N72-27125

19 A LIQUID COOLED GARMENT TEMPERATURE CONTROLLER BASED ON SWEAT RATE

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INTRODUCTION

When a man is isolated from his environment—as is an astronaut in a pressure suit—auxiliary cooling is required to remove excess metabolic heat to maintain thermal balance (ref. 1). The major portion of this cooling is often accomplished by a liquid cooled garment (LCG), and, in current operations with the Apollo LCG, the astronauts maintain comfort by manually adjusting the inlet temperature of the coolant. This method of control has been adequate, but it would be preferable to have automatic temperature control. In an emergency, an astronaut should be free to concentrate entirely on his immediate situation; furthermore, man may be a poor judge of his own thermal state, especially when his attention is distracted so that his reactions to sensations of warmth and cold are delayed. The development of automatic LCG temperature controllers, responding to an astronaut's heat production rate, has been the subject of several studies. Three of these efforts are reviewed, and the design and operation of an Ames-developed controller based on sweat rate is presented in detail.

REVIEW

Three LCG temperature controllers that have been reported are a "metabolic rate" controller (ref. 2 and fig. 19.1), a "constant skin temperature" controller (ref. 3 and fig. 19.2), and a "differential temperature" controller (ref. 4 and fig. 19.3). In the "metabolic rate" controller, the subject's oxygen consumption is monitored and the controller automatically adjusts the LCG inlet temperature to remove the appropriate amount of heat. A linear relation between the metabolic heat produced and oxygen consumption is assumed. Difficulties develop with this approach during periods of rest when slight overcooling sometimes brings about lowering of skin temperature and results in shivering; oxygen consumption then increases, and the controller lowers the temperature still further. Another feedback element would have to be added to the controller to correct this difficulty. In addition, this controller requires a satisfactory method for continuous monitoring of the oxygen consumption of the astronaut in his pressure suit.

The second proposed controller attempts to maintain a constant skin temperature. This system has proved to be stable, but the basic philosophy of a

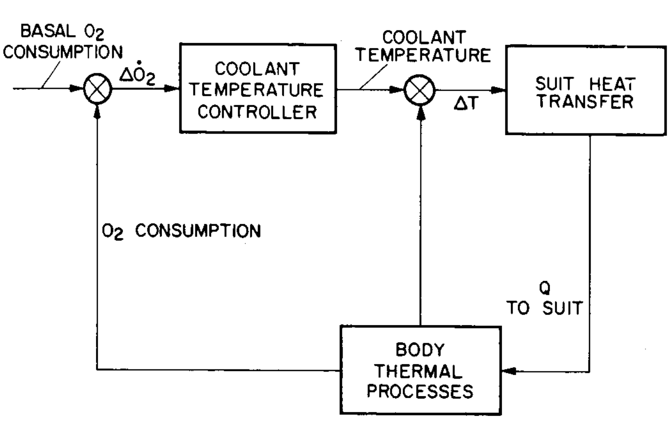

Figure 19.1 *"Metabolic rate" temperature controller (ref. 2).*

constant skin temperature is at odds with the findings of an Ames study (ref. 5) illustrated in figure 19.4, which shows that for optimum comfort, skin temperature should decrease with an increase in heat production. The "constant skin temperature" controller should be adequate for low metabolic rates; however, it may allow an excessive amount of sweating at high metabolic rates when a decrease in skin temperature is desirable.

The "differential temperature" controller attempts to regulate cooling as a function of skin temperature and heat removal. A linear relationship between the heat removal rate and comfortable skin temperature is assumed. Skin temperature is determined by averaging the temperatures at four selected points (right calf, over the right kidney, right lower abdomen, and lift bicep). The heat removal rate is determined by measuring the difference between the LCG inlet and exit water temperatures. For any given heat removal rate the optimum skin temperature is compared with the actual skin temperature, and the LCG inlet temperature is adjusted accordingly.

