The design, construction, and use of a practical ice-jacket for miners

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SYNOPSIS

Microclimate suits have been shown to be very effective in decreasing physiological strain in hot, wet environments, thus enabling men to work without risk in areas that would normally carry a high risk of heat stroke. In this paper, some design considerations in the development of the frozen jacket are described. Water complies with most of the desirable properties required of a coolant material for use in a microclimate suit. The Human Sciences Laboratory has developed a jacket in which ice is used as the coolant and which is designed according to the most acceptable anthropometrical characteristics. The jacket consists of an inner poncho-type waistcoat containing 28 water compartments. Over this is worn an insulating jacket, which minimizes warming of the coolant by the environment. Suitable refrigeration units have been developed to freeze the jackets underground. Laboratory tests have shown that these jackets are effective for about 2,5 hours, irrespective of the wet-bulb environment, when men are working at a moderate rate. Jackets should, however, be used only in environments in which the wet-bulb temperature is in the range of 32,5° to 35,5°C.

SAMEVATTING

Daar is bewys dat mikroklimaatpakke baie doeltreffend is om die fisiologiese spanning in warm, nat omgewings te verminder en so mense in staat te stel om sonder gevaar in gebiede te werk waar daar normaalweg 'n groot risiko van hittesteek bestaan. In hierdie verhandeling word sommige ontwerpaspekte in die ontwikkeling van die bevrore baadjie beskryf. Water beskik oor meeste van die gewenste eienskappe vir 'n koelmiddel om in 'n mikroklimaatpak te gebruik. Die Laboratorium vir Lewenswetenskappe het 'n baadjie ontwikkel waarin ys as die koelmiddel gebruik word en wat ooreenkomstig die mees aanvaarbare antropometriese eienskappe ontwerp is. Die baadjie bestaan uit 'n binneste poncho-tipe onderbaadjie met 28 waterafdelings. Hieroor word daar 'n isolerende baadjie gedra wat die verwarming van die koelmiddel deur die omgewing tot die minimum beperk. Daar is geskikte verkoelingseenhede ontwikkel om die baadjies ondergronds te bevries. Laboratoriumtoetse het getoon dat hierdie baadjies, ongeag die natboltemperatuur van die omgewing, vir ongeveer 2,5 uur effektief is wanneer mense teen 'n matige tempo werk. Die baadjies moet egter slegs in omgewings waar die natboltemperatuur binne die bestek van 32,5° tot 35,5°C val, gebruik word.

INTRODUCTION

Microclimate suits developed by the Human Sciences Laboratory have been tested in the Laboratory as well as in the underground mining environment[1-3]. It has been proved that they are able to decrease physiological strain significantly, thus enabling men to work safely in environments that would normally impose a high risk of heat stroke. The novelty of the idea has, furthermore, stimulated wide interest within the gold-mining industry, and a number of individuals and firms have expressed interest in improving certain features of the microclimate suit. Such active participation is, of course, welcome, but time and effort may be wasted unnecessarily if the work is uncoordinated and repetitious. This paper outlines some basic considerations in the design and development of the jacket, describes its construction, stipulates the refrigeration requirements, and gives some guidelines on the use of the jacket.

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COOLANT USED IN MICROCLIMATE SUITS

A number of methods of microclimate cooling are available. In order not to restrict the mobility of the wearer underground, those that require the use of a trailing hose were rejected. Garments in which cooling is provided by a phase change are better able to permit the necessary mobility. The features that are considered to be desirable in a coolant material for use in such a garment are that it should

(a) have a high latent heat,
(b) display a change of phase at a temperature well below normal skin temperature, but not so low as to cause trauma,
(c) be readily available and inexpensive,
(d) be non-poisonous and non-irritant,
(e) be easily and rapidly reconstituted,
(f) have a low mass, and
(g) be easily incorporated into a garment.

