Diver Emergency Heating Report (1984)

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Date	Reason	Revision
September 1984	Initial publication of report as AODC 026 – *Diver emergency heating*	
March 2017	Following a review it was decided that the report should continue to be made available to IMCA members. In order to ensure continued access, the report was republished as IMCA D 059 with only minor editorial changes	

Diver Emergency Heating Report

Report originally published as AODC 026 in September 1984
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1 Introduction and Aims

Diver emergency heating is an extremely important subject. It has been discussed on many occasions in general and specific terms but has never to our knowledge been reviewed across the board in terms of the various options available.

Due to the importance of the subject and the natural inclination of specific equipment manufacturers to concentrate on their own proposals or products, some claims have been made which have not been substantiated in practice, and much has been written and spoken which has either caused confusion or has been misleading. This situation has tended to cloud much valid work and progress and this report aims to consider the whole subject in an independent manner.

There are two basic types of emergency diver heating or heat conservation equipment, passive and active systems. While at least three makes of passive system are available and widely used, there are many more active heating systems which have been proposed over the years. There is great confusion however as to which specific systems can actually be purchased, let alone their proven performance.

The aim of this report is to provide basic background information on the needs and requirements for emergency diver heating, to identify which systems are actually available and which systems are under development, to consider their performance and finally to suggest the way ahead for improvements in the short to medium term.

It must be stressed that the systems briefly described in this report are those which are known to us, but others may exist or be under development.

2 Acknowledgements

We acknowledge with thanks the contributions made, and the information provided by the various companies which are individually listed (along with details of their products) in this report.

Thanks are also due to the many individuals who have provided opinions and input based on field experience and real incidents. We wish to thank the members of our Safety and Technical Committee, and also:

- Mr D Clarke, Mara Engineering Limited, Aberdeen
- Dr I Light of the Offshore Survival Centre, Robert Gordon's Institute of Technology, Aberdeen
- Mr D Robertson – MATSU, Harwell, Oxfordshire

for their help on many technical matters.

And last, but by no means least, to Crawford Logan, our Technical Secretary, for preparing it.

3 The Requirement for Diver Emergency Heating

3.1 Background

The need for emergency heating for divers trapped in a diving bell underwater has always been apparent, however specific incidents highlighted the need for positive action. The details of these incidents and accidents have varied but in all of them, the divers involved have suffered degrees of hypothermia when the conventional external heating systems failed.

These accidents prompted extensive research and development into means of providing emergency heating for divers and the formal requirements for such heating systems were included by AODC, in February 1980, in the document 'Emergency Diving Bell Recovery – Guidance Notes/Code of Practice'. This states 'The equipment should aim to provide sufficient heat for a period of up to 24 hours in an oxygen/helium environment, with a bell in water at 5°C'. This requirement was further enforced in the UK by the 'Diving Operations at Work Regulations' in July 1981 which required diving bells to be provided with 'a means by which the lives of trapped persons can be sustained for at least 24 hours or, where that is not practicable, sustained for as long as is practicable'.

The research and development which was carried out in 1979 and 1980 was mainly focused on providing active emergency heating, i.e. devices which generated heat in order to keep the ambient internal atmosphere of the diving bell at a suitable temperature or keep the divers themselves warm. The overall insulation of the diving bell was considered and, while helpful in reducing heat loss and thus reducing the required heat input, could not in itself resolve the problem as it would not be practicable to insulate the diving bell to provide sufficient heat conservation for a 24-hour period.

A number of active heating devices were developed to the prototype stage and at least one device was marketed. It became apparent however, when many of the prototypes were tested, that they did not perform as efficiently as had been hoped and that in the main they were bulky and heavy, thus imposing other penalties on the diving bell.

While the development of active heating devices was under way parallel developments were in hand to insulate the trapped divers individually, to minimise their personal heat loss without heating the ambient atmosphere inside the bell. It soon became apparent that this could be done relatively simply and further that this insulation, coupled with a small heat exchanger to conserve the expired gas heat loss and topped up with the heat generated by the exothermic reaction of the chemicals used to remove CO_2 from the divers' exhaled breath, should be sufficient to maintain the divers in thermal balance. This method became known as the passive system.

Three passive systems were developed and showed various advantages over active systems, not the least of which was that they were immediately available to provide protection to divers in a lost bell situation.