A disadvantage of the "differential temperature" controller (and also of the "constant skin temperature" controller) is the requirement that transducers or sensors be affixed directly on the body of the subject. Skin sensors, when used for extended periods, are likely to cause discomfort; thus, the acceptability of these controllers is likely to be limited. The

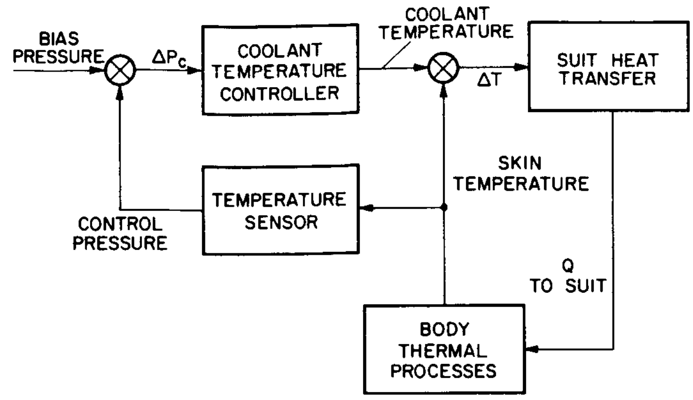

Figure 19.2 *"Constant skin temperature" thermal controller (ref. 3).*

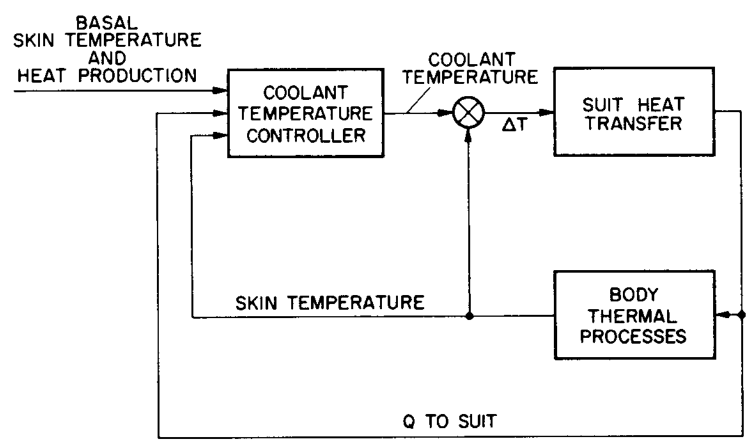

Figure 19.3 *"Differential temperature" thermal controller (ref. 4).*

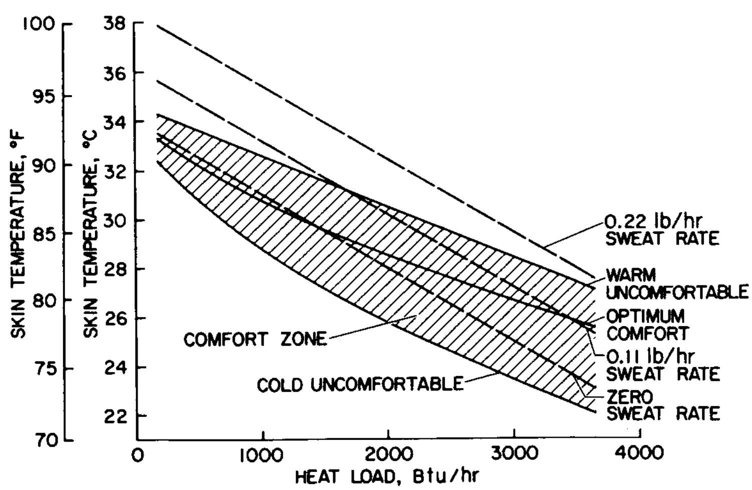

Figure 19.4 *Conduction cooling comfort zone (ref. 5).*

Environmental Control Research Branch at Ames Research Center has, therefore, undertaken the development of an LCG automatic controller that does not require skin sensors.

AMES CONTROLLER DESIGN

The comfort and sweat rate data in figure 19.4 illustrate three interrelated concepts applicable to subjects wearing a cooling garment such as the Apollo LCG.

