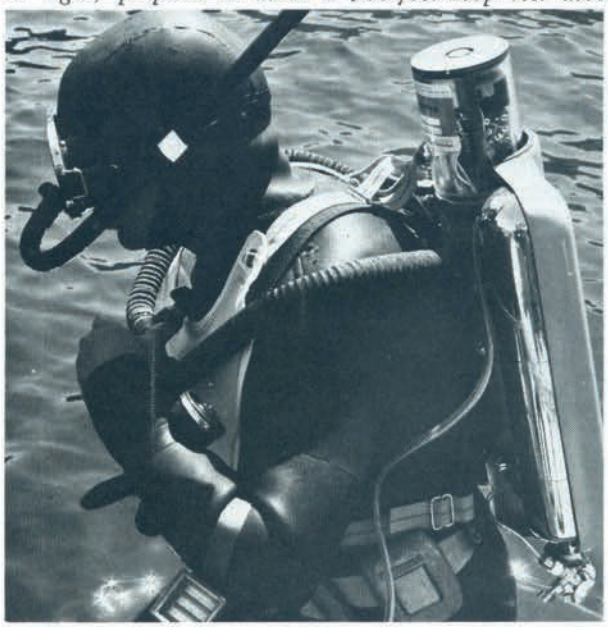
On my first descent I found that if I did not valve the inert gas in fast enough, the bag would flatten against my chest and I could not make the next inhalation. On the other hand, if I valved in too much gas, the bag would overinflate like a big pillow and I would gain too much positive buoyancy. After a few practice runs up and down the anchor line, I found that one can easily coordinate the correct flow of inert gas with the rate of descent. Once mastered, it is no problem. Also, I quickly discovered the left hand must remain free of cameras or other accessories in order to manipulate the inert gas valve—another subtle alteration in diving method.

With the Electrolung, you can breathe as fast or as slow as you want since the frequency of inhalation does not effect the gas supply or duration of the dive. However, Dr. Starck suggests breathing

(Continued on Page 70)



Electrolung divers are finding that clear-headedness and the lack of bubbles are just two advantages in deep sea research and photography. In addition, they are able to remain longer at depths without narcotic effects and subsequent lengthy decompression. Dr. Glen Egstrom of UCLA (upper right) checks out the unit in all possible underwater positions while author Tzimoulis (lower right) prepares to make a 300-foot-deep test dive.



about twice the rate of compressed air scuba in order to keep the CO_2 level as low as possible. This increased breathing rate speeds up the circulation of the gas through the baralyme scrubber. However, inhalations should be shallower than normal.

I was amazed at the underwater handling qualities of the Electrolung—I hardly knew it was there! It rides flat against the back with very little drag. It is thinner and better balanced than single tank scuba. The electronic computer compartment is quite buoyant and causes the upper portion of the unit to float high and away from the diver's head. Not once did I find the Electrolung banging against the back of my head.

It takes about 10 to 15 minutes to become accustomed to the rhythm of the Electrolung's O_2 mixing cycle. The first few times the beeper alarm went off, I found myself over-reacting by scanning the pO_2 meters for a problem. The reassuring hiss of the solenoid promptly relieved my concern, and after a little while the beeper became a normal part of the routine. You can tell the Electrolung is functioning as it should by just listening to it.

I experienced a slight amount of water leakage during the first few minutes—again due to my unfamiliarity with the breathing bag. When not handled properly, the bag's buoyancy can cause a tug at the mouthpiece just enough to cause a trickle. Fortunately, the water merely collects in the bottom of the breathing bag and can be purged.

My second dive with the Electrolung was far more enjoyable; in fact, it was an absolute ball! I had made the transition to closed-circuit scuba and now felt completely at ease with the unit. I had the breathing bag coordination down pat and made my 180-foot descent without hesitation. It was just a matter of valving in the inert gas at a slow, steady rate as I swam down the anchor line. I was no longer preoccupied with the Electrolung's basic functions and I really began to enjoy its advantages.

Diving is much quieter with closed-circuit scuba, and one becomes much more aware of the little sounds made by fish, shrimp, and other creatures on the reef. Two of our divers were wearing regular scuba, and you could hear them approaching from 200 feet away. They sounded like a couple of Sherman tanks motoring across the sea floor—no wonder the fish madly dashed for cover as these noisy intruders arrived!

My final check-out dive to 300 feet was perhaps the greatest thrill of my life. Penetrating the deep reef zone is like entering a whole new world of the sea—a strange and fascinating ecosystem of brightly-colored gorgonia, unidentified corals and even unnamed fish. There was no need to expend unnecessary effort in swimming since we could maintain excellent control and direction by altering the buoyancy of the breathing bag. An extra shot of inert gas would slow or stop descent while an exhaust would resume our downward travel.

The absence of nitrogen oppression was remarkable, and diving at 300 feet felt as simple as 30 feet . . . there was no dulling of the senses, no fumbling of the hands, no blurred, warped vision. Everything seemed crystal sharp. Dr. Starck's Luminaut headlamp lit up a 100-foot square of the coral wall, revealing a Picasso patchwork of vivid reds, yellows, and orange marine life.

We began our ascent very slowly, taking a full five minutes to get from 300 to 200 feet. There was no need to rush and no need to exert ourselves, for the Electrolung contained more than enough gas supply for the lengthy decompression. We kept our breathing bags slightly fuller now than during descent, adding just enough buoyancy for easy ascent. We continued our slow and easy rise up the anchor line until we reached 35 feet, where it was time to switch over to pure oxygen.

The procedure was simple; first the inert gas supply is shut off. Then the system is purged by exhausting all of the gas in the breathing bag and replacing it with pure oxygen via the oxygen by-pass valve. The purging procedure is repeated several times until all three pO_2 meters read 100, indicating a pure oxygen mix. The dive and decompression were completed without a hitch.

There is no doubt that the Electrolung has a bright future in diving, but skeptics may ask, "Is it practical—is it perfected?" (Especially at $2975.00.)

Unlike cyrogenic scuba or other experimental diving devices, the Electrolung has already graduated from the prototype stage. Beckman Instruments' assembly plant in Fullerton, California, is currently building the units as fast as possible. Over 30 units are presently in the field, being used for practical work in the 150 to 250-foot range. The Makai Range successfully used Electrolung units along with standard gear during their Aegir underwater habitat experiment last June. A growing number of professional underwater photographers are beginning to utilize closed-circuit scuba because of the absence of exhaust bubbles and narcosis.

At this point in history, the Electrolung stands as the newest, most exciting milestone in the further development of scuba equipment. It provides the key for extending the boundaries of safe undersea exploration, and opens the door to a whole new plateau of discovery.