Two types of coolant material were originally considered suitable for the purpose: namely, those whose cooling action depended on their heats of hydration, and those that exerted a cooling action by their heat of melting. Initially, garments in which the heat of hydration was used to exert a cooling action looked promising as they would easily satisfy requirement (a). However, investigations revealed that, of the likely salts, only Glauber's salt was worth consideration. This compound satisfies requirements (a), (c), (f), and (g) but not (b), because it loses water of crystallization endothermically at 32,38°C, i.e., only 3 to 4°C below normal skin temperature. It is also very difficult to recrystallize and therefore does not satisfy property (e). Whether it is toxic, or whether it is an irritant is not known. The possibility of mixing Glauber's salt with other ingredients should be investigated.

Table I shows the cooling that is potentially available from the latent heat of various materials. No coolant has yet been found with properties better than those of ordinary tap water. When frozen, water has a high latent heat; it undergoes a phase change at 0°C, i.e., well below skin temperature; it is readily available, inexpensive, non-poisonous, easily frozen, and can easily be sealed in plastic bags for use in a garment. Its only disadvantage is its mass.

It is a common misbelief that brine has properties that make it a better coolant than water. The following calculation of the heat absorbed during melting and warming shows that brine has a lower melting point but not a greater cooling effect than water.

Total heat absorbed = heat absorbed during melting + heat absorbed during warming to skin temperature
= mass {latent heat + specific heat (35—melting temperature)}

	Ice	*Brine*
Latent heat	335	225 kJ/kg
Specific heat	4,2	3,8 kJ/kg
Melting point	0 °C	—9 °C

∴ Heat absorbed per kg:

Ice 335 + 4,2 (35—0) = 482 kJ

Brine 226 + 3,8 (35 + 9) = 393/kJ.

Pure water is therefore, in terms of the cooling offered per unit mass of material, 23 per cent more efficient than brine.

Solid carbon dioxide (dry ice) also warrants consideration as a material that displays phase change. It has a cooling capacity 50 per cent higher than heat of water, as is shown in Table I. However, at this stage its disadvantages overshadow its advantages. Dry ice sublimes at —78 °C and can therefore, especially when it is being handled, easily cause damage to skin. It is rather expensive, not readily available, and difficult to recycle, and the release of large quantities of carbon dioxide into any environment may be hazardous. Its potential should, however, not be overloooked, and further research in this direction should be encouraged.

TABLE I
MAXIMUM CAPACITIES OF VARIOUS AVENUES OF COOLING

Coolant	Initial Conditions	Energy transforms	Quantity required per 100 W of cooling
Water	At 0 °C	Heat to 35 °C	2,5 kg/h
Ice	At 0 °C	Melt, heat to 25 °C	0,75 kg/h
Liquid air	At —162 °C and 10 bars	Vaporize, heat vapour to 35 °C at 10 bars, expand to 1 bar, reheat to 35 °C, saturate with water vapour	0,67 kg/h
Air	Dry at 0 °C and 1 bar	Heat to 35 °C	11 kg/h ≈ 9,2 × 10³ l/h
Air	Dry at 0 °C and 1 bar	Heat to 35 °C, saturate with water vapour	2,8 kg/h ≈ 2,5 × 10³ l/h
CO_2	Solid at —78 °C	Sublime, and heat to 35 °C	0,55 kg/h

MATERIALS USED, AND CONSTRUCTION OF AN ICE–JACKET

Ice can be incorporated in a garment either in sealed compartments in the garment or in individually removable bags inserted into holders in the garment. If loose bags are used, those that develop leaks can be replaced. However, loose bags have disadvantages that outweigh their advantages. First, additional labour and time are required to put each bag into its holder. This would not only increase running costs and wear and tear, but would also decrease cooling efficiency. Secondly, loose bags are more likely to be used for 'unofficial' purposes. Thirdly, contrary to common belief, freezer equipment for loose bags could not be smaller than that required for the cooling of sealed garments. Special racks would have to be provided to allow free circulation of air around each bag, and it is basically the total mass of water to be frozen that determines the power requirements, irrespective of how the water is contained.

