C.P. No. 1330

C.P. No. 1330

PROCUREMENT EXECUTIVE, MINISTRY OF DEFENCE

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

The Development of Portable Coolers for the Liquid Conditioned Suit

by

G. F. Barlow

Engineering Physics *Dept.,* **R.A.E., Farnborough**

LONDON: HER MAJESTY'S STATIONERY OFFICE

1975

PRICE *£1-60* NET

UDC 614.89 : 621-713 : 629.13.067.2 : 621-71

*C.P. No.1330
August 1974

THE DEVELOPMENT OF PORTABLE COOLERS FOR THE LIQUID CONDITIONED SUIT

by

G. F. Barlow

Engineering Physics Department, RAE Farnborough

SUMMARY

Two portable coolers for use with liquid conditioned suits have been designed and developed at the RAE, one using solid carbon dioxide as the heat sink and the other water-ice. They provide 250W h of cooling at rates up to 350 W with outlet temperatures of 12°C and 20°C respectively; their weights are 5.8 kg and 4.6 kg.

The water-ice cooler can be recharged without replacing the water or battery by connecting it to a recharging unit which has been designed. This greatly reduces the handling problems normally associated with portable coolers.

The results of laboratory and field trials in ambient temperatures up to 40°C are presented, with recommendations for further development.

*Replaces RAF, Technical Report 74114 - ARC 35793

CONTENTS

Neg.Nos. C11602-C11607

1 INTRODUCTION

The clothing assembly worn by the crew of a modern aircraft provides some thermal insulation of the man from his environment and greatly reduces the body's ability to dissipate metabolic heat. This problem is aggravated if the man is in a hot environment, and, if comfort is to be maintained, it becomes necessary to extract heat from the body using a liquid or air cooled suit. The suit itself adds to the insulation and it is desirable to continuously cool the man for the whole period that he is wearing the clothing assembly, not only when he is coupled to the aircraft system. A portable cooler, independent of external supplies, is therefore needed for use in the crew room before flight, in transit to and from the aircraft and during debriefing.

In recent years RAE has been developing the liquid conditioned suit (LCS) and its associated supply systems. A fundamental advantage of the LCS over the air ventilated suit (AVS) is the low pumping power that is required to circulate the suit coolant. Because of the lower volume flow, the LCS has a pumping power advantage of approximately 1000:1. This makes it practical to produce a portable cooler for the LCS that is of reasonable weight and bulk. Typical requirements for such a cooler would be to provide a flow of about 0.8 l/min of water/ethanediol to the LCS at a temperature controllable down to $15^{o}C$. Up to 350 W of cooling should be provided for 40 minutes.

Prior to the work to be reported here, there were two portable coolers available for use with the LCS. The first of these was designed for an industrial use; it is robust but heavy, weighing approximately 14kg fully loaded. It utilises as the heat sink solid carbon dioxide subliming at a pressure of $140kN/m^2$ gauge. The gas evolved powers a diaphragm pump which circulates the coolant. Gas supply to the pump is controlled by a bistable fluidic device. Its performance was reported by Beeny[1] and London[2].

The second portable cooler[2,3] had been produced under contract for the RAE. The heat sink is water-ice which is loaded into the cooler. Dry batteries power a pump to circulate the suit coolant. The unit weighs 9kg fully loaded.

This Report describes the development of two types of portable cooler which are more efficient than those previously available. One cooler, which employs solid CO_2 as the heat sink, has the new feature that the pressure is controlled to the triple point to take advantage of the high boiling heat transfer rates. The coolant pump is driven by the CO_2 gas.

The second unit contains a constant volume of water which is frozen in situ to become the heat sink. Rechargeable batteries power the coolant pump. The complete cooler is therefore rechargeable with the minimum of handling.

2 CARBON DIOXIDE PORTABLE COOLER

2.1 Principle of design

Solid CO_2 is an attractive heat sink for several reasons:

(a) The latent heat of sublimation, which occurs at $-78^{o}C$ at atmospheric pressure, is high; 573 kJ/kg compared with 334 kJ/kg for the latent heat at fusion of water;

(b) the energy of the gas evolved can be used to pump the coolant around the suit, thus avoiding the need for a separate power supply;

(c) the weight reduces as the heat sink is used.

A disadvantage of using subliming CO_2 is the difficulty in maintaining a good contact between the solid CO_2 and the heat transfer surface. It was thought that this problem could be overcome by operating the cooler at the triple point (that is, at a pressure of 518 kN/m^2 absolute and a temperature of $-57^{o}C$) at which liquid is formed. Boiling heat transfer would then be achieved.

A small pressure vessel was built and it proved possible to maintain a steady, high heat transfer into the liquid CO_2. A small gas-driven pump was also developed and a prototype portable cooler assembled.

The circuit of the cooler is shown in Fig.1 and the complete unit is illustrated in Figs.2 and 3.

Coolant returning from the LCS enters the portable cooler and passes into the reservoir, where any air in the liquid is trapped.

The gas-driven double-acting diaphragm pump draws coolant from the reservoir. CO_2 gas is supplied, via a pressure reducing orifice, at 140 kN/m^2 to the fluidic device, which switches the gas flow from one chamber of the pump to the other. A switching signal is transmitted, from one of the two sensing ports in the pump to the fluidic control input, at the end of each stroke. The diaphragms and connecting rod oscillate back and forth drawing coolant into the pump through one pair of non-return valves, and forcing it out through the second pair of valves to the temperature control valve (TCV).

A constant flow of approximately 760 ml/min passes to and from the suit through the self-sealing coupling which allows easy disconnection of suit from cooler.

The TCV is a combined diverter and mixing valve which controls the temperature of the coolant at suit inlet by varying the proportion of the flow which passes through the heat exchanger. The temperature can be varied down to $12^{o}C$ for heat input rates below 400 W.

The heat exchanger is a spiral of 6.4mm OD aluminium tubing, 450 mm in length, fitted close to the bottom of the pressure vessel.

A gas control tap (GCT) controls the flow of gas from the pressure vessel. It can close the gas outlet, it can vent the gas to atmosphere, or it can allow the gas to pass to the pump by way of the pressure reducing orifice and fluidic device.

The pressure vessel is fitted with a pressure gauge and pressure relief valve, (PRV). The PRV vents gas to atmosphere to control the pressure to $450kN/M^2$ gauge once all the solid CO_2 has turned to liquid.

The weights of the individual components are listed in Table 1.

The suit coolant used in previous LCS development at the RAE was a mixture of inhibited ethanediol (ethylene glycol) and water. The low temperature of solid CO_2 tended to freeze this coolant, particularly when the CO_2 was being loaded into the cooler, Even if a eutectic mixture of ethanediol and water was used and flow through the heat exchanger was maintained during the loading, the liquid became so viscous within the heat exchanger that control of the coolant temperature was lost.

It was therefore necessary to change to a fluid of low viscosity and low freezing point. The liquid adopted was a dimethyl silicone fluid, MS 200 with a viscosity of 1 cSt at $25^{o}C$, marketed by Midland Silicones Ltd. The specific heat of MS 200 is 1.4 $kJ/kg^{o}C$ (*cf.* 4.2 for water).

The CO_2 portable cooler has been described in Patent Application No. 8305/71 (Ref.4).

Table 1

Weight breakdown of CO2 portable cooler

Component	Weight, kg
Pressure vessel with fittings	1.55
Insulated case and strap	1.46
Pump	0.41
TCV	0.07
Reservoir	0.07
Tubing, insulation, connector, etc.	0.29
Total empty weight	3.85
CO2 charge	~ 1.95
Total charged weight	~ 5.8

2.2 Operating procedure

The procedure for loading and operating the cooler is as follows:

The top of the insulated case and the lid of the pressure vessel are removed. The GCT is set to 'closed'.

The pressure vessel is filled with chips of solid CO_2; the lid is replaced and locked; the case top is replaced. The cooler is then allowed to stand for approximately five minutes whilst the pressure rises to the triple point value and liquid CO_2 begins to form. When this pressure is indicated the cooler can be connected to the LCS and the GCT is set to 'pump'. Coolant then flows through the LCS and its temperature at suit inlet can be controlled by the TCV.

The pressure remains constant at the triple point value until all the solid CO_2 has become liquid; this takes approximately fifteen minutes. The pressure then rises from the triple point value at $417 kN/m^2$ gauge to a nominal $450 kN/m^2$ gauge at which pressure the PRV vents gas to atmosphere.

When all the liquid CO_2 has been exhausted, cooling to the suit ends abruptly, the pressure falls and the pump stops. The GCT is put to the 'vent' position and the LCS can be disconnected. When the gauge pressure is zero the case top and the pressure vessel lid can be removed.

2.3 Performance

The cooler weighs 3.9 kg empty and approximately 5.8 kg when fully loaded with chips of solid CO_2. It provides a flow of approximately 760 ml/min through the combined circuit of suit and cooler.

Tests were carried out in the laboratory to determine the endurance of the CO_2 cooler whilst maintaining an outlet temperature of 12°C, for various heat input rates, using the method described in section 4. The results obtained are given in Table 2 in terms of cooler endurance and heat accepted by the cooler per unit weight of CO_2.

Table 2

Endurance of CO_2 portable cooler

Ambient conditions	Heat input rate, watts	200	280	350
22°C db 55% RH	Endurance, minutes	70	531	46
	Heat accepted, kJ/kg	455	472	500
40°C db 90% RH	Endurance, minutes	68	52	44
	Heat accepted, kJ/kg	422	439	465

Notes: (1) Weight of CO_2 charge = 1.93 ± 0.085 kg
(2) Heat accepted values calculated from measured charge weights.
(3) Cooler outlet temperature = 12°C
(4) Latent heat of sublimation of CO_2 = 573 kJ/kg

The 'heat accepted', which is simply the heat input rate integrated over the quoted endurance, is in fact less than the theoretical capacity, implying that there is some heat leakage into the cooler from ambient. The fact that the 'heat accepted' decreases with increasing endurance time is consistent with a roughly constant heat leakage rate. Comparing the values of heat accepted with that theoretically available, it can be calculated that there is an average heat leakage into the cooler of 55 W in the 22°C ambient and 75 W in the 40°C ambient.

At a 12°C cooler outlet temperature, the cooler has a maximum cooling rate of 400 W.

A limited number of live subject trials were carried out. These presented no problems although conditions were such that high cooling rates were not demanded and therefore the subject was not subjected to very low ($<15^{o}C$) inlet temperatures (see section 2.4).

2.4 Disadvantages and limitations

The MS 200 suit coolant works well in the CO_2 cooler but has a low specific heat, 1.4 kJ/kg, compared with 4.2 for water. This means that, at the flow rates that have been achieved, a much lower inlet temperature (about $12^{o}C$, cf. $22^{o}C$ for water) to the suit is required for a given heat input rate. Suit inlet temperatures below $15^{o}C$ should be avoided since there is a risk of vaso-constriction[2] below this value.

