Paper read at the Royal Institution of Naval Architects, on Tuesday, 4 February, 1975

UTILIZATION OF ELECTRICAL POWER BY DIVERS

K. R. Haigh, C.Eng., F.I.E.E., F.I.Mech.E., M.I.E.R.E.*

Modern diving systems employ electrical power to an increasing amount in spite of the initial apparent dangers presented by the hazardous environments of sea water and oxygen-enriched atmospheres which exist. Physiological investigations have indicated the acceptable levels of electrical exposure which the human body can tolerate and thus criteria for the safe operation of equipment can be established. For personal use in diver electrical heating for example the current must be low voltage d.c. or high frequency a.c.; normal power frequencies are not acceptable.

Whilst in the water the electrical supplies to the diver for his own use and also for the operation of electrical tools must be protected by safety circuits including very sensitive earth leakage circuit breakers and continuous time sharing monitoring of multi-circuit devices. When employing tools with an earth return, such as in welding and cutting tasks, electrical field gradient detection devices have been suggested for automatic protection and interruption of the supply.

Out of the water the divers live in a pressurized environment breathing a mixture of oxygen and helium which can present a fire hazard, consequently every item must be flame and spark proof. Essential equipment in the environment is subject to unusual problems due to the abnormal conductivity and density of the breathing mixture; in some instances the equipment must be slowly decompressed to avoid the "bends" in a similar manner to the diver himself.

Currently, no code of practice exists for the use of electrical power in a diving environment but a committee has been established to investigate the problems.

INTRODUCTION

The mental picture of a diver working underwater with electrical power tools creates a feeling of apprehension in the minds of many engineers and laymen alike, suggesting that such tools are incongruous to the environment. It is generally felt that such an application would involve exposure to unwarranted risk of death from electrical shock but, nevertheless, there is only one case of a diving fatality from electrocution.[1]

Such a record is completely misleading as the use of electrical power underwater by divers has had very little application until recent years. It could be that previous generations of diving equipment designers were so scared of the application that they avoided the problem wherever possible by using other methods of power and application. Apart from such applications as shallow underwater electrical lighting, the first steps were taken in World War I to make use of electrical power in the field of underwater welding. This particular application is increasing in use and will continue to be used in spite of the fact that the diver holding, often in his bare hands, the comparatively unprotected circuit breaker of an earth return circuit, closes the circuit by striking an arc and in doing so invariably receives a mild electric shock.

The tremendous upsurge in interest in ocean technology in the last two decades has forced designers to face the problems of the use of electrical power underwater as in many instances no other alternative could be used. For well over a century the well known standard diving equipment of a copper helmet, canvas suit and lead-soled boots was in use throughout the world and is still in use in shallow water civil engineering works even today. This equipment was designed by Augustus Siebe and was first used in the salvage of *Royal George* at Spithead in 1840, the necessary breathing gas, in this case, compressed air, being supplied to the diver via an air hose from a mechanical bellows pump, the surplus air being exhausted to the water from the diver's helmet. In latter years submission to progress in the electrical field was the incorporation of a telephone connexion to the diver. As the depth of working became progressively deeper new forms of diving had to be devised and these brought with them physiological problems concerned with keeping the diver alive and at the same time bringing in their train additional hazards in the life support equipment.

Current diving techniques can be broken down into air diving, mixed gas bounce diving and saturation diving. Air diving is usually restricted to a depth of 50 m and includes the sports diver carrying compressed air bottles on his back, the copper helmetted diver together with modern variations of this technique and surface supplied equipment. Deeper than 50 m the nitrogen in air tends to become narcotic and has to be replaced by an inert gas, usually helium although some experimental dives have been carried out using argon, neon and even hydrogen. A mixture of helium and oxygen can be breathed to much greater depths without narcosis although another problem still remains in that the breathing gases are absorbed by the body tissue and bloodstream at a rate depending upon the product of the depth and the exposure, and unless the rate of ascent is strictly controlled the rate of diffusion of the gas out of solution can produce bubbles in the bloodstream which lodge in limb joints producing a phenomena known as "bends". In a bounce dive the time spent at depth is kept very short in order that the time taken in ascending can be kept within reasonable limits. For example, a bounce dive of 15 minutes to 130 m requires a decompression time of the order of 5 hours. In saturation diving the diver is exposed to the point where his bloodstream and body tissue are completely saturated with breathing gas and no matter how long he stays or how deep he goes no more gas can be taken up. At this point he suffers no additional penalty for his increased depth or exposure but from saturation at 300 m decompression times in the order of 10 days are in order.

* Officer in Charge, Admiralty Experimental Diving Unit, Portsmouth.

The equipment required for bounce and saturation diving are very similar in operation but because in saturation the divers can be in such a state for several weeks at a time, a suitable environment has to be provided for their existence. It is in the provision of this environment and in the support of the diver in the water that electrical power is now a necessity which cannot be avoided and which when investigated in detail and suitably applied is not the lethal villain first envisaged.

MODERN SATURATION DIVING SYSTEM

The method of operation of a modern diving system is diagrammatically shown in Fig. 1. The equipment can be mounted either on a fixed platform such as a drill rig or on a completely mobile diving support ship. The elements of the system consist of a pressure chamber complex one part of which can be sealed off and lowered to the sea bed. The divers enter the deck decompression chamber (DDC) through the manlock (ML) after which these two chambers are sealed and brought up to a pressure using the breathing mixture, equivalent to the depth of water in which the divers are going to work. When ready for diving the submerged compression chamber (SCC) is also brought up to pressure and the inter-connecting doors in the DDC and the SCC are opened. The divers transfer from the DDC to the SCC closing the inter-connecting doors so that the SCC can now be lifted from its mating position and lowered over the side of the vessel. On reaching the sea bed the pressure differential across the SCC is zero and the bottom door can therefore be opened without an inrush of water. The divers then exit to carry out their work task and on completion return to the SCC which is then hoisted back to the surface vessel to re-mate with the DDC after which the inter-connecting doors can be opened and the divers transfer to the DDC. All this has been carried out without the divers experiencing any change of pressure and the progress can be repeated any number of times. After the final return from the sea bed on the completion of a task the pressure in the DDC is gradually reduced over a period of several days to bring the divers back to atmospheric pressure, after which they can leave the chamber system.

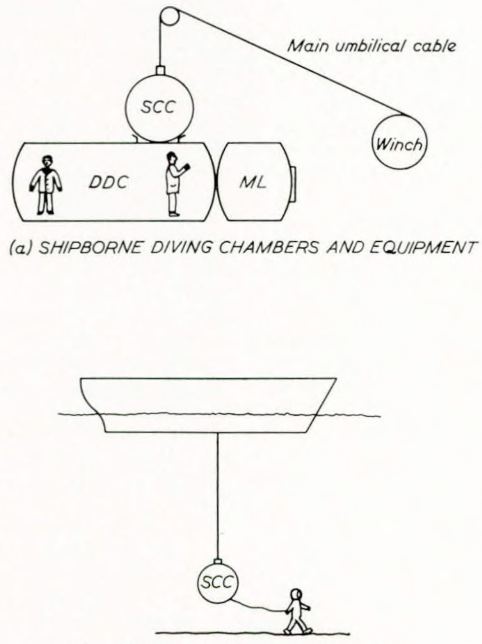

FIG. 1—(a) *and* (b)

In the process of this evolution the divers have been exposed to a number of hazards, first of all from the environment in which they were living in the deck decompression chamber and also when in the open sea as shown in Fig. 1(a), carrying out their work task. In the first instance the environment in the DDC is a fire hazard due to a high partial pressure of oxygen and in the second, whilst in the open sea they are exposed to electrical risks from the additional heat which must be supplied to them for physiological reasons, and from any electrical or electronic equipment directly concerned with their work task or environmental control.

Within any part of the chamber system the gas temperature must be kept very high in the order of 30°C with a variation of less than ± 1°C as when breathing a mixture of helium and oxygen the body loses heat at a rate seven times faster than breathing air and the divers are therefore very sensitive to very small changes in temperature. Even when the SCC is in the water its temperature must be maintained and this is achieved by the use of heating coils supplied with power down the main umbilical which as well as being a strain member contains gas supply hoses, power circuits, communication circuits, navigation circuits and medical monitoring circuits.

Whilst in the water the diver must be kept in thermal balance, i.e. he must be supplied with additional heat to counter-balance that being lost through skin radiation and expiratory heat loss. In deep dives the latter assumes greater importance than radiation loss and necessitates the inspired gas being heated in some manner. One method of supplying this additional heat is by the use of electrically heated undergarments and an electrical heater for the inspired gas. Recent work to minimize the added heat indicates the use of heat pipes between the expired and inspired gas circuits, and heat pumps to extract heat from the surrounding water as two possibilities.

