WATER COOLED GARMENTS: A REVIEW*

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Abstract. Water cooled garments have found a variety of applications in aerospace and industrial settings since 1962 and the pertinent literature is widely scattered. This review includes a brief look at human thermoregulation followed by a history of water cooled garment (WCG) development and a description of current suits in the U.S. and U.K. Discussion includes variables affecting WCG design and operation, the development of automatic cooling control, and possible uses for regional cooling.

1. Introduction

With the growth of technology man ventures into increasingly hostile aerospace and industrial environments. A major problem is heat stress, which occurs whenever heat input to the body exceeds heat dissipation. High external heat loads exist in the metal, glass and ceramics industries. Internal (metabolic) heat can cause stress where man is sealed in impermeable clothing for protection against toxic materials, low pressures, or extreme environmental temperatures. A special case is the astronaut during extra-vehicular activity, where conditions demand that his pressure suit interdict all direct heat exchange between man and environment; even moderate activity would involve forced storage of metabolic heat and rapid collapse were an artificial cooling system not provided (Leithead and Lind, 1964; Roth and Blockley, 1970a, b).

Conventional body cooling by gas ventilation has been found inadequate for many applications, notably for hot industrial trades and for space suits. Since 1962 there has gradually developed a technology of water cooled garment design and operation. A recent search has shown that information on water cooling is widely scattered through the physiological, medical and engineering literature with many items appearing only as government or industrial documents with limited distribution. It therefore seems worthwhile to prepare a literature review for the use of others working with water cooling. Emphasis will lie on medical and physiological aspects of the water cooled garment with no attempt to detail heat sink and pump design.

2. Human Thermoregulation

Human thermoregulation serves the dual function of controlling internal temperature and external heat dissipation (Nielsen, 1966). Despite the description of man as 'homeothermic', his body temperature and internal heat stores normally vary with

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time of day, individuality, and metabolic rate (Dubois, 1948; Minard and Copman, 1963). External heat dissipation is regulated by the same factors and the need to reject excess metabolic heat as well as any added heat from external sources.

The overall requirement is for balanced heat input and output. Tolerance of forced heat storage is strictly limited (Blockley *et al.*, 1954a, b; Kaufman, 1963; Roth and Blockley, 1970; Veghte and Webb, 1961). Storage at first produces activation of compensatory mechanisms and subjective temperature awareness, then discomfort, deteriorating psychomotor capacity, and eventually collapse leading to death (Leithead and Lind, 1964; Webb, 1959). Studies have shown that the physiological tolerance limit at rest is rather uniform with body storage of about 150 kcal (Blockley *et al.*, 1954a, b; Kaufman, 1963) or mean body temperature of 40 °C (Veghte and Webb, 1961; Webb, 1959). Signs of impending collapse include rising rectal temperature, heart rate above 160, generally flushed skin, and inattention to work, while subjects may report fatigue, headache, giddiness and nausea (Blockley *et al.*, 1954a, b; Kaufman, 1963; Webb, 1961).

Where skilled performance of tasks is involved, heat storage must be stopped far short of the physiological limit just described. Argument continues on the philosophical and practical implications of thermal comfort and the amount of heat stress which can be tolerated without performance decrement (Bell and Provins, 1962; Blockley, 1965; Lind, 1963; Webb, 1961; Wing, 1965).

'Comfort' is a highly variable subjective judgement based on past experience (Hatch, 1963; Kerslake, 1964; Yaglou, 1949). On the other hand 'thermal neutrality' refers to objective measurements showing absence of heat storage; in the pure sense it implies that no active thermoregulatory processes are being called into play (Clifford, 1965; Kerslake, 1964; Webb and Annis, 1967a, b). Under less ideal thermal conditions tolerance is achieved only with the aid of active compensatory mechanisms, producing a 'quasi-steady state' limited eventually by fatigue (Blockley *et al.*, 1954a, b; Webb, 1959). Greater stress produces gradual heat storage, the rate depending upon the environment and the effect of physiological mechanisms. As a rough rule it has been said that decrements in psycho-motor performance appear when heat storage reaches about $\frac{3}{4}$ of the tolerance limit (Blockley, 1963; Webb, 1961; Wing, 1965).

In aerospace and industrial applications the goal is work effectiveness; comfort is a secondary consideration which may be sacrificed in system trade-offs (Blockley *et al.*, 1954a, b; Burriss *et al.*, 1965). On the other hand, on long missions thermal status adequate for unimpaired performance necessarily implies comfort. Minimal heat stress may not produce observable reductions in psychomotor performance, yet that performance may be maintained only by dipping into emergency reserve capacities (Bell and Provins, 1962; Blockley, 1965). Attempts to measure such subtle variables have met with only limited success (Bell and Provins, 1962; Blockley, 1965; Kaufman, 1963).

Attempts have been made to define permissable heat stress according to objective measurements of the environment, such indices being developed by producing the desired environment in the laboratory and using human subjects as indicators of thermal stress (Kerslake, 1964; Macpherson, 1960; Webb, 1959; Yaglou, 1949). Empirical indices are then set up for average and minimal individual tolerances of the environment (Lind, 1963). For aircraft such indices were developed by Blockley and others based on measurements of environmental conditions, resultant heat storage rates considering clothing and activity, and average subject tolerance of such storage (Blockley *et al.*, 1954a, b).

Heat exchange between man and environment may be presented as an equation

$$M-S=W+R+C+C'+E,$$

where M = metabolic heat production; S = storage (zero at equilibrium); W = external work; R = radiation in the electromagnetic spectrum; C = convection by motion of fluid (air or water) surrounding the body; C' = conduction by contact with a solid (usually negligible); and E = evaporation, including obligatory and thermoregulatory components.

The relative importance of the five elements on the right side of the equation varies with the physical and physiological circumstances and each can operate as heat source or sink for the body. By convention heat storage within the body (S) appears as a negative quantity. Quantitative measurements, even in the steady state, are extremely difficult because heat exchange actually occurs in the complex microclimate at the skin-environment interface. Therefore, indirect measurements and inferred values are the rule in human calorimetry. There are many excellent reviews of the physical components of the equation (Hatch, 1963; Kerslake, 1964; Roth, 1965; Webb, 1964), some particularly emphasizing applications to aviation (Jurgens, 1968; Kerslake, 1964; Webb, 1961) or extravehicular activity in space (Burriss *et al.*, 1965; Roth, 1966).

Metabolic heat production is determined by the energy needed for basic body processes plus any external work. Since the body operates with less than 100% efficiency, only a fraction of metabolic energy can be applied to do work while the majority appears as waste heat. The body has virtually no capacity to alter metabolic rate for thermoregulatory purposes (Dubois, 1948; Webb, 1961).