Another important disadvantage of the MS 200 1cSt fluid is the fire hazard, since it has a flash point of $38^{o}C$. A less hazardous fluid with a higher specific heat is obviously required.

The CO_2 charge should be completely exhausted before the pressure vessel is vented to atmosphere. If it is vented whilst liquid CO_2 remains, some of it boils off but some re-solidifies and a mass of foam-like solid CO2 forms around the heat exchanger. This low-density solid CO_2 has to be removed before the cooler is reloaded and sublimation is slow since the foam has a low conductivity.

The need to load the CO_2 by hand before each use makes it inconvenient to employ the cooler in large numbers , particularly if they might be required at short notice.

A supply of solid CO_2 is obviously necessary for this type of cooler and this requirement may also limit its application.

The problems associated with the CO_2 cooler have led to the development of the rechargeable water-ice portable cooler which is described in section 3. The CO_2 unit may, however, be suitable for an industrial application where a small number of coolers are required occasionally, e.g. furnace maintenance. All that is needed is a supply of solid CO_2 and a man to load the cooler. This would be a practical solution for irregular usage.

3 WATER-ICE PORTABLE COOLER

3.1 General

The appreciation of the handling problems that are associated with using consumable heat sinks led to a re-assessment being made of the water-ice portable cooler. The requirements that the cooler had to meet had been well defined as a result of experience with other portable coolers. These were:

(a) Weight of the cooler, including the water, to be less than 5 kg;

(b) endurance should be at least 40 minutes, preferably one hour;

(c) the cooler should be rechargeable without replacing the heat sink or batteries, to minimise handling;

(d) cooling rate to be variable with a maximum rate of 350 W. This is more than sufficient to cool the man at the design conditions (40^{o}C db, 90% RH) but to have cooling in hand is psychologically attractive;

(e) the cooler should utilise a suit coolant of high specific heat, i.e. similar to that of water.

Meeting requirements (a) and (b) depends on the cooling capacity of the heat sink. Water has a relatively low latent heat of fusion (334 kJ/kg) compared with the latent heat of sublimation of solid CO2 (573 W/kg). However, if the sensible heat of ice and water is included, between -14^{o}C and 20^{o}C say, the heat capacity is--raised to 446 kJ/kg (28 kJ/kg comes from the solid phase and 84 kJ/kg from the liquid phase). This figure compares favourably with the cooling capacity of about 460 kJ/kg achieved with the CO_2. Some 2.2 kg of water was thought to be sufficient.

A rechargeable cooler was achieved by freezing water-ice in situ and using nickel-cadmium batteries to power the pump motor, thus satisfying requirement (c).

The water was to be frozen by pumping chilled coolant through the heat exchanger from an external refrigerated supply. Heat exchanger surface area and its distribution, to give a reasonable freezing time (three hours), were determined in laboratory tests. The design then gave a maximum cooling rate in excess of that of requirement (d).

Freezing the water from the heat exchanger makes it unlikely that the expansion of the ice will damage the cooler since as ice forms around the heat exchanger, water flows up into the volume allowed for expansion.

Ethanediol/water suit coolant can be used with a water-ice heat sink and during recharging, thus meeting requirement (e). The coolant liquid employed is a mixture of inhibited ethanediol and water, in the ratio 3:7 by volume. The ethanediol used is a corrosion-inhibited antifreeze to BS 3150, Type A. The 3:7 mixture ratio gives[5] a suitable depression of the freezing point without producing an excessive increase in coolant viscosity or decrease in specific heat. The minimum temperature that it is practical to supply this coolant to the cooler is approximately $-14^{\circ}C$.

3.2 Description of cooler

3.2.1 Prototype coolers

Two prototype coolers capable of having the ice frozen in situ were manufactured in the RAE early in 1971. The circuit diagram is given in Fig.4 and the cooler is shown in Figs.5 and 6.

The lower part of the cooler is a water container with double walls separated by polyurethane foam insulation. The volume of the water container is 2.5 litres but this is filled with only 2.2 litres of water to allow for expansion on freezing.

Within the water tank, completely immersed in the water, are three coils of 6.4mm OD aluminium tubing, each 1.45 m in length. These coils are connected in parallel and act as the heat exchange surface for both freezing the water, and for cooling the suit coolant when the cooler is connected to a LCS.

The removeable lid of the cooler encloses the reservoir, non-return valve, temperature control valve, battery, pump and motor, and the connecting tubing. The non-return valve allows the chilled coolant to by-pass the pump during recharging. The TCV, which is similar to that used in the CO_2 cooler, controls the proportion of the flow that passes through the heat exchanger.

The battery is a rechargeable nickel-cadmium 12V, 1.2A h battery supplied by SAFT (UK) Ltd. This battery will accept a three-hour charge current, irrespective of its state of charge, without damage.

An automotive pump, supplied by Trico-Folberth Ltd. is used to circulate the coolant. This flexible-vane pump gives a flow of approximately 1 l/min through the combined circuit of suit and cooler for a power consumption of 10 watts.

3.2.2 'Airscrew' coolers

A batch of 17 portable coolers, based on the prototype RAE units, were produced by Airscrew Fans Ltd. early in 1972 under contract. The water tank and outer case are vacuum formed from sheet ABS and polyurethane is foamed between them as thermal insulation. The coolant circuit is modified to ensure that during the refreezing period all the chilled coolant passes through the heat exchanger, regardless of the position of the TCV. This introduces two non-return valves to by-pass both the pump and the TCV. The reservoir is designed to be automatically filled during the refreezing cycle. A line diagrame of the Airscrew cooler is given in Fig.7 and Figs.8 and 9 are photographs of this unit.

3.2.3 Modified 'Airscrew' cooler

In an effort to reduce the leakage of coolant that occurred in some of the Airscrew coolers during field trials (see section 3.4.2) and to simplify assembly, one cooler was modified by Airscrew Fans Ltd.

The many pipe connections within the lid are eliminated (compare Figs.9 and 10). The pipework is replaced by channels machined in a PVC block with a cover sheet of perspex which seals the channels but allows the flow to be seen. Non-return valves are built into the PVC block and the air trap connections made within its modified body. Although this modification was fabricated from sheet and solid materials, the aim was to produce a design that could eventually be moulded.

The coolant circuit is further simplified by replacing the three parallel coils of the heat exchanger with one coil of 7.9mm OD aluminium tubing 4m long. The heat exchange area is increased by 9% but the volume the coil occupies is increased by 36%. This means the water container will accept a charge of only 2.15 litres, this could easily be compensated for by a small increase in the outside dimensions of the container, e.g. increase the height by approximately 2.5 mm.

The modified cooler, with its simplified coolant circuit and single heat exchanger coil, is probably more representative of the portable cooler as it would be produced in quantity. The system occupies less space than previously and the overall height of the cooler could be reduced by approximately 35 mm.

3.3 Operation of cooler

To make the water-ice portable cooler ready for use the water container is initially filled with 2.2 litres of water. This is a once-only operation and when the filler cap and the cooler lid have been replaced they need only be removed again if the cooler becomes unserviceable.

The cooler can then be charged. The battery charging connections are made and the charger is switched on. The self-sealing connector is used to connect the inlet and outlet pipes to the supply of refrigerated coolant.

The coolant flows through the portable cooler and freezes the water surrounding the heat exchanger coils. In the prototype cooler, the TCV must be in the maximum cooling position to ensure that all the liquid passes through the heat exchanger, air in the reservoir must be vented through the reservoir lid. Both these operations are unnecessary in the Airscrew units,

After three hours the cooler is both electrically and thermally charged, the electrical and liquid connections can be uncoupled and the cooler is ready for use. If not required immediately, the cooler can be left connected to the recharging unit to maintain it in a frozen condition.

To use the cooler with a LCS the self-sealing connector is mated with that on the suit and the pump is switched on. The suit inlet temperature is controlled by the TCV.

3.4 Performance

The water-ice coolers have been tested extensively in the laboratory and used in several overseas trials of the liquid conditioned suit and its associated systems.

3.4.1 Prototype cooler

The prototype cooler weighed 4.75 kg including 2.2 kg of water and measured 30.5cm long × 10cm wide × 29cm high.

(a) Field trials In August 1971 the coolers were employed during a trial[6] in Cyprus of the LCS and an aircraft system.

Two prototype coolers were used for a total of 16 hours 24 minutes, the average period of use being 26½ minutes. Adequate cooling was always available and the coolers remained serviceable throughout the trial. In two endurance tests on the coolers, adequate cooling was available for 80 minutes. The average rate of cooling demanded by the subject, who was walking and exposed to the sunlight during the test, was 155 W. Ambient conditions for the periods in the trial when the coolers were in use ranged from 38°C to 52°C globe temperature, 27°C to 33°C dry bulb and 23°C to 25°C wet bulb.

In February 1972, in support of aircraft system trials at Woomera, these coolers were again used for the walk to and from the aircraft. Ambient conditions ranged from 35°C to 40°C dry bulb, 18°C to 23°C wet bulb. Adequate cooling rates were available and no coolers became unserviceable.

(b) Laboratory tests The endurance of the water-ice coolers has been determined in laboratory tests for a range of heat input rates after various periods of refreezing. The test method was similar to that for the CO_2 cooler (see section 4). The ambient conditions were 22°C db, 55% RH.

The results are presented in Table 3 in terms of cooler endurance and the heat accepted by the cooler per unit weight of water. Figs.11 and 12 have been plotted using these results.

Table 3

Thermal endurance of prototype water-ice portable-coolers

Refreezing period	Heat input rate	150 W		200 W		250 W		350 W		450 W	
	Cooler ident.	a	b	a	b	a	b	a	b	a	
1 hour	Endurance, minutes	54½	58	44	49	36	37	23	27		
	Heat accepted, kJ/kg	223	237	240	267	245	252	220	258		
2 hours	Endurance, minutes	85	82	66½	67	51½	50	35	39		
	Heat accepted, kJ/kg	348	335	363	365	351	341	334	372		
3 hours	Endurance, minutes	93	95	72½	72	60	60	42	43		
	Heat accepted, kJ/kg	380	389	395	393	409	409	401	410		
4 hours	Endurance, minutes	102½	99	78½	79	60	61	45	46		
	Heat accepted, kJ/kg	419	405	428	431	409	416	430	439		
5½ hours	Endurance, minutes									34	
	Heat accepted, kJ/kg									417	430

Ambient conditions: 22°C db, 55% RR
Cooler outlet temperature: 2ooc
Cooler identity: a and b refer to the two prototype coolers separately tested.

Fig.11 shows the thermal endurance of the coolers although the battery capacity limits endurance to approximately 80 minutes.