The microclimate suit currently in use* consists of an inner poncho containing 28 built-in sealed water bags and an outer insulating jacket. The inner poncho is made of a plastic-coated nylon material ('Wavelock'). It is double-walled, the joints and seams being formed by high-frequency welding. Three special eyes are provided at each end so that the jacket can be suspended from brackets in the refrigeration unit. The water pockets are made from polythene flat-lay tubing sealed by heat in sections of 100 by 120 mm. This material does not become brittle when the water is frozen. Prior to being sealed, each pocket is filled with approximately 160 ml of tap-water tinted with a dye. The 28 bags are sealed in their different positions between the two walls of 'Wavelock' material. The water bags are capable of withstanding an outside pressure of 8,3 bar without leaking.

*From Mine Safety Appliances Company (Africa) (Pty) Ltd, P.O. Box 1680, Johannesburg.

Good contact is maintained between the garment and the covered surface area of the body by the fastening of two (19 mm by 1,4 m) nylon straps that are supplied with the inner garment. In order to prevent skin damage due to contact with material at sub-zero temperatures, it is essential that a thick woollen or cotton vest be worn underneath the pre-frozen jacket.

The outer jackets are made of a woven nylon material coated with plastic that has a high resistance to abrasion and tear. The jacket is constructed by the stitching together of two layers of material with nylon thread, to enclose between them a 10 mm-thick sheet of plastic foam. To the bottom of the jacket is added a 100 mm-long skirt of the same strong nylon material, which serves as a flap over which the lamp belt is fastened to provide further sealing of the ice-jacket. Three pairs of nylon straps (each measuring 19 mm by 300 mm) and a waist band secure the outer jacket.

The dimensions of the inner garment are given in Fig. 1, and those for the outer insulating jacket for Bantu in Fig. 2. These dimensions were derived from the anthropometric data of Morrison *et al*[4]. A somewhat larger outer jacket is recommended for Whites.