1. Skin temperature should decrease with increasing heat load
2. Zero sweat rate is not necessary and may not be preferable at the higher heat loads
3. Sensible cooling of the skin can be directly related to the increase of sweat rate with increasing heat load

With these concepts defined, the Ames controller development has been based on the utilization of sweat rate as a primary input signal.

Three approaches were considered in formulating the logic for a sweat rate controller.

1. The controller could be designed to adjust coolant inlet temperature T_{IN} to the LCG such that the subject's sensible heat loss is kept proportional to his latent heat loss, thereby maintaining an acceptable balance between the normal modes of heat transfer. The heat losses would be determined from measurements of the inlet and outlet LCG and ventilating air temperatures and the subject's sweat rate. The T_{IN} to the LCG would be increased or decreased depending on whether sensible heat loss was too large or too small with respect to the latent heat loss.
2. Sweat rate could be kept constant at a set level (i.e., 100 g/hr). The controller would vary T_{IN} inversely with respect to any change in sweat rate. To perform correctly, the controller set point would have to be above the subject's normal insensible water loss rate; therefore, a slight amount of sweating would occur at all times.
3. The controller could be designed such that T_{IN} would be inversely proportional to the subject's latent heat loss as evidenced by evaporative water loss. This logic is similar to that of approach 2, but sweat rate would be permitted to increase with increasing work rate.

In the study described here, the third controller logic approach was used because the instrumentation and computation requirements for its implementation were considered to be the simplest. A block diagram of the logic is shown in figure 19.5. The controller in this system regulates LCG coolant inlet temperature T_{IN} as a function of two parameters: (a) a basal inlet water temperature T'_{IN} and, (b) the increment $\Delta\dot{S}$ in evaporative water loss rate with respect to a basal rate $\dot{S}'$. The T'_{IN} is the coolant temperature that provides comfort for the subject in a sedentary mode, and $\dot{S}'$ is the corresponding rate of evaporative water loss (which includes insensible water loss as well as loss due to active sweating). The controller algorithm is

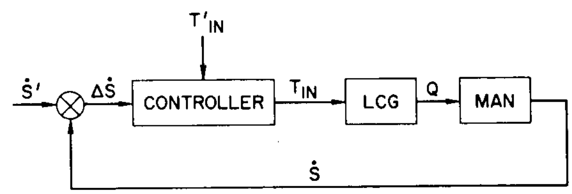

Figure 19.5 *Temperature controller logic.*

$$T_{IN} = T'_{IN} - K_1(\Delta\dot{S})$$

Evaporative water loss (which is representative of latent heat loss) can be determined from measurements of specific humidity (dewpoint) in the outlet and inlet air lines of the subject's pressure suit or similar ventilating garment. If inlet air dewpoint is maintained at a constant low value, then $\Delta\dot{S}$ can be expressed simply as a function of air flow rate $\dot{w}$, the outlet air dewpoint T_{dp} during exercise, and the outlet air dewpoint T'_{dp} measured with the subject in the sedentary mode described above

$$\Delta\dot{S} = K_2(\dot{w})(T_{dp} - T'_{dp})$$

ECRB CONTROLLER OPERATION

Experiments with the controller were conducted with subjects wearing a whole-body air-ventilated suit over an Apollo LCG. The dewpoint of the suit inlet air was kept approximately constant at -2° C. The inlet air temperature was maintained at 20° C with an air circulation rate of 29 m^3/hr. The dewpoint of the suit outlet air thus became the only variable used in controlling T_{IN}. The subjects exercised on a treadmill at various metabolic rates; the metabolic rates were calculated based on oxygen consumption measurements during the tests. During initial tests, subjective evaluations of thermal comfort were recorded while several values of the proportionality constants K_1 and K_2 were set in the analog computer, which served as the controller for the tests. Based on these evaluations proportionality constants selected for the controller equations were $K_1 = 0.09[(°C \cdot hr)/gm]$ and $K_2 = 0.40[gm/(m^3 \cdot °C)]$.

