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The safe use by divers of a high current pulse generator in studies of the behaviour of marine fish in electric fields

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Experiments on the response of marine species to electric fields are more likely to give accurate information if the experiments are conducted on animals in their natural environment. The principal difficulty in conducting such experiments is that high energy current pulses must be used, so that there is a risk of human observers experiencing dangerous or even fatal electric shocks. The effects of electric currents on humans are reviewed. Apparatus and experimental procedures which have been used satisfactorily by divers to conduct underwater experiments with electric fields are described. Divers in neoprene wet suits were able to approach to within 1 m of energised electrodes, at 70 V potential difference, spaced 1 m apart, without experiencing electric shock. The safest position from which to observe an electrode array on the sea bed is from the side, in line with the electrodes. If conditions require observation from above, the diver should be positively buoyant and not approach closer than 1½ times the electrode spacing.

Introduction

There has been considerable interest over a long period of time in the reactions of marine fish (including shellfish) to electric fields (Kreutzer, 1964; McRae and French, 1965; Klima, 1968; Nikonorov, 1969; Le Mèn, 1971). This stems from the highly successful use of electric fields in fresh water for fish management and capture (McMillan, 1928; Lethlean, 1953; Hartley, 1967), and has been stimulated by the hope that the behaviour of marine fish in electric fields might also be of a type which could be used to develop more efficient methods of capture.

The involuntary reactions of fish to electric fields are well known (Bary, 1956). Pulsed electric fields induce muscular contractions, leading to tetanus as the frequency is raised. In a DC field above a certain threshold level the muscular contractions compel fish to swim to the anode (electrotaxis) and at some higher field level fish are stunned (electronarcosis). These reactions can be readily produced in an aquarium (Bary, 1956) where uniform electric fields can be set up.

The sea is an unbounded medium, and a set of electrodes develops an extensive field, which is of high intensity only near the electrodes and has a large low intensity fringing region. Before fish enter a high intensity field zone they must in general pass through a zone of low intensity. Their behaviour in this latter zone, which will be of a non-reflex nature, is clearly of fundamental importance in the use of electric fields for fish capture. It is necessary to assess the degree of "scaring" produced by a weak electric field, and the ability of the fish to sense the position and direction of the stimulus.

Although involuntary reactions can be studied in aquaria and accurate results obtained, the non-reflex types of reaction are difficult to study in artificial conditions. The results of such experiments are notoriously unreliable as predictors of how animals in their natural habitat will respond to the same stimuli. Reliable behavioural information of this type can only be obtained by conducting experiments in the sea on animals which have not had their sensitivity to stimulation altered by the artificial conditions and variety of abnormal stimuli in an aquarium. The stimulation equipment should be taken to the animals and not vice versa, so that the reactions of naive specimens in natural conditions can be investigated.

Sea water has a resistivity of around 25Ω·cm, and in order to produce electric field strengths large enough to affect fish relatively intense current levels are required. The sea water resistance between electrodes can be less than 0·1Ω, and pulsed systems with high peak current levels must be used to minimise power consumption. Typically, an electrode array may present a resistance of 0·1Ω, and to develop 100 V DC pulses of 4 ms duration at 20 Hz across the electrodes, pulses of 1000 A instantaneous peak amplitude, with a peak power demand of 10^5 W and a mean power demand of about 3 kW are required. To conduct behavioural experiments on fish in natural conditions therefore, a high current pulse generator and electrode array must be taken to the sea bed and deployed near the fish.

Since simple economics ruled out the use of a manned submersible for making observations, other techniques had to be employed. Underwater television was used in some initial experiments but gave limited information, and it was decided to use divers to conduct the tests as they could accurately position the apparatus and, having a wider field of view, could make observations over a much greater area. The depths at which the experiments could be conducted were controlled by decompression requirements, and limited to 30 m for sufficient time to be available to conduct a useful number of tests without decompression stops on ascent. Depth limitation can be a handicap in this work since many of the commercially important marine species are rarely found at depths less than 30 m.

