15

A FLIGHT-RATED LIQUID-COOLED GARMENT FOR USE WITHIN A FULL-PRESSURE SUIT

Richard Carpenter and William R. Winter
NASA Flight Research Center
and John D. Wilde Computing and Software, Inc.,
Edwards, Calif.

INTRODUCTION

Many of the flights conducted at the NASA Flight Research Center (FRC) require the use of pressure suits for high-altitude operation. In the summer on the Mojave desert, temperatures inside these suits can become extremely hot because of insufficient cooling air during preflight, standby, and taxiing. To reduce temperatures to comfortable levels, a liquid-cooled garment (LCG) was considered desirable for use by pilots when wearing full-pressure suits.

Most of the development of self-contained liquid-cooled garment systems (ref. 1) has been directed toward the particular problems of spacecraft extravehicular activities. The approach taken by the FRC has been to attempt to cool a pilot seated in a closed cockpit of a research aircraft by using a limited supply of cooling air. For aircraft use, the desired system had to be lightweight and self-contained on the pilot because of weight and space limitations on aircraft such as the lifting bodies. Actual requirements precluded placing electrical components inside the pressure suit and required a system proportioned to fit comfortably inside the suit and not interface with pilot tasks.

This paper presents the results of tests conducted at the FRC to define the heat removal requirements of a pressure-suited pilot wearing an LCG when seated in the cockpit of a research vehicle. The system that was developed and fabricated to meet these requirements is described, and results of actual tests conducted to evaluate the performance of the system are discussed.

DESIGN CRITERIA

The thermodynamic design criteria for the cooling system were established by experiments at the FRC with subjects wearing pressure suits and the Apollo type of liquid-cooled garment (ref. 2 - 4), which is cooled by external refrigeration and completely covers a subject except for his face. These experiments were conducted in a cockpit simulator exposed to the sun at zenith with the subjects performing typical pilot tasks. Measurements included garment coolant inlet and outlet temperatures and flow rates. For all experiments, cockpit temperatures were maintained at 66° C (150° F). These tests were performed using different canopy configurations, and significant changes in heat loading values were noted; for example, the heat loading was one-third less with an X-15 type of canopy having a 0.3-m^2 (3.2 sq ft) window surface than on the subject with an HL-10 type of canopy with a window surface area of 1.6 m^2 (17.5 sq ft). Thus, the change in solar radiant energy significantly affected the heat loading on a subject wearing a full-pressure suit. These tests also indicated that when the suit was ventilated, lower cooling rates were required to prevent the subject from sweating. Therefore, a 57-liter (2-cfm) air supply, which is typically available in research vehicles, was used for suit venting. These findings led to adopting a reflective outer garment and a 57-liter/min (2-cfm) air ventilation rate for the pressure suit to minimize the heat absorbing requirements for the cooling system heat sink.

Maximum temperature tests were again conducted with subjects wearing a reflective garment over a ventilated pressure suit. The measurements indicated that a garment heat absorption rate in the range of 250 kg-cal/hr (1000 Btu/hr) to 175 kg-cal/hr (700 Btu/hr) would generally prevent sweating and maintain comfort for a 70 percentile pilot seated in a cockpit with 1.6 m^2 (17.5 sq ft) of canopy glass.

SYSTEM DESCRIPTION

Figure 15.1 is a block diagram of the cooling system components. The pulse pump converts pneumatic pressure to hydraulic pressure that circulates the coolant through the garment and the heat sink. The temperature controller regulates the amount of flow through the heat sink, depending on the garment inlet temperatures. For aircraft operations during hot weather, the controller does not allow coolant flow through the heat sink below 24° C (75° F), and as the temperature inside the pressure suit rises, the controller gradually allows an increasing coolant flow through the heat sink until full flow is established at a garment inlet temperature of 30° C (86° F). At altitude, because of external pressure changes, the volume of the coolant tubing changes, which reduces the coolant pressure. To compensate for this volume change, an accumulator is included in the system to ensure that a slug of coolant is always fed into the pump, thus assuring continuous operation during rapid altitude changes.