A number of types of electrically heated undergarments have been produced involving electric blanket techniques with a heating element sewn into the fabric, the use of woven carbon cloth patches, the use of conducting polymer heat panels, the use of a fabric suit containing a pattern of plastic tubing filled with mercury to provide the electrically continuity and several other such devices. The main criticism with most of these is that they are inflexible or if they are flexible there is a danger of the electrical circuit breaking through the fabric and making a circuit contact with the body. In the case of the mercury-filled tube suit a severe flexing of the tube could break the electrical circuit and open the heating circuit.

HAZARDS FOR THE DIVER

Electrical Shock

The magnitude of the electric current flowing through the body determines the severity of the shock received. Dalziel[2] has shown that the threshold of perception of a current flowing varies with the electrical contact point with the body. The most sensitive region of the human body is the tongue, where a flow of 45 μA can be detected. Normally in a dry environment on shore the possibility of receiving an electrical shock through the tongue could be well nigh discounted but in the diving application of a mouth-held breathing apparatus with an inspired gas heater, the danger could be very real. Other parts of the body are much less sensitive, the hand for instance is unaware of any current flow below about 5 mA using d.c. and 1 mA using a.c. power frequencies. These figures are for males while the fairer sex are approximately one third more sensitive. Increasing the current flow above the threshold of perception induces a condition of muscular contraction which increases in severity until the muscle is so contracted that it cannot be voluntarily controlled. In the case of a hand-held electrode the subject can no longer release the electrode and he freezes to the circuit. The current value immediately before the freeze is known as the "Let Go" current. The value of this let go current takes on an added importance in the underwater field as in addition to the normal shock condition due to contact it is possible for the diver to be exposed to shock from an electrical field paralyzing his locomotion muscles and thus freezing him without any direct contact with an electrical circuit.

Dalziel and Lee[3] found from results obtained from 134 males and 28 females that the average let go current for 60 Hz supply were 16 mA and 10·5 mA respectively, (Fig. 2). It would be highly dangerous to use the average value of the let go current and for practical purposes a probability level of 1:200 has been used, in this case, 9 mA for male and 6 mA for female. Dalziel and Lee went on to show that the let go current is also frequency dependent as shown in Fig. 3. It will be seen that the common power frequencies are very poorly rated from the electrical shock point of view. In the case of d.c. the physiological conditions resulting from the passage of current are different to the a.c. case. Dalzie! and Massoglia[4] found that d.c. produced sensations of internal heating rather than muscular contraction. Sudden changes in current produced severe muscular contractions and interruptions of the current produced a very severe shock. It was found that the experiments were mainly a test of endurance rather than the let go limit. Fig. 4 shows the results from 28 men who had a mean release current of 73·7 mA.

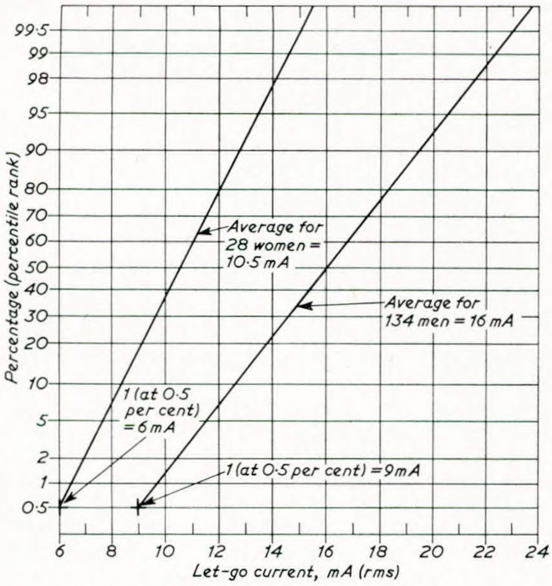

FIG. 2—*Let-go current at 60 Hz*

It is now generally accepted that the causes of death from electric shock are due to:

a) ventricular fibrillation;
b) respiratory inhibition;
c) cardiac arrest;
d) damage to the central nervous system;
e) deep burns with associated rise in body temperature;
f) serious burns.

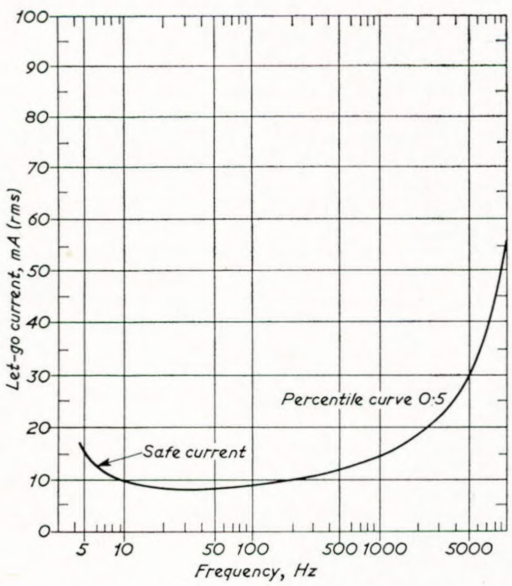

FIG. 3—*Effect of frequency on Let-go current*

Ventricular fibrillation is caused by disturbing the controlling impulses of the heart muscles creating uncoordinated contraction of these muscles and rendering the heart useless as a pump. Physical damage need not necessarily be caused to the heart but the rhythmic pumping action ceases and in consequence the brain is starved of oxygen and begins to die in 2-4 minutes after the supply of oxygenated blood is interrupted. This is the most dangerous and the most common of the electric shock hazards because once fibrillation has started it rarely stops spontaneously. It is interesting to note that one de-fibrillating technique consists of applying very strong short shocks to the heart. It has been shown[3] that the fibrillating current is proportional to body weight and inversely proportioned to the square root of the shock duration. Experimental work was carried out on a range of mammals and by extrapolation to man it is believed that ventricular fibrillation is unlikely if the shock intensity is less than $116/T$ mA where T is in seconds. Fig. 5 shows the relationship between average fibrillating current and the duration of the shock for a number of animals including man, derived by a number of workers. A considerable uncertainty exists because of the extrapolation, the large statistical variation between individuals and for short duration shock the time in the cardiac cycle has an effect of fibrillation. The shape of the curve of Dalziel and Lee[3] has been disputed by Biezelmeier and Rotter[5] who maintain that there is a sharp discontinuity at the pace rate of the heart. The International Electrotechnical Commission (IEC) favour another characteristic. TABLE I summaries the d.c. and a.c. effects of electric current on man.

Respiratory inhibition and cardiac arrest can occur when muscles in the region of the chest are subjected to current values in excess of the let go current causing muscular contraction of the respiratory and heart muscles.

If the current path contains the nerve centres controlling breathing, particularly the lower rear part of the brain, asphyxiation can result due to immobilization of the diaphragm. Removal of the current will not restart the respiratory system.

TABLE I[2]—QUANTITATIVE EFFECTS OF ELECTRIC CURRENT ON MAN

Effect	d.c.	60 Hz	10 k Hz
Perception threshold	5·2 mA	1·1 mA	12 mA
Shock—not painful and muscular control not lost	9 mA	1·8 mA	17 mA
Painful shock	62 mA	9·0 mA	55 mA
Let go threshold	76 mA	16·0 mA	75 mA
Severe shock muscular contractions	90 mA	23 mA	94 mA
Possible ventricular fibrillation from short shocks:			
Duration 0·03 secs	1300 mA	1000 mA	1100 mA
Duration 3·0 secs	500 mA	100 mA	500 mA
Ventricular fibrillation, certain death:			
Duration 0·03 secs	3575 mA	2750 mA	3025 mA
Duration 3·0 secs	1375 mA	275 mA	1375 mA

The magnitude of the electric shock received is dependent upon the body resistance and unfortunately divers work in the worst possible conditions for maintaining a high level of resistance. The body resistance is made up of two components, the skin resistance and the tissue resistance. Values have been quoted[6] of several thousand ohms for hard dry skin down to 500 ohms for wet hands. Tissue resistance is fairly constant of the order of 500 ohms between any two limbs. Three hundred ohms for shorter current pathways is possible whilst a figure as low as 100 ohms[6] between temples has been measured. All the foregoing measurements were made in a dry environment with the subject of the worst case standing in a bowl of water. Measurements made of a totally immersed diver[7] gave the following results:

TABLE II

Diver Configuration	Average Resistance value, ohms
Bare skin	65
Wet suit	210
Dry suit	310

The value of the skin resistance is determined by the protective power of the epidermis and if this is damaged by an electric burn the skin resistance drops dramatically. Currents of the let go level are more than sufficient to produce deep burns.

