



are inherent safety problems e.g. water spillage, and the worker is restricted in movement due to auxiliary equipment required to circulate the fluid.

Thus research has now been directed at regional body cooling since it is known that regional cooling can reduce thermal stress (Kerslake,1955). However, although minimal cooling will improve comfort, significant benefits will accrue only where cooling is sufficient to prevent a rise in body core temperature (Kuno, 1956).

In the 1960's interest focussed on cooling the torso (Esposito, 1970) and on head cooling (Brouha,1960; Konz and Duncan, 1969). The latter appears to be particularly effective, however, some researchers claim that cooling so close to the hypothalamus is not a very good idea as the thermo-regulatory 'control centre' is situated there (Personal Communication, R Goldman).

#### **PHASE CHANGE COOLING GARMENTS**

A recent literature search has shown that information on phase change cooling garments is scattered through physiological, medical, engineering and ergonomic journals and books. Additional information appears in government and industrial documents with limited distribution. An attempt will be made to present some of this information from an ergonomic point of view and with due regard to the objectives of the present study.

Phase change garments include dry ice and ice (water) cooled clothing. These garments remove heat by forming a body core-skin temperature gradient due to their cooling effect by latent heat of sublimation and latent heat of melting. The heat exchange is thus primarily due to conduction.

#### **DRY ICE COOLING GARMENTS (DICG)**

A considerable amount of research has been carried out on the design features of dry ice cooling vests, their effectiveness in terms of reducing thermal load, their reliability and the economics of using them as portable cooling micro-environments.

One of the earliest studies (Petit et al, 1966) reported that subjects working in Belgian mines and wearing DICGs had heart rates which were 17 beats/min (bpm) lower. Konz, Hwang, Perkins and Borell (1974) also reported that rectal and skin

temperatures in the Petit et al study were 0.2°C and 1.8°C lower respectively when wearing DICGs.

A large amount of research has also been done by Konz and his co-workers at Kansas State University. They have used iterative design principles in an attempt to identify the most effective design for a DICG in terms of cooling and comfort.

Dry ice removes heat by conduction. When dry ice sublimates i.e. changes from solid to carbon dioxide (CO<sub>2</sub>) gas the latent heat of sublimation has a cooling effect which removes 137KCal/Kg of heat energy. A Japanese study by (Miura et al,1971) showed no appreciable difference in body core temperatures but heart rates were 5 to 10 bpm lower and skin temperature 2°C lower, when wearing DICGs, in subjects undergoing a step test for two hours.

Konz, Hwang, Techapatnarat and Tang (1979) reported a study carried out by (Duncan, 1975) on two males pedaling a bicycle ergometer for 60 minutes, in 11 experimental sessions. One session involved wearing no garment in a neutral environment; two sessions involved wearing no garments in a hot environment; and eight sessions involved using a dry ice jacket in similar environments. The eight sessions incorporated two levels of temperature (35 and 45°C), two levels of pocket insulation (low and high) and two levels of dry surface area (low and high).

The garments had 12 individual slabs of dry ice in 4 pockets, each with three slabs aligned vertically but kept separate by a plastic holder. (Four pockets, each holding 3 slabs are cheaper to manufacture than twelve pockets). Insulation was obtained in part by using plastic air bubbles. The low insulation was recorded as 7.1W/sq.m while the high insulation measured 2.2W/sq.m. The low surface area had 12 square slabs totalling 800 sq.cm while the 'high' had 12 square slabs with a total of 1600 sq.cm.

Duncan (1975) found that the mean heart rate using a dry ice jacket was 16 bpm lower than without it. The mean T<sub>c</sub> was 0.59° C lower with the jacket than without the jacket. The core temperature rose by 0.88°C for the high insulation garment and by 0.71°C for the low insulation garment; and by 0.83°C for the low surface area compared to 0.76°C for the high surface area.

The findings reported by Konz et al (1979) and Duncan & Konz (1975) suggest that the dry ice jacket certainly helped to maintain thermoneutrality. However there was a

problem of intense cooling near the lower slabs due to greater sublimation i.e. the cold CO<sub>2</sub> gas from the upper slabs sank down and blanketed the lower ones.