The coolant supply system (fig. 19.6) introduced considerable mechanical delay (of the order of 3 min) into the overall controller response time because of backlash in the hot and cold metering valves, slow reaction in the heat exchanger, and a long coolant supply line to the LCG. Nonlinearity of the hot and cold metering valves also affected the response of the controller. The problems of nonlinearity and delay were overcome, for these tests, by operation of the controller in a sample data system mode. The sampling rate was made proportional to the difference between LCG inlet temperature $T_{IN}|_{actual}$ and the desired inlet temperature $T_{IN}|_{control}$ as computed by the controller. At each sample time the hot and cold metering valve motors were energized for a short, fixed length of time (approximately 50 msec) so that $T_{IN}|_{actual}$ was, in effect, caused to approach $T_{IN}|_{control}$ in steps. This mode of operation reduced the effects of the inadequacies of the coolant supply components and resulted in relatively quick and stable response of the system.

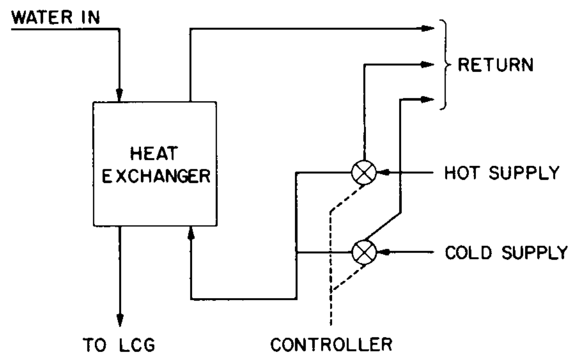

Figure 19.6 *Coolant supply system.*

Figures 19.7 and 19.8 show recorder tracings of treadmill speed, $T_{IN}|_{control}$, and $T_{IN}|_{actual}$ for two levels of exercise. The subjects were kept thermally comfortable during the tests illustrated, and for all tests with work rates up to about 3000 kJ/hr. The only major difficulty with the controller occurred for a subject exercising at a high work rate (4200 kJ/hr) for 1/2 hr. In this test, the subject could not be adequately cooled, especially around the head and neck (the Apollo LCG provides no head or neck cooling). A

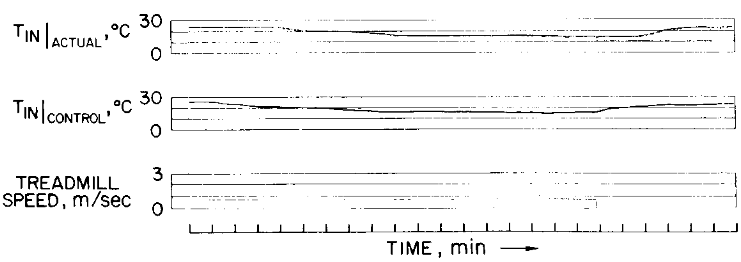

Figure 19.7 *Test results–work rate 1250 kJ/hr.*

portion of the subject's sweat was not evaporated by the ventilating air, but was absorbed by the fabric of the LCG. When the subject stopped exercising, the absorbed sweat began to evaporate; the controller sensed this as continued sweating and maintained an LCG temperature lower than was comfortable for the subject. In other respects, the performance of the sweat rate automatic controller was promising. Continuing tests are scheduled with the hardware modified to eliminate the causes of most of the nonlinearities and transport delays of the original system.

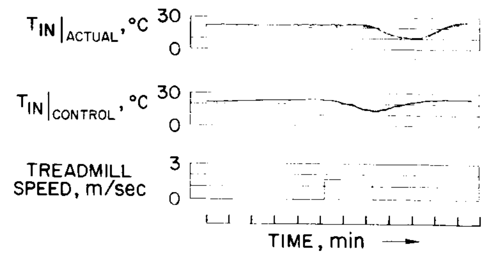

Figure 19.8 *Test results–work rate 2900 kJ/hr.*

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