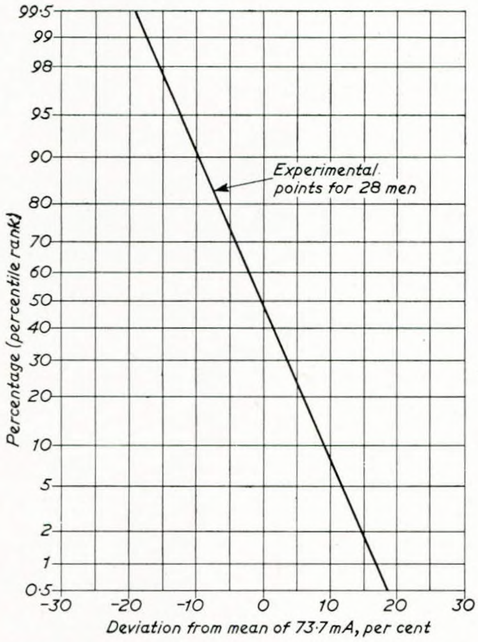

FIG. 4—*D.c. release current deviation curve*

Conditions for receiving an electric shock

In addition to the normal circumstances relating to receiving an electric shock by physical contact with live conductors, there is the additional hazard underwater of exposure to an electric field created by for example, welding apparatus or the breakdown of insulation. If two electrodes with a potential difference between them are placed in a sea water conducting medium a potential field is established between the electrodes with the current flow being dependent on the configuration of the electrodes, the field boundaries and the resistivity, in this case 22 ohm cm. Now if an object which has either a larger or smaller resistivity than the medium is placed in the electric field then it will distort that field and a diver, for example, exposing his hand to these conditions would suffer a current flow through his body depending upon his position and orientation relative to the live electrodes and also upon the type of diving suit he was wearing. A naked swimmer for example has one fifth the resistance of a diver in a dry suit.

Underwater, the circumstances in which a shock can be received by direct contact with a live circuit are enhanced by low body resistance and possible increased contact area unless precautions described later are taken. Even the best dry suit has been known to leak and if the wearer also happened to be wearing an electrically heated undergarment the potential hazard increases tremendously. One puncture of the insulation of the undergarment can provide a wide contact area to the body with a high resistance path to earth, In all probability the divers' hands will be exposed, or at the best encased in free flooding gloves providing a low resistance path to earth.

Design Criteria

Wherever possible the principles of inherently safe design practice should be employed, i.e. a design incapable of delivering a lethal electric shock under all adverse conditions. The term intrinsically safe design is deliberately not used as death can result from other factors, such as deep burns, as has been seen. Also now defined are certain design limits such as body current, frequency and acceptable length of the shock. By using normal a.c. power frequencies the maximum body current acceptable is 9 mA and therefore the use of power at shoreside voltages and frequencies is not feasible in an inherently safe design where the objective may be achieved either by the current or voltage limitation principles. In a current limited system, power is supplied from a constant current source where under fault conditions the maximum current cannot exceed the supply current which is made equal to the maximum safe current. In the constant voltage situation the maximum voltage applied to the water under fault conditions cannot exceed the supply voltage and this can be equated to the maximum safe current, given the divers' body resistance.

Mole[8] has shown that d.c. systems can be made inherently safe only for the transmission of small amounts of power, that is up to about 2·5 kW. Constant voltage d.c. systems can transmit power only over short distances, e.g. 1 kW over 50 m. A supply voltage of 30 V with a body resistance of 500 ohms producing the maximum safe current of 60 mA. Because of the high current needed to supply a useful amount of power, the main design problem is that of the volt drop in the cable. At the power level involved transmission efficiency is not important, so a substantial amount of power may be dissipated in the cable if necessary. It is easily proved that the smallest cable required to supply a given load is obtained when the power dissipated in the cable is equal to the power taken by the load, such cables being produced by extruding polyethylene insulation over an extruded conducting polyethylene core.

Constant current d.c. systems are capable of transmitting small amounts of power over distances of many kilometres. A high voltage is required in order to supply a useful amount of power, and a practicable design appears possible for the transmission of power up to 2·5 kW using a voltage up to $\pm$25 kV at a constant current of 60 mA. The distance over which the supply can be transmitted is determined by the risk of shock due to energy stored in the capacitance of the cable, the most severe condition arising when the conductor of the cable is assumed to have zero resistence on the whole of the stored energy may then be dissipated in the diver.

Using the maximum safe peak current the maximum safe capacitance can be calculated from

$$C(\text{farads}) = \frac{0{\cdot}054\, Rd}{V2}$$

where Rd = internal body resistance

For a cable working at 25 kV this gives a maximum safe length of about 350 m. For a cable having a resistance of 100 kilohms operating at 25 kV the maximum safe length is 9 km approximately. Mole also showed that high frequency constant voltage systems are possible to transport power up to about 100 kW over distances up to several kilometres. The difficulty here, however, is the generation of HF power.

It may not always be possible to provide power supplies that are inherently safe where the let go current can never be exceeded. In these circumstances protective devices incorporating circuit breakers with a current/value time characteristic within the limits indicated in Fig. 5 must be provided.

The designer of underwater power systems must aim to achieve the following conditions:

i) an inherently safe power supply;
ii) a system which requires two faults before dangerous conditions arise;
iii) early warning of possible fault conditions;
iv) protective devices with anti fibrillating characteristic;
v) a fail safe protection system.

The land practices of single and double insulation, and protective screens do not give the amount of basic protection required underwater; this can only be provided by using isolated floating supplies where a fault condition on one side of the supply does not necessarily give rise to a shock condition until the second fault develops.

Early warning of possible fault conditions can now be obtained from Line Insulation Monitoring (LIM) equipment where a low voltage d.c. supply is used to monitor the resistance between isolated lines and earth. Provided the connexions are made at an appropriate point, the insulation may be monitored whether the circuit is on or off and is equally useful on a.c. or d.c. lines. Continuous readout of the insulation resistance is provided and the circuit is broken when the resistence falls below a preset value.

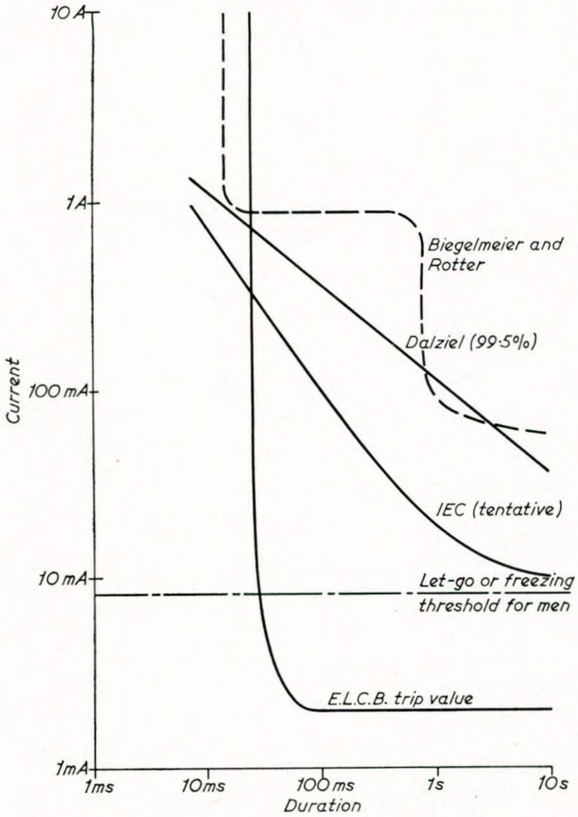

FIG. 5—*Fibrillation current for 60 Hz, sine wave*

It is clear that conventional fuses and circuit breakers do not possess either the time or current characteristics required to protect against ventricular fibrillation. The use of transistorized earth leakage circuit breakers (E.L.C.B.) does, however, offer acceptable characteristics where currents as low as 1 mA will interrupt the supply. Such a device is described by Dalziel[9] and is shown in Fig. 6. The operating characteristic of this type of equipment is shown superimposed on the fibrillation characteristics of Fig. 5. As long as the load circuit remains balanced the core of the differential transformer remains unmagnetized and the voltage of the secondary winding is zero. However, if any current flows to earth the magnetic balance is upset and a voltage appears across the secondary winding terminals. When this voltage reaches the switching voltage of the solid state switching device Q1, the circuit breaker is tripped by energy supplied from the control transformer.