An important component of human thermoregulation (particularly for water cooling) is internal conductance, which governs the flow of heat from body core to periphery (Robinson, 1963; Sheard, 1967). This conductance depends upon the core-skin temperature gradient and on tissue insulation, the latter including conductive and convective (vascular) elements. In 1882 Fredericq wrote that the cutaneous circulation is unique in its primary responsiveness to general body thermal state rather than to local tissue metabolic needs. Large amounts of heat are transported by the blood stream because, like water, blood can store significant amounts of heat with little temperature change (Sheard, 1967). Within a limited temperature range cutaneous vasomotor control may act as the principal mechanism of human thermoregulation, a condition associated with subjective comfort (Dubois, 1948; Hertzman, 1959; Robinson, 1963; Sheard, 1967).

Cutaneous vasomotor control is not uniform over the body, a fact sometimes neglected in calorimetric studies. Major regional differences exist in blood flow rates, vascular anatomy, and vasomotor innervation (Hertzman, 1959; Robinson, 1963), as will be further discussed below.

Consideration of skin temperature is important in artificial cooling. Pertinent measurements include not only mean skin temperature ($\bar{T}_s$) but temperature range and distribution. For resting subjects $\bar{T}_s$ for comfort is about 33 °C with a 6 °C longitudinal gradient, the head being warmest and the hands and feet, coolest (Kerslake, 1964). As metabolism rises the $\bar{T}_s$ associated with comfort and absence of sweating falls (Allan, 1966; Webb and Annis, 1967a, b).

The importance of a normal skin temperature distribution for comfort has been supported by British workers designing cooling equipment (Burton, 1966; Burton and Collier, 1964, 1965). In contrast, Hall and Klemm showed that men exposed to widely disparate radiant environments on opposite sides of the body find the situation comfortable if the resultant $\bar{T}_s$ is normal (Hall and Klemm, 1969).

Many studies of human thermoregulation have been done on resting subjects exposed to controlled environments. This allows full utilization of natural defense mechanisms, unlike the thermally restrictive situations to be discussed in connection with cooling. As the temperature is lowered through the comfort zone there is generalized cutaneous vasoconstriction until conductance is reduced to its minimum (obligatory) value, attributable to tissue heat conduction. Any further temperature decrease involves passive body cooling; when cooling exceeds metabolic heat production the major defense mechanism is to increase the latter by shivering or voluntary activity (Kerslake, 1964).

Environmental temperature rising through the zone of vasomotor control produces cutaneous vasodilatation, warming of the skin, a decrease of the core-skin temperature gradient, and increasing conductance. In heat stress the cutaneous circulation may demand a significant portion of cardiac output (Brouha, 1960; Rowell *et al.*, 1969a, c; 1970). As the heat load increases beyond some threshold temperature, sweating begins and is gradually increased along with further vasodilatation (Hertzman, 1959; Kerslake, 1955; Kuno, 1956). The physiological reaction to a given heat load depends partly upon whether the source is internal (metabolic) or external (Roth and Blockley, 1970a, b).

Sweat evaporation enables men to work in hot environments, especially when heat acclimatization has occurred, but high sweat rates may produce fluid and electrolyte imbalances and eventual collapse (Genin and Golovkin, 1966; Kuno, 1956; Leithead and Lind, 1964; Webb, 1967). Provision of drinking water during heat exposure does not solve the problem, as heat storage paradoxically causes subjects to avoid drinking, with ensuing voluntary, clinically significant dehydration (Blockley, 1965; Kaufman, 1963; Webb, 1967). Humid environments curtail or even eliminate evaporative cooling, although high sweat rates continue (Webb, 1967).

Further details of thermoregulation may be found in several excellent reviews (Hertzman, 1959; Kerslake, 1965; Leithead and Lind, 1964; Macpherson, 1960; Minard and Copman, 1963; Robinson, 1963; Webb, 1964). Classic works on the subject include Newburgh (1949) and Winslow and Herrington (1949).

3. Limitations of Gas Cooling

The Gemini and prototype Apollo space suits relied upon gas flow over the body to remove metabolic heat by combined convection and evaporation. Gemini plans allowed for sustained cooling at 350 kcal/h with transient peaks to 500 kcal/h (Chambers, 1970; Machell, 1967). In fact the inherent awkwardness of pressurized suits increased the metabolic cost of even simple tasks to 400–600 kcal/h two to four times the cost in unpressurized suits (Streimer *et al.*, 1964; Tiller and Greider, 1958; Wortz *et al.*, 1967).

At the same time altitude chamber runs showed that ventilation had only a limited cooling capacity and was marginal for work rates over 300 kcal/h (Albright *et al.*, 1964; Burriss *et al.*, 1965; Harrington *et al.*, 1965; Roth, 1966; Wortz *et al.*, 1964). Even at low metabolic rates it was found that, at any reasonable inlet temperature, nearly all cooling was by sweat evaporation rather than convection, causing heat stress and eventual dehydration (Allan, 1966; Clifford, 1965b; Genin and Golovkin, 1966; Veghte, 1965; Wortz, 1964). Men working at higher levels suffered heat storage, discomfort, and sometimes were unable to finish their tasks.

The gap between heat production and actual cooling is illustrated in Figure 1. Streimer and co-workers predicted that with the Gemini suit extravehicular activity (EVA) would have to be drastically curtailed (Streimer *et al.*, 1964).

Experience with Gemini EVA confirmed the predictions. Attempts to work in space (Gemini IX and XI) ended with fogged face plates, high pulse rates (170–180 bpm) and astronaut fatigue which necessitated abrupt termination of EVA (Kelly *et al.*, 1968; Machell, 1967). Although no direct measurements of metabolic rate were available, it was estimated that for the seemingly simple tasks, heat production had reached 550 kcal/h with peaks to 900 kcal/h (Chambers, 1970; Hedge, 1968), grossly overloading cooling and CO_2 removal capacities of the suit. Since immediate system improvement was impossible, further EVA was tailored to the suit's limitations and the

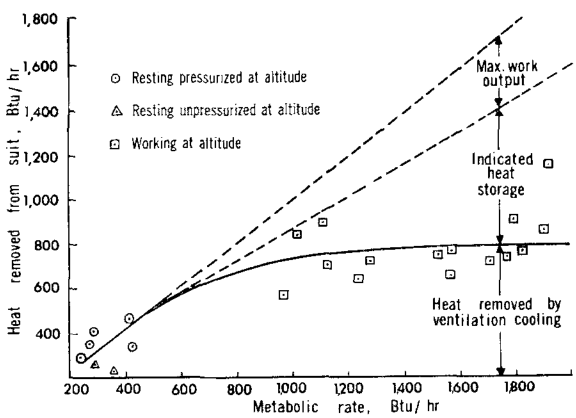

Fig. 1. Thermal inadequacy of air cooling. In a pressurized space suit cooling capacity was limited to about 800 Btu/hour (200 kcal/hour) so that rising metabolic rate caused increasing heat storage in the wearer (from Roth, 1966, modified from Garrett Corporation Report SS-3056, 1964).

astronaut on Gemini XII successfully paced himself so that heart rate only briefly exceeded 140 bpm; little actual work was accomplished. Ground monitors were prepared to halt all activity had heart rate exceeded 160 bpm (Kelly *et al.*, 1968).