REFRIGERATION OF GARMENTS UNDERGROUND

The poncho-type ice-jackets have been so designed that they can be

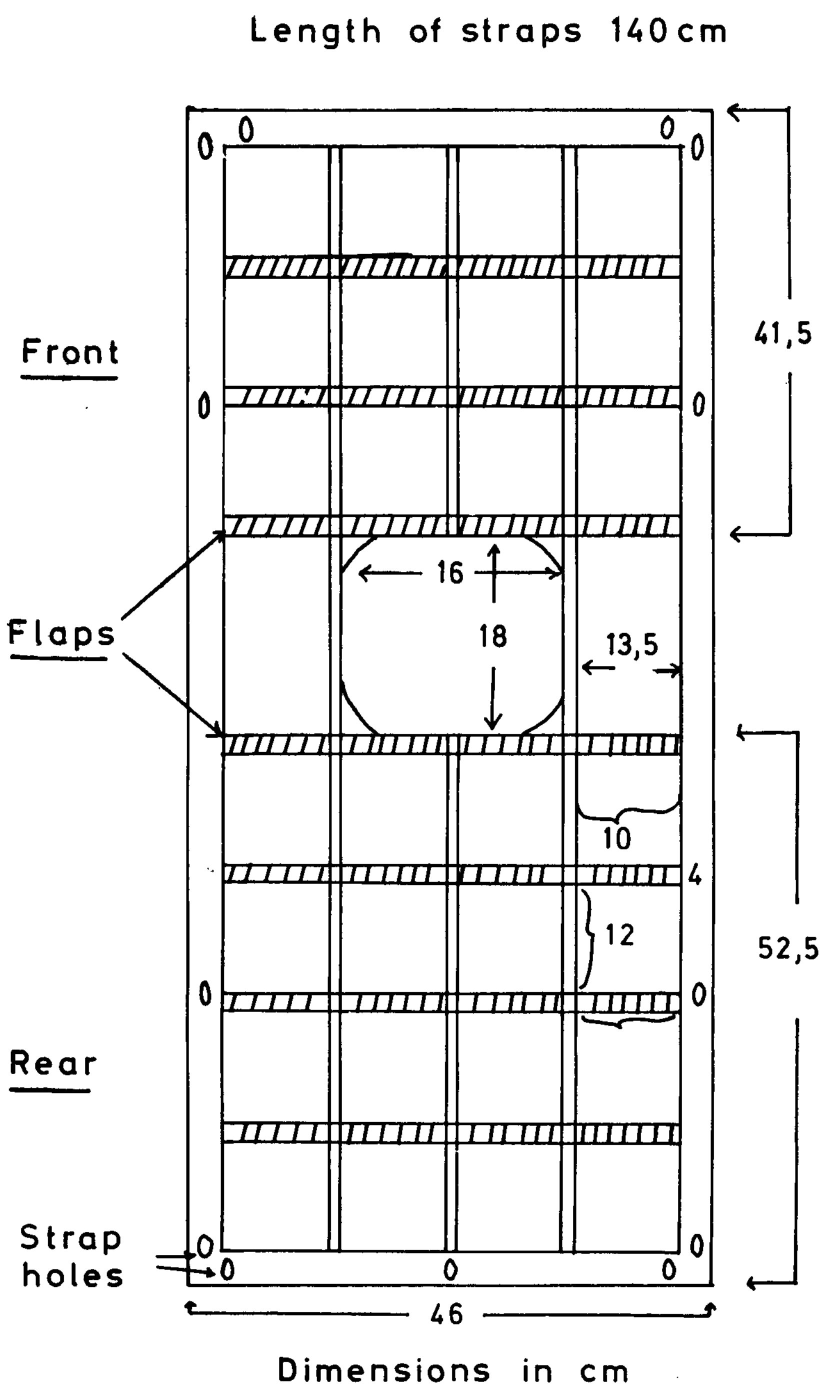

Fig. 1—Dimensions of inner ice jacket

hung next to one another on brackets in a freezer room or box. Freezer rooms, the walls of which are constructed of vermiculite bricks and insulated on both sides with 70 mm-thick foamed polystyrene, can be built underground. Alternatively, ready-made rooms can be purchased. These have double walls constructed of galvanized iron, the 150 mm cavity between which is filled with polystyrene, and are provided with a door. Walls, ceiling, and floor can be dismantled in sections measuring not more than 1,22 by 2,13 by 0,15 m for ease of transportation underground, and the room can be erected rapidly at the required site. The inside dimensions of a room capable of holding 60 jackets are 2,13 by 1,52 by 1,52 m. Such a room costs approximately R450. Units holding 120 jackets are also available. For reasons of logistics, where underground transport is difficult, it is recommended that several small units be acquired and erected near the working places. However, if the transport of frozen jackets is feasible, a large central unit could be erected, in which case polystyrene-insulated wooden, steel, or glass-fibre boxes capable of holding 8 to 10 jackets could be employed to transport the frozen jackets to the working places.

The cooling capacity of the refrigeration equipment necessary to provide the freezing temperatures inside the cooling boxes or rooms depends on the number of jackets to be frozen. For 120 ice-jackets to be cooled from an initial temperature of about 35 °C to 0 °C within a period of eight hours, a 4 kW unit will be required. The present cost of such a unit, excluding the box, would be approximately R2700*.

PERFORMANCE OF ICE-JACKETS

Period of Effective Protection

One of the major obstacles to the widespread use of pre-frozen ice-jackets and, for that matter, of all self-contained microclimate units, is the relatively short period for which they afford protection. The longer the period for which they can be made effective, the more acceptable the idea of microclimate cooling will be to mine managements. Two possible ways of increasing the period of protection lie in the provision of better insulation of the outer jacket or in the use of a larger amount of ice.

The results of tests conducted in the wind tunnel at the Human Sciences Laboratory indicated that the present outer jacket functions adequately; provided it is fastened correctly, hardly any cooling power is lost to the environment. Attempts to improve the sealing of the openings at the armpit and neck is therefore unnecessary and will merely add to the construction costs. The route by which most cooling power is likely to be lost to the environment is that past the waist

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*From Powell's Refrigeration Services, P.O. Box 59072, Kengray, Transvaal.