A Practical Design

To illustrate the principles which have been expounded a practical design of a power supply for a diver heating system is shown in Fig. 7. A single phase 240 V supply is fed down the main umbilical cable to a transformer and rectifier situated in a pressure vessel not accessible to the diver. A smooth d.c. is used for the diver heating circuit. Line insulation monitors are connected to both the d.c. and a.c. feeds. The LIM's incorporate quick acting tripping mechanisms which operate when the resistance value falls below a preset level. The most important advantage of the system is that the first fault below the trip resistance level causes the circuit to be turned off, but this fault will not be lethal as it now simply defines earth for the floating system. In fact a fault could already exist above the trip resistance level (indicated but unnoticed) so that the maximum fault current that could flow after the second fault occurs, for a trip level R ohms, would be $240/R$ amps for a 240 V line. Assuming a discernible current of 3 mA by the diver this sets the trip level at 80 k ohms. The maximum d.c. monitoring current before tripping would then only be $18/80 = 0{\cdot}225$ mA. The operating time of the LIM relay contactor is 30 ms.

Electrical Problems of Underwater Welding

It is not proposed to enter into a discussion on the relative merits of the different types of underwater welding other than to observe that the majority of techniques require the striking of an electric arc either in a totally wet environment or in an underwater habitat with a high pressure gaseous environment from which the water has been forced out but which is still a highly conductive area. Striking the arc allows the whole of the current to flow directly to earth and at the same time establishes a field potential between the electrode tip and the object being worked upon. The previous design criteria laid down are thus seen to be difficult to apply in the case of welding equipment. Fortunately the instability of a.c. arcs has led to the almost universal use of d.c. arcs for the common forms of welding and a basic measure of protection is therefore provided. However, the ripple voltage may be of such a magnitude as to cause fibrillation. If the d.c. is obtained from a rectified single phase supply the ripple will be difficult to remove by passive smoothing circuits. However, if a three phase supply is used with multiphase rectifiers a low ripple content can be obtained.

From Fig. 3 it can be inferred that HF welding would be safer than d.c. but insufficient is known of this possible application.

Arc voltages of the order of 40-60 V are common but the open circuit voltage may be considerably higher. The use of arc plasma cutting underwater will require voltages very much higher in the order of 500 V at 1000A. Such conditions will produce dangerous potential fields and automatic detection of these fields will be required. One method which has been suggested is the fitting of monitoring electrodes to various parts of the diver's suit so that on entering a potentially dangerous field the monitor initiates an alarm circuit and finally breaks the supply.

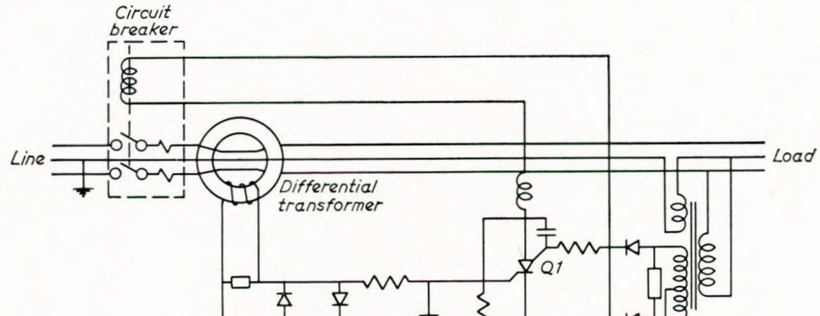

FIG. 6—*High speed tripping current*

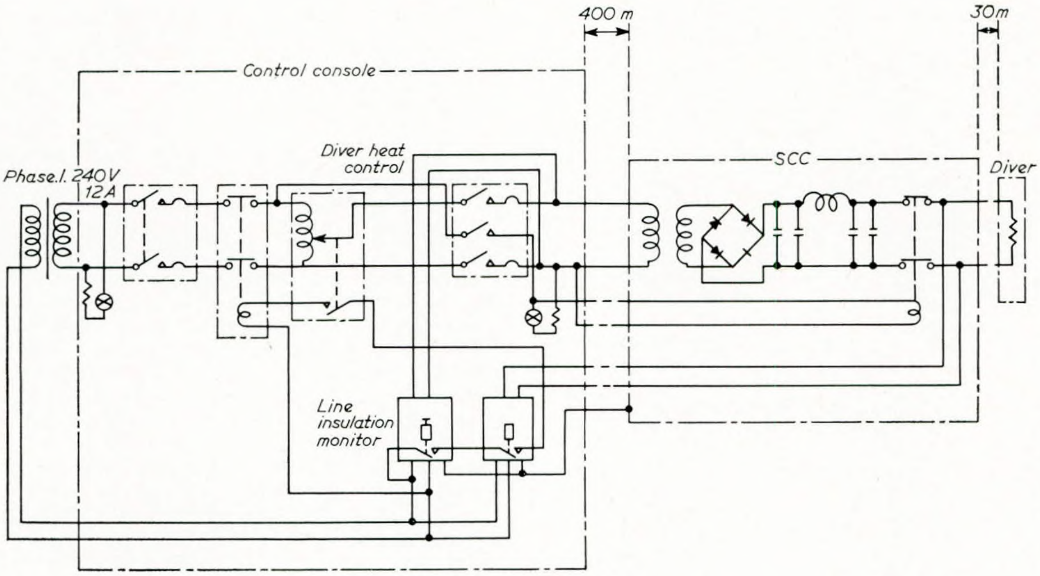

FIG. 7—*Diver heating circuit*

FIRE HAZARDS

Happily, the incidence of fires in diving chambers is low as a great deal has been learnt from the fatalities which have occurred. In a normal environment the first essential is to remove any humans from the area of the fire; in a diving situation this is virtually impossible if they are undergoing decompression. Any crash return to atmospheric pressure would result in a massive embolism with certain death. In practice, a chamber fire spreads so rapidly as virtually to eliminate any human intervention. In one incident it was calculated that the inside temperature reached 450°C within 14 seconds. With such hazards it is vital that every possible precaution against fire should be taken.

Any fire, no matter where it is, requires three things:

1) a source of ignition;
2) a fuel;
3) an atmosphere to support combustion.

Electrical sources of ignition are arcs, including electrostatic ones resulting from friction and hot surfaces. Other complementary sources are sparks caused by mechanical impact, frictional heat sources such as rogue solids propelled in a gas supply system, adiabatic compression, resonance ignition created by a rise in gas temperature in dead end cavities in a gas supply system when subjected to shock waves, and spontaneous ignition of metal films under rapid rupture.

It is very easy to create an oxygen enriched atmosphere in a diving system. Using compressed air a chamber system operating at 10 m contains twice as much oxygen as at the surface so dangerous conditions exist immediately.

The gaseous environment of the compression chamber system must be kept under strict control at all times to ensure that it does not infringe the acceptable physiological limits. A lower level of partial pressure of oxygen (pO_2) of 0·2 bar is required whilst the upper limit is set by the expected length of the exposure. For saturation diving an upper limit of 0·6 bar pO_2 is set to avoid the possibilities of chronic oxygen poisoning (lung damage), but for shorter exposure times a pO_2 of up to 1·75 bar is permissible; above this value there is the danger of acute oxygen poisoning (epileptiform fits). Under certain stages of decompression the divers may be breathing pure O_2 from a mask in which case the expired breath should be dumped outside the DDC if the pO_2 of the chamber environment is not to rise very quickly.

In general, at a given pressure the minimum ignition energy varies inversely with the change in volume percent oxygen. For a fixed percent oxygen content the minimum ignition varies inversely with the change in pressure. Depending on the particular combustible there exists a minimum oxygen concentration and a minimum pressure below which ignition from a practical standpoint is not possible. An increase in environmental temperature reduces the minimum ignition energy requirements and enhances the possibility of autoignition[10]. The presence of nitrogen or helium molecules provides a physical obstacle to the effective interaction of a fuel and oxygen molecule and with sufficient inert gas dilution the atmosphere can be rendered incapable of supporting combustion.

Any material taken inside a diving chamber may be considered a potential fuel as under oxygen enriched conditions practically anything will burn to some degree. Materials which smoulder with difficulty in air burn with ferocity with added oxygen. In the electrical field cable and wire insulation are examples; Teflon which will not burn in a normal air environment will burn under pressure with added oxygen, similarly with polythene. Even stainless steel will burn in pure oxygen. In addition to the fire hazard there is the problem of toxic gases given off by insulation at high temperature levels even if the material is not burning; it only requires a few parts per million contaminent of some of the exotic gases to prove fatal.

An investigation into the region of non-combustion in nitrogen/oxygen and helium/oxygen diving atmospheres has been carried out[11] and is summarized in Figs. 8 and 9. The information relates to the combustion of vertical paper strips upon which the physiological diving limits have been superimposed. From these figures it can be seen that the fire hazard is not always present, particularly in the deep saturation dive. The greatest hazard is near the surface especially when diving on compressed air.

