

Cooling and Respiratory Protective Device for Mine Rescue Teams

Dr. A. W. Pasternack

Department of Development • Breathing Protection Apparatus • Draegerwerk AG Luebeck • Germany

ABSTRACT

The cooling and respiratory protective equipment which is designed for operations in ambient atmospheres of 60 to 70°C at very high relative humidities enables mine rescuers to rescue people and salvage property from climates which could be entered without protective clothing for a short time only, if at all. This personal protective equipment is a step toward humanizing work life.

In addition to general theoretical considerations and notes on design, a detailed description of the construction of the equipment and of its function forms the conclusion of the article.

INTRODUCTION

In many work areas, such as smelting plants and power stations, glass and ceramics industries, mine rescue and fire brigade operations, atmospheric conditions arise which necessitate wearing suitable cooling garments. The function of cooling garments is to reduce the physiological stress on persons working under certain atmospheric and work conditions. This is accomplished by reducing heat transfer to the body at high ambient temperatures and by better dissipating the metabolism energy produced when performing work. The qualitative effect of stress reduction when cooling garments are worn may be explained, in a somewhat simplified manner, by

looking at the coolant (in the cooling garment) as a permanent heat sink, into which the heat quantities from the ambient air and from the body disappear without accumulating (Figure 1). In reality, the physiological stress relief only may be accomplished partially or over limited periods of time due to the mass and cooling capacity of the coolants, whereas the greatest possible physical mobility must be provided at the same time.

Nevertheless, individual cooling is important in all those instances when overall cooling cannot be implemented or is uneconomical, especially in cases of firefighting. For mine rescue purposes Draegerwerk AG, Luebeck, West Germany, has developed a cooling and

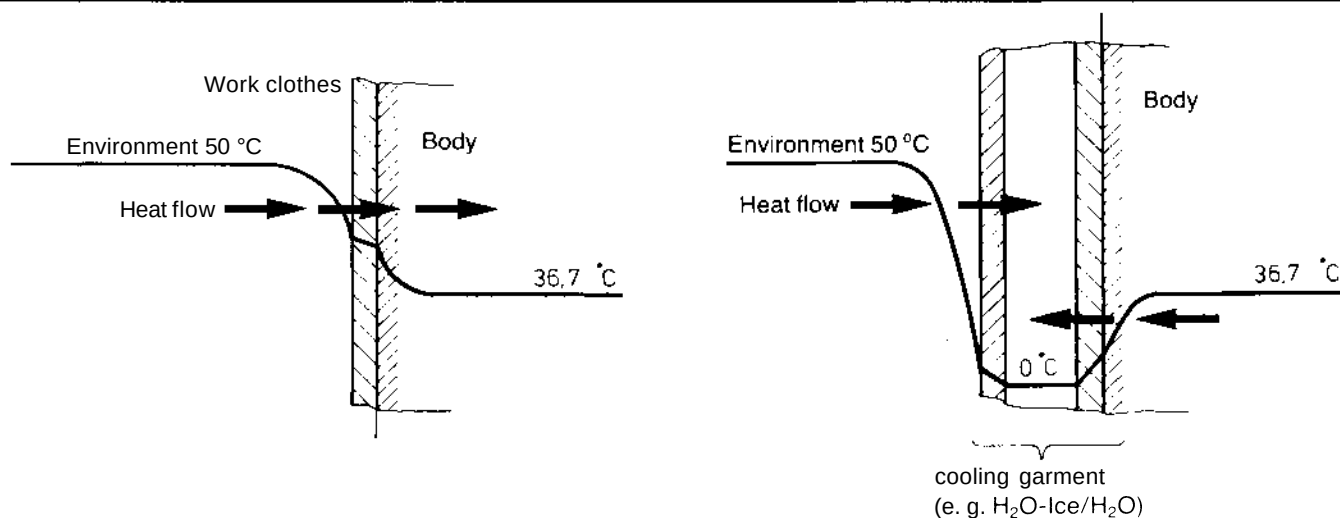


Figure 1

Qualitative curves of the temperature and heat flows with and without cooling garment.

respiratory protective equipment which enables mine rescuers to rescue people and salvage property from climates which could not be entered without such equipment.

GENERAL REQUIREMENTS REGARDING COOLING GARMENTS

In addition to offering good wearing properties, the garment must provide reliable functioning over long periods of use. Unrestricted mobility is called for in many work areas. Only self-sustained cooling systems may be used in these cases, because it is difficult to implement an external supply through connecting lines.

In addition, safety engineering aspects must be taken into account when selecting the cooling garment. Although they are definitely interesting from the energy point of view, coolants with toxic or explosive properties can be used only in perfectly closed circuits; they are not suitable for cooling garments to be worn individually.