The heat accepted by the cooler per kilogramme of water is shown for various refreezing periods in Fig.12. There is some scatter but, as expected, the relationship is asymptotic to the maximum quantity of heat the cooler can absorb (446 kJ/kg from ice at $-14^{o}C$ to water at $20^{o}C$). After two hours refreezing the cooler accepts more heat than the latent heat of fusion of ice (334 kJ/kg) and after three hours the cooler is charged to 90% of its maximum possible thermal capacity.

The heat accepted by the cooler is almost independent of the heat input rate, indicating that there is negligible heat leakage into the cooler under the test conditions. A limited number of tests with the coolers in an environment of $40^{o}C$ db, 90% RH, have shown that there is a heat leakage of approximately 15 W into the cooler under these conditions. This rate can be used to estimate endurances at $40^{o}C$ from the $20^{o}C$ results, e.g. after three hours refreezing, endurance at the 250 W cooling rate is reduced from 60 minutes to 56½ minutes.

At a $20^{o}C$ suit inlet temperature, the cooler has a maximum cooling rate of 450 w.

3.4.2 Airscrew cooler

This model weighs 4.6 kg, including 2.2 kg of water and measures 30.5cm long × 10cm wide × 28cm high.

(a) Field trials Seventeen portable coolers were used for a trial in Cyprus during the summer of 1972. The major aim of the trial was to assess aircrew reaction to liquid conditioning and is reported elsewhere [7].

The coolers were recharged by two recharging units, one at the personal equipment section and one in the debrief room near the aircraft dispersal. Each unit could recharge up to ten portable coolers simultaneously; they are described in more detail in section 3.5.

The trial procedure, as far as it concerned the portable coolers, was:

(i) At the personal equipment section, each aircrew member donned a LCS and flying coverall. He then coupled to a portable cooler to commence personal conditioning.

(ii) The portable cooler was used during the journey to the aircraft and during external aircraft checks. Aircrew disconnected from the coolers immediately before entering the aircraft, having used them for approximately 45 minutes.

(iii) The discharged coolers were returned by the ground crew to the recharging unit in the debrief room.

(iv) As the aircrew left the aircraft after flight, they were supplied with recharged coolers by the ground crew.

(v) The coolers were used from the aircraft, through the debrief session, and during their return to the personal equipment section. Discharged coolers were placed on charge there, having been used for approximately 30 minutes.

There were some problems encountered with the coolers at the beginning of the trial, mainly due to leakage of coolant from the numerous tube connections within the cooler lid. Even a very small leak produced significant quantities of liquid if the cooler was on charge for many hours or, as did happen, for several days. This liquid collected on the top of the water tank and then leaked out when the cooler was in use. The leaks did not affect cooling performance but were of considerable nuisance value until they were cured.

Sufficient cooling was available in the conditions experienced, these were typically 28° dry bulb, 70% RH. Very rarely was maximum cooling selected on the TCV. The bulk and weight of the coolers were acceptable to the majority of aircrew who used them.

The advantage of having a completely rechargeable cooler, rather than one that had to be reloaded before use, became quite apparent in the Cyprus trial. Support of the trial would have been much more difficult if it had been necessary to load ice into all the portable coolers required before and after each flight, possibly at short notice. With the rechargeable coolers there were always some units fully charged and ready for immediate use.

(b) Laboratory tests The endurance of the Airscrew coolers has been determined in a limited number of laboratory tests to compare their performance with that of the prototype units. Results are given in Table 4 and have been plotted on Figs.11 and 12.

Table 4

Thermal endurance of Airscrew water-ice coolers

Refreezing period	Heat input rate	200 W		250 W		350 W	
	Cooler ident.	c	d	c	d	c	d
2 hours	Endurance, minutes Heat accepted, kJ/kg			56 382	54½ 372	39 372	40 382
3 hours	Endurance, minutes Heat accepted, kJ/kg	75 409	74½ 406				44½ 425

Ambient conditions: 22°C db, 55% RH
Cooler outlet temperature: 20°C
Cooler identity: c and d refer to the two Airscrew coolers separately tested.

The endurance is marginally longer than that of the prototype units. This is probably due to better spacing of the heat exchanger coils within the water, together with improved insulation. Endurance for heat input rates and refreezing periods not covered by the results in Table 4 can be estimated from the results of the tests on the prototype units, (Table 3).

3.4.3 Modified Airscrew cooler

This unit weighs 4.8 kg including 2.15 kg of water. The external dimensions are the same as for the standard Airscrew unit.

The thermal endurance of the modified cooler was marginally less than that of the standard unit due to its lower water charge, 2.15 litres. The heat accepted per unit weight of water is, however, similar to that of the standard unit.

3.5 Recharging units

The prototype portable coolers were refrozen using a modified water chiller and later using a smaller unit, built in the RAE, incorporating a ½ hp commercial condensing unit. This portable unit weighs 53 kg and can freeze up to four coolers simultaneously. A line diagram of this freezer is shown in Fig.13. The batteries in the portable coolers were charged by separate constant-current chargers.

To support the trials in Cyprus in 1972, two portable cooler charging units were supplied by Airscrew Fans Ltd. under contract. Each unit provided both thermal and battery charging for up to ten portable coolers in a three-hour period. A schematic diagram is shown in Fig.14. 700 ml/min of ethanediol/water mixture was supplied to each cooler, via insulated flexible tubes and a self-sealing coupling, at an inlet temperature of -8°C.

4 METHOD OF THERMAL ENDURANCE TESTING

The thermal capacity of a portable cooler was determined by replacing the variable heat input from the suit, man and environment by a controlled input from an immersion heater. The circuit including the heater had a pressure drop similar to that of a LCS, Cooler outlet temperature, i.e. the 'suit' inlet temperature, was monitored during the tests.

The endurance of the cooler at a particular heat input was defined as the period of time for which it would maintain an outlet temperature of less than 12°C for the CO_2 cooler, or less than 20°C for the water-ice cooler. The TCV was used to maintain the required temperature during a test. These temperatures are mean values of the suit inlet conditions that are needed to satisfy the extreme cooling requirements. The lower value for the CO_2 cooler is due primarily to the much lower specific heat of the coolant and partly to the lower coolant flow rate.

Coolers were subjected to heat input rates ranging from 150 W to 350 W, a range likely to be encountered due to variations in the environment, suit and the man (see Refs.2 and 6).

Tests were carried out with the coolers in a laboratory environment of 22°C dry bulb, 55% RH and for a limited number of tests, with the cooler in an environment controlled to 40°C db, 90% RH.

During the refreezing periods the water-ice portable coolers were supplied with refrigerated coolant at a flow rate of 800 ml/min with a temperature of -14°C at the cooler inlet.

5 FURTHER DEVELOPMENT

The following suggestions are made for future development work:

5.1 CO, portable cooler

(i) If the CO_2 cooler is to be developed further, an alternative coolant will be needed. Various fluids and their properties are listed in Ref.8, the favoured candidate being FC-75 (3M). The lower viscosity fluids in the Coolanol (Monsanto) range of heat transfer liquids are other alternatives.

(ii) An increased coolant flow rate is needed so that the suit inlet temperature at the high heat extraction rates can be raised since there is a risk[2] of vasoconstriction below a 15°C suit inlet temperature.

5.2 Water-ice portable cooler

The Airscrew water-ice cooler has provided adequate cooling capacity at an acceptable weight and any future design should be aimed at providing reduced costs of manufacture, simpler operation and greater reliability.

The following modifications should be considered in any future design:

(i) A moulded solid-state coolant circuit to eradicate leakage problems.

(ii) Improve the reliability of the pump motor and increase its efficiency to reduce battery weight.

(iii) Cooler stability should be increased by making it approximately lcm wider, height can be correspondingly reduced.

(iv) The pump motor circuit should be broken when the cooler is disconnected from the LCS to avoid accidental battery discharge.

(v) The recharging procedure should be further simplified by incorporating battery charging connections in the coolant coupling and making the charger automatically initiate its charging cycle.

(vi) Alternative methods of construction should be investigated to reduce production costs. It is possible that the water tank can be moulded in a self-skinning polyurethane foam.

5.3 Recharging units

(i) The recharging units must be reduced in size and weight. The ethanediol/water tank in the Airscrew recharging units was unnecessarily large (900 litres) and was a major factor in determining the overall size of the unit. A smaller evaporator with a separate coolant reservoir in the circuit is a possible solution.

(ii) The couplings between the coolers and the recharging unit should be isolated from the environment to prevent condensation and ice forming on them. The couplings could be individually insulated or the coolers could be accommodated in an insulated cabinet during recharging.

(iii) After the normal charge period, the battery charger should switch to a trickle rate to maintain the battery in a charged condition.

(iv) For a full-scale installation, such as would be required in Cyprus, it is advocated that there should be a large recharging unit at the personal equipment section, capable of maintaining the majority of the portable coolers *in* a *state* of charge. The coolers would be stored in insulated cabinets, similar to a conventional deep-freeze chest, to eradicate the condensation problem and protect them from the elements.

A number of smaller recharging units would be placed at judicious points such as crew rooms, debrief room, and at the aircraft dispersal area. Each of these units would be an insulated cabinet holding, for example, ten portable coolers which are supplied with chilled coolant from a ½hp condensing unit.

6 CONCLUSIONS

(1) Two acceptable designs of portable coolers have been developed based upon the phase change of (a) solid to gaseous carbon dioxide, and (b) ice to water.