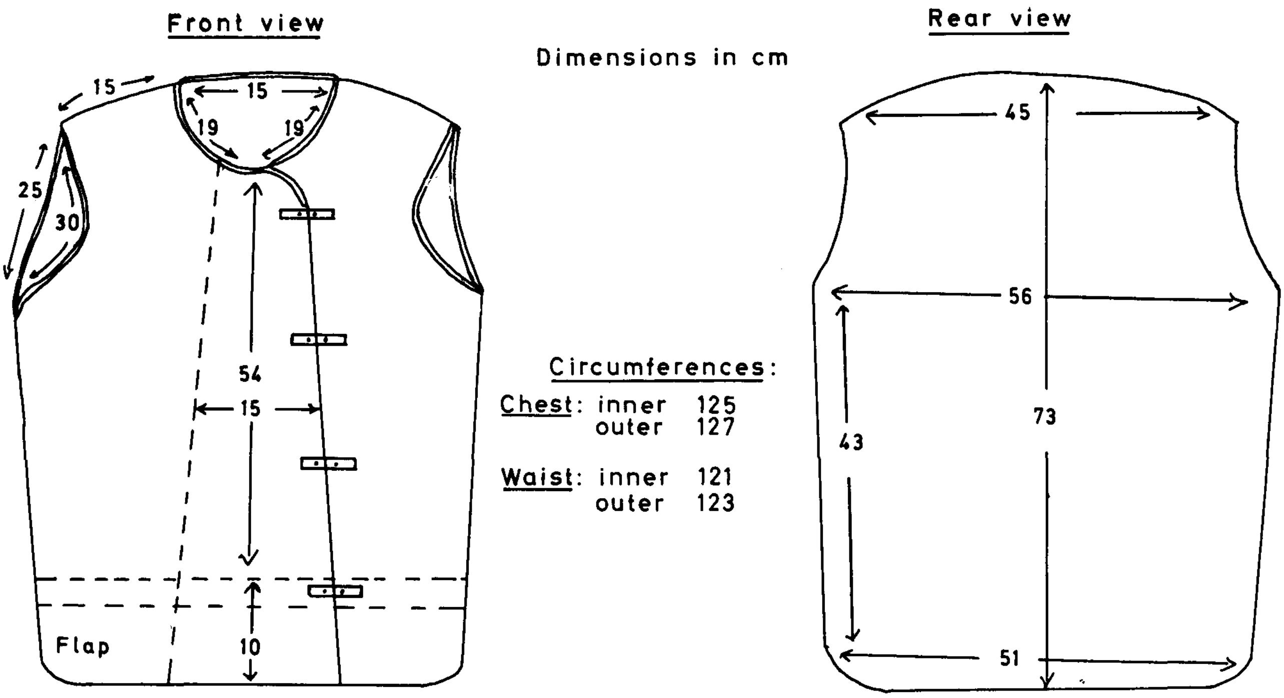

Fig. 2—Dimensions of outer jacket

of the suit, but ample provision has been made to minimize this possible loss. If the bottom strap is fastened securely and if a belt is worn over the skirt, such losses will not occur.

Increasing the water content of the jacket holds more promise, as can be seen in Fig. 3, in which the relationship between mass, work rate, and protection time is indicated. If a man is required to work at 35 W (1,0 litres of oxygen per minute) for a full 6-hour shift without changing jackets, the microclimate suit would have to contain 15 kg of water. It is doubtful whether this is feasible. The additional output of metabolic energy involved in carrying such a mass of water would result in a decrease in work performance. Mobility may also be restricted under such a load. The present jackets contain about 4,5 kg of water.