Electrical Equipment for Diving Chambers

The first requirement for the designer is to remove so far as is possible all sources of fuel and ignition. No undue problems are experienced here as with ingenuity only a very small amount of electrical equipment need be taken into the hazardous environment. Communications equipment is a vital link which does entail electronics in the chamber system. Some hyperbaric chamber systems used for diving research incorporate a degree of electro-medical equipment. Removal of carbon dioxide in the chamber environment is sometimes accomplished internally by circulating with fan assistance, the gas through a canister containing soda lime. The fan can be electrically driven in which case it should be able to withstand the stalling current for long periods without overheating and should be completely flameproof. One instance has occurred of a stalled fan igniting a fire in which there were two fatalities. Currents trends are towards compressed air driven fans on a closed circuit, or removal of the CO_2 externally to the chamber system.

The submerged compression chamber inevitably contains more electrical equipment than the deck decompression chambers, but from Fig. 9 it can be seen that the SCC usually operates in a region of non-combustion; however, there still remains the danger of toxic gases from over-heated equipment.

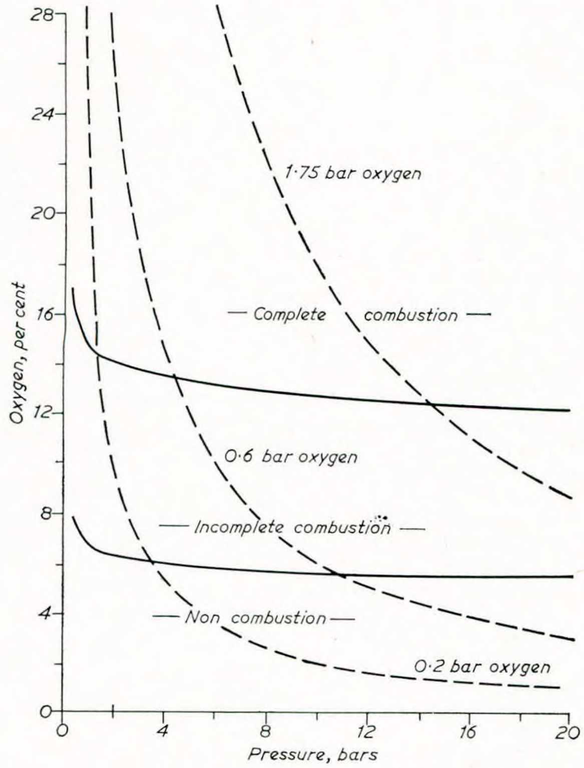

FIG. 8—*Combustion zones for vertical paper strips in* O_2—N_2 *(Adapted from Ref. 11)*

There are two additional criteria to be taken into account by the engineer when designing equipment for use in diving chambers. Firstly, helium conducts heat seven times faster than air and therefore it may be possible to either overrun equipment or make it smaller, and secondly, helium has the property of permeating most conventional types of seals including those used on the glass envelopes of thermionic devices. Components containing voids should be avoided where feasible as the void will invariably become filled with helium. On decompression the gas may not be able to escape in step with the main chamber system and an explosion results possibly at the time of most danger. Particular care should be taken if a piece of equipment is passed through a gas lock in case an explosion results. The danger of explosion from a pressure differential can be avoided by careful selection and testing of components.

Equipment which has to be used inside diving chambers should be designed using the principles of intrinsic safety. Unlike the case of electrical shock there is no secondary danger and the term "intrinsic safety" is applicable, i.e. the design of the equipment must be incapable of producing a spark of sufficient energy which can ignite any flammable material present. Much of the consideration applicable to protection from electrical shock is directly applicable to protection from fire hazards; current limitation in amplitude and time is implicit. The use of Zenner barriers is increasing; a simple protection circuit for a loudspeaker is shown in Fig. 10.

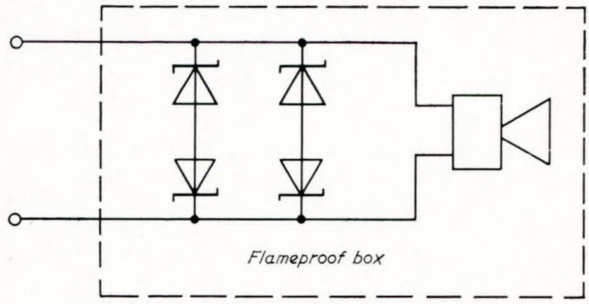

FIG. 10—*Intrinsically safe loudspeaker*

CODES OF PRACTICE

Currently no code of practice exists for the design of diving equipment. A great deal of work on safety in inflammable atmospheres has been carried out by such bodies as the Safety in Mines Research Establishment and the Fire Research Establishment but none of this work has been carried out at pressures above 1 bar, or in oxygen enriched environments. The construction and testing of flameproof enclosures of electrical apparatus is covered by BS. 4683 Part 2 but here again, the special problems of a diving environment are not covered. Likewise, with the Department of Industry's BASEEFA Certification Standard SFA. 3012—1972 Intrinsic Safety.

In the field of protection from electrical shock there are a number of standards and codes of practice available but all are applicable to dry land application. Perhaps the closest approach to a standard acceptable to the diving industry

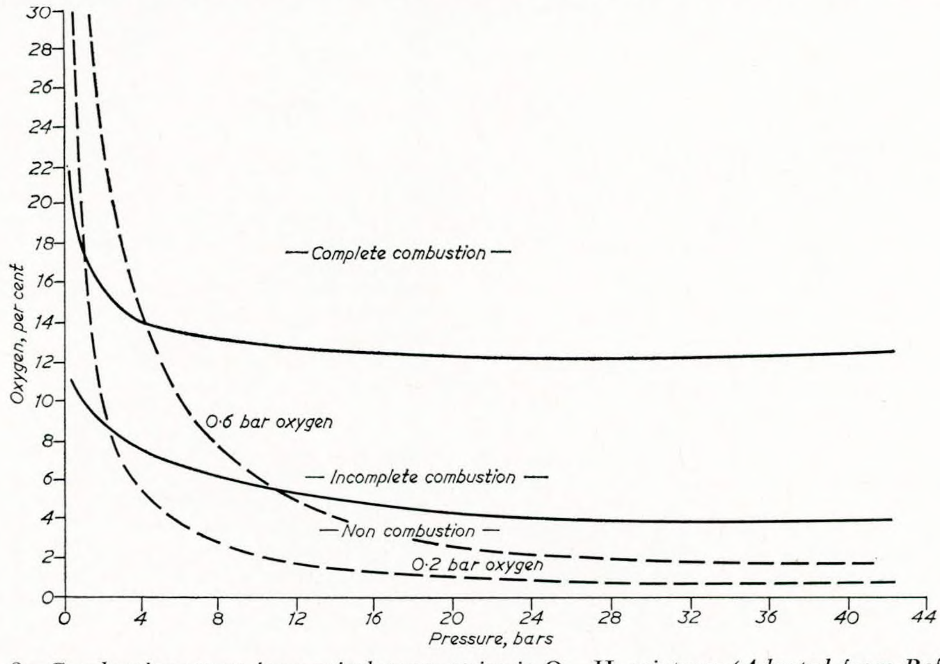

FIG. 9—*Combustion zones for vertical paper strips in* O_2—H_e *mixtures (Adapted from Ref. 11)*

would be that issued by the Department of Health, Safety in Hospitals (Hospital Technical Memorandum No. 8—Safety Code for Electro-Medical Apparatus).

It is to be hoped that the present lack of a code of practice will be filled by work now in hand. In 1970 the Admiralty Experimental Diving Unit placed a contract with the Electrical Research Association for an investigation into electrical safety underwater; from this original investigation has arisen the formation of a committee, under the chairmanship of the author and contains representatives of ERA, IEE, BSI, Factory Inspectorate, RNPL, RARDE and the Department of Occupational Health, University of Manchester. The committee is responsible for establishing investigation into particular problems of electrical equipment underwater and monitoring their progress; finance for the investigation is provided by the Ship and Marine Technology Requirements Board of the Department of Industry. The aim of the committee is to establish a code of practice for diving electrical equipment which will exist in its own right or be incorporated in the code now being prepared by the BSI CVCP/13 Committee on Underwater Working.

ACKNOWLEDGEMENTS

Certain sections of this paper reflect the deliberations of members of the Committee on Underwater Electrical Safety under the chairmanship of the author and acknowledgement to these members is made, particularly to Dr. G. H. Mole of ERA. The original work on electric shock was funded by the Ministry of Defence and continues with finance provided by the S.M.T.R.B. of the Department of Industry. Permission to publish this paper was given by the Director, Admiralty Underwater Weapons Establishment.