It had become obvious that the limits of EVA lay in suit design, specifically in the increased cost of work and low cooling capacity. The degree of frustration encountered may be judged from the statement in a report summary that "Any life support system should be capable of supporting the anticipated peak workloads" (Machell, 1967).

The prototype Apollo suit was very similar to Gemini. Roth (1966) and others (Burriss *et al.*, 1965) predicted that lunar surface activity would involve sustained heat loads of 500 kcal/h with higher transient peaks in emergencies. Apollo levels were nevertheless set at 400 kcal/h with peaks at 500 kcal/h (Callin and Kaufman, 1966; Chambers, 1970), levels which themselves were above the demonstrated limit of gas cooling.

Improvement of suit mobility has remained minimal (Archibald, 1967; Robertson, 1970). Experiments showed that even minor improvements in ventilation cooling capacity involved uncomfortable wind and noise levels (Chambers, 1970) and disproportionate increases in system weight and bulk (Bowen and Witte, 1963; Burriss *et al.*, 1965). Other suggestions included complex proposals for gas cooling plus a 'cold wall' (Felder and Schlosinger, 1963) or 'air-liquid heat exchanger' (Wortz *et al.*, 1964) as supplementary heat sinks within the pressure envelope of the suit. A practical solution appeared in the form of the water cooled garment (WCG).

4. Development of Water Cooling

The concept of a water cooled suit was first suggested by Billingham in 1958 (Billingham, 1959) and the prototype suit was constructed at the Royal Aircraft Establishment in 1962 (Burton and Collier, 1964). Their primary interest was protection of crewmen in hot environments such as sunlit aircraft cockpits, but it was from the first realized that a practical personal cooling system would have many possible applications. The suit was visualized as a sort of form-fitting heat exchanger, an extracorporeal circulation in which water was warmed as it passed in tubes over the skin and was then carried to an external heat sink. By analogy with the circulation, the process is generally called 'convective cooling' (Burton and Collier, 1964), although a few authors refer to it as 'conductive cooling' (Chambers, 1970; Waligora and Michel, 1968).

Theoretical comparison of air and water cooling showed that water's high heat capacity conferred marked engineering advantages in decreased pumping power, lower system weight, and less garment bulk (Burton and Collier, 1964; Crocker *et al.*, 1964). The major question was the efficiency of heat transfer from human skin to water flowing in tubes contacting a relatively small proportion of the body surface. Poor heat transfer would necessitate very low water temperatures and might produce uncomfortable cold sensations along the tubes (Burton, 1966; Burton and Collier, 1965).

A prototype water cooled garment (WCG) was built of 40 polyvinyl chloride tubes

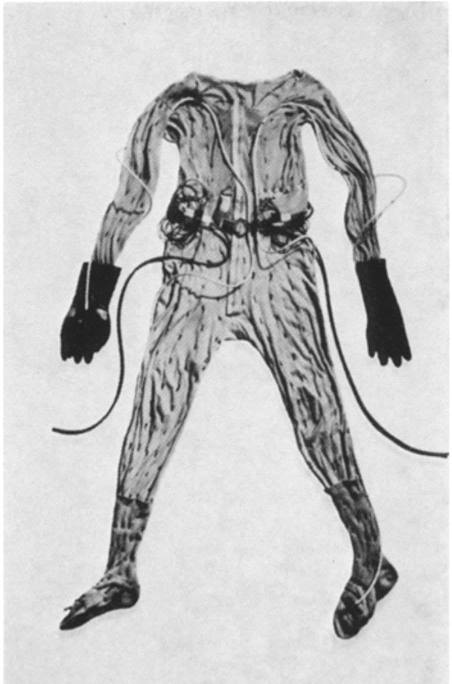

Fig. 2. The first water cooled garment. It was built at the Royal Aircraft Establishment in 1962, and featured water delivery at wrists and ankles with return through 40 small tubes to a central collecting point at mid-thorax. (Crown Copyright, published by permission of Her Britannic Majesty's Stationery Office.)

threaded into a suit of cotton underwear (Figure 2). Water was piped to the ankles and wrists where manifolds distributed it to the smaller tubes which ran back over the limbs to the outlet manifolds at mid-thorax. The head and neck were not cooled. Preliminary tests indicated excellent thermal coupling between the skin and water stream (Burton and Collier, 1964). The suit was comfortable even when high heat loads necessitated low water temperatures and despite the existence of wide skin temperature differences in comparing sites directly beneath cooling tubes with sites lying between tubes (Allan, 1966).

Following a demonstration of the British WCG at Houston (Burton and Collier, 1964), development of similar garments in the United States was undertaken by Hamilton Standard Corporation for the National Aeronautics and Space Administration (NASA) (Crocker *et al.*, 1964; Jennings, 1966). A series of suits was designed with tubing distribution proportional to body mass and water flow from extremities to torso. Experiments demonstrated the practicality of the WCG as sole heat sink for men working up to the 500 kcal/h anticipated for lunar surface activity. Cooling virtually eliminated sweating, and for any given work rate subjective comfort included a surprisingly wide envelope of water flow and temperature combinations. Other results showed that heat output rose sharply over working muscle groups (e.g. leg work vs

TABLE I

Characteristics of current water cooled garments (See text for references)

Suit	Conditions		Design			Comments
	Metabolic rate	Environmental heat	Area Covered	Flow (liters/min)	Water inlet temperature (°C)	
Apollo	Low – Very high	Thermal isolation	Torso, limbs	1.8	6.7–22	Uniform coverage loop flow pattern slip layer 40 tubes, total 90 m backpack sublimator
RAF	Low	High	Torso, limbs	0.7	15–25	Flow extremities to torso tubes held in cloth tunnels 40 tubes, total 120 m portable ice or dry ice
Pilkington	High	Extreme	Torso, limbs	0.7	–	RAF design
U.S.A.F Vest	Low	High	Torso	0.7–1.0	7.–13	Tubing at ½″ intervals covers 0.4 m^2
Rowell	Low – Very high	Neutral (controlled)	Entire body (except face)	8.0	5–45	Apollo type suit used to control skin temperature
Webb	Low – Very high	Thermal isolation	Entire body (except face)	1.5	10–32	Flow extremities to torso no cloth garment variable cooling to five regions used for direct calorimetry

arm work) (Crocker *et al.*, 1964) and that interposition of any material between skin and tubing caused a significant reduction in cooling efficiency (Jennings, 1966).