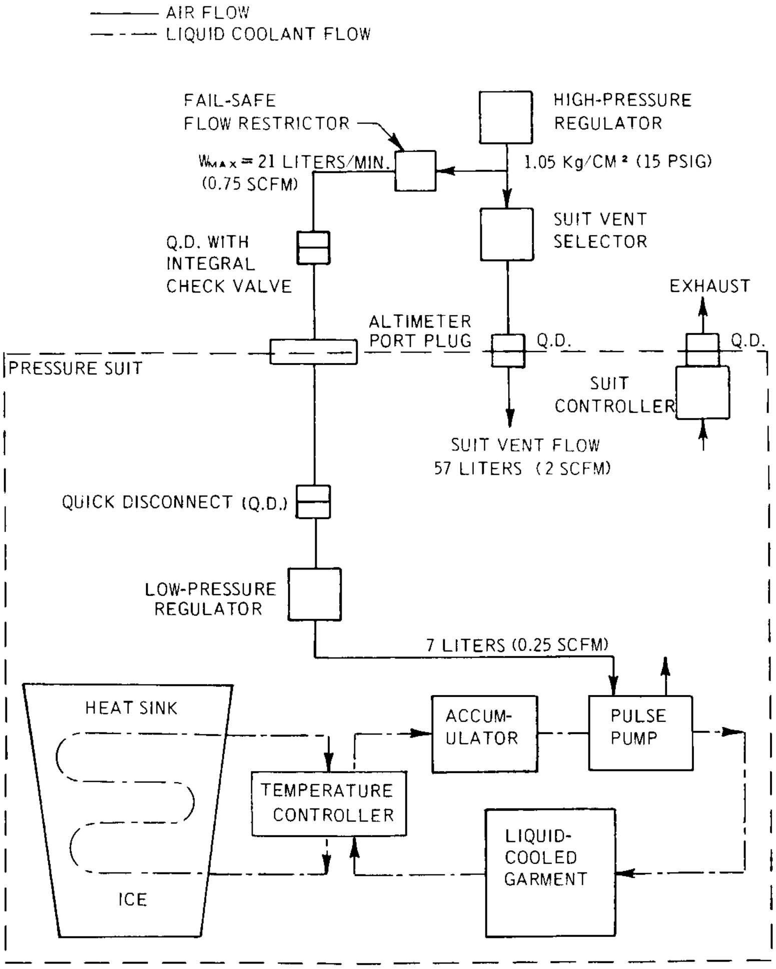

Figure 15.1 *Liquid-cooled garment with pressure suit interface.*

The heat sink is composed of spirally wound tubing (fig. 15.2), with a smaller tygon tube placed inside a larger tube. The inner tube carries the coolant and the larger outer tube contains 2 kg (4.4 lb) of ice. The outer tubing is constructed of neoprene-covered nylon and is further insulated from the wearer by 1.3 cm (0.5 in.) of urethane foam (fig. 15.3). The 3.3-cm (1.3-in.) thick heat sink is designed to fit comfortably on any particular individual by freezing the water while the pliable heat sink is resting on a mold of the pilot's back. The result is a thin, formfitting, backpack heat sink suitable for wear under a pressure suit.