REFERENCES

1) Harter, J. V. and Bornmann, R. C., 1968. "Diving Accidents not Involving Decompression". *J. of Ocean Technology*, Vol. 2, No. 4, pp. 139–143, Oct.
2) Dalziel, C. F., 1956. "Effects of Electric Shock on Man." IRE Trans on Medical Electronics, *PGME-5*, pp. 44–62, May.
3) Dalziel, C. F. and Lee, W. R., 1969. "Lethal Electric Currents." *IEEE Spectrum*, Vol. 6, No. 2, pp. 44–50, Feb.
4) Dalziel, C. F. and Massoglia, F. P., 1956. "Let-Go currents and Voltages." *Trans AIEE*, Part II, Application and Industry, Vol. 75, pp. 49–56, May.
5) Biegelmeier, G. and Rotter, K., 1971. "Electrical Resistences and Currents in the Human Body." Elektrotech. u. Maschinenbau Vol. 88, pp. 104–114, March.
6) Lee, W. R., 1966. "Death from Electric Shock." *Proc IEE* Vol. 133, No. 1, Jan.
7) Bridge, J. F., Glasgow, J. S. *et al.*, 1969. "Comparative Insulation Study of Wet Suits and Standard Navy Deep-Sea Diving Dress for Underwater Welding." Battelle Memorial Institute.
8) Mole, G., 1970. "Intrinsically-safe Underwater Electric Power." *ERA CSA/70/9*, Dec.
9) Dalziel, C. F., 1970. "Transistorized ground fault interrupter reduces shock hazards." *IEEE Spectrum*, 1970, pp. 55–62, Jan.
10) Botieri, P. B., 1967. "Fire Protection for Oxygen Enriched Atmosphere Applications." *Proc. of Fire Hazards and Extinguishment Conference* DDC No. AMO-TR-67-2.
11) Cook, A. G., *et al.* "The Region of Noncombustion in Nitrogen-Oxygen and Helium-Oxygen Diving Atmospheres." Union Carbide Corporation.

Discussion

Dr. G. Mole said that members were fortunate in having the opportunity to discuss a subject which brought together the interests of the M.O.D.—which he preferred to call the Admiralty—and of the underwater industry. There was a danger that technologists already perfected by the former body would have to be rediscovered by the latter. In fairness it should be said, however, that the Admiralty was now very willing to put its experience at the disposal of industry and to collaborate in fields of activity which were of common interest. The paper just presented by Mr. Haigh showed that this policy was being implemented without reserve in at least one field.

The subject of diver safety was a topical one in view of the very high fatality rate for divers in the North Sea. There was at present no evidence on which to estimate the risk from electric power, but this was because reliable statistics were not available, and because there was a tendency to avoid the use of electric power wherever possible; nevertheless, the tasks of the diver could be eased and his environment could be greatly improved by the use of electric power; hence it must be made safe.

This point of view was recognized by the Underwater Engineering Group and by the Department of Industry, both of whom had joined the Admiralty in supporting the investigations at present in progress and in setting up the committee mentioned in the penultimate paragraph of the paper. The overall objective was to produce a code of practice on electrical safety for divers but this would inevitably take some time, so there were some short-term objectives too.

The principal short-term objective was to produce a specification for earth leakage circuit breakers and to issue recommendations which would ensure that they were properly used. In the longer term there was a project to develop a fail-safe protection system that would provide better protection than was possible from earth leakage circuit breakers. The possibilities of inherently-safe supply systems were also being investigated, and in addition it was expected that attention could be turned to safety problems connected with underwater arc welding.

Turning to some of the more urgent problems involved: as indicated in the paper, the earth leakage circuit breaker offered the promise of a safe supply from the a.c. mains by a method which was well substantiated by overland practice. Sensitive earth leakage circuit breakers were available which ensured that no shock current greater than a few milliamperes could persist for longer than a fraction of a second. This was well below the maximum safe current level.

However, because they were electromechanical devices, earth leakage circuit breakers took about 25 ms to cut off the supply. This meant that they were unable to provide any protection during the first 25 ms of the shock. It was of no consequence in the overland situation, for high body resistance (greater than 1000 ohms) limited the shock current to a value that was safe for a period of 25 ms. In the underwater situation, the diver's body resistance was much lower (Mr. Haigh had quoted values ranging from 310 ohms down to 65 ohms). It therefore became necessary to reduce the supply voltage in order to ensure that the maximum safe current level was not exceeded.

Fig. 11 represented the relation between the shock current and the maximum safe duration. The curve normally used in overland practice was the Dalziel characteristic. This was valid for 50 to 60 Hz a.c. and represented the maximum safe current for 99·5 per cent of the population, and for individuals with a minimum body weight of 50 kilograms. At the present time the International Electrotechnical Commission had a Working Group considering these problems, and had already issued recommendations, such as Publication 479:1974. The IEC curves were also shown in this figure. The fibrillation curve was roughly the same as Dalziel's characteristic, but the IEC also gave a "no danger" curve. This was below the fibrilla-

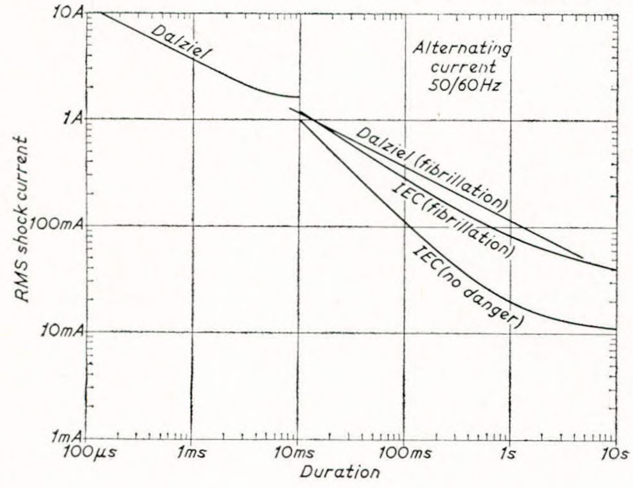

FIG. 11

tion curve because there was a danger of asphyxiation for prolonged shock duration at current levels below the fibrillation level. In Dr. Mole's opinion this curve should be taken as the characteristic relating to divers.

For the 25 ms duration of shock associated with an earth leakage circuit breaker, the maximum tolerable shock current came to about 0·4 amps. Taking Mr. Haigh's figure of 210 ohms as the resistance of a diver in a wet suit, the maximum safe voltage would be 84 V. In practice a somewhat lower value would have to be adopted to allow for unknown factors, but a 110 V earthed centre-tap single-phase supply would appear to be satisfactory, so giving a voltage to the water of 55 V which tied in with the figure mentioned by the Chairman in his introductory remarks. It was also possible to use a three-phase supply, and it would then be necessary to adopt a 110 V three-phase supply with earthed neutral, and in that case the voltage to the water would be 65 V—not very different from the previous figure.

Using these values, it appeared to be practicable to provide a supply which would be useful for many applications, but there was a difficulty. Taking Mr. Haigh's figure of 65 ohms for the resistance of a bare-skin diver, the situation became much less satisfactory, because the maximum safe voltage for 25 ms would then appear to be only 26 V, and would be even lower after applying a safety factor. At this point it was necessary to consider what was meant by the resistance of a bare-skin diver. In the overland situation, where current passed from hand to hand or from hand to foot, the body could be treated as a lumped resistance. In the water there was a three-dimensional field problem. This meant that the relation between the body current and the applied voltage could not be determined by a single resistance value but would depend on the contact areas and the route by which the current entered and left the body. Another factor which came into consideration here was the fraction of the total current passing through the heart, which would also depend on the route by which the current entered and left the body.

A German investigator had attacked the latter problem by taking the potential gradient across the heart as the criterion of fibrillation. He had determined the relation between this potential gradient and the total current for various current paths through the body. While this was a useful guide, it did not provide a complete solution, for what was really needed was a relation between the potential gradient across the heart and the voltage applied to the body, so there were some uncertainties still to be cleared up.

The earth leakage circuit breaker had two major weaknesses and a third which perhaps was not so serious. The first weakness was that, because of the necessity to limit the supply voltage, this put a limit on the amount of power available. The second weakness was that it was not a fail safe device. In other words, if the earth leakage circuit breaker failed to operate in these 25 ms, a dangerous shock could be received. The third weakness was that the earth leakage circuit breaker did not prevent one from getting a shock. The line insulation monitor mentioned by Mr. Haigh was a device which overcame this weakness, because it detected a failure of insulation before a shock could be received.

The fail safe protection system under development used solid state circuitry, and the major advantage of this system would be a reduction in shock duration by a more rapid interruption of the supply. For example, thinking in terms of a switch-off in 1 ms, this would raise the maximum safe current to nearly 3 amperes, as could be seen from the figure. The result was that there should be no problem in providing effective protection on supplies operating on 240 V single-phase or 415 V three-phase. This meant that it would be possible to take as much power as might be needed.