An important factor for successful application of cooling garments is their acceptance by the persons wearing them. A prerequisite is that the wearing properties are optimum, i.e. that the mode of wearing the garment, the cooling effect, and the restrictions of mobility have been solved satisfactorily. The person wearing the cooling garment must always have the feeling that the garment provides stress relief.

The mechanical stresses, to which the cooling garments are exposed, are also of great importance. For instance, a high degree of heat reflection, good insulation, high degree of gas tightness, low inflammability of fabrics, etc. are required in addition to a high degree of mechanical resistance.

Satisfying so many requirements is possible only by finding a weighted compromise.

HEAT EXCHANGE WITH THE ENVIRONMENT UNDER PHYSICAL STRESS

The heat exchange between the human body and the environment should always have a magnitude and direction to maintain a largely constant body temperature. Temperatures outside the 24 to 45°C range are not tolerated by the human body (Newburg, 1975). Thermal equilibrium is achieved by heat regulation mechanism over wide ranges of ambient conditions. For instance, if the environment is cold, heat generation by the body is increased by reducing blood circulation through the skin, thereby diminishing the skin

temperature which is responsible for the heat loss. If there is a warm ambient atmosphere, heat dissipation by radiation and convection is supplemented by perspiration. Thermal equilibrium in the body is then achieved by heat dissipation as a result of increased blood circulation in the skin. This shows that the body is capable of tolerating fluctuating ambient conditions to a large extent, although sensations of discomfort may arise.

As a rule, a sensation of discomfort is preceded by the body being cooled or heated. Studies conducted by Kerslake (1978) show that perspiration of a sitting person begins at skin temperatures over 34.5°C, whereas the metabolic heat generation as a result of thermal regulation sets in at a skin temperature of about 30°C. A natural distribution of the

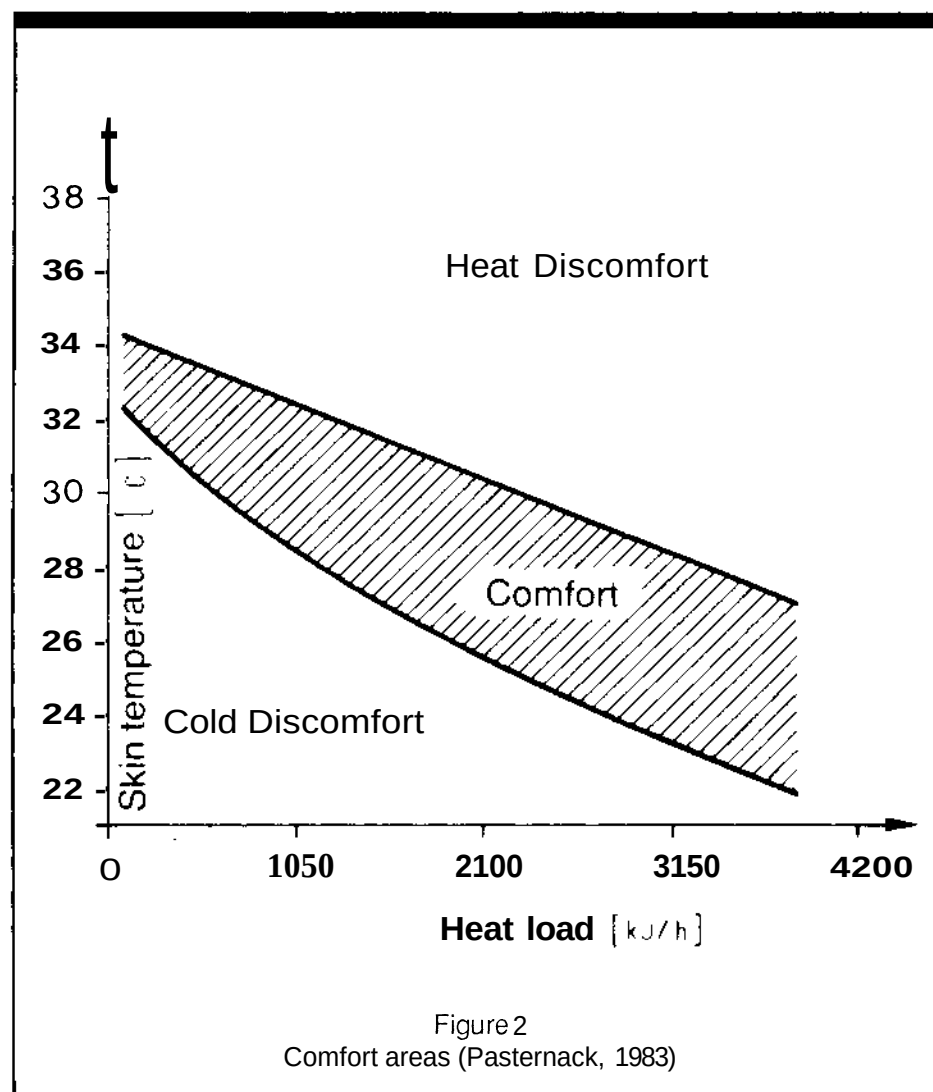


Figure 2
Comfort areas (Pasternack, 1983)

skin temperature, resulting in 33°C as a mean value, is a prerequisite for an optimum sensation of well-being (Pasternack, 1978).