Duncan (1975) found that the mean metabolic rate, measured at 30min. after heat exposure began, while pedaling the ergometer at a controlled speed and torque was 364w; however, when wearing the dry ice jacket, it was 450w. Guyton (1956), when describing shivering, said "non-rhythmical impulses do not cause actual shaking but just increase muscle tone which in turn increases metabolic rate by 50 to 100% without any noticeable shivering". Since no shivering was reported by Duncan, Konz et al (1979) thus hypothesise that the subjects' skin was being overcooled, and therefore resulting in a higher metabolic rate, with no obvious signs of shivering.

To investigate this Konz et al (1979) carried out an experiment using two quilted garments in the form of a jacket and jump-suit. They concluded that the jacket would be a much more practical solution for industrial use, as it is easy to don and doff, than a jump-suit. Using varying levels of insulation they concluded that the suit with the highest insulation proved to be the best in maintaining a lower core temperature. This suggested that a reduction in the intensity of the cooling seemed a desirable feature of the jacket. Though the T<sub>c</sub> was affected there was no significant effect of insulation on the heart rate.

### **FROZEN WATER GARMENTS (ICE COOLED GARMENTS (ICG))**

A considerable amount of research into the use and design features of ice cooling jackets has been carried out to date. A large proportion of the work has been done at the human science laboratories of the South African Chamber of Mines. The literature search also showed interest in the use of ice jackets in the USA and in Europe.

From the articles reviewed, aspects of the use of ICGs as personalised cooling systems have been investigated varying from the different design features and their effectiveness in reducing heat stress on the worker, to issues such as using ICGs in the work situation.

The review to follow has been split into three broad areas:

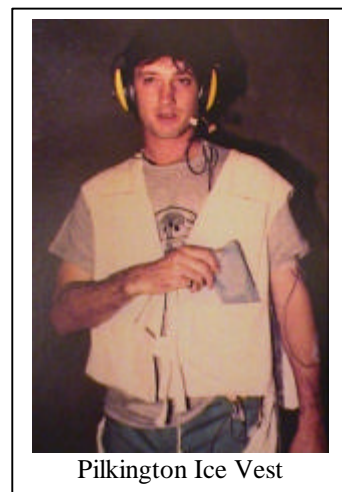
1. the psycho-physiological findings associated with ICGs;

2. the design features such as fastenings, fit and shape etc. and
3. other ergonomic considerations.

The review is primarily of articles published in the English language though it was observed that there were articles available in Japanese, German and French but these were not used as their translated versions were not available.

### **PSYCHO-PHYSIOLOGICAL ASPECTS OF ICGS**

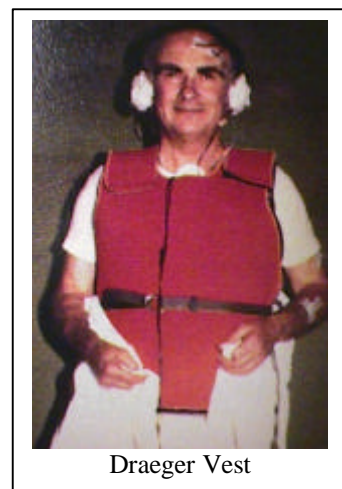
The use of ice jackets in reducing heat load on men working in hot conditions has been investigated by Strydom, Mitchell, Van Rensburg and Van Graan (1974); by Van Rensburg, Mitchell, Van Derwalt and Strydom (1972) in the South African gold mines. By DeRosa and Stein (1976) for mines rescue teams in the USA; by Sweetland & Love (1974) in the British Mines Rescue Service. By Kamon et al (1986) for the US nuclear industry; and by Mucke (1982) on behalf of the German Mining Industry.



Pilkington Ice Vest

The garments used in most of the studies have been sleeveless jackets filled with sealed water pockets, or in some cases 'pockets' of water which are then inserted in the jackets after being frozen in commercial freezers (freezing time 6 - 8 hours).

Pasternack (1982) has reported some work carried out on the Draeger jacket by Engel in a laboratory experiment simulating hot conditions. The subjects performed an exercise task on a treadmill utilising 150w of metabolic energy. The subjects worked for half an hour and rested for half an hour. The cooling vest was changed every hour.