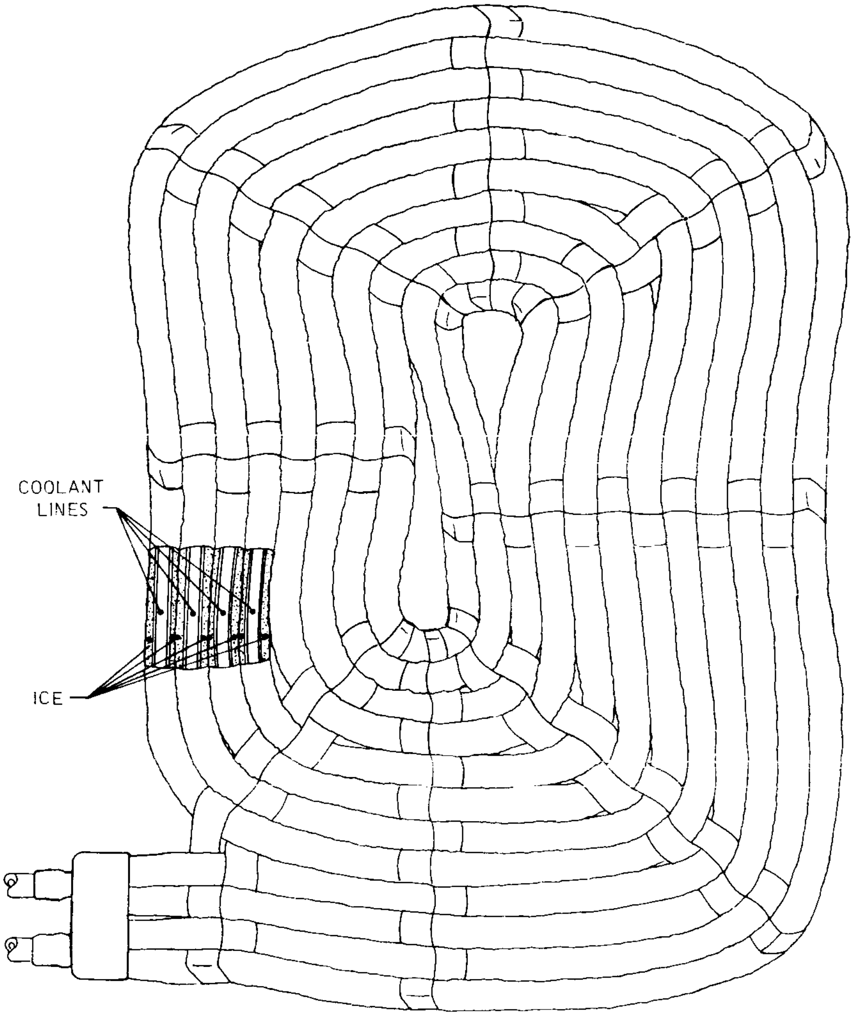

Figure 15.2 *Backpack heat sink.*

Figure 15.3 illustrates the location of the components on a pilot. The garment, containing 89 m (292 ft) of tubing, distributes the coolant over all surfaces of the pilot except for his ears, face, fingers, and the bottoms of his feet. The control hardware and pump are mounted on the left side, which least hinders pilot movement in an airplane. The heat sink is formfitted to the back with the coolant manifolds placed near the lower right abdomen.

The fully assembled system weighing 7.2 kg (16.0 lb), is charged for operation by placing the entire garment system in a freezer at -8° C (+18° F) for 20 hr. To prevent the coolant from freezing, a mixture of 20-percent glycol and 80-percent water is used. The heat sink is positioned on