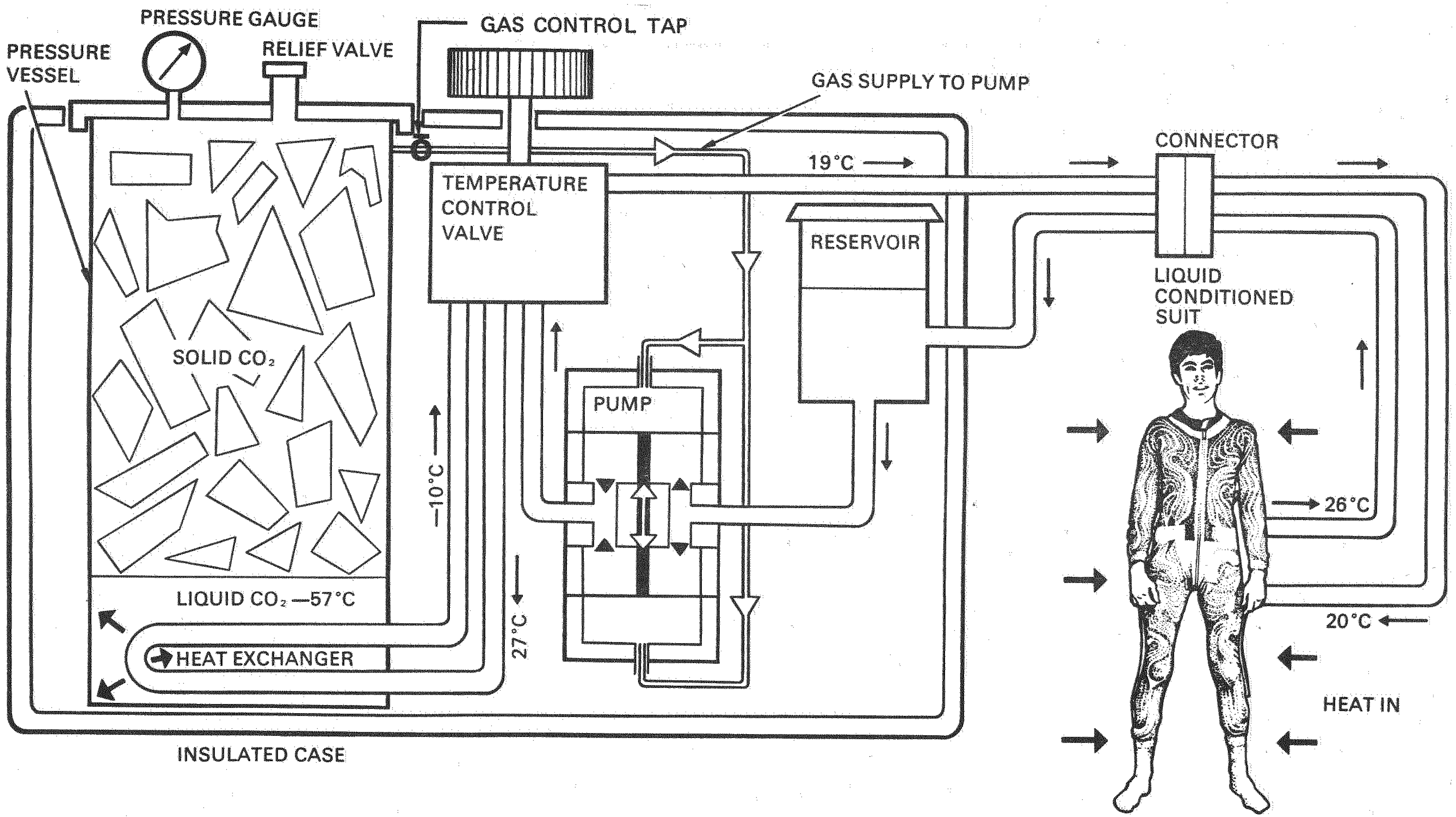
(2) The CO_2 cooler, which was designed to operate at the triple point pressure to improve the heat transfer coefficient, weighs 5.8 kg when fully loaded with 1.9 kg of CO_2 and gives 250 Whof cooling. It was considered that a cooler of this type would be unsatisfactory for large scale use since a regular supply of solid CO_2 is needed, together with the manpower to load each unit.

(3) The water-ice cooler utilises the total heat content between ice at $-14^{o}C$ and water at $20^{o}C$. It weighs 4.6 kg, including 2.2 kg of ice, and gives 250 Whof cooling. Freezing the water *in situ* and using a rechargeable battery allows an automated replenishment system to be employed but necessitates the supply of chilled liquid to freeze the water, and a battery charger. A recharging unit, based on conventional deep-freeze and battery-charging equipment, has therefore been developed in parallel with the cooler.

(4) The water-ice coolers and their support equipment were thoroughly tested during the summer of 1972 as part of a trial to establish the aircrew acceptability of the liquid conditioned suit and its associated systems. The thermal performance of the equipment *was* satisfactory but their usability and reliability could be improved in future designs.

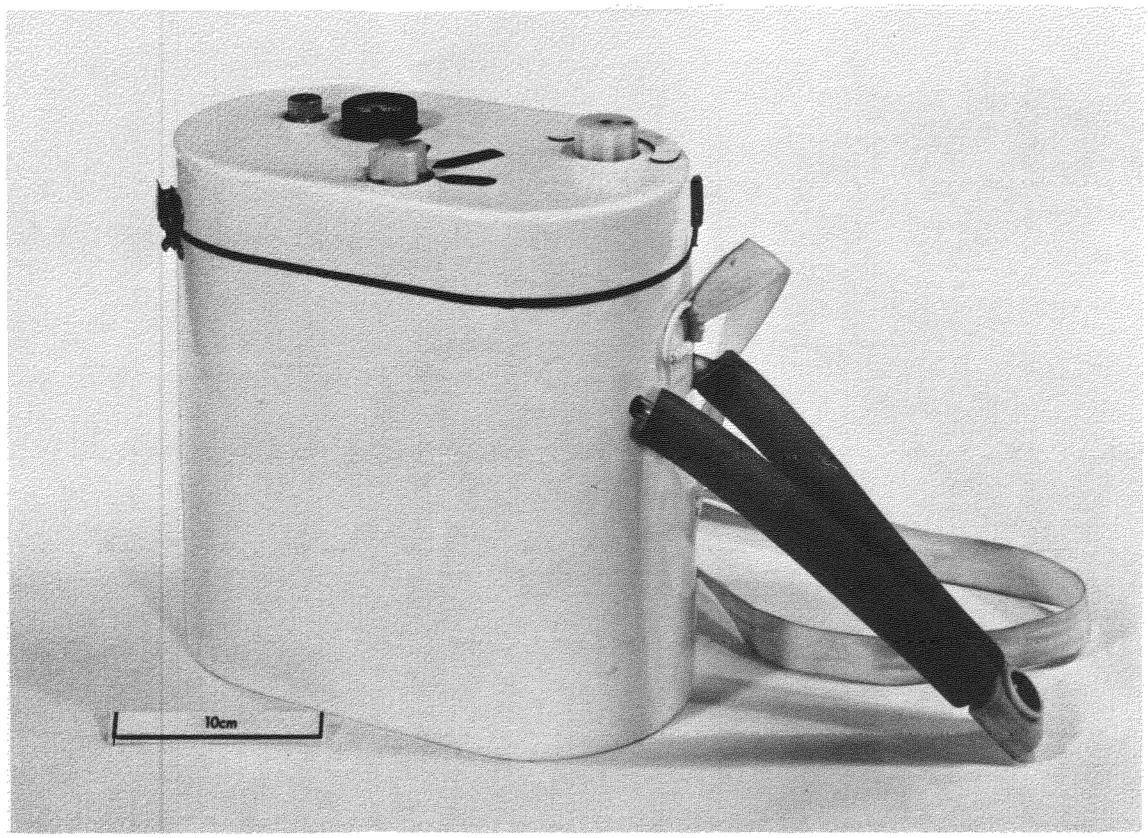
REFERENCES

No.	Author	Title, etc.
1	M.A. Beeny	Performance of the Pilkington/Beaufort conditioner and liquid conditioned suit. Unpublished MOD(PE) material
2	R.C. London	A review of the work in the United Kingdom on water cooled suits. Unpublished MOD(PE) material
3	M.A. Beeny	Performance of chip-ice conditioners type 1112, F000, RNAYR-A. Unpublished MOD(PE) material
4	G.F. Barlow A.D. Bewley	Improvements in or relating to liquid cooled suits. United Kingdom Patent Application No.8305/71 (1971)
5	G.W.G. Camp	The performance of antifreeze solutions in the liquid conditioned suit. RAE Technical Report 67154 (ARC 29868) (1967)
6	M.A. Beeny B.C. Short	Liquid conditioned suit trials - Cyprus 1971. RAE Technical Report 72076 (ARC 34170) (1972)
7	A.D. Bewley *et* al.	The acceptability of the liquid cooled suit to Vulcan aircrew in routine service conditions. RAE Technical Report 73187 (ARC 35300) (1974)
8	W.A. McConarty F.M. Anthony	Design and evaluation of active cooling systems for Mach 6 vehicle wings. NASA Contractor Report CR-1916 (1971)



