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LOCAL HEATING SOURCE FOR SHALLOW WATER DIVERS*

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Summary

A novel method of local heating for divers has been developed. The method involves the use of a granular mixture of magnesium and iron particles packed in small sachets. Exothermic reaction proceeds when these sachets are immersed in sea water, and the heating rate may be predetermined by particle size and mixture ratio of the constituent Mg and Fe particles.

This method has been applied to hand heating and body heating; laboratory and sea trials to date have proved that it can provide adequate supplementary heating for shallow water divers. (Shallow water may be arbitrarily defined as diving to a maximum depth of 50 m.)

1. Introduction

In the past 20 years a great deal of development work has taken place in underwater technology, mainly in the support of the offshore hydrocarbon industries. One of the main problems confronting the diving contractor is the limiting duration of work imposed by excessive body heat loss. In normal conditions the core or deep body temperature lies between 36 and 38 °C. In the absence of supplementary heating, an exposure to cold water produces hypothermia, in which the deep body temperature drops progressively until death occurs at about 28 °C [1].

Water temperature in the ocean ranges from −2 to +30 °C [2]. In temperate regions, the ocean temperature varies with the season between 10 and 18 °C. At a depth of 200 m and beyond, the seasonal influence is negligible, and a permanent thermocline exists, with water temperature reaching 4 °C at 1000 m.

Thus the water temperature surrounding the diver is normally considerably lower than the body temperature, and since the density, specific heat, and thermal conductivity of water are, respectively, about 800 times, 4 times,

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and 25 times greater than those of air, rapid heat loss will result unless the diver is protected thermally. Tests in a shallow pool [3] showed that a diver at rest and protected by a wet suit in 16 °C water, experienced onset of shivering after only 30 min immersion, if supplementary heating was not provided.

2. Diver heating — current practices

Except for naval divers, portable heating devices are almost non-existent. Sporting and commercial divers at present rely generally on the passive control of heat loss by the donning of wet or dry suits.

A method for diver heating which is used quite extensively for dives in extremely cold water or dives of long duration is the free flooding hot water suit described by Long and Smith [4]. This method is both unsafe and extremely wasteful of energy because of the poor insulation and the open circuit configuration, in which warm water is discharged directly into the sea after use.

Electrically heated suits [5] have also been developed; however, the electrical resistance wires are subject to breakage due to constant flexing, and electrical shock is a potential hazard.

The above two methods require umbilical connections and, as a result, the mobility of the diver is restricted. Therefore the development of a portable heating device for free-swimming is highly desirable.

3. Diver heat sources

The requirements for a diver heat source are:

(1) The system must be portable, and free from umbilicals.
(2) The ability to produce the heating rate required for the duration of the dive .
(3) The reactants and products must be pollution-free, with no danger to the environment.
(4) The fuel element must be inexpensive, and easily replaced.
(5) The system must have minimum weight, and be neutrally buoyant.
(6) Some method of control of heat output must be incorporated.
(7) The system must possess adequate safety measures.

A list of possible heat sources is shown in Table 1. Primary (one shot) and secondary (rechargeable) batteries are relatively bulky. Their energy densities are not high when compared with thermochemical or radio-isotope sources. The cost of a radio-isotope source is prohibitive so that its usage would usually be limited to military applications.

Thermal storage using molten lithium salts suffers from high storage temperature (up to 700 °C). At this temperature, heat loss and corrosion considerations would dictate a difficult insulation requirement, and that special corrosion-resistant alloy steel be used as a containment material.

TABLE 1

Comparison of diver heat sources [6, 7]

System	Reactant	Product	Energy density (W h/kg)	Duration of power cycle
Primary battery	Magnesium/$AgCl_2$ seawater electrolytes	Electricity	66	3 - 9 h
Secondary battery	Ag–Zn	Electricity	120	3 - 9 h
	Lead–acid	Electricity	35	
Thermochemical	$2H_2 + O_2$	Heat	220	2 - 10 h
	Mg/Fe*	Heat	1000**	
Radio isotope	Plutonium 238	Heat	202	87 years
Thermal storage	Molten Li salts	Heat	165	

*Short-circuited sea water battery.
**Measured energy based on weight of fuel assembly consisting of Mg and Fe plates.