The resultant requirement with respect to personal air conditioning systems must therefore be:

Creation of a thermal sensation of comfort within a wide range of ambient conditions, while taking into account the work to be performed. Generally speaking, and neglecting some insignificant parameters, the following correlation can be formulated regarding heat exchange in the equilibrium state between a person and the ambient air:

$$\dot{Q}_M = \dot{Q}_R + \dot{Q}_K + \dot{Q}_V \quad (1)$$

Dissipation of the body heat ($\dot{Q}_M$) is thus brought about by radiation ($\dot{Q}_R$), convection ($\dot{Q}_K$) and evaporation ($\dot{Q}_V$). Heat is transported by evaporation in two ways. Since the skin is permeable to water vapor, some of the heat generated is dissipated by evaporation of perspiration, while a small portion is dissipated by the respiratory organs. Convective heat exchange is accomplished primarily by the temperature difference between the skin and the ambient air and by the motion of this air. Due to the relatively small temperature difference between the skin and the ambient atmosphere, energy exchange due to radiation is of minor significance only. An important parameter for the processes of thermal regulation in the body is its internal thermal conductivity which determines the thermal flux from the core of the body to the periphery and thus affects the design of cooling systems. The skin temperature is therefore of prime importance to the dissipation of heat from the body and to the subjective sensation of well-being. Results obtained so far with respect to the subjective comfort sensation can be summarized to the relations shown in Figure 2.

This shows that the skin temperature must be lowered with increasing thermal stress on the body in order to achieve a

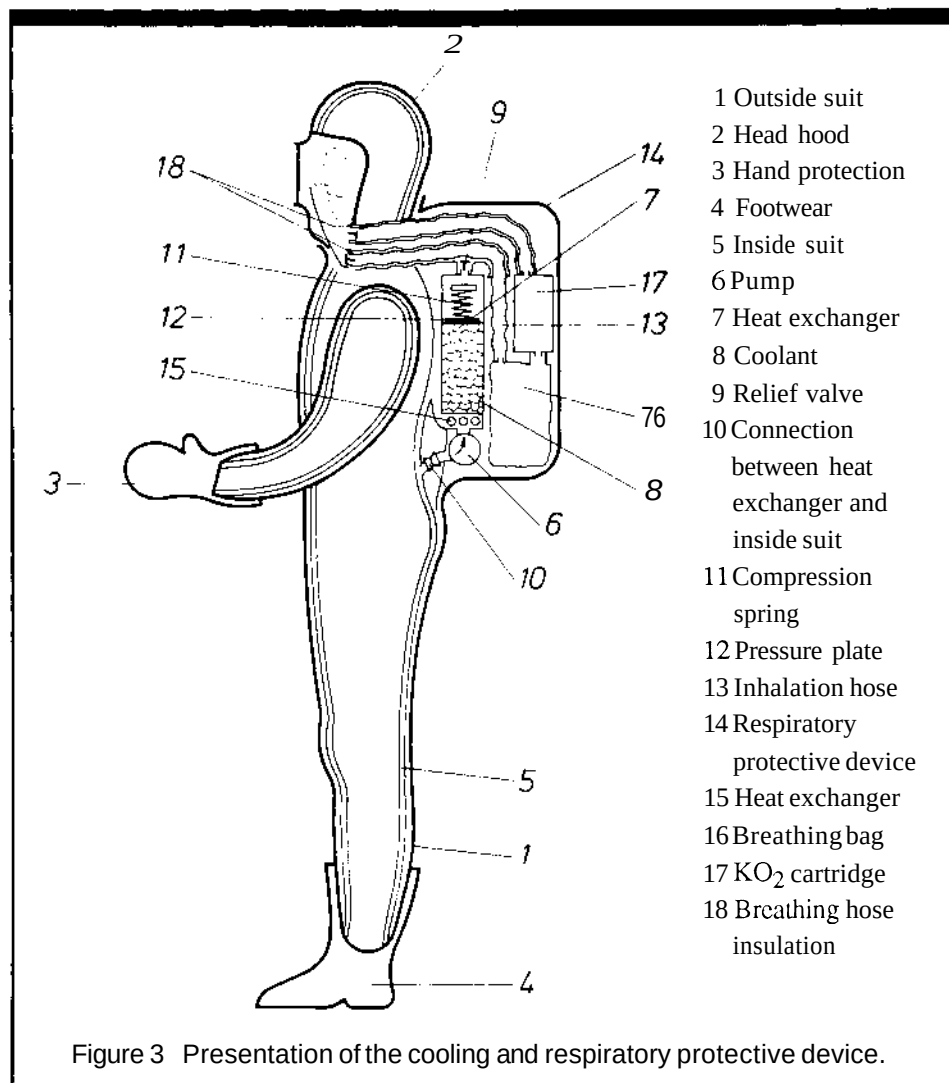


Figure 3 Presentation of the cooling and respiratory protective device.