Typical liquid temperatures are shown

Fig.1 Circuit of CO_2 portable cooler



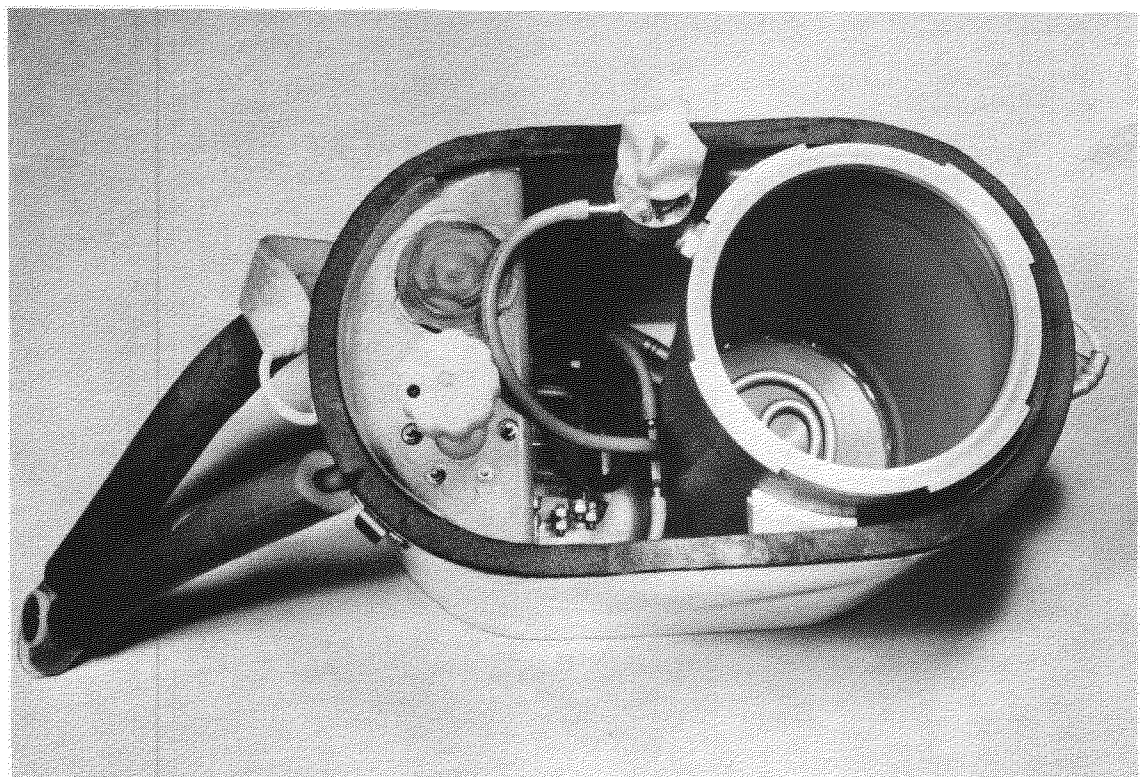
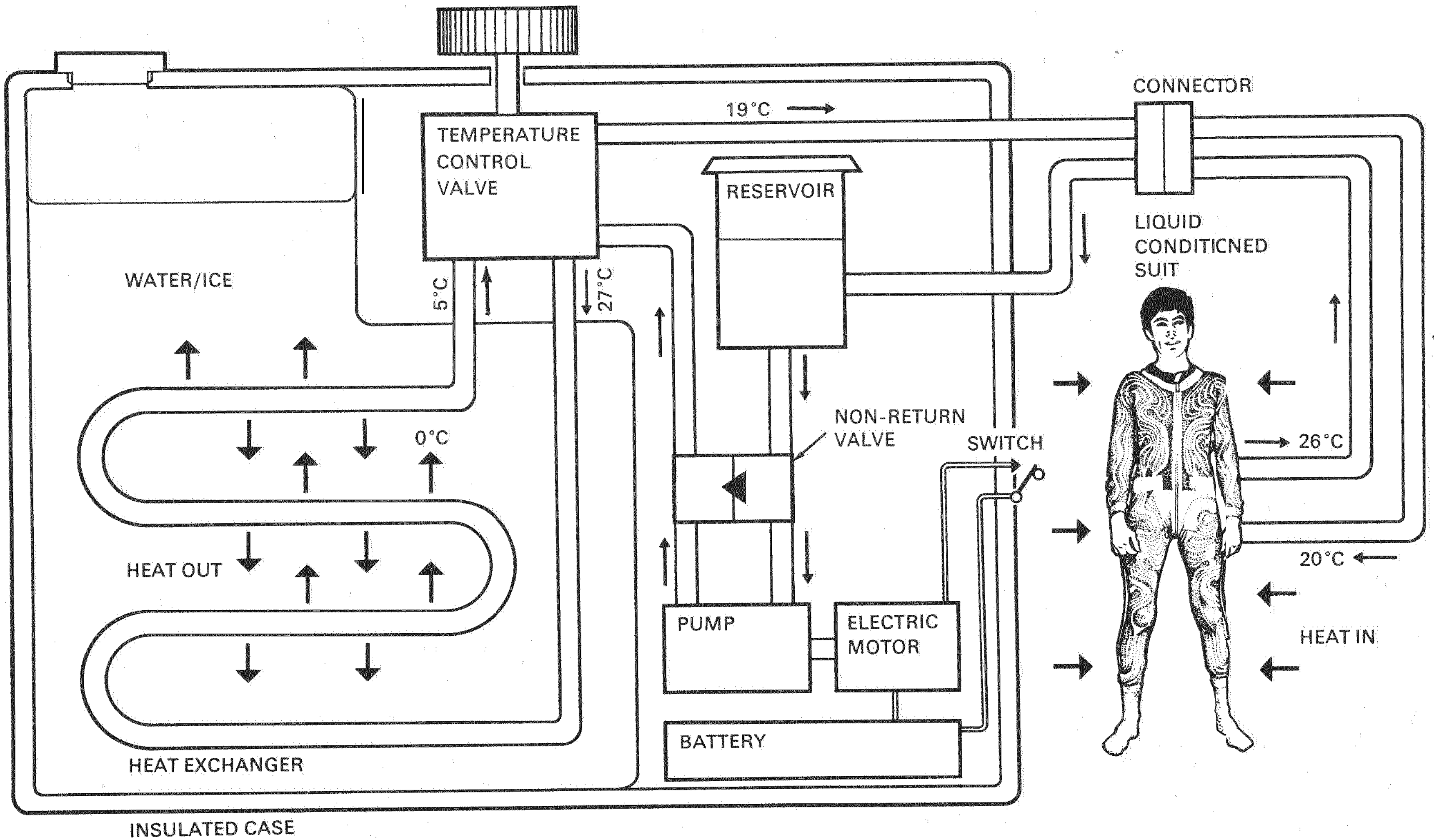
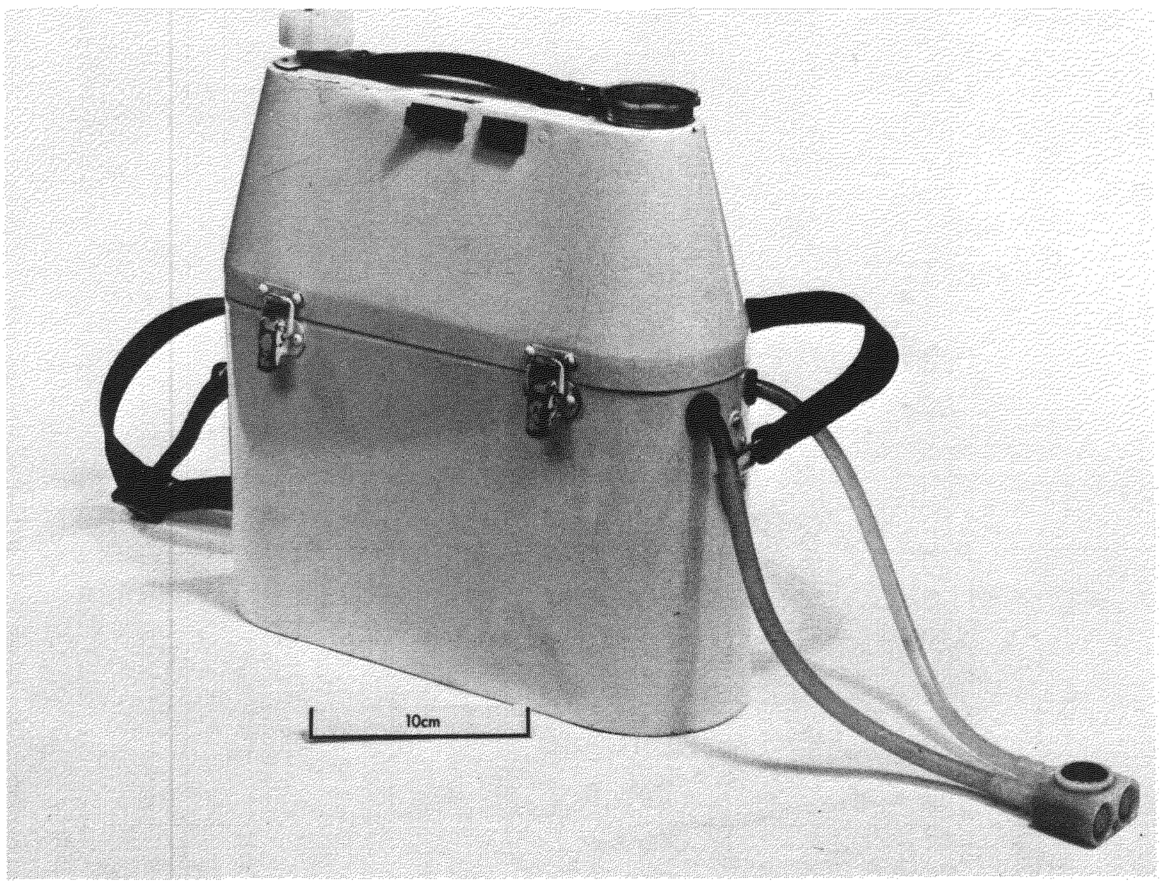