Of the heat sources listed in Table 1, the thermochemical process based on magnesium reacting with sea water in the presence of a cathode (such as iron) is the most promising. An energy density of 1000 W h/kg of fuel assembly may be obtained. This energy density is possible if the fuel constituents (*i.e.*, magnesium and iron) are in granular form and packed in lightweight sachets to form local heating pads, thus avoiding weight penalties caused by containers and ancillary equipment.

4. Theory

Magnesium is chosen as the heat source, because it is non-polluting (it can be extracted from sea water originally). Magnesium sea water batteries are already in use in marine applications; the prime purpose of these batteries is to produce electricity to power emergency lights or radio beacons. A method to produce heat by short-circuiting magnesium batteries has been reported by Black and Sergeu [8]. The purpose of short-circuiting is to accelerate the reaction so that heat is produced at a usable rate; it is also a means by which thermal energy rather than electrical energy is obtained.

The reaction of magnesium with sea water, which is exothermic, is given by the following equation:

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2\uparrow + \Delta h \quad (1)$$

Δh, the heat of formation, has a theoretical value of 4070 W h/kg of magnesium.

Figure 1 shows the electrochemical reactions taking place in a magnesium–iron cell containing sea water electrolyte.

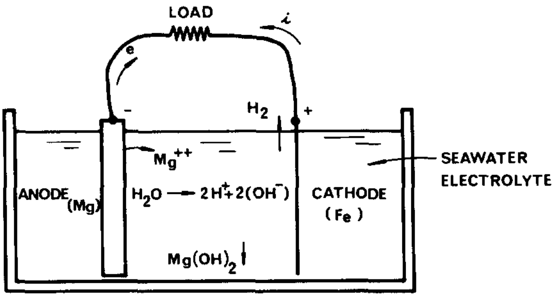


Fig. 1. Electrochemical actions in a magnesium–iron cell.

Since sea water is a reasonably good conductor, and if the magnesium anode and iron cathode are connected electrically through an external circuit, electrons will flow from the anode to the cathode. The following reactions will take place:

$Mg - 2e \rightarrow Mg^{2+}$	anode	(2)
$2H_2O \rightarrow 2H^+ + 2(OH^-)$		(3)
$2H^+ + 2e \rightarrow H_2\uparrow$	cathode	(4)
$Mg^{2+} + 2(OH^-) \rightarrow Mg(OH)_2\downarrow$		(5)

At the anode, magnesium atoms forfeit two electrons and go into solution as positively charged free ions. In the meantime, dissociation of the water molecules produces hydrogen ions (H^+) and hydroxyl ions (OH^-). The positively charged hydrogen ions proceed towards the cathode and receive two electrons from it to form gaseous hydrogen. The displacement of hydrogen gas from the heater assembly ensures that fresh sea water can be introduced automatically to account for the loss of electrolyte due to decomposition, when the heater cell is submerged. The magnesium ion (Mg^{2+}) and hydroxyl ion (OH^-) then combine to form magnesium hydroxide, and this is precipitated from the electrolyte.

The iron cathode merely acts as a conductor and remains intact, but the magnesium anode is consumed in the process. A new heater can thus be made by replacing the magnesium anode only.

5. Local heating pad

In a diver heating system, heat generated by the heat source must be transported to various parts of the body *via* a distribution system. A method for achieving heat distribution is by the use of a tubing suit similar to that developed by Burton and Collier [9]. Warm water in a closed circuit arrangement is circulated in a network of small tubes sewn into the suit, which is used as an undergarment worn beneath a normal wet suit. A heat exchanger is required to transfer heat between the heat source and the circulating fluid.

The heating pad shown sectioned in Fig. 2 is the result of an effort to combine the three functions (*viz*., heat generation, heat distribution, and heat transfer to body) of a diver heating system into a simple package for shallow diving.