It is desirable that the divers conducting the tests should be protected against electric shock. In an already hazardous environment even a slight shock, too weak in itself to be harmful, may be sufficient to trigger some action with fatal consequences. The electric field must be developed throughout whatever volume is necessary to ensure that observations can be made, and the more extensive the field the greater the risk to the divers. It is not possible to design an intrinsically safe experiment in which the capacity of the power supply is limited to less than that required to pass a fatal current through the human body (Mole, 1971) as the parameters of the pulse generator are determined by the needs of the experiment. To be safe therefore, the divers must keep outside the zones of high electric field strength near energised electrodes.

In this paper the apparatus and procedure used for conducting underwater investigations on the response of fish to stimulation by electric fields in their natural habitat are described, with emphasis on diver safety. The technique proved satisfactory in practice and has been used to determine the reactions of the burrowing crustacean *Nephrops norvegicus* (Stewart, 1974a), and of flatfish of the pleuronectid family (Stewart, 1974b) to electric fields.

Physiological aspects of electric shock

Dalziel, Lee and Mansfield (1950; 1953; 1969) have studied the effects of electric currents on humans and on other mammals such as sheep, dogs and pigs. The important factor in electric shock is the amount of current which passes through the body, and the most dangerous shocks are those in which the current path is through the chest and affects the heart muscles. If an alternating current is passed through the human body from electrodes attached to the hands and the current is increased from zero, at some level the presence of the current will be detected and is felt as a warm prickling sensation. At a higher current level the first reaction of importance occurs when involuntary muscular contractions are induced. The sensation of heat and the intensity of the contractions increase with current intensity, and at some value the muscle cannot be relaxed. For a human holding an electrode in his hand this is termed the "let-go" current. Currents in excess of "let-go" clamp the victim to the electrodes and are very painful.

Figure 1 shows Dalziel's measurements of the frequency dependence of the "let-go" current for a sample of 134 men. The responses were normally distributed and several percentile curves are shown. The values for women are approximately two thirds of those for men. It is noteworthy that humans are most sensitive to electric current in the commercial frequency range (50 to 60 Hz). At higher frequencies the "let-go" values rise and clearly high frequencies are essentially much safer than low frequencies. The 0·5 percentile value is taken as a measure of safety since this current is below the "let-go" value for 99·5% of the population. Thus the safe current at 50 Hz is 9 mA. In these tests commercial frequency currents of 18 to 22 mA flowing across the chest temporarily stopped breathing.

DC currents produce heating rather than muscular contractions, but the latter are stimulated by changes in amplitude. Humans have little difficulty in releasing electrodes passing direct current and the maximum tolerable current represents endurance rather than the ability to "let-go". The 0·5 percentile release current for men is 62 mA, but the current at which physiological damage would take place is undoubtedly higher.

Experiments have not been conducted on humans at currents above the "let-go" values, and information on the effects of more intense currents has been obtained from animals. Exposure to these higher currents can disturb the brain centres controlling heart and lung functions and induce paralysis of the respiratory system, cardiac arrest, ventricular fibrillation, burns and fatal damage to the central nervous system. The effects due to muscular paralysis should disappear when the current is stopped. Ventricular fibrillation is caused by currents flowing in the heart, and is probably the most common cause of death from electric shock. The muscles cease their rhythmic contractions and the pumping action stops. The