Fig.2 & 3 CO_2 portable cooler



Typica iquid temperat are shown

Fig.4 Circuit of prototype water-ice portable cooler



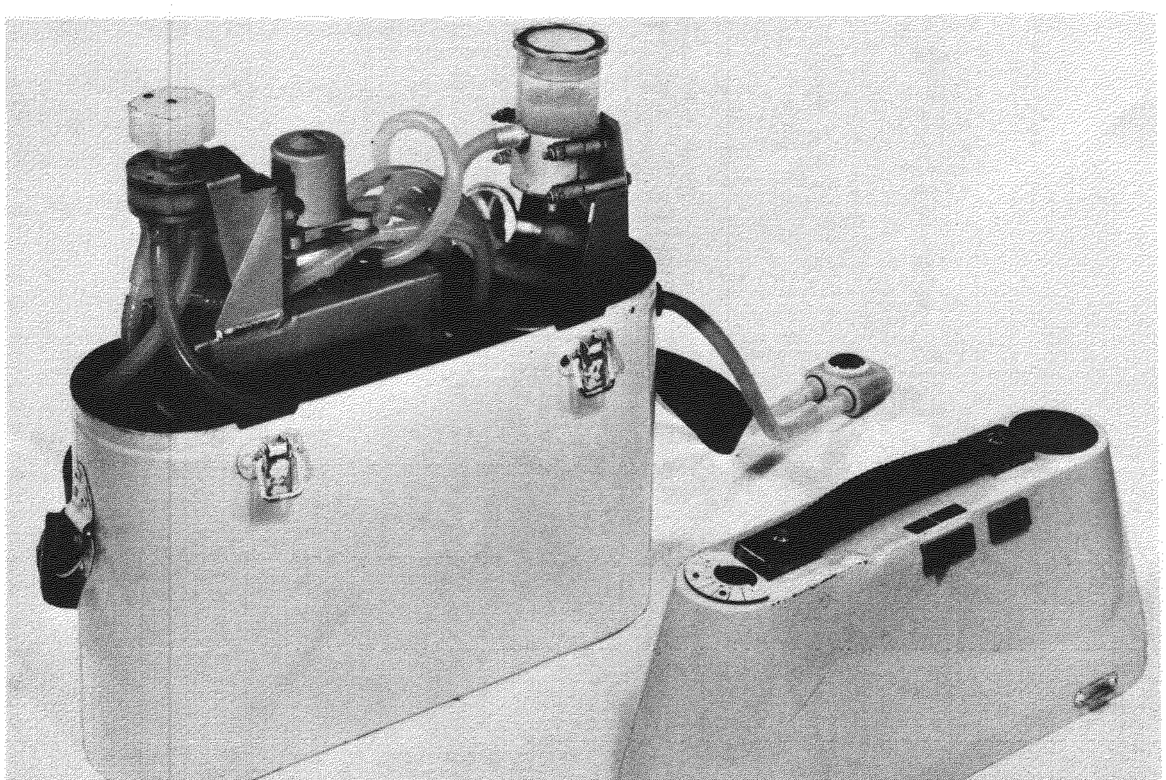


Fig.5 & 6 Prototype water-ice cooler

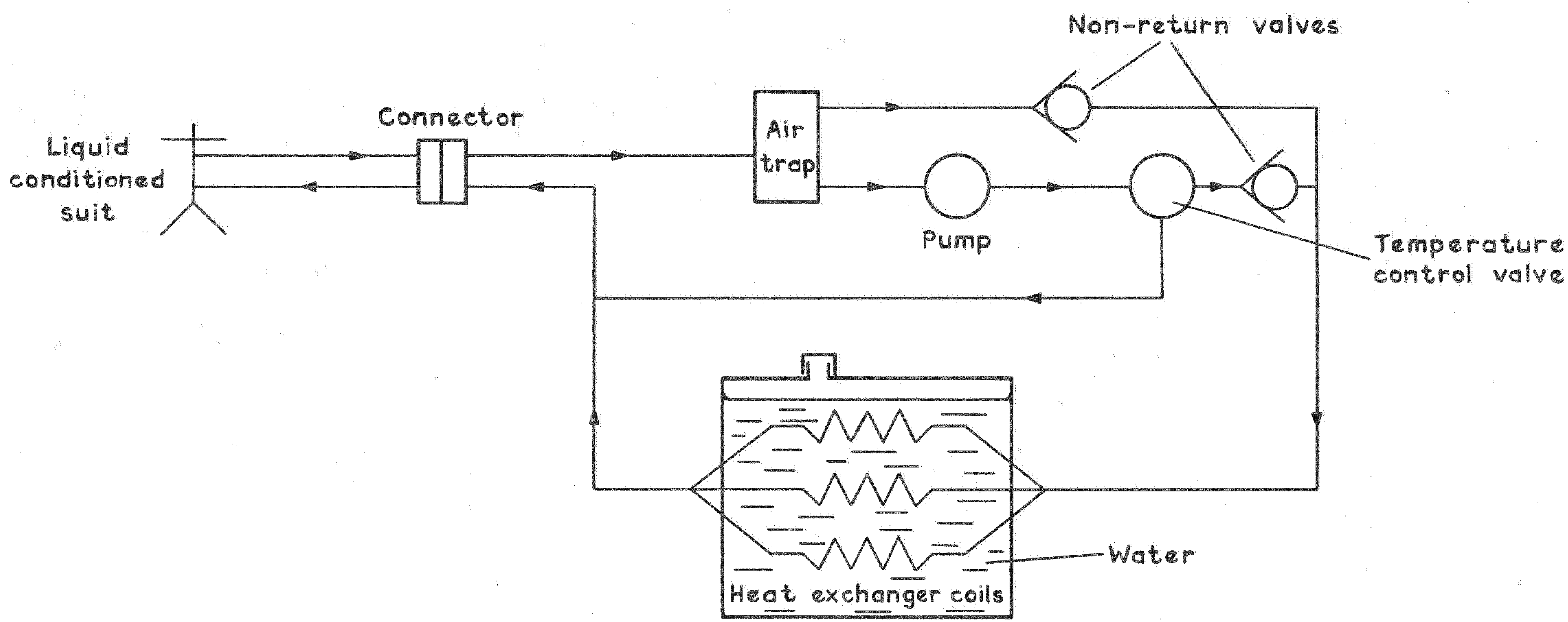
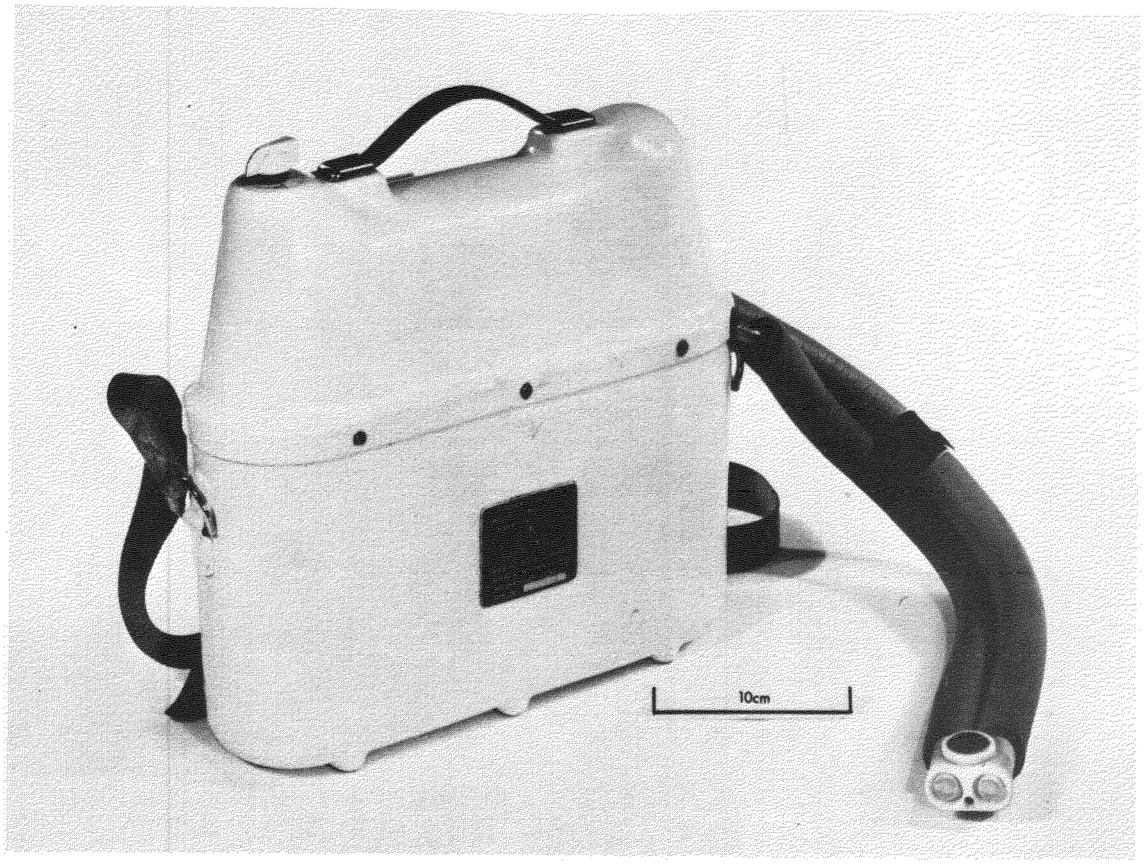