Direct comparison of air and water cooling in pressure suits showed the latter far more effective in reducing signs of heat stress such as sweat rate and rectal temperature rise. Comfort was also much improved by the WCG. These findings applied whether the heat stress was due to a hot environment (Allan, 1970; Veghte, 1965, 1970) or high work rates (Santa Maria, 1970; Webb and Annis, 1968).

5. Current Designs and Applications

A brief summary of current suit characteristics may be seen in Table I. A fuller description of these suits and their applications is given below.

Most famous of the water cooled garments is that used on Apollo flights (Chambers, 1970; Jurgens, 1968; Waligora and Michel, 1968) (Figure 3). It is a system of clear plastic tubes sewn inside a suit of stretch underwear with an added nylon slip layer between tubing and skin. Cooling covers the torso and legs but excludes the head and neck. Water flows through 40 tubes in a loop pattern which begins and ends in mani-

Fig. 3. Apollo liquid cooled garment (LCG). Cooled water is distributed by manifolds at the waist, flows in small tubes through the garment, and returns for collection again at the waist. (Photograph courtesy of National Aeronautics and Space Administration.)

folds located at the mid-torso. Flow rate is fixed at 1.8 liter/min with manual operation of a diverter valve to produce water inlet temperatures of 6.7°, 15.5°, or 22°C. The external heat sink is in the back pack where water from a separate supply is sublimated to space. It is designed to handle loads of 400 kcal/h with peaks to 500 kcal/h. Plans for lunar EVA have been tailored to this limit. In fact lunar surface activities on Apollo 11 and 12 averaged 200–300 kcal/h (Chambers, 1970). Ground tests have demonstrated that the Apollo WCG will handle at most 500 kcal/h (Waligora and Michel, 1968; Webb, personal communication). Sustained work above this level produces heat storage and much discomfort. Since other water cooled garments have shown much higher heat capacities, the limiting factor lies in the suit design. Pertinent factors include the added slip layer, exclusion of the head from cooling, and the uniformity of tubing distribution. Much improvement in cooling quality might result from redistribution of tubing to increase cooling over the legs, since the major lunar task is walking.

The current Royal Air Force suit is manufactured by Beaufort (Air-Sea) Equipment Co. (London, 1969) (Figure 4). Tubing is held in place by cloth tunnels sewn into stretch underwear (Figure 5). Water is distributed distally to the wrists and ankles where 40 tubes return it over the limbs to a collection point at the torso. Tubing totals

Fig. 4. Current Royal Air Force 120-meter suit. It features one-way flow from extremities to thorax. (Crown Copyright, published by permission of Her Britannic Majesty's Stationery Office.)

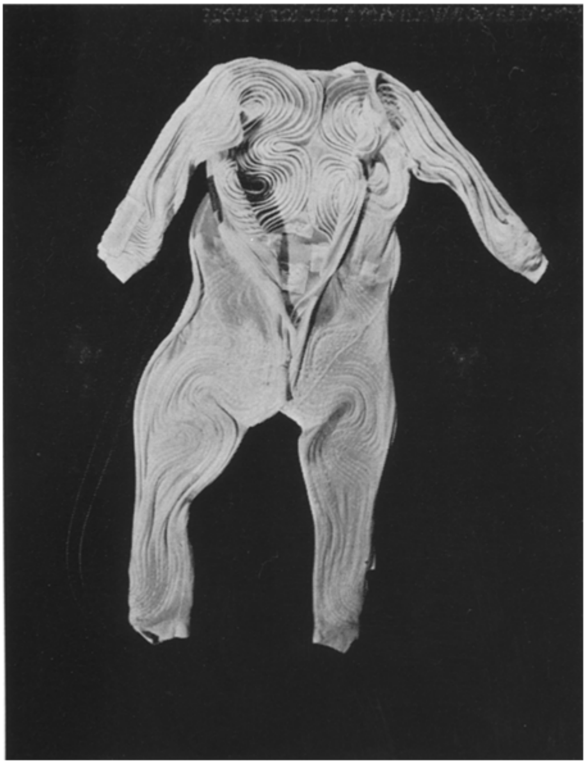

Fig. 5. Current Royal Air Force 120-meter suit. Inside view showing tubing held in place by cloth tunnels sewn to stretch garment. (Crown Copyright, published by permission of Her Britannic Majesty's Stationery Office.)

120 m long, producing uniform flow with little pressure drop across the suit. The suit weighs 1.8 kg filled with water and flow rate is 0.75 liter/min. The RAF's interest lies mainly in men doing mild work in hot environments. Recent experiments include both simulated and actual flights in over-heated aircraft cockpits (Allan, 1970; Clifford, 1965a; London, 1969). The major obstacle to operational use of water cooled garments in the RAF is the practical problem of heat sink installation in high performance aircraft (Allan, 1970).

For flights in tropical climates the U.S. Air Force has developed an abbreviated cooling garment or vest covering the torso and upper thighs or about 25% of the total body surface area (Kaufman and Pittman, 1966). Tubing is sewn inside the vest at $\frac{1}{2}$–1 inch intervals and water flow rate is 0.70 liter/min. Chamber experiments at 50–60 °C (cockpit conditions) have indicated that although the vest does not allow maintenance of thermal neutrality, it does significantly decrease heat strain on resting subjects (Esposito, 1970).

Experiments with the RAF water cooled garment have been conducted in an industrial setting at Pilkington Brothers, a large glass factory where furnace maintenance combines hard physical labor with high radiant heat loads (Hill, 1970; London, 1969). Traditionally such jobs are done by teams of men in aluminized asbestos suits working in brief four minute shifts. The addition of a WCG under the reflective suit allows increased shift duration to 20 or 25 min. Because of the high radiant heat load in the furnace vicinity, head and hand cooling have been found to be especially important (Hill, 1970).