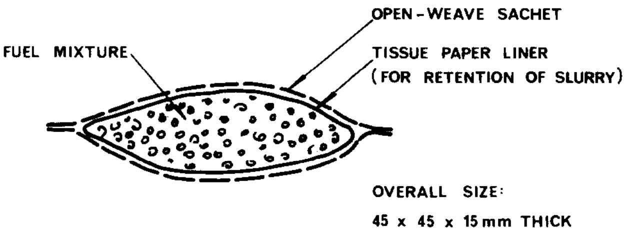
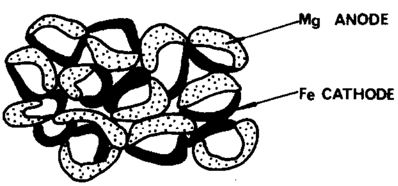


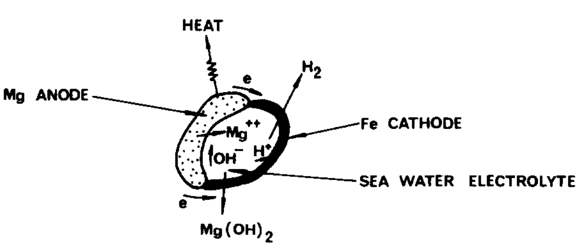
Fig. 2. Cross-section of heating pad.

The heating pad consists mainly of granular magnesium and iron particles, in the form of machine turnings, packed into small sachets of open weave material. A tissue paper liner is used to retain the fuel mixture, and to prevent the magnesium hydroxide (a white precipitate) slurry from leaving the sachet during activation. The porous nature of the tissue paper liner allows release of the hydrogen gas formed during the process and the replenishment of fresh sea water electrolyte for the reaction.

Figure 3(a) is a schematic of the granular anode/cathode system: it shows an ideal mixture of magnesium and iron particles uniformly distributed to form a multitude of heater cells. Electrochemical actions within a single



(a)



(b)

Fig. 3. (a) Schematic of the granular anode/cathode system.
(b) Electrochemical actions within a single cell.

cell are shown in Fig 3(b). The reaction mechanisms are similar to those described in Section 4, but the electrical connections are now made by direct contact between the magnesium and iron particles.

6. Experimental

In order to determine the performance characteristics of the heating pads, an experimental program was conducted to investigate the influence of the following parameters on output and duration of useful heating: (a) particle size, (b) mixture ratio.

Mixture ratio is defined as:

$$MR = \frac{\text{Mass of Mg}}{\text{Mass of Fe}}. \qquad (6)$$

Equation (1) shows that 1 g of hydrogen gas evolved will be accompanied by 176.7 kJ of heat energy; and if expressed in terms of volume, 1 ml of hydrogen (at NTP) will represent 16.004 J of heat energy. It is obvious that two methods exist which we may use to measure the power output of the process. One is to measure the volume rate of hydrogen gas evolved, and the other is to measure the amount of heat generated during reaction. In a non-steady state process such as this, volume measurement is simpler and more accurate than thermal measurement; hence, the first method was adopted.

The test set-up consisted of an inverted measuring cylinder over a 690 × 210 × 330 mm high tank containing fresh sea water; the water temperature being maintained to ± 0.5 °C of the required value. An inverted funnel containing the test heating pad was placed under the measuring cylinder such that the hydrogen generation rate was indicated by the volume of water displaced. A standard sachet size of 45 × 45 mm and standard mixture weight of 10 g were adopted fro the test heating pads containing free particles.

Five British Standard Sieves with apertures of 3350, 2000, 1400, 1000, and 600 μm (micron), respectively, were used to grade the magnesium and iron particles. Laboratory grade magnesium turnings (99.7% Mg) were used, while iron turnings were machined from mild steel bars or cast iron blocks. Initially, Mg and Fe mixtures were combined as free particles to form the heating pads. Later, mixtures were pressed in a hydraulic press at a pressure of 87.5 MPa to form pressed discs (40 mm dia. × 4 mm).