feeling of comfort. In relatively unfavorable ambient conditions, however, this may be accomplished only by reducing the work load or by increasing heat dissipation by means of personal heat protection systems.

DESIGN PRINCIPLES OF COOLING GARMENTS

In addition to the prerequisite of thermal equilibrium when designing personal heat protection systems, there is also the fact that the cooling surface of systems of this type is generally small in comparison to the body surface. This means that the heat from the environment gets into the body through the skin, before it is dissipated by the cooling system. It is very difficult to

estimate the heat input from the warm environment through the cooling system. If the temperature gradient between the environment and the person's skin is fixed, the responsible factors are the humidity and flow conditions of the ambient atmosphere as well as the heat transfer properties of the clothing materials.

The correlation given in equation (2) covers all the energy amounts which determine the cooling power to be installed.

$$\dot{Q} = \dot{Q}_M + \dot{Q}_U = \dot{Q}_M + A_H k_w (T_U - T_H) \quad (2)$$

In principle, however, there are the possibilities, listed in equation (1), of heat exchange between the human body and the environment. For simplicity's sake, the heat quantity to



Figure 4

Front view of the cooling and respiratory protective device.



Figure 5

Side view of the cooling garment.

be drained from the body is termed $\dot{Q}_M$, and the heat quantity coming in from the environment is called $\dot{Q}_U$.

Generally, the body can be cooled by covering it with heat-storing coolants or by circulating cold air or liquids (water, alcohol, oil, etc.) through rubber or plastic hoses which are retained in a wearer suit or vest and have close contact with the body surface (Pasternack, 1983).

Cooling liquids, such as water, which obtain the cooling energy primarily from the phase change of its ice, require outside energy for circulation. This is usually electric energy. Systems which utilize the change from the liquid to the gaseous or from the solid to the gaseous phase for cooling, such as CO_2 , do not require any outside energy for recirculating the cold liquids, but require a fluid which has low viscosity even at low temperatures.

Furthermore, the coolant supply tank must be designed as pressure vessel, in which the fuel gas for the recirculating pump is collected. Both systems are relatively heavy and complicated, are therefore expensive and require an extensive maintenance. They are, however, distinguished by a constant cooling effect and offer sufficiently good wearing comfort over long periods of time.

Although cooling systems, in which air is used for cooling, are of simple design, they require large throughputs of coolant air. The cooling gas passes through distributors and lines and reaches an envelope which surrounds the body and is inflated due to the flow resistances. This results in an uneven cooling effect, undercooling at the point of gas inlet, and restrictions of

movements. Gas cooling systems are therefore suitable only for stationary operations because of the large throughputs.

Cooling systems containing coolant as static heat storage medium are therefore much simpler. The cooling effect of cooling garments of this type is based on the close contact between the cold generator and the body surface of the person wearing the garment. The body is cooled by conduction, and the coolant is either liquefied or evaporated in the process. The coolant must be kept in pockets and must be carefully distributed over the body surface to be cooled. In order to avoid undercooling, insulation must be provided to suit the particular application. The cooling comfort of these systems can be adjusted manually by reducing the insulation or by

applying greater pressure on the cooling areas, respectively.

DESIGN FUNDAMENTALS FOR THE COOLING GARMENT

As has already been outlined, the cooling garment of a person working under unfavorable thermal conditions must bind the energy input from the environment and dissipate effectively the heat generated by the body. Regarding the cooling energy to be consumed per time unit, this results in the correlation in the stationary state as

per equation (2); regarding the total supply of cooling energy required, i.e. during the overall period of use, the following equation holds:

$$\dot{Q} = \dot{Q} \times t \quad (3)$$

The cooling garment should thus be able to make available the supply of cooling energy required. However, this requirement may be met only as long as the quantity of coolant to be carried along permits a tolerable manner of carrying and does not affect the wearer of the garment too much.