The water cooled garment has found laboratory use as a tool for exact control of skin temperature in cardiovascular research (Rowell *et al.*, 1969a, b, c, 1970). The effect is comparable to immersion in a temperature controlled bath, yet the suit allows continuous physiological monitoring and such complex procedures as heart catheterization. The suit is of the Apollo design but covers head, hands and feet, leaving only the face exposed. It is operated at a high flow rate of 8 liter/min over a wide range of temperatures to provide either cooling or heating effect. Experiments have shown that

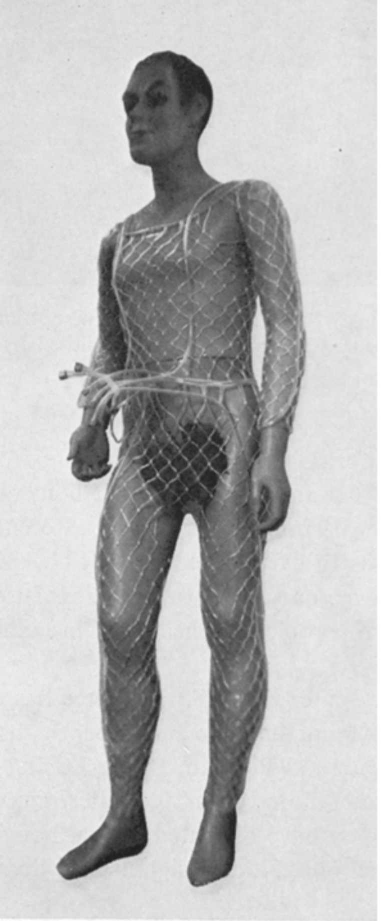

Fig. 6. Diamond pattern suit for direct calorimetry. Note that no supporting garment is involved. (Photo courtesy of Webb Associates, Yellow Springs, Ohio.)

high skin temperatures are associated with significant increases in cardiac output, the bulk of the increase going to skin circulation (Rowell *et al.*, 1969a, c, 1970).

The reverse application is the use of the WCG as a calorimeter for direct determination of metabolic heat output. Such measurements require maximal body coverage by the suit and thermal isolation of the man from his environment. Two suits have been specifically designed by Webb and co-workers for calorimetry. The first (Figure 6) consists of vinyl tubing in an open diamond network which conforms to the body without a cloth supporting garment (Webb and Annis, 1967, 1968; Webb, 1966). The second consists of rubber tubing fastened inside a foamed neoprene wet suit (Webb *et al.*, 1968). Subjects dressed in the WCG and outer insulating garments perform known quantities of external work in a thermal chamber controlled to minimize environmental heat exchange. A close match has been achieved between heat production and suit heat extraction plus external work (Webb and Annis, 1967, 1968; Webb *et al.*, 1968, 1970).

Other uses for water cooled garments are currently under investigation. They have been worn by racing car drivers, where the situation is similar to an aircraft cockpit (London, 1969). A WCG has been used to cool a surgeon during an operation where elimination of sweating was a primary concern (London, 1969). Water cooled garments are under consideration for use in heating deep sea divers, where the combination of high pressure and extreme conductive cooling makes passive thermal protection nearly impossible (Burton and Collier, 1964; Sanders Nuclear Corp., 1966).

6. Design Variables

A number of factors affect water cooled garment performance; some are characteristics of suit design and operation while others depend upon the environment and the man being cooled. The more important variables which have been explored will be summarized here with appropriate references. The interested reader is referred to a quasi-mathematical treatment of the subject by Burton (1965).

1. Environment

External heat may reach the cooling tubes directly or may be absorbed by the subject with eventual transmission to the garment. The ratio of direct to indirect effects increases as the total quantity of tubing rises (Burton, 1965).

(a) Air temperature (Allan, 1966; 1967).

(b) Wind speed.

(c) Radiant environment.

(d) Humidity. In a hot, damp environment there is increased heat load on the cooling system because of water condensation on the cold tubing. In British experiments the subject was little affected so long as system cooling capacity was not exceeded, and the major problem was wetting of clothing (Allan, 1967). Another study showed that subject sweat rates rose despite cooling when the environment was humid (Gaudio *et al.*, 1967).

2. Subject

Physiological factors listed here were discussed earlier under Human Thermoregulation.

(a) Metabolic rate (Webb and Annis, 1967, 1968).

(b) Conductivity. This includes individual differences in the circulation and in tissue insulation (adiposity).

(c) Acclimatization.

(d) Subjective comfort.

3. Suit design

(a) Tubing characteristics.

(1) Heat transfer qualities of tubing material and wall thickness (Burton and Collier, 1964; Burton, 1969).

(2) Diameter. The surface-volume ratio affects the transfer of heat by conduction from skin surface to convective fluid.

(b) Total tubing contacting skin (Burton, 1966, 1969; London, 1969).

(c) Distribution of tubing. Assuming equal flow for each tube, cooling is proportional to density of tubing over a given area. Details of regional distribution will be discussed later.

(d) Flow pattern.

(1) One-way flow with fluid distribution by manifolds at extremities and return to a central collection point at the torso (RAF garments and Webb's suits). Reversal of this pattern might be useful for a heated suit (Sullivan *et al.*, 1967).

(2) Loop flow with both distribution and collection manifolds at the torso (Apollo pattern).

(3) Length of individual tubes. This affects temperature gradient along the tubes and closeness of water outlet temperature to the skin temperature (Burton, 1969; London, 1969).

(e) Fit. Cooling is affected by contact pressure and uniformity as well as flow interruption if tubing becomes compressed or kinked, particularly during work (Jennings, 1966; London, 1969).

4. Associated clothing and equipment

(a) External insulation (between WCG and environment).

(1) Basic garment containing tubes. This is usually a knit stretch material.

(2) Other protective clothing or coverall. A notable example is the aluminized reflective suit worn in radiant environments (Hill, 1970; London, 1969).

(b) Internal insulation (between WCG and the man).

(1) Undergarments.

(2) Slip layer (Jennings, 1966; Waligora and Michel, 1968).

(3) Hair (n.b. head cooling).

5. SYSTEM CHARACTERISTICS

(a) Specific heat of fluid (water = 1.0).

(b) Mass flow rate. Heat extraction is related to flow rate but in a non-linear fashion. For the RAF suit it was found that flow rates above 1 liter/min produced little improvement in cooling (Burton, 1969; London, 1969). A family of curves can be plotted showing inlet temperature versus flow for selected heat removal rates (Burton, 1966).

(c) Water inlet temperature (T_{wi}). Several experimenters have tried varying both flow rate and T_{wi} for cooling control, but all found it simpler to set a reasonable flow rate for the anticipated cooling range, using T_{wi} as the sole controllable variable (Burton and Collier, 1965; Webb and Annis, 1967). Absolute limits of T_{wi} are 0°C (frostbite) and 45°C (pain threshold); practical limits are narrower, depending upon comfort and suit design (Chambers, 1970; London, 1969; Webb and Annis, 1967).

(d) Water temperature change across the suit. This is dependent upon the interaction of many factors including heat load, T_{wi}, suit geometry, and flow rate.