As a result, all diving contractors purchased passive systems and almost overnight the developers of active systems were left with very little prospective market – accordingly, development stopped.

The effectiveness of passive systems has now been comprehensively tested and there is reasonable evidence to suppose that, if correctly designed and used, these systems will considerably increase survival times in a lost bell. In one incident in 1981 when a diving bell in the North Sea was trapped for ten hours, a form of passive system was used and the divers' survival was undoubtedly assisted by the equipment.

It is apparent however that active heat systems are still desirable, in order to increase the chances of survival during a prolonged entrapment and also to provide 'belt and braces' security against malfunction or misuse of the passive systems. It must be accepted however that passive systems offer considerable technical attractions and will always be used as the primary safety protection.

3.2 Discussion

The problem of the maintenance of thermal balance of the human body in a cold environment is well researched and documented, particularly in terms of groups such as mountaineers and members of the armed services who are regularly exposed to such situations. The problem affecting divers in an atmosphere of oxygen and helium, at elevated pressure, is however unique and considerably more severe.

In air at atmospheric pressure the main heat loss from the human body is by convection and conduction from the body surface. Due to the much higher thermal conductivity of helium and the increased density of oxygen/helium under hyperbaric conditions, the rate of heat loss is markedly increased. The major sources of heat loss from a human in such conditions are convection from the body and respiration heat loss from the lungs. The latter is particularly dangerous as it causes rapid 'deep body' cooling which can quickly become critical.

A typical ambient temperature inside a diving bell during normal operations is 30°C while the water temperature on the outside can be as low as 2°C and normally, in the North Sea, around 5°C. A substantial temperature gradient of the order of 25°C plus therefore exists, with the heat loss from the bell being in the region of 3 to 7 kW. If normal heating to the bell is cut off, rapid cooling results, even with a high standard of bell insulation.

The human body has a normal core temperature slightly above 37°C and even small variations can have serious effects. Typically a fall in core temperature to 35°C will see the onset of hypothermia.

Consideration of the thermal status of a diver in an oxygen/helium environment at an arbitrary 300m gives the following figures:

a)	Unprotected respiratory heat loss:	
	– at rest	135 watts
	– shivering or light work (depending on breathing rate	200 to 600 watts
b)	Protected respiratory heat loss:	
	– at rest	10 watts
	– shivering or light work	15 watts
c)	Metabolic heat production:	
	– at rest	100 watts
	– shivering or light work (depending on breathing rate	300 watts
d)	Heat loss from a typical bag and undersuit which have been offshore for some time:	300 watts
e)	Heat loss from a damp bag and undersuit	500 watts

		At Rest (w)	Shivering (w)
Losses:	Protected respiratory loss	10	15
	Typical bag and undersuit	300	300
Input:	Metabolic heat production	100	300
Net loss:		210	15

It can therefore be seen that even under 'ideal' conditions, i.e. minimised respiratory heat loss and a properly fitted survival bag and accoutrements, a diver at rest loses 210 watts. If the respiratory loss is not protected and the bag is damp his net loss could increase to 535 watts. In the 'worst case' situation the heat loss could be 800 watts or more.

It must be remembered however that in an emergency the conditions could be quite different. At the commencement of the emergency the diving bell ambient temperature will be about 30°C and this will decay dependent on the efficiency of the bell insulation system. Initially, the divers will be active and will generate metabolic heat at a higher rate than when they are at rest. If the divers are injured or under stress, their metabolic rates may increase substantially, causing rapid heat loss. There is also the risk that they may not use the emergency heating systems properly or early enough, thus losing more heat.

The need for diver emergency heating equipment is self-evident and in the conclusions to this report some suggestions are made as to possible future improvements over the existing passive systems.

4 Passive Systems

4.1 Introduction

A passive system is one which relies only on minimising the diver's body heat loss and conserving the respiratory heat losses, without any external heat generating source.

4.2 Types

There are three types commonly available and widely used. All three are based on similar technical solutions.

All types are thermally regenerative and incorporate a CO_2 scrubber system and a small oral/nasal mask worn by the diver. Heat from the diver's exhaled breath is retained in the system and this is supplemented by the heat generated by the chemical agents in the CO_2 scrubber as a result of the exothermic nature of the reaction. It is claimed that by this means most of the exhaled heat is conserved.