We can start from the fact that the cooling garment represents a heat

exchanger, through which coolant is conducted which is heated along the flow path (body surface) and thus brings about the cooling effect. The cooling power can be described by the equation:

$$Q = m C_F (\dot{V}_{KA} - \dot{V}_{KE}) \quad (4)$$

If the temperature gradient between the outlet and inlet of the cooling is fixed, the specific heat of the coolant is of decisive importance.

If a specific cooling power is to be supplied, the temperature gradient between the skin and the coolant must be large, if there is low **recirculation** of the coolant. This results in a large temperature gradient particularly at the inlet of the cooling garment and therefore in a high local thermal flux, whereas the temperature of skin and coolant at the outlet are very close to one another. Cooling systems with low coolant throughputs provide an uneven cooling effect and require good insulation of the coolant ducts at the garment inlet. The insulation must decrease continuously towards the outlet. A disadvantage is that such systems can be used within a narrow range of ambient temperatures only, and that the wearing comfort is affected adversely.

If large throughputs are chosen, the temperature gradient between the inlet and outlet is smaller, resulting in even cooling of the body and in elimination of the insulation. This is the case particularly if the direction of coolant flux follows the direction of the rise in skin temperature, namely from the extremities to the trunk. From the point of view of comfort, this possibility appears to be better. For practical reasons, however, the temperature gradient between the inlet and outlet of the cooling system is generally larger than the natural gradient of about 6°C between the extremities and the trunk.

Large throughputs are, however, subject to disadvantages as well. For instance, they require large cross-sections of the flow ducts, or else they generate a

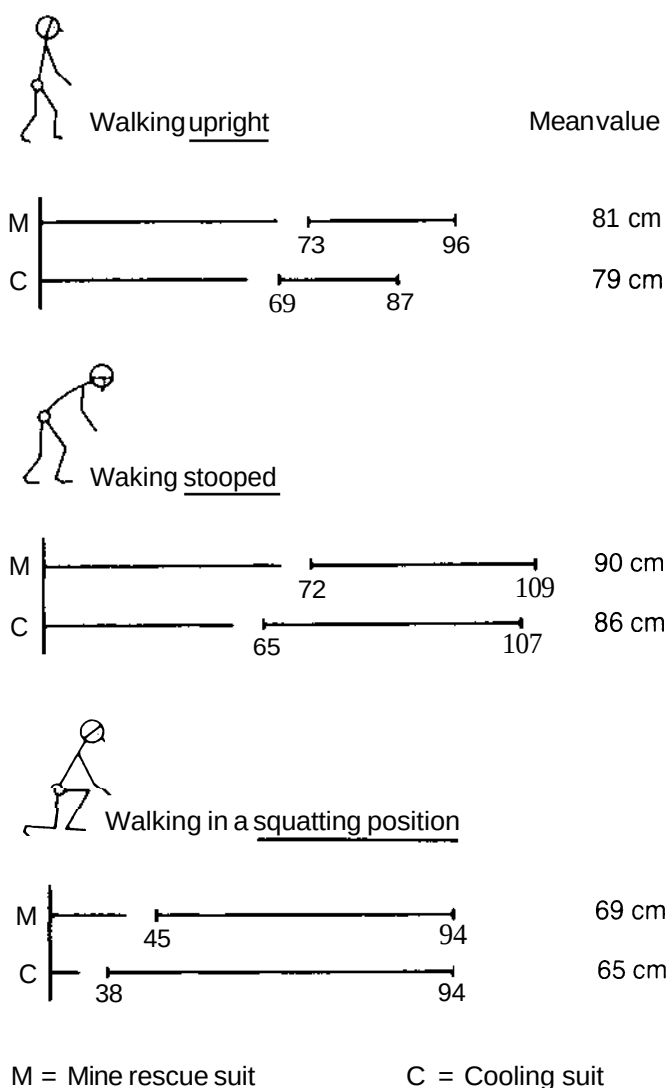


Figure 6

Presentation of the walking motions (step length in cm)
(Pasternack, 1983)

high flow resistance and thus require a higher pumping power.

Assuming that the thermal quantity must be dissipated at a specific temperature gradient, equation (4) can be restated to yield the coolant throughput:

$$\dot{m} = \frac{\dot{Q}}{C_F(\dot{V}_{KA} - \dot{V}_{KE})} \quad (5)$$

This results in a pressure loss. As is known, the pumping power required to deliver this quantity of coolant is calculated as follows:

$$N = \frac{\Delta p \cdot \dot{m}}{3} \quad (6)$$

When equations 4 and 6 are combined, a correlation is obtained which should represent optimum fulfillment of the design parameters as well as of the physiological and biomechanical parameters for the application under consideration.

$$\frac{\dot{Q}(\dot{V}_{KA} - \dot{V}_{KE})}{N \cdot \Delta p} = S_{CF} \quad (7)$$

For the same heat quantity to be dissipated - this equation shows that coolant of which the product S_{CF} is larger, requires a lower pumping power, i.e. that liquids require less pumping energy than gases for about the same S_{CF} because their density is higher by about three decadic powers.