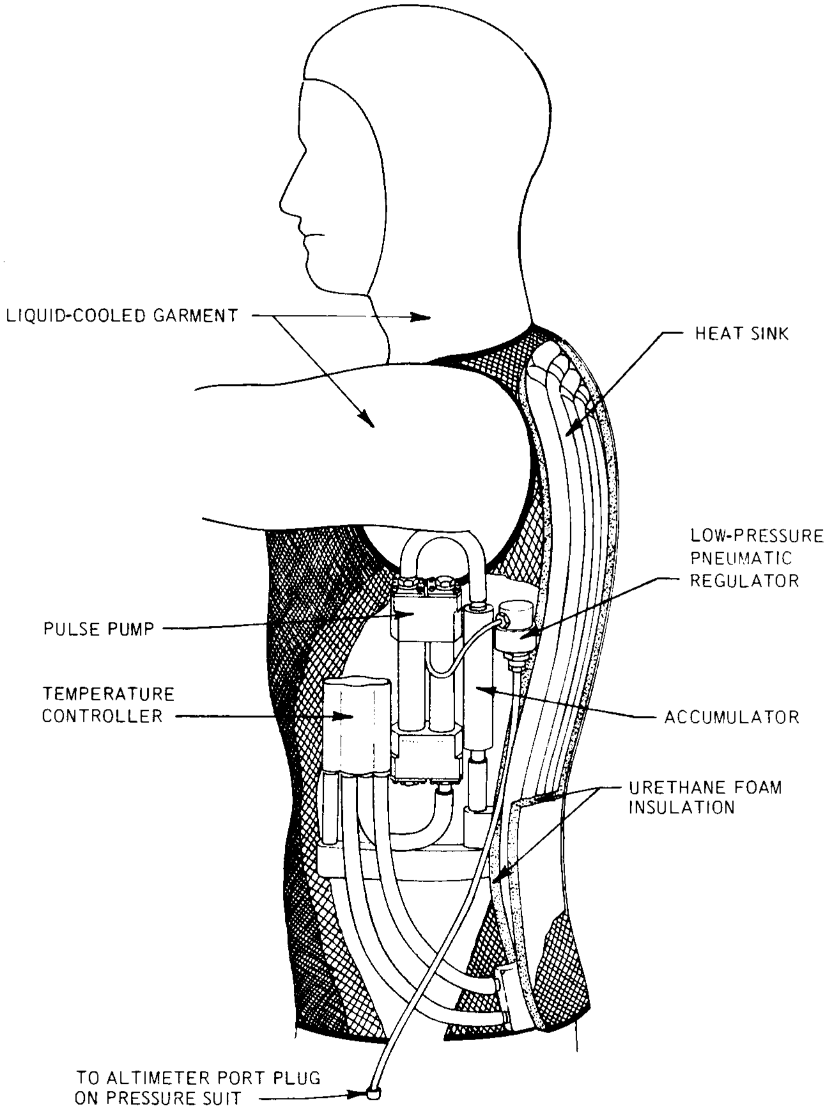

Figure 15.3 *Cooling system components positioned on a pilot.*

a mold of the back of the pilot who intends to use the system and formfitted during the freezing process to fit the pilot. After 20 hr the fully assembled and charged system is ready for use and may be donned immediately by the pilot.

With an assistant, the time required for a pilot to dress in this cooling garment system is approximately 90 sec (fig. 15.4); about 2-1/2 min are required if the pilot dresses himself. The cooling system does not add any appreciable time to that required to put on a pressure suit; however, if a pressure suit is nearly skintight, a suit of the next larger size may be required to accommodate the extra thickness of the heat sink backpack. Experiments have shown that physical movement is normal when the cooling garment is worn with the pressure suit fully inflated to 0.245 kg/cm^2 (3.5 psig).

Figure 15.4 *Dressing sequence.*

TESTS AND TEST RESULTS

The cooling garment system was tested for heat absorption capability in a typical cockpit configuration (fig. 15.5) with subjects wearing full-pressure suits and reflective garments. Figure 15.6 illustrates where measurements of coolant flow rate and temperatures were taken during these tests. The heat-absorbing rates of the system were determined from flow rates and inlet and outlet temperatures of the garment.

Figure 15.7 shows the cockpit temperatures and the differential temperatures measured across the garment. The cockpit temperatures generally stay at 66° C (150° F), and the difference in temperature between the inlet and outlet valves of the garment decreases from 3.2° C (5.8° F) to 2.4° C (4.3° F) during a 40-min period.

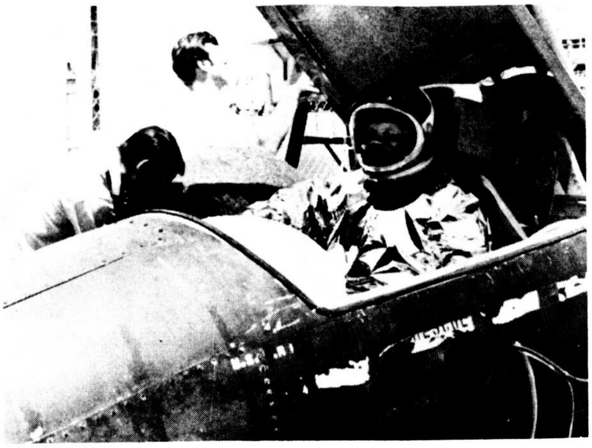

Figure 15.5 *Pressure-suited subject in cockpit simulator during high-temperature tests.*