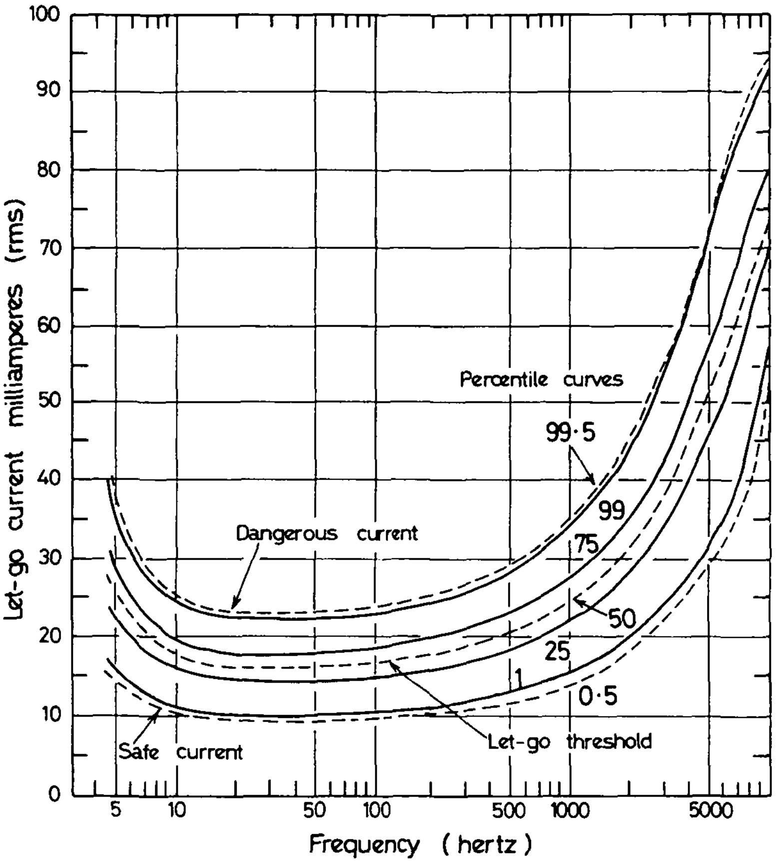

Figure 1. Frequency dependence of "let-go" current for men.

effect is derangement rather than damage, and is dangerous because once the normal pumping action has been stopped, it rarely restarts spontaneously. The brain cells begin to die within 2 to 4 minutes and resuscitation must be started immediately. An electric impulse can induce defibrillation, and artificial respiration and cardiac massage may also rectify the condition. Experiments on animals have shown that two factors govern the current intensity needed to induce ventricular fibrillation; these being body weight and shock duration. The minimum commercial frequency current (I) needed to induce fibrillation (0·5 percentile value) is proportional to body weight and inversely proportional to the square root of the shock duration (T). From these empirically derived relationships for animals it can be postulated that ventricular fibrillation will not be induced in an average size adult human if $I < 116 \sqrt{T}$ mA.

At higher frequencies the "let-go" current rises, but the heating effect increases and can be a hazard if allowed to persist. The human body can dissipate 200 W during active exercise and may be able to tolerate an additional 20 W dissipation. This factor then controls the maximum safe high frequency current.

The work described above defined safe current levels within the human body. When conducting underwater experiments with electric fields however, the important factor is the electric field strength in the water which can generate currents higher than these safe levels in a completely immersed human body. Smoot and Bentel (1964) have investigated safe electric field strengths in sea water in the context of a study of the safety of swimming pool electrical equipment. They observed the reactions of human subjects partly immersed in sea water through which a 60 Hz electric current was passing, and found that muscular control was lost at an electric field strength of approximately 8 V/m.

Dogs have been made to swim into electric fields (Dalziel and Lee, 1969). They lose muscular control

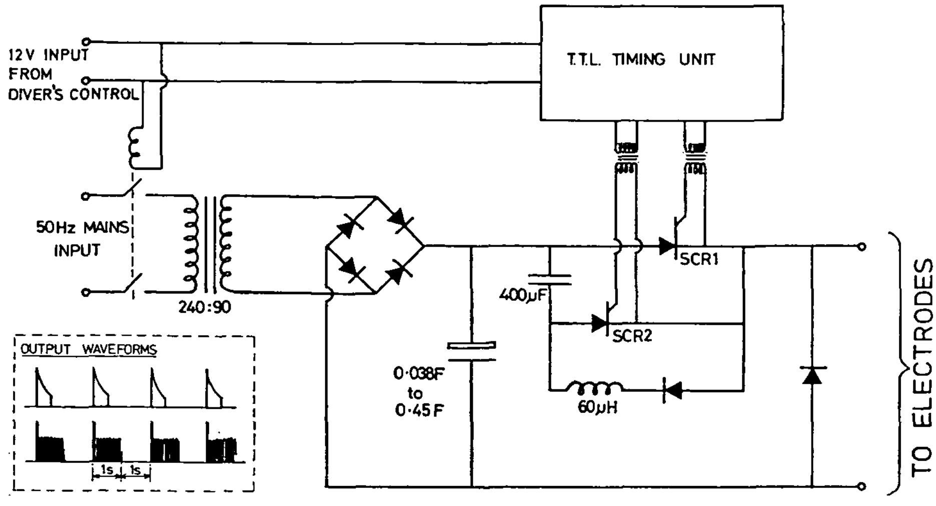

Figure 2. Pulse generator circuit.

and stop breathing. Death is from anoxia and not from drowning.