For this reason it was decided to develop a cooling garment with liquid coolant recirculation.

The question as to the coolant to be used is of fundamental importance to the design of personal heat

protection systems. The size of the apparatus, the safety aspects, logistics, etc. depends on the selection of the coolant. When the usability of the currently available coolants (cf. table 1) is evaluated with respect to individual cooling, the following information is arrived at:

1.

From the thermodynamic point of view, utilization of the heat of evaporation of water seems to make the most sense. However, this project cannot be implemented in individual cooling systems with closed circuit (boiling temperature too high). The sole application remaining is the use of H₂O ice as static coolant or recirculation of its melted water. To this end, however, outside energy is required which must be designed to be intrinsically safe in accordance with the application conditions, if it is electric power.

2.

Ammonia is well suitable for personal

protection systems in the range of both phase change points. Until now, its application has been impeded by the irritation caused by its vapors.

3.

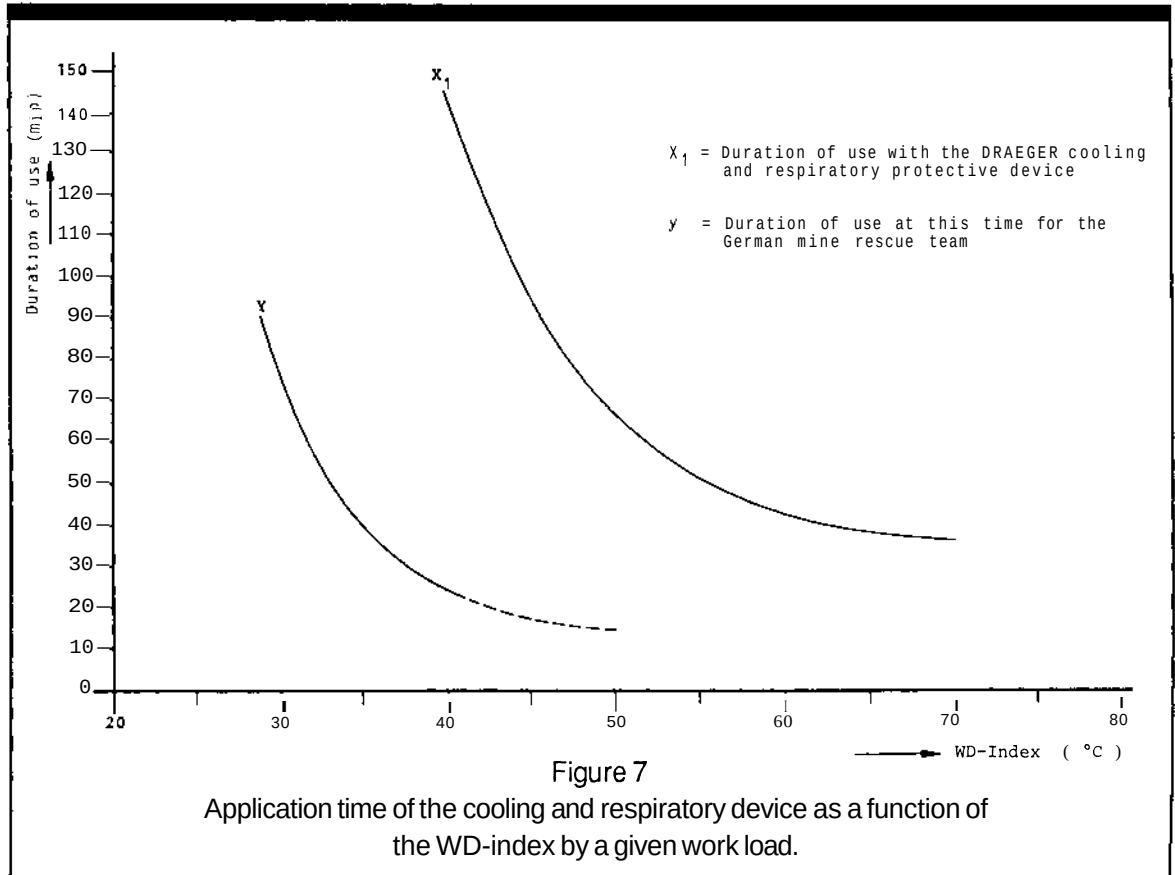
On the basis of the evaluations given above, CO₂ is preferred in many instances. It is suited both as a static coolant and as coolant in liquid-cooled cooling garments. Its gas can be used as propellant for recirculating the coolant, so that these systems are self-sustained and thus offer advantages over, for instance H₂O ice.

4.