Fig.7 Circuit of 'Airscrew' portable cooler



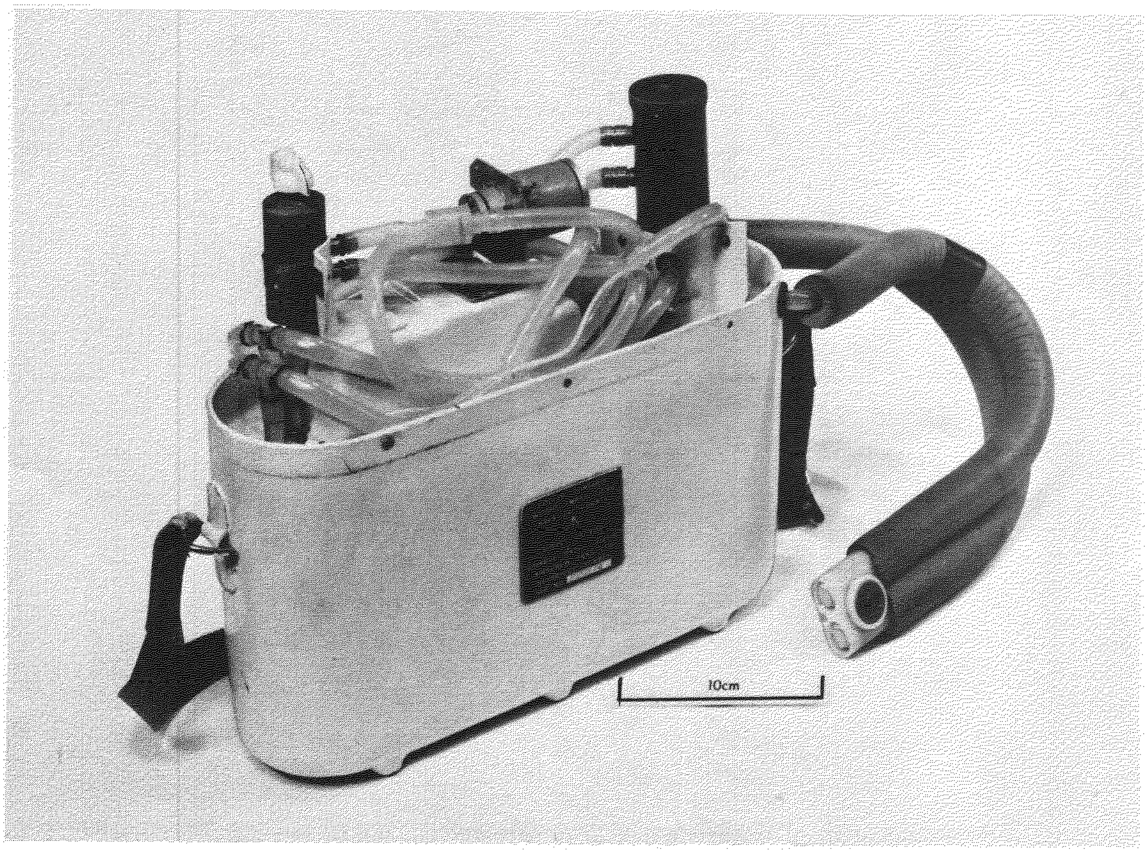


Fig.8 & 9 'Airscrew' water-ice cooler

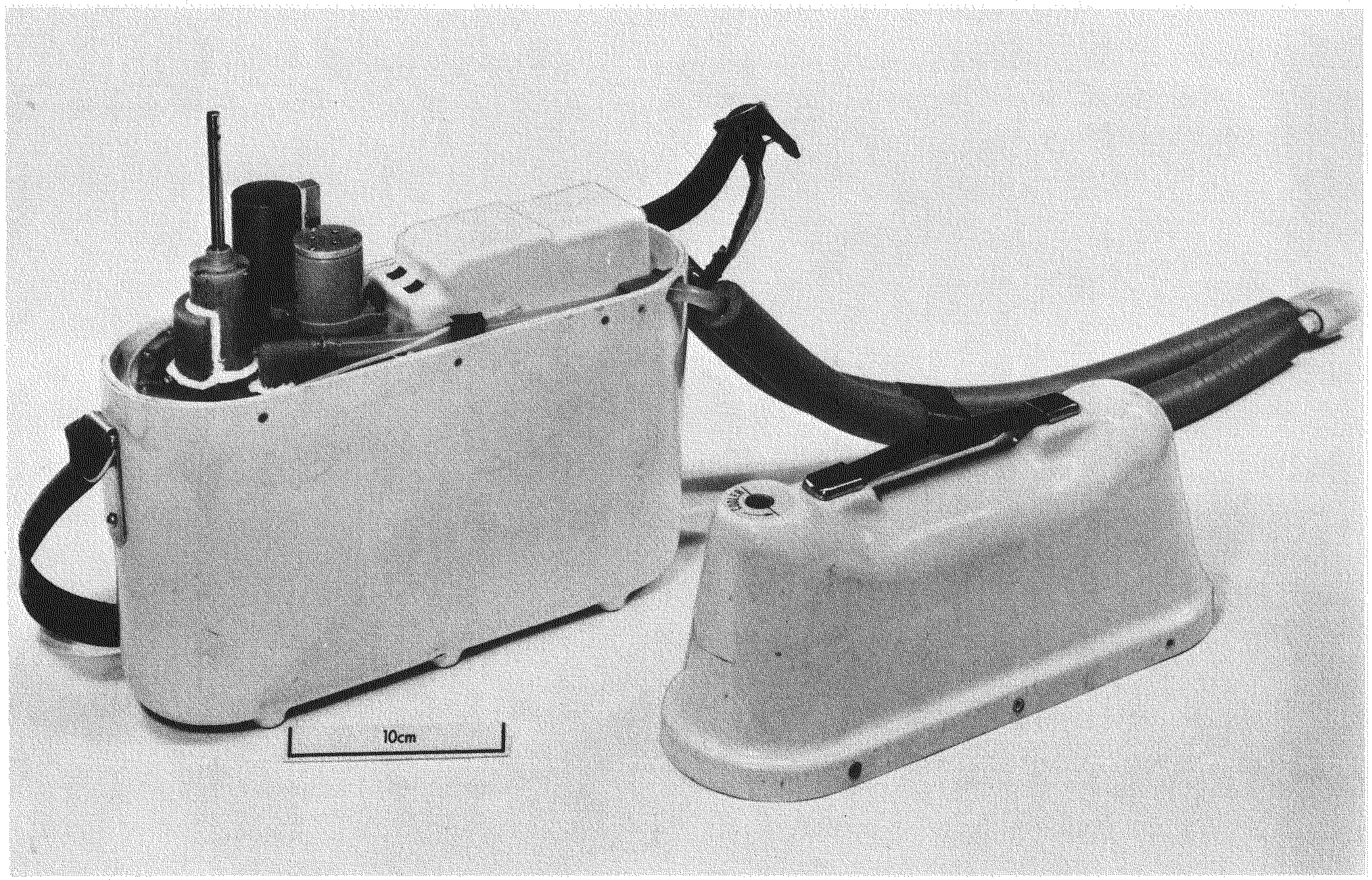


Fig.10 Modified 'Airscrew' cooler

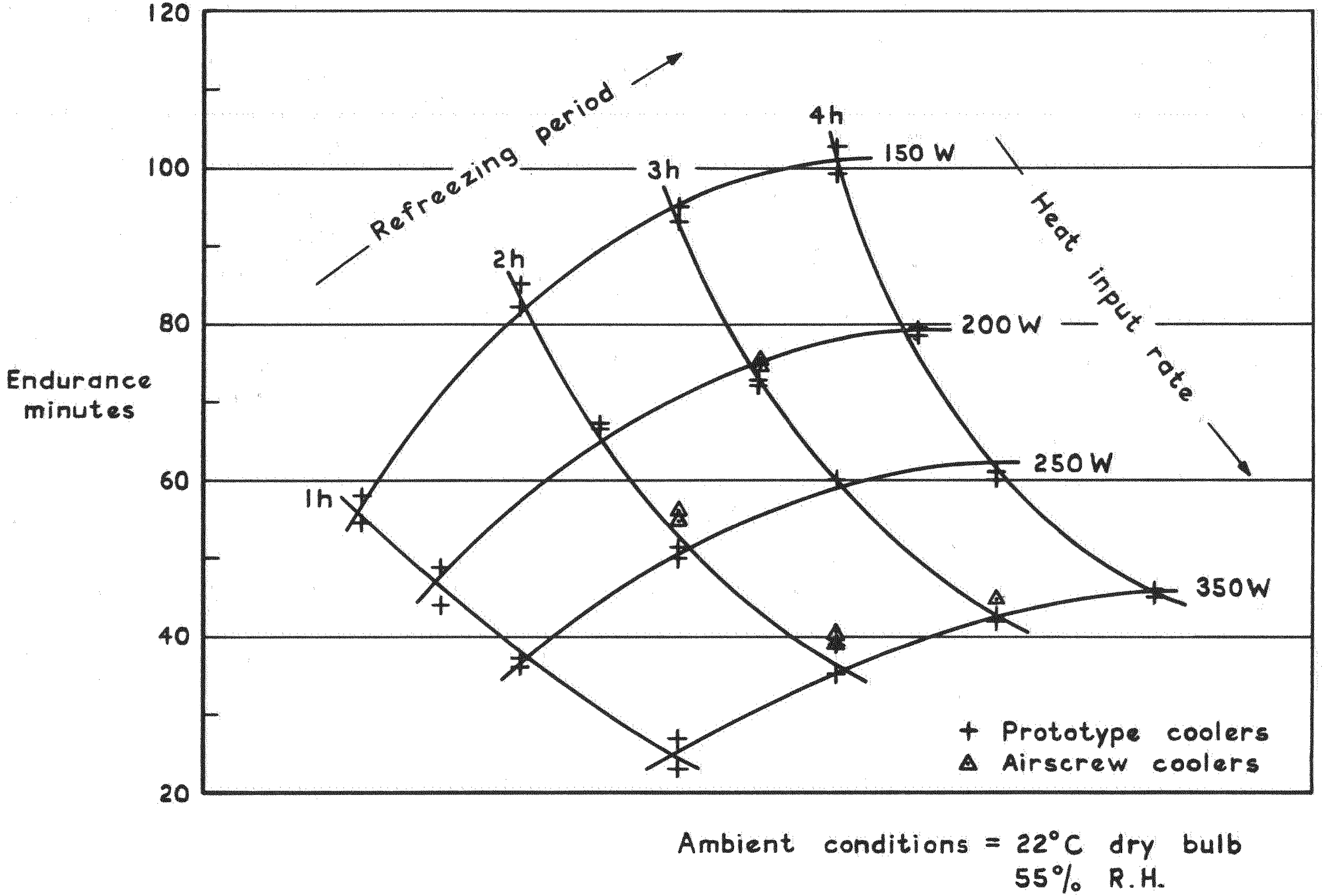


Fig. 11 Thermal endurance of water – ice coolers

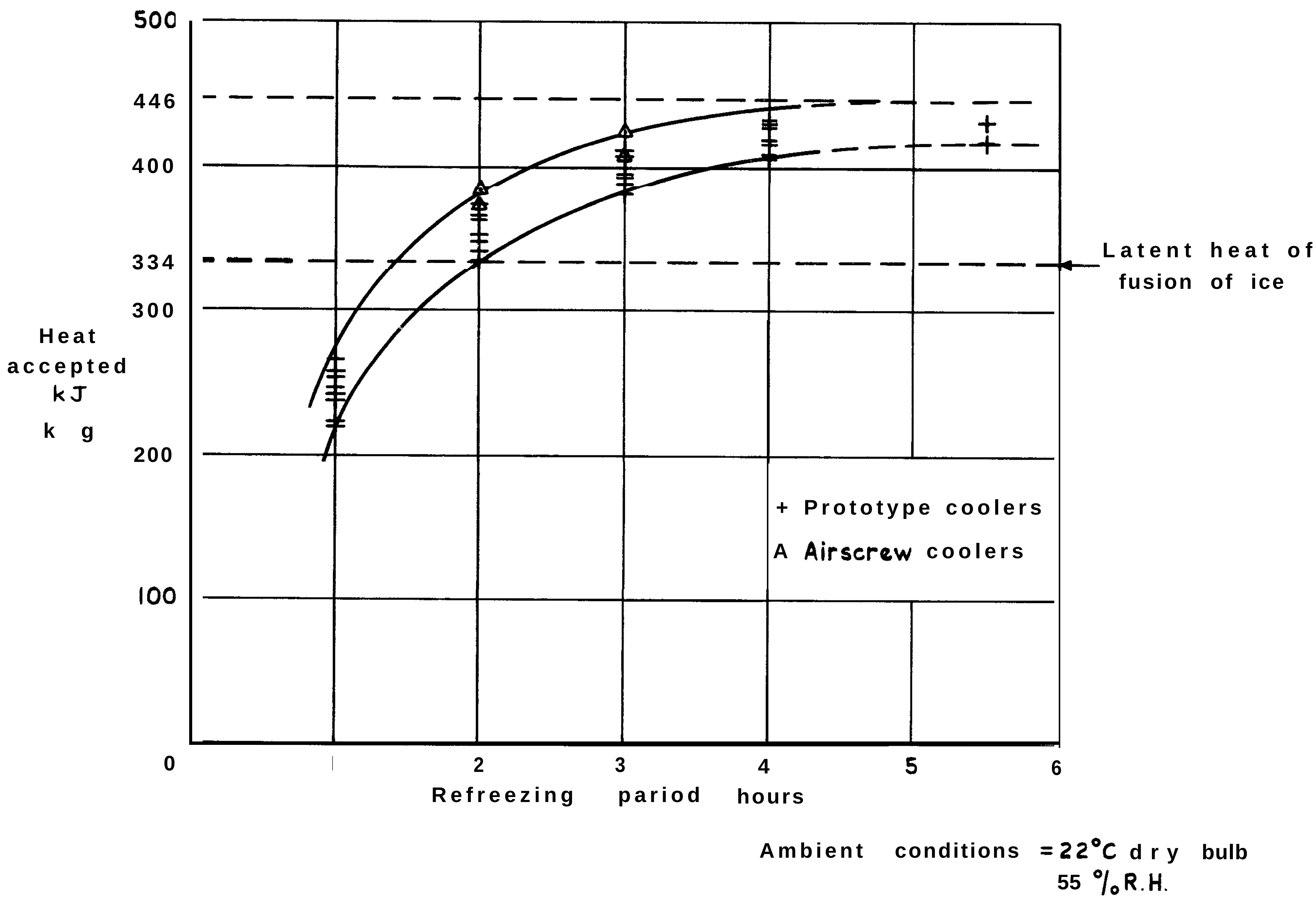


Fig. 12 Heat accepted by water -ice coolers

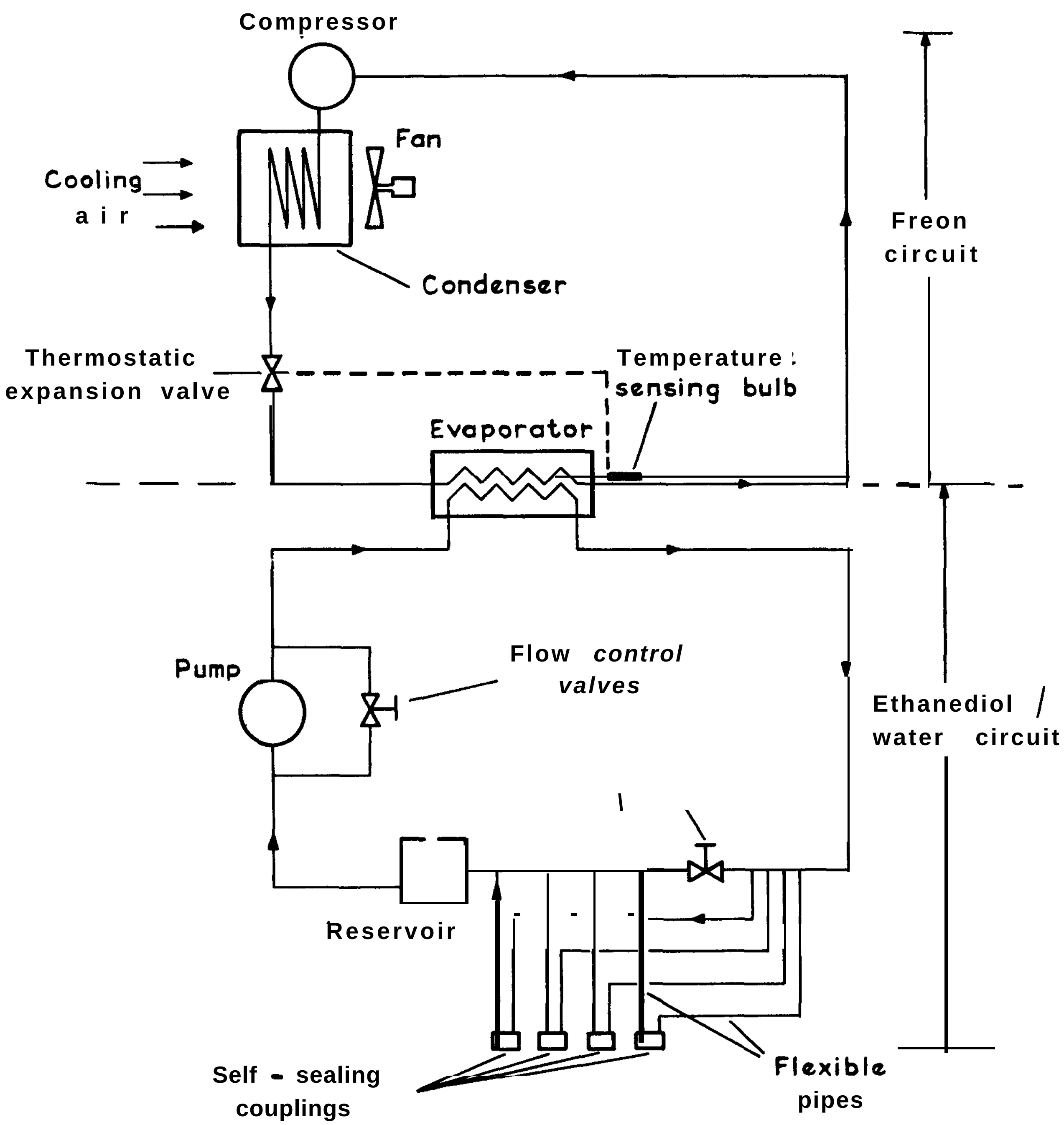


Fig. 13 Circuit of RAE portable refreezing unit

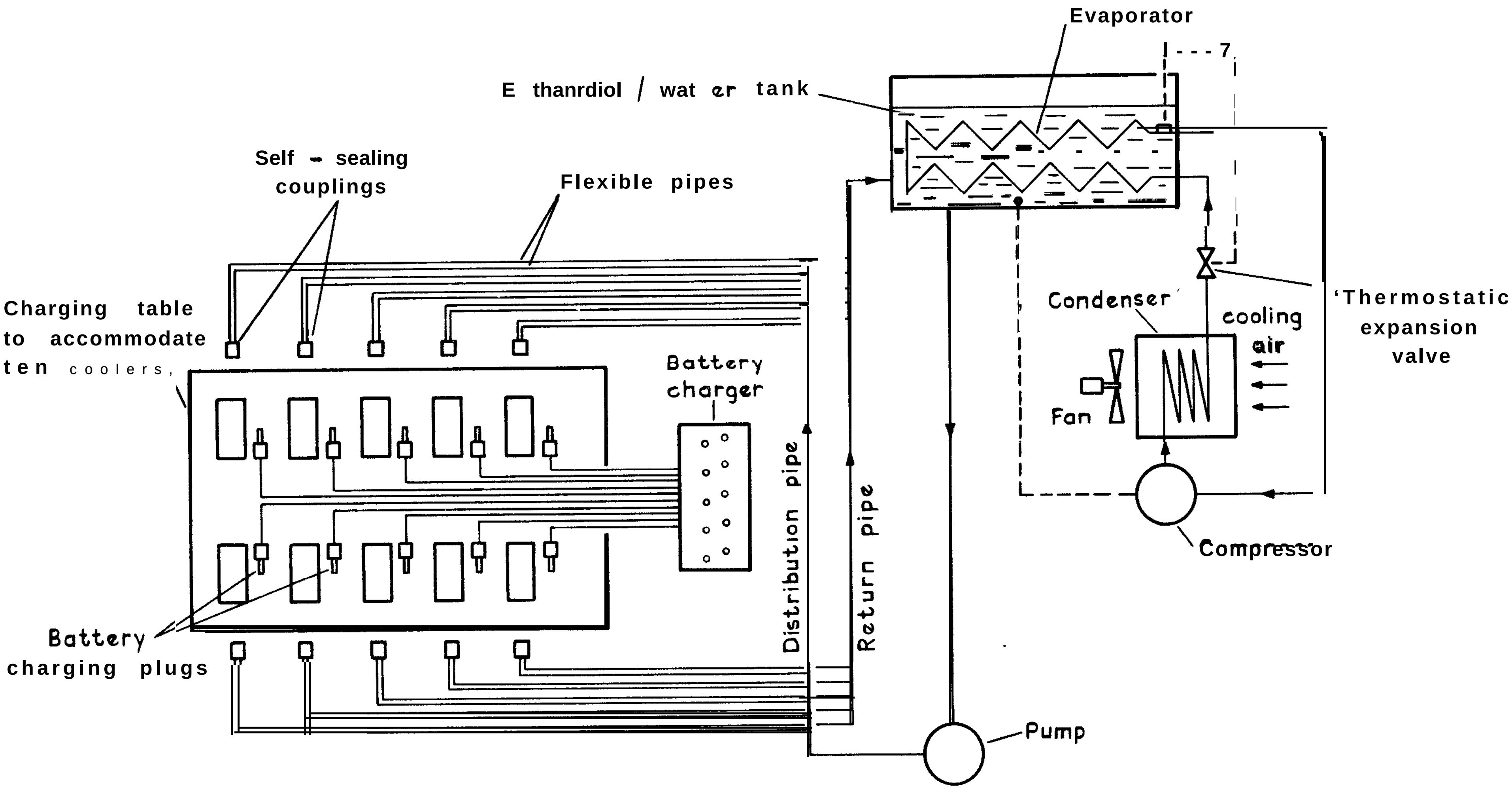


Fig. 14 Circuit of 'Airscrew' recharging unit

Printed in England for Her Majesty's Stationery Office by the Royal Aircraft Establishment, Farnborough. Dd 289030 K5 10/75

ARC CP No.1330
August 1974

614.89 :
621-713 :
629.13.067.2 :
621-71

Barlow, G. F.

THE DEVELOPMENT OF PORTABLE COOLERS FOR THE LIQUID CONDITIONED SUIT

Two portable coolers for use with liquid conditioned suits have been designed and developed at the RAE, one using solid carbon dioxide as the heat sink and the other water-ice. They provide 250 W h of cooling at rates up to 350 W with outlet temperatures of 12°C and 20°C respectively; their weights are 5.8 kg and 4.6 kg.

The water-ice cooler can be recharged without replacing the water or battery by connecting it to a recharging unit which has been designed. This greatly reduces the handling problems normally associated with portable coolers.

The results of laboratory and field trials in ambient temperatures up to 40°C are presented, with recommendations for further development.

ARC CP No.1330
August 1974

614.89 :
621-713 :
629.13.067.2 :
621-71

Barlow, G. F.

THE DEVELOPMENT OF PORTABLE COOLERS FOR THE LIQUID CONDITIONED SUIT

Two portable coolers for use with liquid conditioned suits have been designed and developed at the RAE, one using solid carbon dioxide as the heat sink and the other water-ice. They provide 250 W h of cooling at rates up to 350 W with outlet temperatures of 12°C and 20°C respectively; their weights are 5.8 kg and 4.6 kg.

The water-ice cooler can be recharged without replacing the water or battery by connecting it to a recharging unit which has been designed. This greatly reduces the handling problems normally associated with portable coolers.