The current which passes through a human body when a voltage is applied to the extremities is determined by the contact, skin and body resistances. The accepted value for the body resistance between major extremities is 500 Ω (Dalziel, 1953). The contact resistance is negligible when the skin and contact are immersed in salt solution. The skin resistance can vary and can be broken down by high currents and voltages. For the calculation of safe current levels it is reasonable to assume complete breakdown of skin resistance and use the value of 500 Ω as the resistance presented by the human body.

Equipment

Design requirements

The experimental requirements imposed several constraints on the design of the system which affected its safety in use. The underwater pulse generator had to be strong enough to be towed over the bottom by small boats, and small enough to be moved around by divers. The former requirement meant that a metal housing was needed to be strong enough to withstand impacts, but the use of a conducting material to contain energised electrical equipment creates an electric shock hazard. The latter requirement ruled out the use of a bulky battery pack, and meant that power had to be supplied from a generator at the surface. This is an advantage in an experimental situation where the total power requirements cannot be accurately predicted in advance, as a relatively unlimited power source can be used. An additional disadvantage of a battery pack is that the unit would have to be brought ashore at frequent intervals for recharging, but with a cable supply it could be left on the bottom indefinitely. Experimental sites are not always close to the shore, and it was clear that the generator would frequently have to be mounted on a raft or boat, probably made of insulating materials. The underwater pulse generator could not therefore be protected against electrical faults by an earthing system, and the operating procedure was designed to accommodate this situation. Even if it had been possible to securely "earth" the pulse generator housing, the unit would still have been dangerous, and the existence of earth links, themselves liable to faults, might only have engendered a sense of false security in the divers.

Pulse generator

A pulse generator was designed capable of feeding exponential shaped pulses up to 80 V in amplitude into loads of 80 mΩ or more, giving a peak pulse current of 1000 A. The unit was capable of generating continuous pulses, or bursts of pulses, at 2 to 50 Hz, with pulse durations of 4 to 40 ms and burst frequencies of 0·5 to 1 Hz. The basic circuit (Gutzwiller, 1967) is shown in Figure 2 with an insert showing typical output patterns. This is a silicon controlled rectifier switched capacitor discharge circuit with a low mean and high peak power. The timing unit was built from integrated circuit modules. Electrolytic capacitors were used to store energy. The units selected for the capacity bank operated

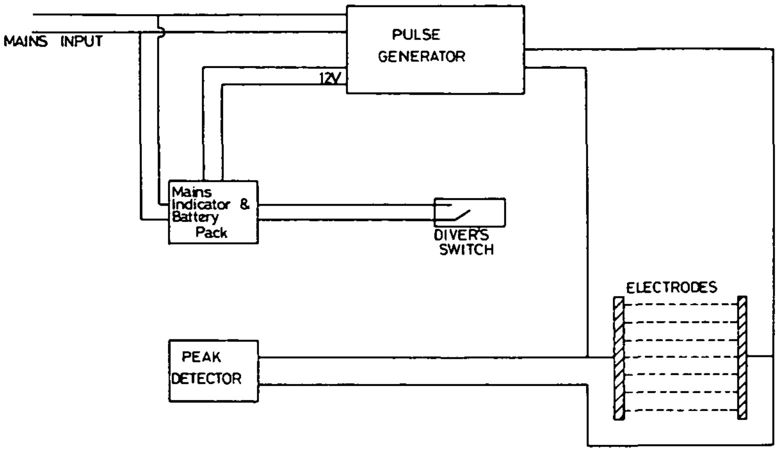

Figure 3. Schematic diagram of apparatus and interconnections for underwater experiments.

within their RMS rating and have proved satisfactory. When SCR1 conducts, current limiting is provided by the regulation of the mains input transformer and 1 kVA and 2 kVA rated units have been used. The pulse generator was housed in a steel cylinder 80 cm long and 40 cm in diameter, mounted on a buoyed frame for easy handling. The pulse pattern was selected by a switch mounted on the end plate.