The other coolants have very little significance due to the relatively low storage capacity per mass unit.

5.

Since all substances passing through a phase change are subject to cold loss when they are stored at temperatures above the phase change temperature, the cooling garment must be filled with the coolant just before being used.



COOLING GARMENT

Draegerwerk AG has been developing for some years individual cooling garments, some of which provide incorporated breathing protection or can be worn with self-sustained respiratory protective apparatus (e. g. compressed-air breathing apparatus, closed-circuit breathing apparatus). Facilities have been created thereby which permit more humane work under relatively adverse climatic conditions or open up new approaches of applications under conditions which would be intolerable otherwise.

Inspired by requirements and conditions prevailing in the mining industry, Draegerwerk AG has developed a cooling and respiratory protective device for mine rescue teams. This apparatus, which resembles an astronaut suit, provides heat and breathing protection up to ambient conditions of 70°C and about 100% rel. humidity for a specific time. This development will probably be a trail-blazer for many other fields of application in high-temperature technology. When suitable materials for the outer garment are selected (e. g. Al-coated glass fibre, rubber-coated fabric), the system may also be used as heavy heat protection garment or gas protection equipment.

The cooling and respiratory protective system is shown in Figure 3.

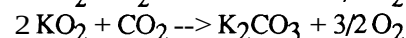
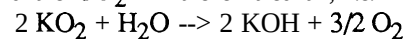
The wearer of the garment is surrounded by an outer garment (1) which consists of the head area of a helmet-covered head hood (2) and is fitted with hands (3) and feet (4) protectors. The outer garment is designed so that the heat input from the outside is minimized while the wearer of the garment is offered adequate mobility. The garment has a water vapour barrier and is equipped with an insulating barrier

towards the inner garment. The partition into pants, jacket and head hood assures good biomechanical properties. The inner garment (5) fits the body surface of the wearer of the apparatus tightly and is used to accommodate the circuit intermediate-coolant-carrier. The circuit medium which is carried in plastic hoses connected in parallel is a silicon oil which is of sufficiently low viscosity at low temperatures (- 80°C). The circuit medium is pumped through the inner garment and the heat exchanger (7) by means of the delivery pump (6) which is powered by a CO₂ gas motor incorporated in this pump. While the circuit medium remains in the inner garment, it absorbs the heat quantity produced by the wearer of the garment as well as the heat which has filtered in through the outer garment, and feeds it to the heat exchanger. After the heat has been transferred, the circuit medium is fed back to the inner garment and cools the human body.

The heat quantity withdrawn from the circuit medium in the heat exchanger causes sublimation of the coolant CO₂ (8). The CO₂ gas produced in the process is kept at a specific pressure in the heat exchanger by means of a pressure relief valve (9) and used to operate the delivery pump by means of the gas motor. The connection between the heat exchanger and the inner garment is established by means of the automatically locking couplings devices (10). Positive operation of the cooling apparatus is achieved by means of the constant pressure devices (11) (pressure spring). In addition to reliable operation, these devices also ensure better heat transfer by constantly

pressing the solid CO₂ (8) against the heat exchanger surfaces (15), thereby preventing formation of a CO₂ gas buffer which would impede the heat transfer.

In order to cool the breathing air, the excess CO₂ gas from the heat exchanger and gas motor is collected and fed to the insulation (18) forming an annular groove around the inhalation hose (13). In mine rescue operations, breathing protection is required primarily in addition to effective body cooling. This protection is achieved by a respiratory protective device (14) which can be coupled to the cooling unit and contains chemically bound oxygen in the form of potassium superoxide (KO₂) (17). Oxygen generation is based on the reaction of the KO₂ with the moisture and the CO₂ in the exhaled air, i.e.



The heat of reaction generated during this process leads to a higher temperature of the inhalation air which is cooled by the CO₂ gas and a chiller incorporated in the breathing bag (16) and flows through the inhalation hose (13).

The development of this apparatus was rendered optimum regarding the practical usefulness, the biomechanical and physiological conditions as a result of support from the West German Federal Ministry for Technology and Research and participation of the

- Mine Rescue Centre, Essen
- Federal Institute for Work Protection and Accident Research in Dortmund, and
- Institute for Work Physiology and Rehabilitation Research of Marburg University and its Hessisch Lichtenau Department.