7. Generalised performance curves

The performance curves, *viz.*, the power curve (P *vs.* t) and the energy curve (Δh *vs.* t) have the generalised forms indicated in Fig. 4. The power curve is related to the energy curve by the following relation:

$$\Delta h = \int P\, dt, \qquad (7)$$

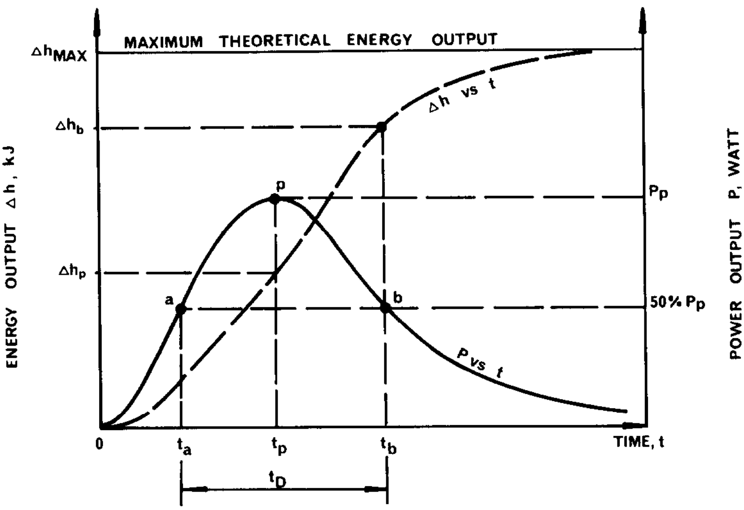


Fig. 4. Generalised performance curves for heating pad — symbols defined.

and since Δh was deduced from the experiment, heating rate (P) during any period in the test may be evaluated by differentiating the energy curve, such that:

$$P = \frac{d(\Delta h)}{dt} . \tag{8}$$

For the purpose of this analysis, points a and b on the power curve are chosen such that the line representing 50% peak power intersects the power curve at these two points. Hence, duration t_D represents the period when the heating rate was equal to or greater than 50% of peak power output:

$$t_D = t_b - t_a . \tag{9}$$

Average power (from commencement of reaction to 50% peak power on the trailing portion of the power curve) is defined as:

$$P_{av} = \frac{\Delta h_b}{t_b} . \tag{10}$$

t_b is defined as the "duration of useful heating", after which time the heat produced is considered residual heat only.

8. Test results

Test results of the free particle mixtures are presented in Table 2. Tests 1 - 10 consist of mixtures of Mg and Fe particles of the same size. Generally, start-up time (as indicated by t_a) is shorter for mixtures with fine particles, and, consequently, these mixtures also take less time to reach peak power (*cf.* t_p of Tests 1 and 9). Thus for the same amount of Mg in the mixture,

TABLE 2

Test heating pad details and test results
Sea water temperature: 21 °C.

Test no.	Size of Mg turnings (μm)	Size of Fe turnings* (μm)	Mixture ratio Mg/Fe by wt.**	t_a (ks)	t_p (ks)	t_D (ks)	Average power, $\Delta h_b/t_b$ (W)	Peak power, P_p (W)
1	< 3350		0.375	4.3	8.5	12.5	1.43	2.26
2	> 2000		0.5	2.4	5.6	10.0	1.98	3.07
3	< 2000		0.375	2.4	5.8	16.0	1.12	1.62
4	> 1400		0.5	3.6	7.0	12.4	1.74	2.70
5	< 1400		0.375	4.4	7.8	9.7	1.36	2.42
6	> 1000		0.5	3.6	11.8	22.4	1.12	1.63
7	< 1000		0.375	2.3	4.5	8.0	2.01	3.09
8	> 600		0.5	2.4	4.8	15.4	1.55	2.36
9	< 600		0.375	1.7	2.0	5.5	3.26	6.00
10			0.5	1.6	3.6	6.6	3.24	4.92
11	< 3350 > 2000	< 600	0.375	3.6	9.4	16.0	1.33	1.97
12			0.5	1.9	8.0	18.5	1.61	2.20
13	< 600	< 3350 > 2000	0.375	3.0	6.5	9.0	2.05	3.20
14			0.5	2.2	4.1	5.4	3.42	5.57
15			1	4.0	5.4	5.5	3.89	7.50

*Mild steel turnings.
**Total mixture wt. = 10 g.

one with fine particles will give higher average power, but shorter duration of useful heating than a mixture with coarse particles.