Control equipment

A 12 V battery pack to supply the timing unit, a mains indicator, warning lights, and a peak detector to measure the electrode voltage were mounted in separate small housings with inspection windows. These housings were also mounted on the main frame. Separate mounting of the battery pack meant that it could be replaced without taking all the apparatus to the surface. A schematic diagram of the apparatus is presented in Figure 3. The diver controlled the unit with an on-off switch (in a PVC box) which applied 12 V to the main housing. The switch was spring-loaded so that it had to be held on.

Electrodes

The electrode material chosen was stainless steel (BSS 365). This has been found to suffer very little from corrosion in sea water, and the chemical action which does take place on the electrode surface does not significantly affect the passage of current (Stewart, 1973). Stainless steel warp (1 cm diameter) was used for the electrodes, linked to the pulse generator by heavy copper cable.

Operating experience

General

The equipment has been used in two experiments; to determine the reactions of burrowed *Nephrops norvegicus* to electric fields, and to investigate the reactions of flatfish to electric fields.

The divers conducting the tests experienced fewer problems than anticipated, and this was considered to be due to the fact that it was unexpectedly easy to tell whether or not the electrodes were energised. The passage of current into sea water causes electrolysis, and the gas bubbles generated at the electrodes were easily seen. At low frequencies the bursts of bubbles corresponding to individual pulses could be discerned. During operation the large current drain tended to reduce the supply voltage, and hence the brightness of the mains indicator light varied with

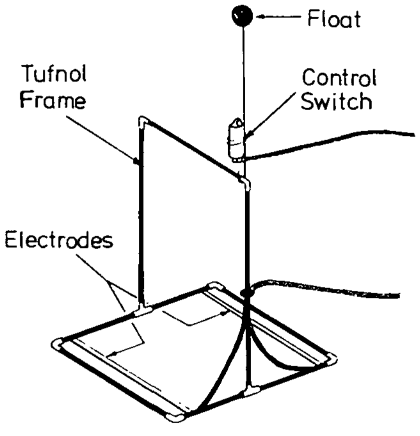

Figure 4. Electrode frame for *N. norvegicus* experiment.

the pulse generator output. This was clearly seen by the divers up to 10 m away. The flickering of the light and the generation of bubbles were always a definite indication that the electrodes were energised.

The divers conducting tests with this apparatus were dressed in neoprene wet suits and wore gloves of the same material. The only uncovered part of the body was the face around the mouthpiece. Wet suits are normally assumed to have little or no insulating value in electric fields and a simple test showed that the resistance through a wet glove was 20 Ω.

Experiments on *Nephrops norvegicus*

The objective of this investigation was to induce the animals to leave their burrows. *N. norvegicus* excavates extensive burrows on muddy ground and is rarely found at depths less than 30 m. The mud is thick and sticky with a finely divided surface layer. A site was found with a relatively dense colony in as little as 20 m. The site was surveyed and burrows marked out. The pulse generator was taken to a cluster of burrows and the electrode frame laid over a burrow. A diver then collected the control switch, hovered over the electrode frame, applied the stimulus and observed reactions. On completion of the test, power to the electrodes was switched off and the same diver moved the electrodes to another burrow and repeated the test procedure. Only one man at a time was responsible for moving the electrodes and operating the switch. Another diver hovered above the experimental area as a safety precaution, but did not handle the apparatus.