All three types include thermal insulation garments and bags which seek to minimise heat loss from the diver's body.

These systems are normally stored inside the diving bell in containers packaged so as to minimise the amount of space taken up.

4.3 Good and Bad Features

Passive systems have a number of good features:

- Virtually no moving parts and therefore little possibility of malfunction in an emergency.
- Light weight and therefore minimal effect on diving bell buoyancy or handling.
- Require virtually no involvement by the diver after initial donning. This means that the system should continue to function even if a diver loses consciousness.
- Require virtually no offshore maintenance.
- Simplicity of design should ensure adequate operation even if divers are confused or disorientated.
- If used correctly, the restraining harnesses will ensure that an unconscious diver does not fall, injuring himself or blocking access to the bell by a rescuer.
- Low initial purchase price.

There are however a number of bad features:

- Due to the compact packaging it is periodically necessary to return systems to shore for checking and maintenance.
- It is impossible to guarantee that the system has not been affected by damp due to the high humidity within the diving bell.
- Stowage can be difficult in some diving bells due to the confined space.
- Donning the system can be extremely difficult inside the confines of a diving bell and requires agility. It may be impossible if the diver is injured or unconscious.
- The insulating properties of the suit are reduced after periods of being compressed in the packaging.
- High heat loss occurs if, once the bag has been donned, it is opened to carry out functions within the bell.

4.4 Testing

There have been a number of simulated 'lost bell' tests carried out to investigate the effectiveness of passive thermal protection. The results of these tests are available and it is recommended that they be studied by any company considering the provision of such equipment. They include:

1. Astronaut Trial, section one : Passive Systems. P.A. Hayes et al AMTE(E) 403 October 1981
2. Polar Bear III S Tønjum et al NUTEC 21-82 January 1982
3. Report over test with personal survival equipment for deep divers in distressed diving bells (Lost Bell) at the Swedish Navy Diving Centre in March 1982.

5 Active Systems

5.1 Introduction

An active system is one in which an external source generates heat, which is used directly or indirectly to heat the diver's body.

5.2 Types

There are a number of different types of active heating system in various stages of development. Their principles of operation can be categorised into one of five basic concepts:

1. Catalytic burning of hydrocarbon fuel
2. Release of latent heat from a cooling substance
3. Electrolytic reaction
4. Exothermic chemical reaction
5. Electrical resistance heating.

Each type comprises a container or containers which stores the fuel or energy source plus, in most cases, a means to transfer the heat produced to the diving bell.

They all require space on the outside of the diving bell and add significantly to its overall weight and complexity.

5.3 Good and Bad Features

Active systems have a number of good features:

- The majority require little or no space inside the diving bell.
- The majority require no action from the divers once they have been initiated and continue to function even if a diver becomes unconscious.
- They do not restrict divers' movements (as do the bulky passive systems) and thus communication checks and other actions in the bell cause no loss of heat.

They do however have a number of bad features:

- The majority are bulky and heavy. They have to be fitted on the outside of the diving bell and could therefore affect other equipment. Their bulk and weight affect the bell's buoyancy and increase its weight in air.
- Their operation cannot be guaranteed in an emergency. A malfunction probably cannot be repaired by the trapped divers in the bell.
- In many cases they cannot be regularly tested as they are intended for 'one shot' use.
- Some systems are not controllable and could provide too much heat.
- Some systems require positive control by a diver in the bell. This could be difficult if the divers are confused, injured or unconscious.
- In some cases their initial capital cost is significant.

5.4 Details

Set out below are brief descriptions of systems which are either under development or are known to have been developed to a prototype stage. Fuller details can be obtained from the individual manufacturers, whose addresses are given at the end of this report.

5.4.1 Divematics

Working on the principle of the catalytic burning of propane, the system produced by this manufacturer has been in development for a number of years and is scheduled for field trials in 1984. The system, known as EBHU, is contained in a pressurised J size cylinder located on the outside of the bell. In addition, an oxygen cylinder of similar size is required to support the combustion process. During bell operations the EBHU is maintained in the standby mode using the electrical supplies to the bell. Should the electrical supply be cut off then the EBHU will automatically move in to the active mode and will start to generate heat.