(e) Heat sink capacity.

(1) Sustained cooling rate.

(2) Emergency peak cooling rate.

(3) Total capacity of portable systems, i.e., quantity of consumables such as ice.

(f) Supplementary cooling by normal thermoregulatory mechanisms, such as evaporation into the ventilating gas stream, if any.

6. COOLING CONTROL

(a) Selection of control input

(1) Subjective comfort (Allan, 1966; Burton, 1966; Burton and Collier, 1965; Chambers, 1970.)

(2) Objective, based on metabolic rate, heart rate, or sweat rate (Webb, 1969, 1970; Webb and Annis, 1967).

(3) Automatic controller (see later).

(b) Lower limit of cooling. During prolonged periods of rest a small control error can gradually produce extremely uncomfortable heating or chilling, e.g. the overcooling experienced during the astronauts' stay in the Apollo 11 Lunar Module.

7. Cooling Control

Water cooling is a powerful mechanism which can overcool a man even at high metabolic rates. A serious problem is therefore the development of rational cooling control. Ideally the WCG provides a heat sink closely coordinated with the body's needs so that the required cooling occurs in the 'comfort zone' (Figure 7), which coincides with vasomotor thermoregulation but may also include minimal levels of sweat secretion (Chambers, 1970; Webb and Annis, 1968). The man should never be cold or obviously sweating, no matter what the variations in environmental conditions and work load (Chambers, 1970; Webb, 1970; Webb and Annis, 1968; Webb *et al.*, 1970).

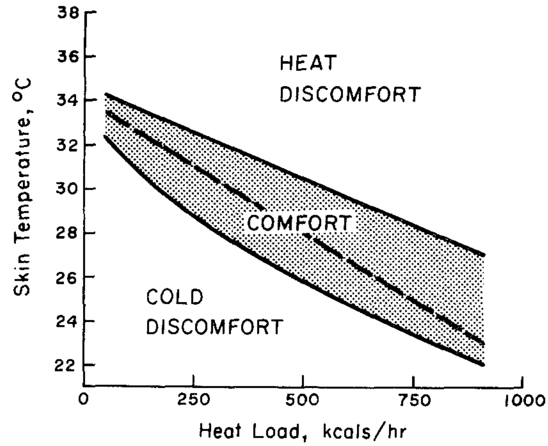

Fig. 7. Comfort zone for water cooled garments. At each heat load there is a range of comfortable mean skin temperatures which coincides with vasomotor thermoregulation and a minimal amount of sweat secretion. Heat discomfort includes obvious sweating and heat storage. Cold discomfort implies shivering. The dashed line is the lower limit of active sweating. (Modified from Chambers, 1970.)

Both the British and Apollo water cooled garments have been used with subject control of water inlet temperature. This offers the advantage of simplicity, but, depending upon the subject's past experience with the water cooled garment and his preoccupation with other tasks, he often makes gross errors in cooling control with resulting discomfort, thermal stress, and inefficient use of consumables (Burton, 1966; Burton and Collier, 1965; Chambers, 1970; Webb, 1970; Webb *et al.*, 1970). Such mistakes are not always immediately reversible. For instance, overcooling at work onset may produce vasoconstriction and decreased heat extraction with a chilly sensation which persists long after a more reasonable cooling level is resumed (Annis and Webb, 1967; London, 1969).

One of the major difficulties in subjective cooling control is timing. Early in work with water cooled garments it became clear that there is a temporal dissociation between metabolic heat production and heat output to the water stream (Webb, 1966). Following a step change in work load there is a considerable delay before heat output reaches its new plateau. The delay represents an obligatory period of heat storage after work onset and an equal period for destorage after work ceases; apparently there is a resetting of the internal thermostat so that the body runs warmer as metabolic rate rises (Nielsen, 1938; Webb, 1966; Webb and Annis, 1967, 1968).

Considerable interest has been shown in the development of automatic cooling control by means of variable water inlet temperature at a fixed flow rate. Control may be based on any signal proportional to metabolic heat production, provided the factor of physiologic delay is included.

Webb and co-workers studied the time courses of several physiologic variables as a man goes from rest to work or changes work levels (Webb and Annis, 1967; Webb

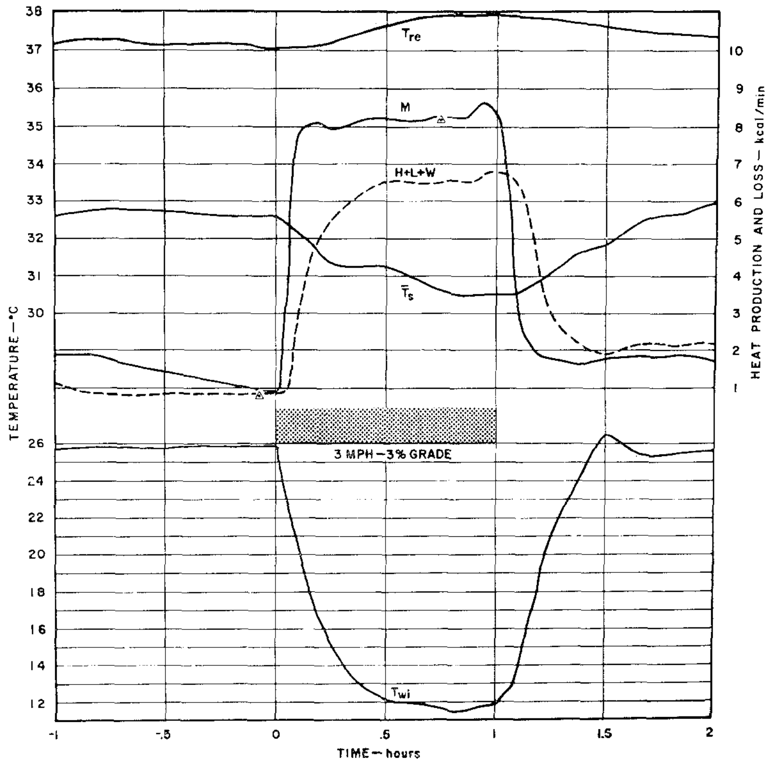

Fig. 8. Time courses of physiologic variables. Data from an experiment with a subject wearing a water cooled garment and thermally isolated from the environment. Record includes heat production (M), heat extraction by the garment (H), obligatory evaporative loss (L), and external work (W). The sum ($H + L + W$) represents total measured heat output. Temperatures shown include rectal (T_{re}), mean skin ($\bar{T}_s$), and water inlet (T_{wi}). Note time courses of variables after work onset and during recovery (Webb, 1970).

et al., 1970). Their subjects wore the WCG under insulating garments and performed measured amounts of work while T_{wi} was controlled to prevent sweating. The results are illustrated in Figure 8. It was found that oxygen uptake and heart rate showed almost immediate stabilization at levels appropriate to the new work load. Skin temperature (related to T_{wi}) was somewhat slower, while rectal temperature and heat output required nearly an hour to reach their new plateaus. In approaching a new steady state level, each variable showed an exponential curve which could be described by a characteristic time constant. This in turn made possible the construction of a biothermal model of man and the development of equations for automatic controller design (Troutman, 1970; Webb, 1970; Webb *et al.*, 1968).