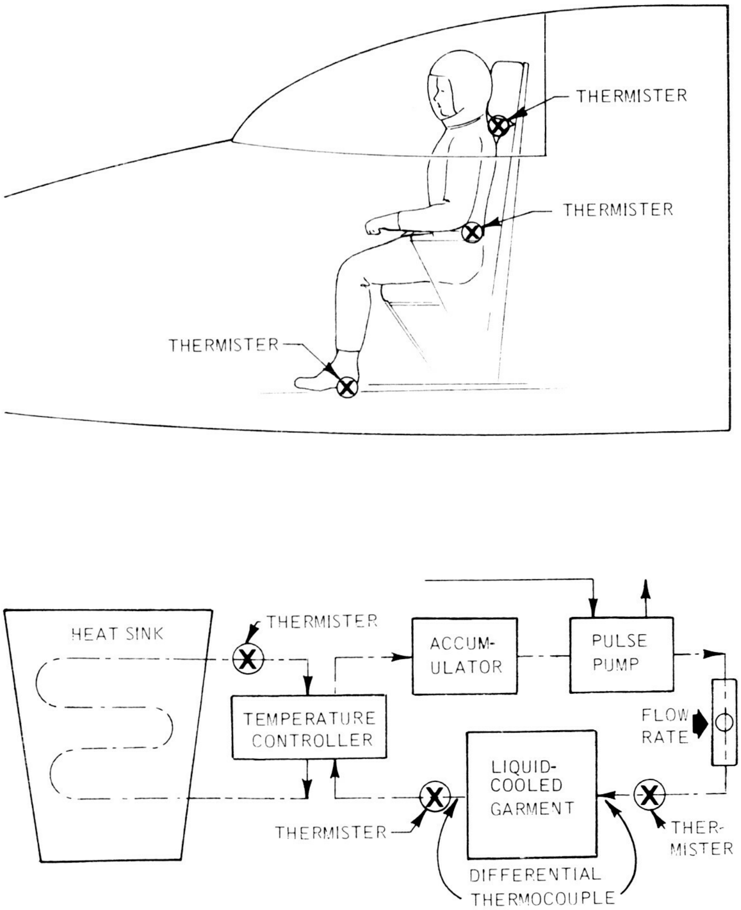

Figure 15.6 *Location and types of measurements made during tests.*

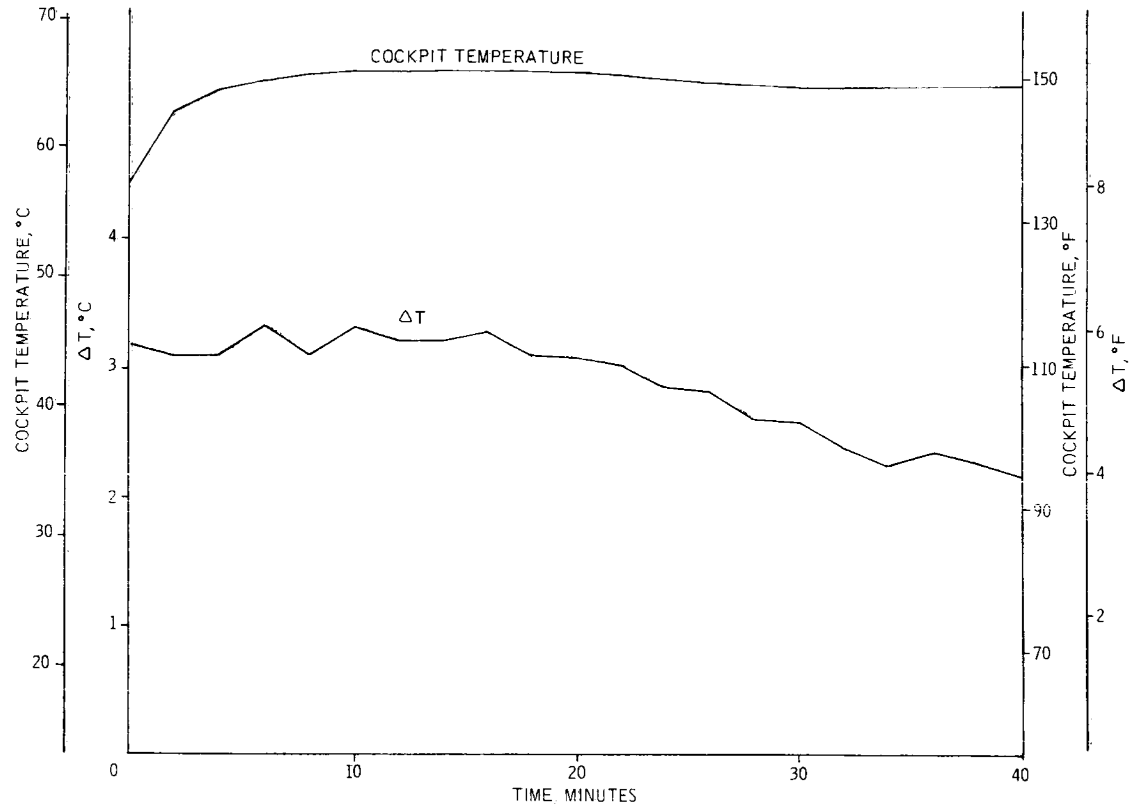

Figure 15.7 *Typical time history of cockpit temperature and the differential temperature of the liquid-cooled garment.*

Figure 15.8 illustrates the effect of the temperature controller on the heat sink outlet temperature and the inlet and outlet temperatures across the suit. As the garment inlet temperature increases, the valve opens allowing an increased flow through the heat sink. The temperature controller acts only to prevent too much cooling to the pilot. When the heat sink temperature equals the garment inlet temperature, the valve is fully open and no further reduction in temperature is possible.