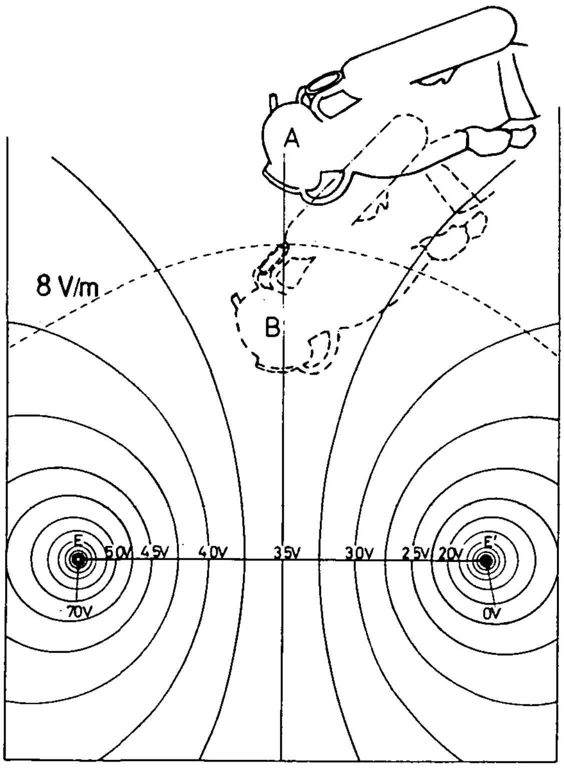

Figure 5. Equipotential lines in plane perpendicular to electrodes produced by applying 70 V.

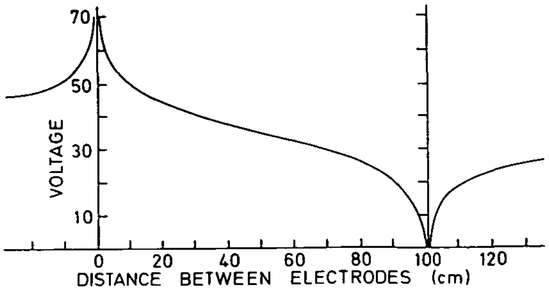

Figure 6. Potential variation along line EE′ in Figure 5.

The electrodes used in this experiment were two 1 m long pieces of 1 cm diameter stainless steel warp, mounted 1 m apart on an insulating Tufnol frame (see Fig. 4). This electrode array presented a load resistance of 0·3 Ω. The mud was found to have a resistivity close to that of sea water, and so would not distort the electric field. The calculated voltage distribution at the electrodes is shown in Figures 5 and 6. Figure 5 shows the equipotential lines in a plane at right angles to the electrodes at their mid point, and in Figure 6 the voltage distribution along the line EE′ in Figure 5 is plotted. In Figure 5 two possible positions of an observer are shown: A being the position frequently used, and B being the closest a diver has actually approached to the energised electrodes. The 8 V/m contour is also shown. For simplicity, the distortion of the field lines caused by the presence of the diver has been omitted.

Experiments on flat fish

This investigation was carried out to determine the effectiveness of an electric field as a "tickler", i.e. a stimulus which could induce the fish to rise off the bottom. Fish reactions were studied by towing a manned sledge, carrying a pulse generator and electrode array, over the bottom. Figure 7 is a schematic diagram of the apparatus as used in the experiment. The sledge was towed by a 5 m launch, and carried two divers lying side by side. One, acting

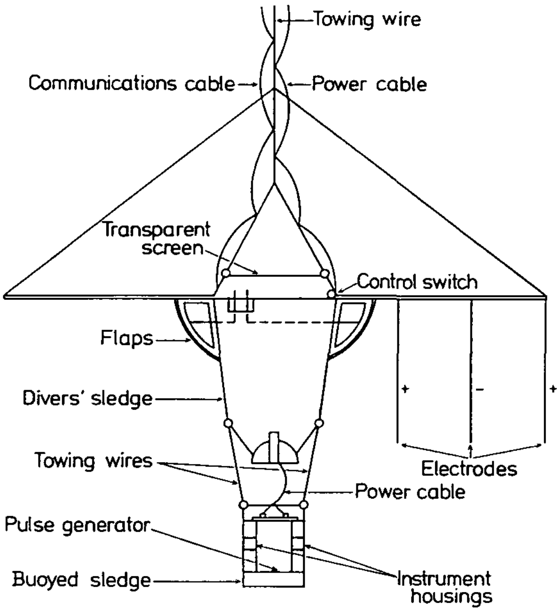

Figure 7. Schematic diagram of towed underwater sledge as used in flat fish experiments.