Physiologic signals used in objective or automatic cooling control have included oxygen uptake (Troutman, 1969; Webb *et al.*, 1968), heart rate (Troutman and Webb, 1970), skin temperature (Merrill and Starr, 1967; Starr, 1970; Starr and Merrill, 1968; Troutman and Webb, 1970; Webb *et al.*, 1970), and sweat rate (London, 1969; Webb and Annis, 1968).

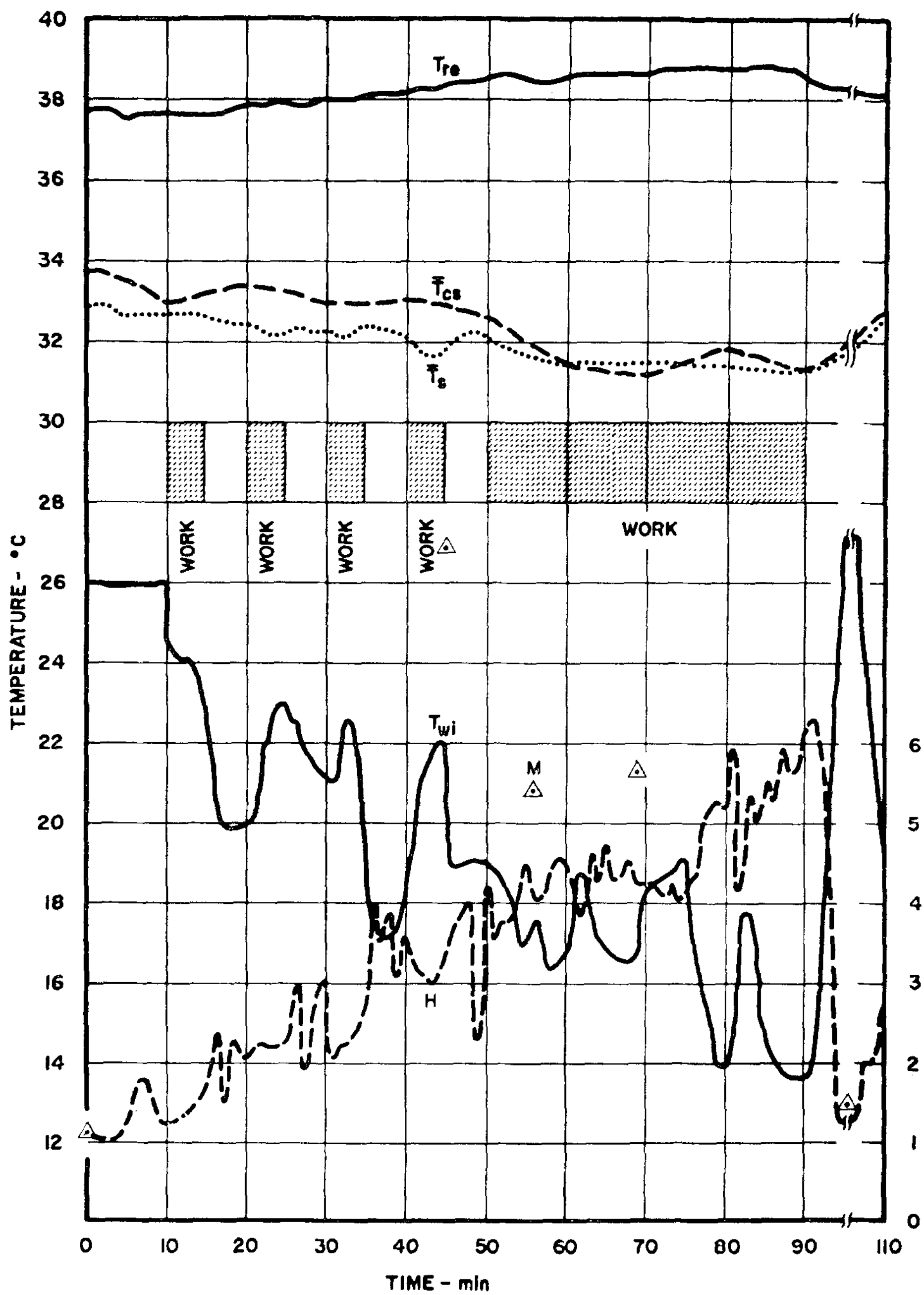

Fig. 9. Automatic cooling control. A single experiment with the ΔT controller (see text) where the subject alternately worked and rested in 5 min segments for 40 min. The average of four skin temperatures used as a control input ($\bar{T}_{cs}$) is shown with mean skin temperature ($\bar{T}_s$). Metabolism (M) was measured by the standard technique of collecting expired air and analyzing its composition; these data are shown as triangular symbols. Other symbols as in Figure 8 (Webb and Troutman, 1970).

For practical use an automatic controller should involve only simple instrumentation. In addition to the primary control signal such as those mentioned above, there should be a secondary or feedback signal to prevent controller drift (Troutman, 1970). This is particularly important if the WCG is to be worn during long rest periods when a small error in heat extraction can gradually produce severe heat storage or chilling. Specifically, if shivering occurs there is a rise in metabolic rate which can paradoxically signal for further cooling (Troutman, 1970).

Design of controllers for space applications has concentrated upon physiological signals already available in the Apollo backpack, namely the heart rate (HR) and temperature change across the water cooled garment (ΔT). Both rise with metabolic rate. An easily obtained feedback signal is skin temperature (T_s) at selected sites. Prototype controllers using electronic logic circuits have been designed for $\Delta T/T_s$, HR/T_s, and HR alone as input signals (Troutman, 1969; Troutman and Webb, 1969, 1970; Webb, 1970).

An interesting approach has been the development of a fluidic device designed to control separately the T_{wi} for each of four garment zones, each including one limb and the adjacent torso (Merrill and Starr, 1967; Starr, 1970; Starr and Merrill, 1968). Control is based on stabilization of skin temperature (T_s) at an uncooled site. As heat load (internal or external) increases at the site, the measured T_s rises and signals for a lower T_{wi}. A new balance is reached only when thermal outflow to the WCG compensates for heat load in the uncooled area.