Figure 15.9 is a typical graph of the system heat removal rate, Q, based on the equation $Q = Wc_p\Delta T$, where the coolant flow rate, W, ranges from 1.2 liters/min (2.7 lb/min) to 1.0 liter/min (2.3 lb/min) and the differential temperatures, ΔT, across the garment range as previously stated from 3.2° C (5.8° F) to 2.4° C (4.3° F). The specific heat, c_p, is unity for the coolant. The flow rate gradually decreases with time as the temperature controller diverts more flow through the heat sink, which increases the system pressure drop. Heat absorption rates decrease from approximately 224 kg-cal/hr (890 Btu/hr) to 143 kg-cal/hr (570 Btu/hr) in 40 min. The first 30 min are generally very comfortable for the subject; during the remaining minutes, a gradual heat load builds up which results in mild sweating during the last few minutes of the test.

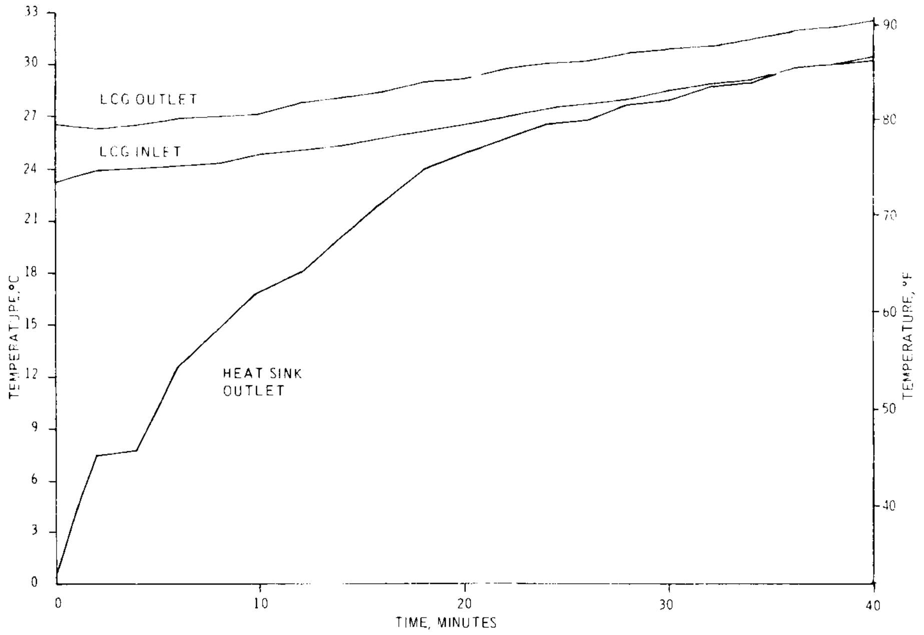

Figure 15.8 *Typical time history of liquid-cooled garment inlet and outlet temperatures and heat sink outlet temperature.*