The gas would be vapourised and introduced into the catalytic furnace where it is ignited. The catalyst causes the gas and oxygen to burn chemically, the heat being passed into a heat exchanger and propane evaporator. The operating system is a closed cycle and the exhaust gases are recirculated by means of a fan. A metering system ensures that the oxygen content is maintained at the correct level. The products of combustion will be partially discharged into the sea, with the remainder being mixed with oxygen and propane to obtain the ideal stoichiometric mix.

The water created as a by-product of the process is retained in a reservoir at the base of the heater. The circulating pump and control system are maintained by a battery contained in the system. The heated water is piped into the bell and circulated through tube suits worn by the divers.

The system is designed to maintain 1500 watts output for a 24-hour period, having a gross capacity of 36 kW hours.

The EBHU-5 can be incorporated into a normal diver heating system (also developed by the company) if required, however it does require the use of a closed circuit tube suit.

Tube suits, however, have not been enthusiastically received in the past.

The final stages of development of the system are being funded by the UK Department of Energy and it is likely that it will be the first commercially available and proven unit, on the market.

5.4.2 Rocket Research/DUI

The Rocket Research Company of the USA are in the preliminary phases of development of an active emergency heating source based on the catalytic burning of hydrocarbon fuel. This development is being carried out in close conjunction with DUI of San Diego, California.

No specific details are available.

5.4.3 ECA

The system developed by this French company was derived from work done on a self-contained heating system for lock out submersibles. The bell system derived from that development is intended as a normal means of diver heating with the added bonus that it can operate in an emergency without any surface power. It uses the latent heat released from molten salts which are contained in an external vessel (400mm in diameter and 1500mm long), which is considerably larger than a normal bell bottle. In principle the system appears simple, in that the salts are maintained at a temperature of 430°C and capable of storing a total 45 kW hours of energy. A heat exchanger inside the vessel produces steam from a closed fresh water circuit which heats a sea water circuit, which is pumped to the diver's tube undersuit. The system can also be connected to the bell heater.

The salts are heated in the vessel by an internal resistance bank, powered via the umbilical. In normal operation the salts would be melted and held at their storage temperature by a surface charger with power via the umbilical merely maintaining a trickle charge to overcome thermal losses. The vessel is well insulated and therefore the normal power required when diving is small. A battery is used to power the control system and circulating pumps.

In case of an emergency, such as breakage of the umbilical, the system can supply all of the 45 kW hours of energy for emergency use.

The original system developed for use with diver lock out submersibles is known to be in operation, however its use for emergency bell heating is not widespread and no information is available on practical test results. The system relies on specially designed tube suits although there seems no reason why the hot water produced should not be used to partially heat the diving bell atmosphere.

5.4.4 Kinergetics

The Kinergetics seawater battery is commonly used on hyperbaric rescue chambers, and has been accepted as a means of producing self-contained heat over an extended period of time. The battery contains a series of magnesium and iron plates held apart in a canister and activated by the circulation of sea water.

In 1979 Kinergetics packaged one of these batteries in a container, designed to replace a standard diving bell gas storage cylinder. However under test the unit ‘silted up’ rapidly and the heat output diminished. The unit was not marketed or further developed although it is known that at least one company purchased the components of a sea water battery which they then packaged and mounted externally on a diving bell which is currently in use in the North Sea.

The system has one major disadvantage, in that it cannot be tested, as it is intended as a ‘one shot’ unit. The premature entry of even small quantities of sea water during normal operations could cause the unit to be initiated and partially used up.

5.4.5 DUI

In 1979/80 DUI demonstrated the principle of an exothermic chemical reaction but did not take development to a prototype stage. The company feels that the principle has considerable potential but is unable to continue development in the absence of funding.

5.4.6 General Diving Systems

Several years ago GDS demonstrated a prototype chemical reactor heater. Working on the principle of the mixing of two chemicals (neither of which was sea water), it gave a heating arrangement which was controllable and could be initiated, throttled and stopped by the diver.

A particularly novel feature of this system is that the container for the reagents is mounted directly on the external surface of the diving bell and under the layer of thermal insulation. The system uses the internal wall of the diving bell as a radiator and thus removes many of the problems suffered by other systems in actually conveying the heat produced to the divers without high heat losses, use of pumps, heat exchangers and consequent waste of energy. The disadvantage of this feature however, is that it has to be fitted to the diving bell during manufacture or else entails substantial modification to an existing bell.