Some work was also being done on inherently safe systems but this was regarded as a longer term matter, the problems involved being more fundamental. There were two methods. One was to use direct current. In this case they were limited to about 2·5 kW. Another limitation was that, if one relied entirely upon the inherently safe characteristic, it involved a shock at the "let go" level. This was not really tolerable, so it was necessary to put in a primary protection system which would operate in the majority of cases and prevent a shock from occurring. If the primary protection system failed one fell back on the inherently safe characteristic. With high-frequency systems this limitation did not occur but there were problems of transmitting and controlling high-frequency power which had to be solved before a satisfactory system could be produced.

Finally, Dr. Mole pleaded for a cautious approach on protection against shock from divers' suit heaters. There were two reasons for this. One was that the body resistance from chest to back or across the chest could be very low. This meant that a low voltage could produce a high body current. The second reason was that if current entered the body at the chest, a large fraction of it could pass through the heart.

MR. W. F. TAYLOR said that his company made divers' breathing gear and heated suits.

The author had referred to the need to limit the temperature variation in the chambers to $\pm 1^\circ C$. These seemed to be extremely tight limits and although the conductivity of helium was seven times greater than air, it would require considerable gas circulation in the chamber to maintain these limits.

On the subject of electrically heated suits, fault finding or malfunction was dependent on "earth leakage circuit breakers" and "line insulation monitors". He asked the author if he could say how reliable these were, and did they always "fail safe" if they themselves had a failure?

With regard to the partial oxygen pressure in the chamber, the author had limited it to a figure of 0·6. If the diver was using a semi-closed circuit set on an umbilical supply and working at maximum oxygen consumption of 3 litres per minute, he would have to be supplied with a different gas from that in the chamber. Did that present any difficulties?

Finally, he asked whether the author had any idea if the use of Velcro fasteners presented any fire hazard.

MR. H. W. TURNER said that, with Dr. Mole, he had been working on a number of topics which were involved with this question of shock hazard, principally on the project that Dr. Mole had mentioned concerning the protection of divers underwater. He was also concerned with hazards in swimming pools, where the problems were of a similar nature. People had had electrocution problems from underwater lighting in the United States, where they used 110 V. There were other electrical problems associated with larger power underwater which did not involve divers. As Dr. Mole had indicated, there were possible devices of a fail safe nature which could operate very fast indeed, and it seemed likely that a second generation of these could be made to operate so rapidly that no sensation of shock would be felt in the event of passage of electric current through the diver. This would be of some value where the diver was in such a situation that the physical reaction of receiving the shock could cause him to injure himself by leaping back and striking sharp edges, etc. In the course of this work Mr. Turner had had to write to a range of people in the industry with a questionnaire asking them, among other things, about their experience of electrical use underwater and their ideas about it. From the replies he had received, and from the subsequent contacts and correspondence, he had gained the impression that there was a considerable desire for an extensive use of electric power underwater because of its extreme flexibility and the wide range of tools both in the form of portable hand tools and also more powerful equipment of a static or mobile type which would then become available to divers and which could be used underwater, once this problem of electrical shock could be satisfactorily solved.

Mr. Haigh might care to speculate on the apparent situation that there would be a considerable expansion of the underwater use of electrical tools once this shock problem had been satisfactorily settled.

Mr. D. Seigne, M.I.Mar.E., said that, although not directly involved with Mr. Haigh's work, he was particularly interested, in that the paper gave quantitative figures of current, rather than "airy-fairy" voltages such as had been discussed in the past. With regard to electrical calculations, when wishing to find out the sort of damage that could occur in a power circuit during a fault, electrical engineers talked about "let through" values and about the current squared × the time. This was related to the damage that could be done during a fault, and it was interesting that one of the curves shown bore this out for electric shock as well. There was a time factor to take into account, as well as a frequency factor—which very strongly backed up the case for research.

With regard to shock time: it was interesting to learn that work was being done by Dr. Mole of the E.R.A. on the question of the cutting off of the power. With modern electronics it should be possible to have a completely fail-safe circuit. One need not depend on electronics to protect in the normal overcurrent trip sense; rather, one was depending on the working of the electronics to let the power through, so that if there were any fault the electronics would fail-safe. This seemed to be the right way to work.

Mr. Seigne was glad there had been talk of inherent safety, for intrinsic safety had a quite different connotation in regard to flammable atmospheres where ignition sources were quite taboo.

With regard to Fig. 10 of the paper he was not quite sure whether the loudspeaker was meant to be outside the box. He thought there was meant to be a Zenner barrier technique for intrinsic safety, with only the barriers in a flameproof box.

Coupled with the intrinsic safety question, could Dr. Mole or Mr. Haigh give any information on the explosion protection techniques used? Electrical equipment was normally certified for particular types of gases at normal standard temperatures and pressures and he would like to know of the effect where these might be varied. In the curves shown it could be seen that the flammability went up. What effect did this have on the actual ignition source?

He wondered particularly why the use of electrical energy was favoured for divers' suits. Was it merely that those concerned did not want to have trailing "water cables" as well as wires, or was there some particular reason? It seemed that for such an application it would be safer to use hot water, warmed electrically if desired.

Mr. R. Morton said that Mr. Haigh had stated that the inherent resistance of different persons varied. This must, he thought, mean some selectivity in regard to personnel. Was it possible to discover which personnel would be suitable and which would not? What tests, if any, were there?

Correspondence

Mr. D. J. Peddie wrote that he had studied the paper and wished to ask two questions:

In discussing ventricular fibrillation due to the ripple voltage associated with underwater welding equipment, the author appeared to be considering equipment in which conversion to d.c. was achieved by using rectifier diodes, and voltage regulation by using series a.c. reactance. Was this the case?

There were applications where control over the welding current was required, this being achieved by using phase controlled rectification. When phase controlled multiphase rectification was used, considerable voltage ripple was present, the magnitude of the ripple voltage being dependent on the phase conduction angle. The maximum peak-to-peak ripple voltage and the ripple frequency were dependent on the number of phases used. In a 3 phase six pulse system the peak-to-peak ripple voltage at low values of d.c. output voltage was considerable, approaching the peak value of the a.c. supply voltage as the mean output voltage tended to zero. Did the existence of this considerable ripple voltage preclude the use of phase controlled rectification techniques for underwater welding?

Mr. P. J. Cornish wrote to say that in 1974 he had led an expedition to Norway to attempt to locate the British midget submarine X5 which attacked *Tirpitz* in September 1943. The expedition had had the use, together with skilled operators, of a Side Scan Sonar Unit from the Ministry of Defence, a Protonmagnetometer, and the use of a Decca Sea-Fix Navigational System. The shattered wreckage of an X-craft was located on the sea-bed of Kaafjord and the intention was to go back in 1975, remove this wreckage and bring it back to the United Kingdom.

This purely amateur expedition, operating with very limited resources, had been trying to develop the use of underwater floodlighting in order to:

a) see clearly on the bottom at 140 to 150 ft (42 m to 45 m);
b) take 16 mm colour cine photographs of the wreckage.

It was to this end that the expedition was particularly interested in developing reliable underwater floodlighting of a suitable light temperature to achieve these ends. It was also hoped that underwater television could be taken on the proposed 1975 expedition.

Mr. Cornish wondered if the author had any experience in these two fields since, to date, it had not been possible to gather much direct evidence and any help which could be given would be more than welcome.

Author's Reply

MR. HAIGH said, in answer to Mr. Morton, body resistance did not vary significantly from individual to individual, but one could get situations where the body resistance varied tremendously in the same person, depending upon where it was measured and the contact area. The result measured between the hands was completely different from that between back and chest. The variations in comparison paths did not alter from person to person. They were reasonably stable, but the multiplicity of paths encountered in the diving condition was enormous. There could be a small path between minor parts of the body due to a water leak through a suit which might only involve an inch or two of the body. It was very difficult to quote really accurate figures for body resistance because there was such a variation, depending on the path within any particular individual.

There was no question of selection of individuals to produce a high body resistance; he only wished it were possible.

With regard to Mr Seigne's point about certification, he felt that this was bound to come eventually. At the moment there was no legislation for any of this work, but there was a committee sitting now on the legislation for this implementation. He believed that certification of diving equipment was coming. At the moment the various standards quoted for flameproof containers were followed, but again they were only for one atmosphere. What happened when these were used in oxygen enriched atmospheres was something to be investigated.