as pilot, operated the flaps and was in direct communication with the launch coxswain. The other, acting as observer, controlled the supply of energy to the electrodes and his descriptions of fish reactions were continuously tape recorded. The pilot held the sledge a few centimetres off the bottom giving a relatively smooth ride. The pulse generator was mounted on a separate smaller frame (the same one as was used in the *N. norvegicus* experiment) towed astern of the main sledge. This frame was again buoyed to reduce its weight and carried the instrument housings. Power was supplied from a generator in the launch via a cable lashed to the towing rope and to the frame on the underside of the manned sledge. The electrode array was made from the same 1 cm diameter stainless steel warp, and consisted of three parallel electrodes in contact with the bottom. The electrodes were attached, 1 m apart, to a polythene sheathed steel pipe, balanced by an identical pipe on the other side of the sledge. The pulse generator was controlled by the same 12 V system and the diver's PVC switch box was mounted at the front of the sledge where it could be operated only by the observer. Whilst the electrodes were energised both divers were on the sledge and thus remained in a fixed position relative to the electrodes. If the observer moved off the sledge he had to release the switch box thus de-energising the electrodes.

Safety considerations

Mole and Hudson (1971) have recently reviewed safety in the use of electrical equipment underwater. They define a safe electrical system as one in which the current likely to flow through a diver's body under the worst possible fault conditions is limited to less than the "let-go" current. The apparatus described above was designed to produce certain experimental conditions and was inherently dangerous.

The pulse generator output voltage and the power source voltage, if fully developed across a diver's body could induce currents of up to 150 mA and 450 mA respectively, to flow. These currents would almost certainly prove fatal.

The divers conducting these experiments were only at risk when they approached the energised apparatus; either the electrodes, the power cable, the pulse generator or the switch box. Two main areas of risk are apparent; the energised electrodes and equipment faults.

Electrodes

When the experiment was being planned the only firm information available on safe electric field strengths underwater was that obtained by Smoot and Bentel (1964). They observed that a field strength of 8 V/m at 60 Hz caused their experimental subjects to lose muscular control. An 8 V/m contour is sketched in Figure 5, and in the initial trials the divers treated this as the danger zone and positioned themselves about 5 m from the electrodes. To obtain a better view of events in the electrode area they slowly moved closer and reached position A in Figure 5 without experiencing any effects due to the electric field. One individual approached to position B without detecting the presence of an electric field. It was considered that to approach the electrodes so closely was unnecessarily hazardous, and the bar fitted to the top of the electrode frame ensured that the observers remained at a safe distance (see Fig. 4) even in conditions of poor visibility. It can be seen from Figure 6 that outside the electrodes the electric field strength falls rapidly. This was the position used for observation in the flat fish experiment.

No diver was aware of current passing through his body. The observations of Smoot and Bentel suggest that divers in positions A and B should have felt the presence of an electric field. They did not however, and this is probably due to two factors. Firstly, the diving suits could have afforded some protection, and secondly, the divers tended to lie along the equipotentials so that the net voltage developed across the body was low. The degree of protection offered by wet neoprene will be variable, and any diver conducting a series of tests should start about 5 m from the electrodes and then carefully move in to a suitable position for observation. Experience has shown that with up to 100 V applied to the electrodes, a useful limit would be 1½ times the electrode spacing.

In the *N. norvegicus* experiment the divers were required to move the electrode frame and pulse generator between test sites, and this was potentially more dangerous than the flat fish experiment in which the divers remained in fixed positions outside the high field zone. In the former experiment however, it was not necessary for a diver moving the electrode frame to touch the electrodes, as the frame could be lifted by the crossbar without the diver having to approach closer to the electrodes than 1·25 m. The divers were weighted so as to be slightly positively buoyant and had to hold on to the frame to stay down. By this means their legs were kept up and clear of the field. During the tests there was never any doubt about whether or not the electrodes were energised, and consequently moving the electrodes did not appear to be a hazardous procedure.