Draeger Vest

Engel (1982) found that the Draeger jacket retarded the rise in core temperature and heart rate. He also found that sweat loss was reduced in subjects when wearing the Draeger jacket.

Pasternack (1982) carried out further research on the Draeger jacket under identical conditions as those reported by Engel, but shortened the work and rest phases to 15 minute intervals. Pasternack found that in the case of the 15 minute interval the subjects core temperature drops much less then in the 30 minute interval experiment.

The climatic conditions and type of work under which these garments were tested are summarised in Table 1. As can be seen the climatic conditions range from low to severe heat stress. All the studies report a retardation of the progressive rise in core temperature during their effective cooling period, thus permitting the worker to work for longer periods of time in stressful conditions.

TABLE 1 SUMMARY TABLE OF FINDINGS FROM SOME OF THE STUDIES

Group	Weight Jacket	Of Effective Time	Climatic Condition (DB/WB)	Work
Strydom et al (1973,1974)	4.8 kg	2.5 hrs	35.5/33.8	Normal mine to 37.2/35.6 work
Sweetland & Love (1974)	6.0 kg	1 hr	40.0/39.0 to 54.0/39.0	Carrying wood blocks
DeRosa & Stein (1976)	4.5 kg	2 hr	30.1/26.7 to 45/31.7	Treadmill Walking 5.6 km/hr
Mucke (1982)	2.75 kg 3.50 kg	1 hr	40/22	Treadmill walking 4 km/hr at 3 gradient
Engel (1982) (30 minute work/rest cycles)	3.8 kg	1.25 hr	40 DB	Treadmill at 3.3 km/hr at 3 gradient
Kamon et al (1986) (5 minute work/rest cycles)arm cranking	3.8 kg 6.2 kg 7.2 kg	1.25 hrs 2.5 hrs	35/55	Treadmill at 25 mph 3 mph & 5min

Subjective perceptions also appear to be reported positively in the literature. For instance Johannes, Van Graan, Strydom and Van Heerden (1976) reported that workers were much more cheerful and positive when wearing ICGs, even at the end of 6 hour shifts. In another group of studies the subjects reported feeling much more thermally comfortable when wearing the cooling garments (DeRosa & Stein, 1976; Van Rensburg et al, 1972; Van Graan, 1975; and Sweetland & Love,1974).

Strydom, Mitchell, Van Rensburg, and Van Graan (1973, 1974) and Mucke (1982) have shown that the weight of the garment significantly increased the energy expenditure of the wearer, thus reducing the overall effectiveness of the garment. They further noted that the bulk of the ice packets reduced the wearers mobility in some situations.

The physiological findings further confirm the reduction in thermal load e.g. DeRosa and Stein (1976) also found the heart rate to increase at a lower rate and to stabilise after 30 to 60 minutes at values below the permissible exposure limits.

From the psycho-physiological point of view the jackets have been found to reduce the stress imposed on the worker by the metabolic and environmental heat loads. Some of the studies have reported the ICGs to be acceptable to the worker. The ICG increases the exposure time of the wearer to heat stress while maintaining the physiological parameters within the limits set by the ACGIH and WHO.

#### **DESIGN ASPECTS**

One important drawback of ICGs is their limited time of usefulness as reported by various researchers. Strydom et al (1973, 1974), Pasternack (1982) and Gillies (1972) suggest that for a person to work a shift of 6hrs at least three jackets or ice packs are required. This can be seen from the effective time in Table 1 which varies from 1-2.5hrs. Another problem with the ICGs is that the design of the garment and the bulk of ice around the torso reduces the functional movements of the wearer. However, being portable systems, they allow the wearer to walk freely from one place to another.

In two important papers by Strydom et al (1973, 1974) the same teams of researchers discuss important design aspects of the ICG. The features desirable in a coolant are:

- A. high latent heat;
- B. to exhibit a phase change 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.

To date it seems that water meets these criteria best since it

1. has a high latent heat;
2. undergoes a phase change at 0°C, well below skin temperature;
3. is readily available, in-expensive, non-poisonous; and finally
4. it is easily frozen and sealed into packets.