The practicality of automatic control has been demonstrated in the laboratory with the Apollo WCG, using intermittent work and changes in work load to challenge the controllers. Such an experiment using the $\Delta T/T_s$ controller is shown in Figure 9. It is notable there that, conforming to the time constant involved, cooling fell a half-cycle behind the intermittent work periods. Nevertheless, total cooling ($H+L+W$) closely matched total heat production (M) and the subject was comfortable (Troutman and Webb, 1970). Similar experiments have successfully used the HR/T_s and HR only controllers (Troutman and Webb, 1970). Such controllers may see use in future space flights (Chambers, 1970).

8. Regional Cooling

The body consists of several regions with distinct thermoregulatory characteristics. A useful classification separates the hands and feet, limbs, torso, and head. The cooling capacity of a given region depends upon its surface area, local heat production, tissue insulation, vascularity, and maintenance of thermal exchange when chilled by the cooling medium. Subjects prefer to concentrate the cooling over areas of working muscle, and studies have shown that large amounts of heat reach the surface there (Crocker *et al.*, 1964; Webb and Annis, 1967). For optimum effect, cooling distribution ideally should differ for tasks involving resting, walking, and heavy arm-shoulder work. External heat loads may also be localized; in some aerospace and industrial environments the head and hands are subjected to particularly high radiant heat loads (Allan, 1970; Hill, 1970).

Except over areas of working muscle, cutaneous vessels of the limbs promptly constrict on exposure to cold, a reflex mechanism which limits heat loss from the periphery (Clifford, 1961; Hertzman, 1959; Hill, 1921; Maddock and Coller, 1923). The head and neck vasculature lack such a constricting mechanism (Blair *et al*; 1961; Fox *et al.*, 1960, Hertzman and Roth, 1942) and will maintain large heat transfer rates to a cold fluid (Clifford, 1961; Froese and Burton, 1957). In most situations the head is exposed to the environment, whether cold or hot, and is also important to subjective judgement of thermal comfort (Veghte, 1970). Studies have shown that a significant portion of metabolic heat may be extracted through the head surface (Froese and Burton, 1957; Nunneley *et al.*, 1970; Shvarz, 1970). It is interesting that subjects walking on a treadmill and allowed to select cooling for five independent suit segments chose high cooling rates for the legs and head with lower rates for the arms (Webb, 1970; Webb and Annis, 1967).

Such regional characteristics should play a role in the design of water cooled garments. An example of the consequences of ignoring regional factors is the Apollo WCG which has tubing evenly distributed over the body and is reasonably comfortable at rest, but during treadmill walking with high total cooling rates there is a chilly sensation over the torso and arms while the legs feel persistently hot (Webb, personal communication). Other WCG designs have allowed appropriate variations in regional cooling by control of water flow (Webb and Annis, 1967), by separate temperature control to each of the limb quadrants (Starr, 1970; Starr and Merrill, 1968), or by design of cooling distribution for a particular task such as walking.

It has long been known that cooling of a limited portion of the body can reduce general thermal stress (Burch and Sodeman, 1944; Byrne, 1968; Hill, 1921; Kerslake, 1955). Such cooling may be used alone or in combination with other protective clothing for alleviation of moderate heat stress. It offers practical advantages in terms of simplified equipment and less encumbrance of the wearer. Although minimal cooling will improve comfort, significant benefit will accrue only where cooling is sufficient to lower central blood temperature (Burch and Sodeman, 1944; Hill, 1921; Kuno, 1956). Recent interest has focussed on cooling the torso (Esposito, 1970; Gold and Zornitzer, 1968; Hock and Dart, 1967; Kaufman and Pittman, 1966) and on head cooling (Brouha, 1960; Clifford, 1965; Konz and Duncan, 1969; Nunneley *et al.*, 1970; Shvarz, 1970). The latter appears to be a particularly effective, comfortable, and convenient site for body heat removal.

9. Conclusions

The advantages of water cooling may be briefly summarized here. The WCG offers virtually unlimited cooling capacity at no physiological cost and with great comfort to the wearer. For portable or self-contained systems it offers significant engineering advantages over gas cooling. The WCG is easily combined with other protective clothing.

Practical problems still remain in WCG design and operation. The full suits are expensive and must fit the wearer closely with little or no material intervening between tubing and skin. Suit reliability is a problem under hard daily use where a water spill could have serious consequences including wet clothing, electrical short circuits, or steam production causing burns. Practical, portable heat sinks and methods of cooling control require further development.

Provision of some minimal gas ventilation across the body under the WCG, often simply the venting of the respiratory air supply as in the Apollo design, is helpful in removing the small amounts of water vapor which might otherwise accumulate.

Use of abbreviated WCG's or regional cooling in some situations offers adequate heat relief while obviating many of the problems mentioned above. Such equipment is cheaper than a full garment, easier to fit and maintain, and cooling control is less critical because uncooled body areas may exert normal thermoregulatory effects. The main disadvantage is their inherently limited cooling capacity, depending upon the size and characteristics of the area cooled.

The future may see the application of water cooled garments in all-purpose survival suits offering a sealed microclimate including thermal insulation, flotation, air supply, and possibly dual operation allowing the cooling garment to serve also as a heat source when needed (Sullivan *et al.*, 1967).

For future space suits alternatives to water cooling are still under consideration. Though it is unlikely that a purely passive system can be adapted to the active astronaut (Hedge, 1968; Richardson, 1967; Schlosinger, 1970), a passive-active hybrid might emerge (Richardson, 1969). Other possibilities include more direct coupling of the astronaut's skin to the heat sink of outer space, with elimination of the water circuit and its power requirements (Bitterly, 1970; Brown and Myers, 1970; Schlosinger, 1970). Direct cooling is offered by the Space Activity Suit where use of an elastic leotard without a sealed gas envelope around the body allows natural thermoregulation by direct evaporation of sweat to space at 100% efficiency (Webb, 1968a), a mechanism successfully demonstrated in near-vacuum altitude chamber runs.

At present each set of conditions must be individually evaluated for possible use of water cooled garments. System analysis should include such interacting items as thermal load, task duration, reliability, unit portability, and economic considerations (Brouha, 1960; Brown and Myers, 1970; Burriss *et al.*, 1965). Currently appropriate applications include cooling for pressure suits (Chambers, 1970) and other sealed protective clothing (Allan, 1970; Gaudio *et al.*, 1967; Jurgens, 1968; Veghte, 1970) as well as for extreme thermal environments (Hill, 1970). In all these situations the unique qualities of water cooling offset its costs and users can be specially trained in WCG care and management of cooling control.

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