The results of laboratory and field trials in ambient temperatures up to 40°C are presented, with recommendations for further development.

Cut here

ARC CP No.1330
August 1974

614.89 :
621-713 :
629.13.067.2 :
621-71

Barlow, G. F.

THE DEVELOPMENT OF PORTABLE COOLERS FOR THE LIQUID CONDITIONED SUIT

Two portable coolers for use with liquid conditioned suits have been designed and developed at the RAE, one using solid carbon dioxide as the heat sink and the other water-ice. They provide 250 W h of cooling at rates up to 350 W with outlet temperatures of 12°C and 20°C respectively; their weights are 5.8 kg and 4.6 kg.

The water-ice cooler can be recharged without replacing the water or battery by connecting it to a recharging unit which has been designed. This greatly reduces the handling problems normally associated with portable coolers.

The results of laboratory and field trials in ambient temperatures up to 40°C are presented, with recommendations for further development.

ARC CP No.1330
August 1974

614.89 :
621-713 :
629.13.067.2 :
621-71

Barlow, G. F.

THE DEVELOPMENT OF PORTABLE COOLERS FOR THE LIQUID CONDITIONED SUIT

Two portable coolers for use with liquid conditioned suits have been designed and developed at the RAE, one using solid carbon dioxide as the heat sink and the other water-ice. They provide 250 W h of cooling at rates up to 350 W with outlet temperatures of 12°C and 20°C respectively; their weights are 5.8 kg and 4.6 kg.

The water-ice cooler can be recharged without replacing the water or battery by connecting it to a recharging unit which has been designed. This greatly reduces the handling problems normally associated with portable coolers.

The results of laboratory and field trials in ambient temperatures up to 40°C are presented, with recommendations for further development.

Cut here

DETACHABLE ABSTRACT CARDS

DETACHABLE ABSTRACT CARDS

C.P. No, 1330

1975

Published by
HER MAJESTY'S STATIONERY OFFICE

Government Bookshops
49 High Holborn, London WC1V 6HB
13a Castle Street, Edinburgh EH2 3AR
41 The Hayes, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
Southey House, Wine Street, Bristol BS1 2BQ
258 Broad Street, Birmingham B1 2HE
80 Chichester Street, Belfast BT1 4JY
Government Publications are also available through booksellers

C.P. No. 1330

ISBN 011 470940 8