The unit could be packaged in a conventional way for mounting externally on the bell, although it would then be necessary to transfer heat to the inside of the diving bell by an additional system.

General Diving Systems are currently building a longer version of this system for use with a diver lock-out submersible.

5.4.7 Raychem

Development of a heat tracing system for pipework brought about the development of materials whose resistance varies with their temperature. The compounds from which the materials are made can be varied to alter the characteristic temperature at which the material stabilises. Since the power source can only be electrical the resulting system must rely on conventional storage batteries. The principle is to produce an undersuit made of tapes which will be designed to maintain a given surface temperature. These can match the desired levels of skin temperature for the diver and, by being self-regulating, maximise power conservation whilst maintaining accurate control over the diver's temperature. Current thinking is to produce an undersuit (which can be worn during diver lock out) aimed at a power range between 600 and 1000 watts. Equipment should be available in the field within six to twelve months.

For the emergency situation a much lower level of electrical supply could be fed from batteries to provide 'top up' heat inside a passive survival system, although this is not intended at the moment by Raychem.

Raychem is also investigating a suit into which this material is layered but is encountering problems with the stiffness of the resulting garment.

The obvious major disadvantage of this system for emergency heating is that the quantity of electricity which can be carried by conventional batteries on the bell would not provide sufficient energy for long term diver heating, although it could provide partial heating.

6 Future Developments

A number of other developments are known to be under consideration and some of these are briefly described below.

6.1 Passive Systems

The thermal regenerator device has probably been developed to a point at which further improvements in performance (provided the device is properly used) are likely to be so small as to be of little significance over a 24-hour period. For this reason further development is unlikely.

The ability of the CO_2 absorbent to generate heat is limited and it is unlikely that further development in this area would be productive.

The heat loss through the bag and other portions of the system can however be high, particularly after prolonged storage or if dampness is present and current systems aim to strike a balance between bulk when stored (undesirable) and bulk when in use (desirable) as insulation properties depend on bulk. New materials are being developed however, and Development Engineering (Aberdeen) Limited is working on a system using the material 'Mylar' in an inflatable multilayered bag which has small bulk when stored but, after inflation, provides substantial bulk for insulation. Other companies are considering the use of the material 'Thinsulate' which has the ability to retain most of its insulating qualities when wet.

6.2 Active Systems

Developments not even currently contemplated may yet be made in active systems. Three possible developments have been proposed during the preparation of this report and although few details are available a brief description of them is given below.

6.2.1 Magnesium Packets

The concept is simple and relies on the chemical reaction when magnesium and water mix. The resultant oxidation is exothermic and if the magnesium is mixed with small quantities of iron filings the reaction can be speeded up to give reasonable amounts of heat. The problem is that the reaction also produces hydrogen, which is highly undesirable. Although this concept may be further developed it seems to be similar in basic philosophy to units already being developed by a number of companies and outlined in this report.

6.2.2 Heat Emitting Gel

It is claimed that a certain material, when heated to its liquid phase and allowed to cool naturally, remains as a gel while still retaining all of the latent heat normally liberated during the liquid to solid phase change. The gel is totally stable and the phase change from gel to solid can be controlled, liberating substantial quantities of heat in the process. Details are, however, still sketchy.

This proposal appears in principle to answer the requirement for emergency heating as it is simple, foolproof and of low bulk. However the claims have not yet been demonstrated under independent observation.

6.2.3 Inspired Gas Heating

A proposal has been made that a small, electrically heated device be fitted in a breathing mouthpiece to allow a diver in a bell to breathe warmed gas. Whilst the electrical requirements needed to maintain a diver's thermal balance over several hours are so large as to make the method impractical, there is no doubt that this device, if used with a suitable passive system could contribute to the maintenance of a diver's thermal balance over a long period even if only modest electrical power was available.

Other future developments can only be guessed at but it is entirely possible that improved methods of active emergency heating could be developed.

7 Discussion

There is no doubt that the passive survival systems in widespread use increase the chances of survival of divers in a lost bell situation.