In the compilation of the data represented by the curves in Fig. 3, it was assumed that all metabolic heat was to be absorbed by the jacket. It should, however, be borne in mind, firstly, that body temperature will always increase with work rate even in a cold environment so that some heat will always be stored in the body rather than in the jacket, and, secondly, that some heat will still be lost from the exposed areas of skin not covered by the ice-jacket. A period of at least 30 to 40 minutes is normally required for body temperature to reach its exercise value, and it has been shown[1] that the total sweat rate from exposed areas of the skin is much the same regardless of whether an ice-jacket is worn. The periods of time for which the jacket is effective as given in Fig. 3 could therefore be increased with safety. In fact, experiments have indicated that the curves of Fig. 3 give an underestimate of 30 to 40 minutes in the period for which the ice-jacket is effective.

It has been shown that there is nothing to be gained by the use in the water pockets of a sponge-like material such as foam plastic to decrease the extent of movement of coolant in the pocket and thus prolong the period for which the coolant remains solid. No difference between normal bags and sponge-filled bags could be detected with regard to the time taken for them to heat up to a temperature of 30 °C.

As shown in Fig. 3, the rate of work plays an important role in determining the period of cooling of the ice-jacket. The greater the rate of work, the shorter the effective operating period. When the work rate is high (1,5 litres of oxygen per minute), a change of jackets will be necessary after two hours of work, and three pre-frozen jackets will be required per shift. However, few underground tasks can be classified as hard work. Of greater concern are those individuals who do not work even moderately hard and for whom the ice-jacket may be too cold. In such cases, extra garments and even woollen jerseys should be worn underneath the ice-jacket.

Performance at High Environmental Temperatures

Wet-bulb temperatures of up to 35,6 °C had very little influence on the period of time for which the microclimate suits are effective. It has been shown that, even at this high temperature, the ice-jackets are effective for about 2,5 hours.

Although the period of effectiveness of the jackets (2,5 hours) at these higher wet-bulb temperatures is about the same as it is at 33 °C, studies in the laboratory have indicated that physiological factors determine the upper limit of environmental temperature at which men can work safely in microclimate jackets. Table II gives an indication of the average fourth-hour rectal temperatures and heart rates of men working at various wet-bulb temperatures and at an oxygen consumption rate of 1,0 l/min. Jackets were renewed after 2,5 hours of work.

TABLE II

PHYSIOLOGICAL CONDITION AT DIFFERENT WORKING TEMPERATURES

Working temperature Wet-bulb °C	Dry-bulb °C	4th h rectal temperatures °C	4th h heart rates beat/min
35,6	37,2	38,8	150
35,0	36,7	38,3	140
34,25	36,1	38,2	130

It seems reasonable to expect the rate of cooling from those areas of the body surface not covered by the jacket to decrease at high wet-bulb temperatures. Both rectal temperature and heart rate increase with increase in wet-bulb temperature. Rectal temperatures higher than 38,8 °C in the underground situation are dangerous, and it is recommended that microclimate cooling by means of ice-jackets should not be generally applied in stopes in which the wet-bulb temperature is greater than 35,6 °C. More research will have to be done on the relationship between exposure time and body temperature if men are to be required to work at wet-bulb temperatures of more than 35,6 °C.

USE OF ICE-JACKETS UNDERGROUND

Although unacclimatized personnel, especially supervisors, would benefit considerably from wearing pre-frozen jackets in environments in which the temperature is as low as 31 °C wet-bulb, it has been found that highly acclimatized men will not readily use the jackets when the wet-bulb temperature is below 33,0 °C unless they are required to work hard continuously. It is therefore recommended that these suits should be used only at environmental temperatures of 33,0 °C wet-bulb and above.

It is essential that the operation and checking of the freezing unit should fall within the jurisdiction of the mine ventilation department. The operation of the scheme should be the responsibility of the miner, under the direct supervision of the shift boss. A team leader should be put in charge of the scheme. His personal responsibilities should be:

1. handing out frozen jackets,
2. assisting Bantu in fastening the jackets correctly,
3. collecting all jackets after use,
4. spraying and cleaning all jackets with water to remove sweat and grit,
5. hanging up jackets in the freezer unit,
6. collecting, cleaning, and hanging up all overjackets at the end of shift,
7. distributing water and/or mid-shift feed,
8. checking for leaks and replacing leaking bags (no