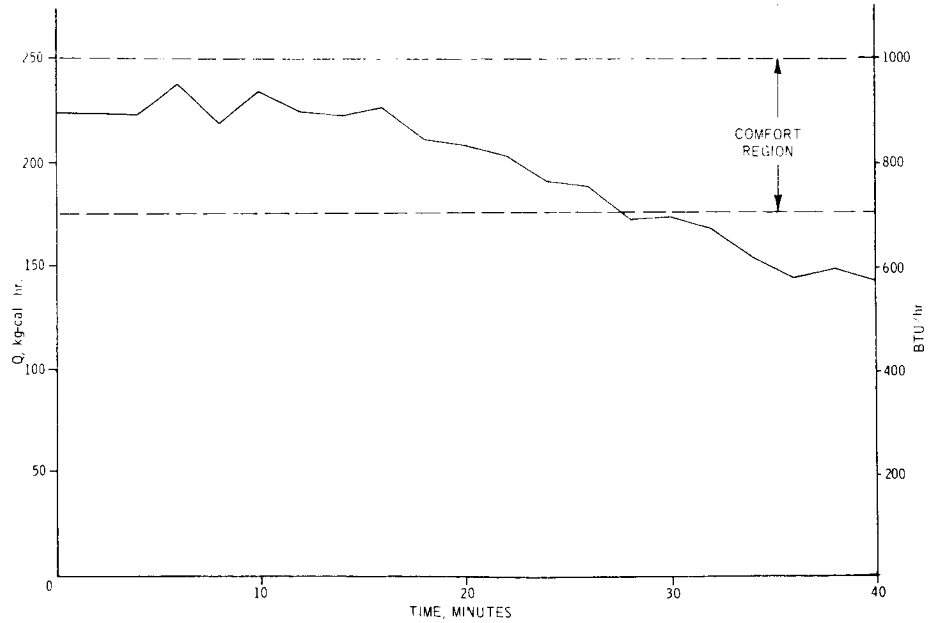

Figure 15.9 *Typical time history of liquid-cooled garment heat absorption rate.*

DISCUSSION

Under actual flight conditions, after a maximum of 40 min, the pilot will be airborne and a generous supply of cold air will be available in the cockpit for cooling. In the event the pilot is quickly airborne and rapidly cooled, the temperature controller reduces the flow to the heat sink to prevent too much cooling. During cold or long operations without the heat sink in the loop, the pump continues to circulate liquid through the garment, which evenly distributes the body heat.

A prototype cooling system garment (fig. 15.10) has been flown in high-performance aircraft (F-104B) with the test pilot wearing a regulation summer flight suit over the cooling system. Figure 15.11 illustrates the lack of bulkiness of the system and the pilot's freedom when the cooling system is being worn. These first flight tests will be followed by full-pressure suit flights. During the first test flights, the pilot reported that the garment was comfortable and provided adequate cooling in the hot cockpit during standby and taxiing. The FRC is buying four of these cooling garment systems for use with pressure suits. The garments will be evaluated by NASA test pilots during high-altitude flight missions.

PILOT COOLING SYSTEM

THIS LIQUID COOLING GARMENT SYSTEM, WORN BENEATH A PRESSURE SUIT, WILL KEEP A PILOT FROM PERSPIRING FOR 60 MINUTES IN A CLOSED COCKPIT AT 155° F. DURING THIS TIME, THE AVERAGE HEAT REMOVAL IS 800 BTU / HR. THE PUMP IS DRIVEN PNEUMATICALLY AT 15 PSI AND AT A FLOW RATE OF 0.25 CFM. OPERATION IS CONTINUOUS TO PRESSURE ALTITUDES OF 35,000 FEET. SYSTEM IS CONDITIONED FOR USE BY PLACING IN A FREEZER FOR 20 HOURS AT 10° F. WEIGHT IS 14 LBS.

Figure 15.10 *Flight-rated liquid-cooled garment.*

Figure 15.11 *Pilot wearing liquid-cooled garment.*

SUMMARY

Aircraft operations in the desert have shown a need for additional crew cooling during the ground phases of a mission when pressure suits are being worn. Tests at the FRC with pressure-suited subjects exposed to high temperatures inside a cockpit simulator have indicated that comfortable conditions may be achieved with the combination of a reflective outer garment, a suit vent of 57 liters/min (2 cfm), and a liquid-cooled inner garment capable of absorbing heat in the range of 250 kg-cal/hr (1000 Btu/hr) to 175 kg-cal/hr (700 Btu/hr).

A flight-rated liquid-cooled-garment system for use inside a full-pressure suit has been designed, fabricated, and tested. High-temperature tests with this system have indicated that heat is absorbed at a rate decreasing from 224 kg-cal/hr (890 Btu/hr) to 143 kg-cal/hr (570 Btu/hr) over a 40-min period. The first 30 min are very comfortable; thereafter a gradual heat load builds that results in mild sweating at the end of the 40-min period.

In flight tests during hot weather when this cooling system was worn under a regulation flight suit, the pilot reported that temperatures were comfortable and that the garment prevented sweating.

REFERENCES

1. Nunneley, Sarah A.: Water Cooled Garments: A Review. Space Life Sciences, vol. 2, 1970, pp. 335-360.
2. Chambers, A. B.: Controlling Thermal Comfort in the EVA Space Suit. ASHRAE, March 1970, pp. 33-38.
3. Jurgens, F.: Aircrew Cooling Study. TG-945, Applied Physics Laboratory, Johns Hopkins University, 1968.
4. Waligora, J. S.; and Michel, E. L.: Application of Conductive Cooling for Working Men in a Thermally Isolated Environment. Aerospace Med. vol. 39, 1968, pp. 485-487.