SYMBOLS USED IN FORMULAS

A _H	Skin surface
N	Pumping power
Q	Supply of cooling energy
$\dot{Q}$	Cooling energy flow
Q _K	Convective heat flow
Q _M	Heat generated by the human body
Q _R	Heat flow due to radiation

$\dot{Q}_U$	Heat flow from ambient
$\dot{Q}_V$	Heat flow due to evaporation
W _D	Index
C _F	Specific heat of the liquid phase
K _W	Heat transfer coefficient
$\dot{m}$	Coolant flow
t	Period of use

Δp	Pressure Drop
$\dot{T}_H$	Skin temperature
$\dot{T}_{KA}$	Coolant outlet temperature
$\dot{T}_{KE}$	Coolant inlet temperature
$\dot{T}_U$	Ambient temperature
$\dot{T}_{UF}$	Wet temperature
$\dot{T}_{UT}$	Dry temperature
ρ	Coolant density

The result of this development is shown in Figures 4 and 5.

Excerpts of the results obtained in the course of development are listed in Figures 6 and 7.

In Figure 6, the step length is shown as a function of the walking motion for the cooling and respiratory protective device and for the protective equipment currently worn by mine rescue teams. When we look at the calculated mean values of the various walking styles, the cooling and respiratory protective device may be seen to have slightly inferior performances, which is, however, not significant. Similar results were obtained for the other parameters of motion restrictions which are not discussed in this article.

All in all, the difference is so small that there is no question of serious restrictions of motions when the cooling respiratory protective device is worn, as compared to the mine rescue suit in use at the present time.

The performance parameters of the cooling system, shown in Figure 7, may be considered as result of the work physiological investigations.

This relationship ties the ambient atmospheric conditions as summarized by the WD-index together with circulatory ratings, thus providing the basis to determine acceptable duration of application time.

The WD-index (wet-dry) is a climate sum rating, serving as an indicator of extreme and exhausting climatic conditions which can only shortly be ensured by working person. The index

simply contains the values for the ambient dry and humid temperatures as denoted by the formula

$$WD = 0,85 \vartheta_{UF} + 0,15 \vartheta_{UT} \quad (8)$$

In case the ambient air humidity is 100% (as often being the case in mining industry), the WD-index is equal to the ambient air temperature.

As physical strain such type of work has been chosen (lifting and running) as being typical for a mining rescue brigade. In general the exercise was stopped once the rectal temperature or the heart rate went up to 38.4°C or 180 min⁻¹, respectively.

As shown by a. m. formula (8) the strain to cope with a severe ambient atmosphere is primarily a function of its humidity content, such that a rise in humidity affects a person approximately 6 times as bad as a rise in temperature.

This fact has to be borne in mind for any planned work session. Otherwise at a completely saturated ambient atmosphere durations for work sessions are approximately 2,5 h at 40°C or 50 min at 70°C, respectively. Once the work load gets reduced (i.e. doing inspection work) a prolongation of an acceptable work session is to be expected. But these variables also demonstrate that as a safety precaution all work sessions with these devices must get closely controlled, thus protecting the bearer of this device from any harm which might result out of overbearing.

The importance of this device for mining rescue brigades is also

demonstrated by the approval that has been obtained from the respective German authority for mining rescue brigades.

Underground tests performed in the meantime have shown that a successful use of the equipment can be expected in mining rescue operations.

CONCLUSION

The results of laboratory and trial tests conducted so far have shown that a noticeable relief of the stress on the circulatory system on the persons wearing the apparatus may be achieved by means of the personal cooling garment discussed.

The more effective dissipation of the body heat leads to a lower rise of the rectal temperature, lower pulse rate, reduced perspiration, etc., and improves the sensation of comfort, a fact reflected by the positive evaluation by the persons wearing the apparatus. The overall statements made by the test persons also indicate that there is no major obstruction of movements.

By creating whole-body cooling systems, it has not only become possible to obtain a humanizing effect on the work, but also to achieve effective rescue of people and salvage of property from climatically adverse areas. Summarizing the results, it may be said that the personal cooling garment provides effective relief for the person wearing the equipment and makes it possible to advance to climatically adverse areas under more humane conditions in order to perform work successfully there.

BIBLIOGRAPHY

- Kerslake, D. McK.: The physiological requirements for environmental comfort in terms of the microclimate.
- Newburg, L. H.: Physiology of heat regulation and the science of clothing. University of Microfilms Inc. Ann Arbor, London, Page 78.
- Pastemack, A.: The cooling vest - another step towards rendering work more humane. Draeger-Heft No. 310 (1978).
- Pastemack, A.: Individual portable body cooling systems. Draeger Review No. 51 (1983).

TABLE 1
Thermal Data Of Some Coolants

Coolant	Melting point data		Boiling point data	
	Melt temp.	Melt heat	Boil. temp.	Heat of Evap.
	(°C)	(J/kg)	(°C)	(kJ/kg)
CO ₂	- 55.6	196	- 78.52	573.13
NH ₃	- 77.9	332	- 33.35	1368.5
H ₂ O	0	333	100	2258
C ₂ H ₄	-169.5	104	- 103.5	483
CH ₃ Cl	97.6	128	- 24.5	429