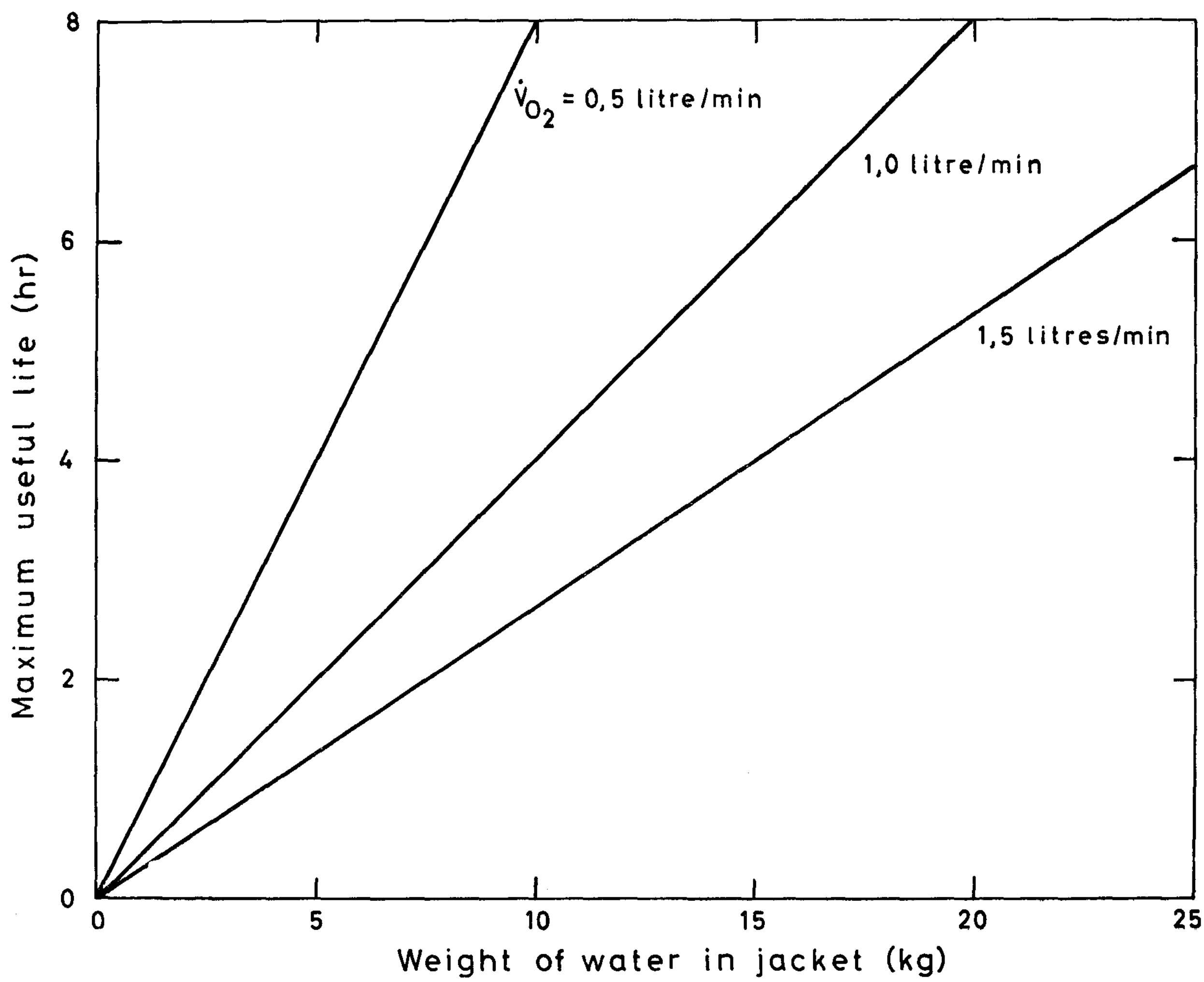

Fig. 3—Maximum useful life (in hours) assuming all metabolic heat is absorbed in the jacket and no heat is stored in the body