Peak power as a function of particle size and mixture ratio is plotted on Fig. 5. It is interesting to note that the curve representing MR = 0.5 crosses over the MR = 0.375 curve at particle size between 2000 and 1400 μm, and tests with the larger mixture ratio (MR = 0.5) actually produced less peak power than tests with the "leaner" mixture of magnesium. This may suggest that an optimum particle size has been reached for which any increase in mixture strength (by increasing the magnesium content) will not necessarily produce higher peak power.

The surface area ratio between the magnesium and iron particles, the porosity (and, hence, the spacing between the electrodes), and the distribution of the two constituent particles are considered to be the controlling factors in the reaction mechanism; in particular, they will affect the rate of hydrogen gas release and its subsequent travel through the matrix of contacting particles. However, the interactions between these factors are complex, and more experiments are required for their understanding.

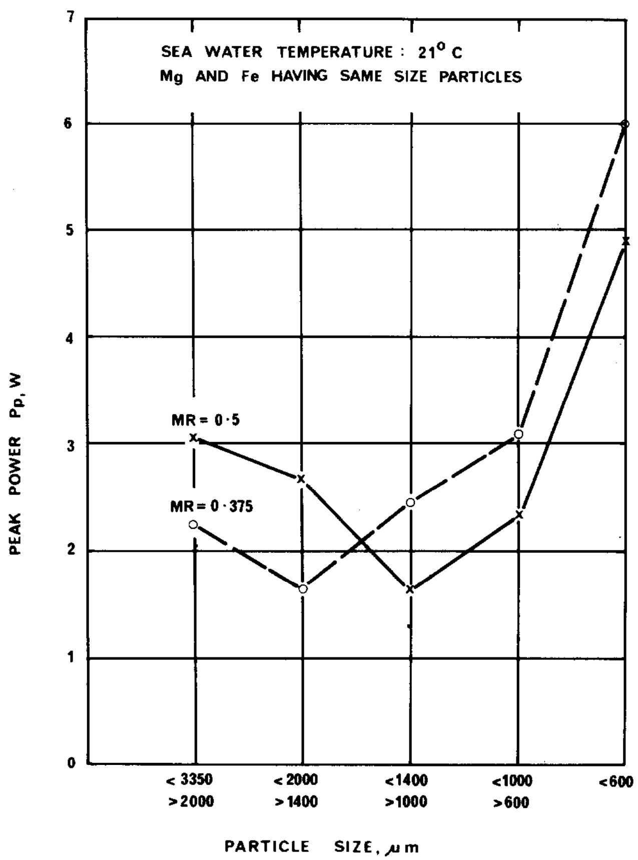


Fig. 5. Peak power as a function of particle size and mixture ratio.

Figure 6 illustrates the difference in power curves between heating pads with free particles (curve 1) and as pressed discs (curve 2) using mixtures of the same composition: Mg and cast iron particles < 600 μm; MR = 0.5; and total mixture weight of 10 g. The free particle heating pad has a slower heating rate (half life of 6.6 ks) than the pressed disc (half life of 2.3 ks). Thus, heating pads in pressed form would suit fast heating, short duration applications. There is no significant difference in heat rate between Mg–cast iron mixtures ① and Mg–mild steel mixtures ③ in free particle form.