In particular the thermal regenerator and CO_2 scrubber limit the respiratory heat loss to a value low enough to be acceptable over a prolonged period. The bag and other parts of passive systems are however difficult to accurately assess in terms of performance due to variables which can seriously affect their efficiency, including damage during stowage, reduced effectiveness if damp, and in particular the physiological condition of the diver before the system is put on. As a result of these variables and the possibility that in a real emergency some of them may act unfavourably, present day passive systems on their own can only be relied upon to provide safe 24-hour life support in terms of thermal balance for divers if used correctly.

Although, to the best of our knowledge, no proven active heating system is currently available, we believe that most of the developments could not be relied on to provide sufficient heat to counter the effects of heat loss from a diving bell. This could be of the order of 7 kW. This is due to a number of reasons which include the possibility of malfunction in an emergency and the fact that active systems currently proposed simply do not produce enough heat over an extended period to maintain the internal temperature of the diving bell at the required level.

We are left therefore with a situation in which existing passive systems can only be relied on to perform adequately over an extended period if used correctly and in addition, that no suitable alternative active heating device is currently available at the moment.

We consider that a totally reliable emergency heating system requires a combination of the two methods.

The calculations and tests carried out on passive systems generally started from the supposition that the bell internal ambient temperature will drop fairly quickly to 5°C or lower, compared to approximately 30°C required for comfortable maintenance of the divers' thermal balance. Similarly, most tests have assumed that no external heat input would be available to the divers in addition to the protection offered by a passive system.

The use of an active heating system could therefore be considered in addition to the provision of passive protection for a number of reasons:

a) If an active heating source could be used to heat the diving bell atmosphere, it would slow down the rate of cooling of the atmosphere, thus shortening the time during a hypothetical 24-hour survival period when the bell temperature would be at its lowest. Similarly the heat input would stabilise the eventual ambient temperature of the bell at a higher level than otherwise. As the performance of passive systems is directly proportional to the temperature gradient between the diver and the bell ambient temperature, any increase in ambient temperature would improve this performance.

   Assuming therefore a heat loss from the bell of 3 to 7 kW at the initial ambient temperature of 30°C (depending on the efficiency of its thermal insulation), a possible heat loss of only 1 to 3 kW is likely when the ambient temperature drops to 15°C. Input of, say, 1.5 kW from an active heat source could possibly maintain the internal ambient temperature at 15°C which would considerably increase the probability of a complementary passive system maintaining a diver in thermal balance for 24 hours, even allowing for lower than optimum performance by the system.

b) One of the tests carried out on a passive system concluded that if about 600 watts were applied directly to a diver (using a passive system) then he could be maintained in thermal balance for at least 24 hours. An active heat source providing 1.2 kW (between two divers) would therefore give additional protection, considerably improving the chance of survival.

c) There is general agreement that the first two to three hours of an emergency are critical and that the actions and condition of the divers during this period will influence their chances of long term survival. It is during this early phase that tension and metabolic rates will be at their highest. Divers will also be at their most active, as they prepare to rig the bell for extended survival, operate communications equipment and most importantly unpack and put on the passive survival system correctly.

   There is therefore considerable merit in the suggestion that an active heating device be used to *supply* high heat levels for at least the first two to three hours of an emergency, thus ensuring that the passive systems are given the best possible conditions to operate in, when they are eventually used.

As most active heating devices cannot be switched on and off like a light switch, it is likely in practice that a combination of the methods outlined above will eventually be adopted. Emphasis may be on high initial heat input followed by a period of progressive decay during which the ambient bell temperature drops and finally, all heat being directed inside the passive system which, with this active heating assistance, could be virtually guaranteed to ensure the survival of trapped divers for at least 24 hours.

8 Conclusions

a) Tests carried out on passive systems show that they considerably increase the time before divers in a ‘lost bell’ become seriously incapacitated by hypothermia.

b) Tests show that currently available passive systems largely depend for their success on being correctly stowed, maintained and used. As these variables cannot always be guaranteed in a real emergency it is probable that present day passive systems alone can only be relied on to provide a safe 24 hour capability if maintained and used correctly.

c) At the time of writing this report no proven active heating system is readily available and demonstrated to work under realistic conditions though a number of them are under development.

9 Companies Mentioned in the Report

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