In a recent paper, Saila and Williams (1972) described experiments conducted in very shallow water on the behaviour of *Homarus americanus* in electric fields. In their experiments a human touched the electrode array energised at 38 V and 1·3 Hz and experienced muscular contractions, but was able to move away from the electrodes in the interval between pulses. This would be an unacceptable risk at 20 to 35 m.

Equipment faults

Short circuits caused by cable faults or water leaking into the housings would be detected by instruments on the surface and would cause the supply to trip out; a fail-safe condition for the diver. Should a cable be damaged in such a way that two conductors were bared to the sea water, the current caused to flow would generate bubbles, and consequently the unit and cabling were always inspected for the presence of bubbles before tests were begun.

The 12 V supply could not pass a lethal current through a human body, but partial short circuits between the 240 V, 50 Hz circuit, the 12 V circuit and the steel housing could be dangerous. With "floating" (unearthed) circuits, one inter-circuit fault will rarely create a complete current path, and a second fault is required before current can flow. Such faults could raise the potential of the pulse generator housing or the mechanism in the diver's switch to 240 V. It was necessary for the divers to approach the pulse generator to operate the pulse pattern selector switch and, in the *N. norvegicus* experiment, to move the unit. To eliminate risks the selector switch was operated only when the input power was switched off, and a rope sling was attached to the unit so that the diver could move it without coming within 2 m.

Since the on-off switch was the only piece of electrical equipment which was actually handled by the divers, an indirect method of switching (optical or acoustic) ought to improve the safety of the procedure by electrically and mechanically isolating the diver's switch from the pulse generator. The possibility of using an acoustic switch is being investigated. In these experiments an electrical switch was used, with several safety features. The switch was housed in a PVC box so that the diver could never be brought into a fault circuit; the switch was spring loaded so that it had to be held in the "on" position; the 12 V supply to the pulse generator was activated through a secondary relay, and neon bulbs were connected between the 240 V and 12 V lines so that they would be illuminated if the circuits became linked by a fault. More elaborate safety devices would not rule out every possibility of dangerous faults developing, and safety in the use of the apparatus was considered to be principally dependent upon strict adherence to a safe operating procedure.

The electric shock hazards associated with the pulse generator input could be eliminated by using a high frequency supply from the surface, as described by Mole. Based on a maximum dissipation of 20 W in the human body, at 40 kHz such a system would require to be either current limited at 100 mA or voltage limited at 100 V. Such a power source would however, greatly increase the cost, complexity and handling problems of the system.

If a battery powered generator was used, the supply cable and its associated risks would be eliminated, but at the cost of greatly increasing the size and weight of the unit, and requiring frequent manhandling to the shore for recharging. The hazard of a DC shock at 75 V would then exist but according to Dalziel and co-workers, DC currents in the human body are much less dangerous than 50 Hz currents. Neither of these changes would affect the form of the output, which is dictated by experimental conditions, and therefore has a lethal current capacity. Any pulse generator designed for this type of experiment will be hazardous for human operators and the operating procedure will necessarily be similar to that described above.

Conclusion

The apparatus and experimental procedures described have been found satisfactory in use. Divers in neoprene wet suits were able to approach to within 1 m of energised electrodes at 70 V potential difference, spaced 1 m apart, without experiencing electric shock. The safest position from which to observe an electrode array on the sea bed is from the side in line with the electrodes. If conditions require observation from above, e.g. on soft mud, the diver should be positively buoyant and not approach nearer than 1½ times the electrode spacing.

The use of high current capacity electrical equipment underwater is dangerous and diver safety depends upon the observation of a safe operating procedure. The procedure must ensure that the diver is either kept at a safe distance from energised apparatus, or that any apparatus which he has to handle is designed to be incapable of delivering a dangerous shock. Accidents are frequently the result of unexpected combinations of events, and consequently a diver must be prepared to terminate an experiment whenever conditions would, in his judgement, require him to bypass the safe procedure e.g. if visibility dropped to 1 m he would have to approach dangerously close to the electrodes to make observations. Experience has shown that it is possible to conduct safely underwater experiments with electric fields using a systematic test procedure which takes account of the hazards.

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