Its only disadvantage is its mass. Solid CO<sub>2</sub> is worth mentioning once more in that it has a cooling capacity 50% higher than water. However, its disadvantage is that it sublimates at -78°C and can, therefore, cause "cold burns" to the skin. Additionally it is expensive, not readily available and can be poisonous if CO<sub>2</sub> builds up in an enclosed area.

Strydom and his colleagues go on to describe the construction of an ICG supplied to them by MSA Ltd. which has 28 built-in sealed water pouches in the inner poncho which is made from plastic coated nylon (Wavelock). Each pocket of water is made from polythene, flat-lay tubing sealed under heat as this material does not become brittle when frozen. Each pocket measures 100 by 120 mm and contains 160 ml of water. The 28 bags are sealed into different positions between the layers of wavelock material and are capable of withstanding a pressure of 8.3 bars before leaking. Straps are used to ensure good contact between garment and skin. They suggest that to prevent discomfort and skin damage a thick woollen or cotton vest be worn underneath the jacket. The suit was designed using anthropometric data from Morrison et al (1968) on Bantu mine labourers.

## **OTHER ERGONOMIC CONSIDERATIONS**

Strydom et al (1973, 1974) describe various units which they used to freeze jackets underground. Their purpose built jackets were designed so that they could be hung next to one another on brackets in a freezer room or box. The boxes were designed so that they could be easily dismantled, put together and transported and could hold

about 60 jackets. This type of a box they said would cost about R450 (approximately £100). They suggest that where underground transport is difficult it is recommended that several small units be used close to the working place. However, if the transport of ICGs is feasible, a large central unit could be erected. In this type of a situation a polystyrene insulated wooden, steel or glass fibre boxes capable of holding 8-10 jackets (jackets remain frozen in box for up to 6 hours) could be used to transport the frozen jackets to the working place.

They further costed the price of a unit that would hold 120 jackets and freeze these jackets from 35°C to 0°C within an 8 hour period requiring 4 kw at R2,700 (approximately £540).

One problem which has already been mentioned earlier is the limited period of usefulness. A solution to this, Strydom et al suggest, is to insulate the ice jacket or use larger amounts of ice.

Strydom et al (1974) claim that unacclimatised personnel, such as supervisors, would benefit considerably from wearing pre-frozen jackets in WB temperatures as low as 31°C. However, they also note that highly acclimatised men will not readily use the jackets when wet bulb (WB) temperature is 33°C or less unless they are required to work hard continuously. They thus recommend that these jackets should be used only at environmental temperatures of 33°C WB and above.

Strydom and his co-workers have looked at some important ergonomic issues concerning ice jackets and their uses; for instance, the design of the garment, the cost of associated work, the uses of ice jackets and the possible ways in which the use and management of these garments is carried out. They suggest that a team leader should be in charge of issuing, assisting the men, and maintaining the jackets. The leader should also be responsible for observing workers and instructing them when to change the jackets. All these factors could have some effect on work organisation and presumably on productivity.

In 1976 Johannes et al investigated the use of ICGs under practical conditions in stopes. Their aims were:

- (a) to determine the acceptability of the pre-frozen jackets to workers;
- (b) to observe the influence of jackets on production;

(c) to determine the costs involved in introduction of ICGs and compare these costs with those of cooling the environment to acceptable levels and;

(d) to test the ICG for wear and tear over long periods.

They installed 2 freezer units at a cross cut near the entrance to an experimental stope. The stope was 8m high. For the duration of the experiment the usual stope cooling and ventilation practices were discontinued, allowing the ambient conditions to rise to temperatures of 34.2-35.5°C WB and 34.8-36.0°C dry bulb(DB).

The labour force consisted of 24 machine men, 12 winch drivers, 17 general workers and 7 team leaders. All these workers had to wear the ICG when they entered the stope.

The workmen were given freshly frozen inner jackets after 2-2.5 hours. No physiological measures were taken but the researchers questioned the labourers frequently about the effectiveness of, and their attitude towards, the pre-frozen jackets. The garments were checked weekly for wear and tear.