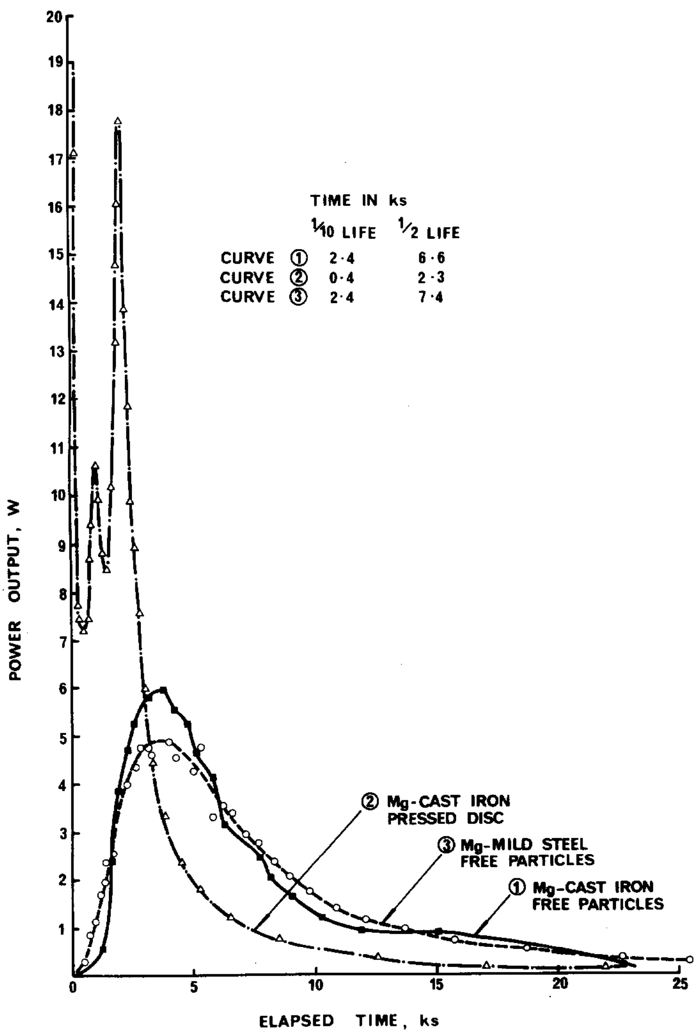


Fig. 6. Power curves of heating pads with fine magnesium and iron particles.

9. Preliminary design curves

Due to the large number of permutations of particle size and mixture ratio possible, the number of tests presently conducted is insufficient to provide a complete indication of the behaviour of these heating pads. However, useful data have been collected to produce the preliminary design curves in Fig. 7. The Figure relates the following parameters:

(a) Power density, P_{av}/W_t represents the average power per unit mass of Mg and Fe mixture, where P_{av} is the average power and W_t the total mixture weight;

(b) Duration of useful heating, t_b;

(c) Mixture ratio;

(d) Magnesium particle size.

For example, for a power density of 0.31 kW kg^{-1}, fine Mg particles will be required, and the heating pad will be expected to give 6.5 ks (1.8 h) of heating with a mixture ratio of 0.375.

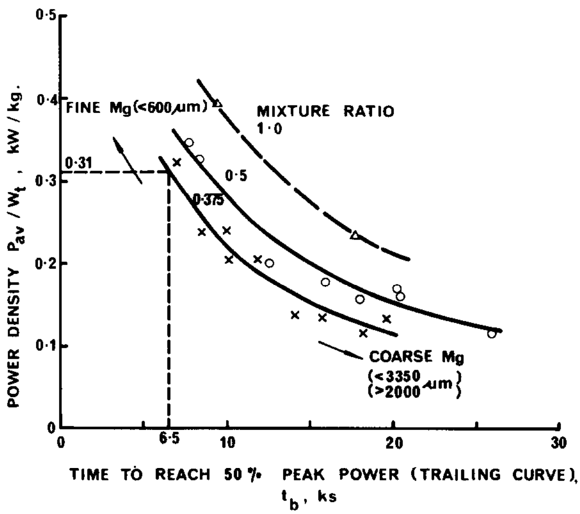


Fig. 7. Preliminary design curves.

10. Applications

From the above test results, the concept of a local heating pad is feasible for diver heating; and a usable heating rate was obtained with the granular electrolytic cell system.

There are at least two possible applications of these heating pads: *viz.*, (1) hand heating, (2) body heating.

Hand heating may be achieved by having a perforated pocket (for the insertion of heating pads) sewn onto the inside of a Neoprene glove. When sea water is introduced into the glove, as in the normal wet suit, heat from the reaction will warm the water within the glove. The sea water is used both for the reaction and as the heat carrier.