Mr Turner had asked him to speculate on the use of tools if all these problems were overcome. There would he agreed, be an "explosion". At the moment the diving industry was scared stiff of using electrical power under water. Once it could be demonstrated that methods of protection could be provided he was sure the industry would start making demand for tools to do all sorts of things.

With regard to the temperature variation, when the divers were living in the chambers for a month at a time they complained if the temperature varied by half a degree. It only required a range of about 1 to 1·5°C to go from what they called shivering to being too hot. The temperature had to be kept within that close tolerance. This was not too easy when the diving chamber was in the water.

Similarly, when the diver was in the water he must be supplied with the amount of heat he lost, and kept in thermal balance. Surgeon-Commodore Rawlins was an expert on this and could speak about thermal balance.

With regard to the partial pressure of oxygen, there was no difficulty in supplying the diver with a separate supply, but really it was not necessary, even though the percentage of oxygen was very low; he could still get an uptake of 3 litres from that very low percentage. He could breathe the atmosphere in the submerged compression chamber, and in the push/pull system the SCC atmosphere was taken, compressed additionally, and fed straight out of the diver. The exhaled gas was then sucked back from him, scrubbed, and returned to the chamber. As long as the diver could get 3 litres of oxygen or so the percentage was not desperately important.

With regard to fault finding, Dr. Mole had said that the ELCBs were not fail safe and that one had to suffer a shock to start with; the E.L.C.B. was supposed to cut off the current before it reached the dangerous levels but it did not stop one getting a shock, whereas the line insulation monitoring was continuous, and if one fixed a trip level there would not be a shock, as with the E.L.C.B.

He did not know the answer with regard to the Velcro fastener. He did not think that these fasteners would generate a spark from static electricity with sufficient energy to ignite anything when ripped apart. It was conceivable near the surface, perhaps, where the pressure was much lower and the oxygen percentage high. This was worth looking into.

He was grateful to Dr Mole for his kind remarks about the M.O.D. and the AEDU. They were trying now to make their expertise available to British industry as far as possible, particularly in the diving field, where they had a great deal to offer. He was personally determined to get them back to the top of the "diving league" where they had been a few years ago.

In answer to Mr. Cornish: The simplest system for underwater illumination for monochrome work was to use a tungsten filament lamp which operated as a source of black body radiation between 2800 and 3400°K. For long term use a better life could be obtained operating lamps on d.c. rather than a.c. as the rate of deposition of the tungsten on the envelope was at a lower rate. For increased luminous output mercury vapour lights could be used but the spectral output was concentrated in small regions two of which were transmitted fairly well by seawater; the blue line at 4358° and the green line 5461Å°. From a diving point of view there were complications using these lights as they were usually designed to be self-starting from an a.c. supply and required a ballast resister. For underwater colour photography the thallium-iodide light was essential for reasonable colour rendition. For general purpose television camera use underwater the vidicon tube was the most satisfactory. Manipulation of lights and TV cameras underwater placed the diver in hazardous conditions and he should be protected by the incorporation of the safety devices discussed in the paper.

In answer to Mr. Peddie: Ripple on a d.c. current, no matter how it arose, could be dangerous. Within the frequency range 10 Hz to 1 kHz presented roughly the same shock risk as a direct current, having five times its magnitude. Conversion to d.c., be it by rotating machinery, or rectification single or multi-phase, resulted in some ripple. For safe operating conditions the design criteria enumerated in the paper should be adhered to.

SURGEON-COMMODORE J. S. P. RAWLINS, R.N. said he had worked with Mr Haigh for many years, and had had considerable experience of swimming in electrically heated wet suits. and they had also been out in the USA together. There was an absolute dearth of information, they had found, on what might happen. In the USA they used a 24 V DC supply. He got in touch with Prof. Dalziel, who agreed that there were a number of dangerous situations but was not prepared to go into detail without a very substantial contract, which the US Navy would not offer. There had been many electrical failures, with hot spots on the skin where suit elements had fractured. But they had never had a shock. Nevertheless, they were quite apprehensive and had a medical device called a de-fibrillator standing by for the occasion when somebody happened to get a shock with a failure in some disadvantageous position. There was still very much that was not known about electrical hazards under water.

When he was first learning to use electrical welding under water in the early 'fifties he had worn the conventional hard hat, and the petty officer in charge had given him some rubber gauntlets. He went down with the electrical welding system and when he came up he said that he could not understand the need for the gauntlets, as the hands were bare when working in sea water. He could understand it on the surface but why under water? The petty officer's reply was, "You don't have to wear them." The next time he took down the electrical welding system he struck an arc and got the most terrific shock and looked at the petty officer, who said, "That's what the gloves are for. You don't have to wear them".

MR HAIGH said that the field had been disturbed, and, depending on the resistivity of the hands and the rubber, the field was diverted either through the hands or through the rubber glove. It looked as if the speaker's hand had diverted far more of the field than the rubber glove did.

Paper read at the Royal Institution of Naval Architects on Tuesday, 11 March 1975

ENGINE PLANTS IN TRIPLE SCREW CONTAINER SHIPS

E Kongsted*

Among the several third generation container ships trading in the Far East five vessels are distinguished by being diesel driven triple-screw ships. These vessels are powered by three direct coupled slow speed diesel engines with a total continuous rating of 55 MW (75 000 bhp) and maintain an average service speed of more than 26 kn in the fully loaded condition. This paper deals with the propulsion plants selected for these vessels with special regard to those in the two Danish owned vessels *Selandia* and *Jutlandia*. The first section of the paper deals with the reasons for the choice of diesel machinery and triple-screw propulsion for these vessels. Also, considerations regarding choice of propellers, as well as generating plant, are dealt with. In the second section the engine plant in the two Danish vessels is described. No attempt is made to give a complete description of these engine plants but problems regarding control systems and safety systems for the triple-screw propulsion plants are dealt with in more detail. The third section deals with results obtained during the trials and in the fourth section mention is made of actual service results as well as the special conditions encountered during the energy crisis when the vessels were operated at reduced speed. The last section of the paper describes some initial teething troubles during the first service period.

INTRODUCTION

This paper deals with the engine plant selected for the diesel-powered third generation containerships which were put into service on the Far East route in 1972/73. These four vessels are owned by Wilh. Wilhelmsen, Oslo, The Swedish East Asiatic Co. (Brostrom), Gothenburg, and the East Asiatic Company Ltd., Copenhagen. They are operated by ScanDutch together with two steam turbine powered vessels owned by Nederlandshe Lloyd and one steam turbine driven vessel owned by Messageries Maritime. Apart from these Scandinavian diesel ships, a similar diesel driven triple-screw containership is owned and operated by Mitsui, OSK, Tokyo.

The paper is in five sections:

1) A description of the basic considerations which led to the selection of triple-screw diesel plant for these vessels.
2) A description of some of the more interesting technical construction details of the engine plant.
3) Some interesting trial results.
4) A short description of service results.
5) Description of some initial teething troubles and how they were overcome.

Sections 2–5 are written with special regard to the two vessels owned by EAC.

1. BASIC CONSIDERATIONS REGARDING SELECTION OF PROPULSION PLANT

The task of the preliminary planning of the four Scandinavian vessels was performed by a technical committee with members from the owners' technical staffs. Other working groups formed by the Scandinavian owners had already laid down detailed basic requirements for these newbuildings. These may be summarized as:

a) a sailing schedule with details concerning speed, steaming time at sea, number of port calls, time in port etc;
b) average service speed during ocean passages to be 26·5 kn;
c) bunkers sufficient for a steaming range of 17 000 nautical miles at full service speed;
d) container capacity (20 ft units, slot weight 12·5 t), below deck about 1600, on deck (per layer) about 600;
e) maximum draught limited to 11·25 m (37 ft);
f) hull dimensions to allow for unrestricted passage through the Panama Canal.

Anybody who has been involved in the construction of third generation containerships will be familiar with these requirements.

On basis of preliminary studies of hull dimensions, displacement block coefficient etc, the necessary horsepower for the project was established to be about 55 MW (75 000 bhp). With this power, the speed on loaded trials was estimated to be approximately 28 kn.

Choice of Machinery

An owners' selection of propulsion plant for newbuildings is guided by a number of factors the most important of which may be summarized as:

i) reliability;
ii) overall economy in operation;
iii) off-hire time estimated for maintenance, overhauls and classification surveys;
iv) manning problem;
v) initial investment;
vi) weight of machinery plus necessary bunkers;
vii) space requirement;
viii) vibration and noise;
ix) however, tradition and experience also play important roles.

In the preliminary stages a number of different propulsion plants were studied including gas turbines. Although advanced machinery plant might present interesting possibilities from a technical point of view, it must be borne in mind that containerships represent big investments with a carrying capacity

* The East Asiatic Company Ltd., Copenhagen.