Production figures were obtained for two months preceding the use of the ICG and for three months during the experiment.

They found that despite the fact that environmental conditions were more severe and the numbers of men working per shift was lower during the experimental period productivity increased by approximately 25 per cent and continued to do so until the third month following the introduction of ICGs.

Most of the men - 90 per cent, both white and black, spoke highly of the ICGs. Some of the men refused to wear the ICGs initially but wore them when they were told that that was a mine's requirement and no-one could enter the stope without an ICG. From their methodology one wonders if the 'frequent' questioning/observation was having a Hawthorne effect as noted by Mayo and his team at the Hawthorne Electric Works in the USA (Blackler and Shimmin, 1984). Assuming this is the case then perhaps further investigation ought to be carried out as the increase in productivity would obviously be a positive aspect in influencing the introduction of ICGs.

The findings that the initial and maintenance cost of ICGs were only 10 per cent of the costs incurred in cooling the air by ventilation would suggest that the use of ice jackets would be a viable consideration for any management team.

The durability of the jackets was found to be good though they identified certain features such that the seams at the shoulders gave way after four months. The first set of vests rotted through fungal infestation. However, these problems were overcome by strengthening the shoulder seams and by using a fungicide to clean the ICGs.

Once again certain important ergonomic aspects concerning the use of the jackets have been researched by Johannes et al as shown above.

From the literature reviewed so far it would seem that ICGs are a viable proposition compared with using conventional methods of reducing heat stress in workers exposed to high ambient temperatures. The ICGs it seems increase productivity, are cheap to implement and seem obviously to be reducing the heat stress to the extent that they help maintain, under given conditions, the body core temperature and heart rate within the limits defined by the NIOSH, ACGIH and WHO.

It would also appear from the literature that the criteria laid down by the ACGIH, WHO and NIOSH concerning work-rest patterns and TLVs could be reviewed for the use of ICGs in thermally stressful environments. The reason for this being that the ICGs appear to provide an increased margin of safety in protecting the men from thermal stress. However, further investigations would be required before any changes can be made to the recommended criteria.

Certain ergonomic features concerning ICGs and their uses do not seem to have been investigated i.e. mobility and manoeuvrability when workers are wearing the ICGs. The need for training the workers, changing facilities and the ability to recognise when it may be dangerous to continue working and when to stop after using the ICGs need further consideration too.

Another consideration is that not all men will be working at the same rate though the environmental conditions under which they are working will be roughly the same. For example Strydom et al (1973) have noted that some workmen are prone to suffer excessive cooling because they might be doing a sedentary job operating machinery compared with their counterparts who may be performing moderately heavy tasks. Here there is great risk that the person whose workload is low may suffer hypothermia.

From the literature (Konz et al, 1979) it also appears that the wearing of ICGs increases energy expenditure. This point requires further investigation as other studies have not shown or investigated this particular aspect.

Johannes et al (1976) concluded that the use of ICGs should never be regarded as the only answer to hot underground environments. Strydom et al, (1974) concluded that ICGs should only be used for WB temperatures of 33°C and above. Furthermore, they suggest that the ICG should not be used if conventional means are viable and that use of ICGs should be made only in emergency situations or as a temporary measure.

However, Kamon et al (1986) point out that ICGs could play an important part in reducing thermal stress on men working in the nuclear industry and that the ICG's would also increase their productivity/efficiency. Pasternack (1982) suggests that the ICG may be beneficial in hot work sites such as mines, coking plants, metallurgical plants, power stations and by firemen, and both Kamon et al and Pasternack suggest that ICGs can be used well with other protective clothing e.g. breathing apparatus.

From the literature reviewed so far it seems that ICGs are both cost effective and physiologically beneficial to the worker.

### **CONCLUDING REMARKS**

This literature review was carried out as part of a research project for a Masters Degree in 1988 at the University of London. Ice jackets may be useful in situations where the total flow of heat into the ice (cooling garment) jackets exceeds the flow of heat into the environment suggesting that this type of cooling methods may be more appropriate in humid conditions (personal communication from Geoff Crockford, 1998).

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