Assuming a skin temperature of 28 °C, and a thermal conductance of 8.61 W m^{-2} $°C^{-1}$ for 6.4 mm Neoprene rubber, the calculated heat loss rate for heating one hand is about 5 W in 10 °C water. Since shallow dives seldom exceed 2 h, this quantity of heat can be supplied by two sachets (each of 10 g mixture wt., MR = 0.375) with a total average power output of 6.3 W.

For body heating, a special heating vest which contains rows of pockets sewn onto its front and back is used. A suitable type and number of heating pads are inserted into the pockets as required. The heating vest is worn over a "farmer John" type Neoprene wet suit, with an outer long-sleeve torso garment of Neoprene foam. Thus the skin is protected from direct contact with the heating pads. Upon activation by sea water, heat generated by the heating pads is distributed by the water contained between the wet suit and the diver's body over the torso area. It is interesting to note that this add-on body heating system (heating vest plus twenty local heating pads) weighs only 400 g, and its usage does not require modification to existing equipment.

11. Laboratory and sea trials

To investigate the effectiveness of the local heating pads for hand heating, laboratory tests were conducted on three subjects, each with a gloved hand immersed in 10 °C water. Thermocouples were used to monitor the skin temperatures of the finger and palm. It was found that with the glove unheated, the subjects reported stiff fingers after 60 minutes' immersion, and shivering after 80 minutes; finger temperatures approached 10 °C at 110 minutes.

Similar tests with two 10 g sachets in the gloves, however, gave finger temperatures around 20 °C after 110 minutes' immersion. They show that the supplementary heating had prevented vaso-constriction, an automatic body mechanism which reduces blood flow to areas where cold stress is experienced.

Sea immersion trials in shallow water with water temperature around 11 °C also proved the concept of hand heating. One subject (with one gloved hand heated only) reported that his arm with the heated hand was warm right up to the shoulder, and the heated hand was still comfortable after 2 h immersion.

A sea trial using the special body heating vest was conducted on an abalone diver off the East Australian coast in winter. In the trial, the heating vest was charged with twenty local heating pads (representing 50 W of heating output) evenly distributed around the front and back of the torso area. The diver was engaged in his normal task of abalone harvesting in 11 °C water with a depth of between 10 and 15 m.

The diver was asked at regular intervals for his subjective assessment of the effect of the supplementary heating system. A seven point "temperature" scale ranging from "very hot" to "very cold", and a four point "comfort" scale ranging from "comfortable" to "uncomfortable" were used. Figure 8 shows the results of such a subjective assessment in one of the several tests during the sea trial, as compared with his thermal conditions when no supplementary heating was provided. It may be seen that at the end of the two hour dive, he was still "warm" and "comfortable"; a marked improvement to the "very cold" and "very uncomfortable" conditions which he normally experienced. Similar results were obtained with two CSIRO divers in open waters of 12 m depth.

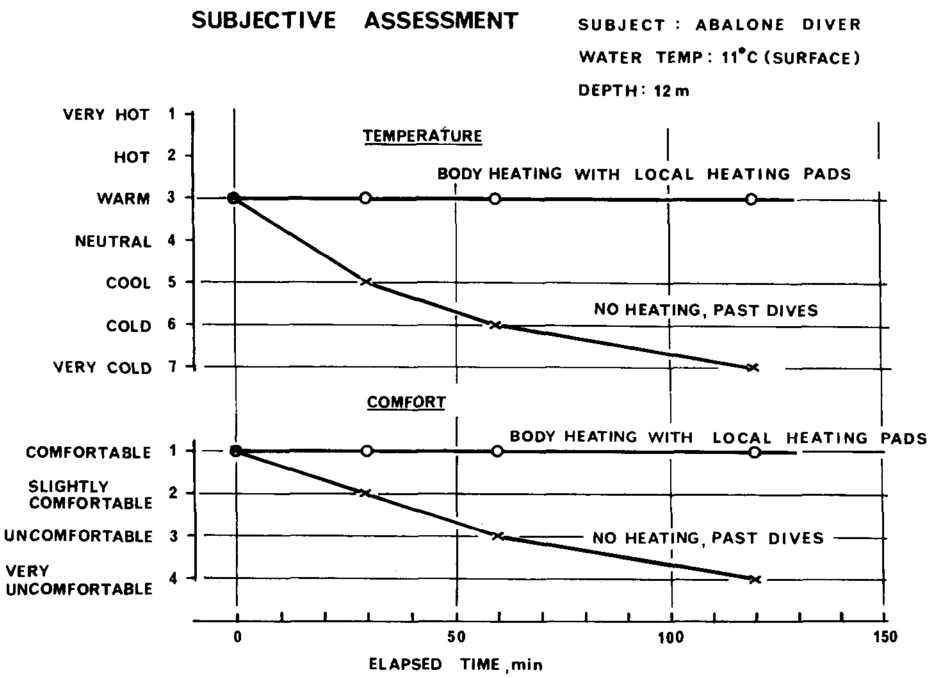


Fig. 8. Results of body heating trial.

At present, local heating pads with four hours useful heating duration have been successfully applied in open sea trials.

12. Application in estuary waters

One of the sea trials was conducted in estuary waters. The task for the diver was ship's hull defouling in the lower reaches of the Yarra river, near the port of Melbourne, Victoria. The location where the ship was moored was subject to tidal influence, thus the water was a mixture of fresh water and sea water. Because the task had to be performed in winter time, a severe cold stress problem existed.

Without heating, the dives in the 10 °C water were usually terminated after $1\frac{1}{4}$ h due to extreme cold.

For this particular trial, in addition to the normal twenty local heating pads, the diver was also loaded with weight salt packs to increase the salinity of the water within the torso suit. As a result, useful heating was obtained, allowing the diver to remain underwater for three hours. It is probable that these salt packs were completely dissolved in one hour.

A water sample was taken from the river and later its electrical conductivity was measured. The river water gave a salinity of 9000 ppm as compared with sea water's salinity of 35 000 ppm.

13. Conclusions

A simple, portable, inexpensive, and non-polluting local heating pad has been devised. Laboratory and open sea trials have shown that this method of local heating is suitable for body heating and hand heating, especially in shallow (less than 50 m) dives of up to 4 hours' duration.

The method is novel, as it uses a granular mixture of magnesium and iron particles which, on flooding with sea water, form a multitude of short-circuited electrolytic cells. The resulting exothermic reaction takes place locally where heating is required.

The lack of a suitable portable heating device for sporting and commercial divers to date suggest that there is merit in further investigation of this diver heating concept.

References

1 L. A. Kuehn and K. N. Ackles, Thermal exposure limits for divers, in C. E. Johnson, N. L. Nuckols and P. A. Clow (eds.), *Hyperbaric Diving Systems and Thermal Protection*, OED, Vol. 6, ASME Book No. H00134, 1978.
2 A. C. Vine, Physical Oceanography, in J. J. Myers, C. H. Holm and R. F. McAllister (eds.), *Handbook of Ocean and Underwater Engineering*, McGraw-Hill, New York, 1969, Ch. 1.
3 D. R. Burton and C. Y. L. Chan, unpublished data, 1977.
4 R. W. Long and N. E. Smith, Hot water: an economical approach to increase diver performance and safety in the offshore oil industry, *Offshore Technol. Conf., Paper No. OTC 1563, Dallas, 1972.*
5 D. C. Pauli, G. P. Clapper, E. L. Beckman and N. R. Frey (eds.), *Sealab II Project Group, Project Sealab Report* — An experimental 45 day undersea saturation dive at 205 feet, Dept. of Navy, Washington, D.C., 1967.
6 W. Penzias and M. W. Goodman, *Man Beneath the Sea*, Wiley-Interscience, New York, 1973.
7 E. L. Beckman, Thermal protective suits for underwater swimmers, *Mil. Med., 132* (1967) 195 - 209.
8 S. A. Black and S. S. Sergeu, Development of a self-contained heater for military divers, *IEEE Ocean 75 Conf., San Diego, CA, 1975.*
9 D. R. Burton and L. Collier, The development of water conditioned suits, *Tech. Note Mech. Eng. 400*, RAE, Farnborough, U.K., 1964.