FLOW OF HEAT AND VAPOR THROUGH COMPOSITE PERM-SELECTIVE MEMBRANES UNDER SIMULATED CONDITIONS

by

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University of Rhode Island
Kingston, Rhode Island

Contract No. DAAG17-67-C-0061

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UNITED STATES ARMY
NATICK LABORATORIES
Natick, Mass. 01760

Clothing and Organic Materials Laboratory

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FOREWORD

This report was prepared by the University of Rhode Island, Kingston, Rhode Island, under Contract No. DAAG17-67-C-0061, "Flow of Heat and Vapor Through Composite Perm-Selective Membranes under Simulated Conditions." The work was administered under the direction of the Advanced Projects Division, Clothing & Organic Materials Laboratory, U.S. Army Natick Laboratories, Natick, Massachusetts, with Mr. Leo A. Spano as Project Monitor.

This report summarizes the performance during the contract period January 1967 to January 1968.

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ABSTRACT

An experimental study was made of the heat and mass (water vapor) flow rate through several different composite clothing systems. Cooling of a simulated skin surface was obtained through vaporization of water from a wet wick in the clothing system. Tests were conducted at both reduced and at atmospheric pressure.

In the reduced pressure tests, cooling rates as high as 182 Btu/ (hr. x sq. ft.) were obtained with a simulated skin temperature of 91°F. Excellent control of the simulated skin temperature at widely varying heat flow rates was possible. Temperature control was obtained by controlling the wick vaporization pressure.

Both forced and natural convection were used in the atmospheric pressure tests. Forced convection was obtained by blowing air from a large fan across the surface of the clothing systems. The air velocity was approximately 7 ft./sec. While the heat flow rate depended somewhat upon the temperature and the humidity of the room air, which were not controlled in these tests, the results indicated that high cooling rates were possible. For a simulated skin temperature of 91°F, cooling rates as high as 200 Btu/ (hr. x sq. ft.) for forced convection and 121 Btu/(hr. x sq. ft.) for natural convection were obtained with room air.

FLOW OF HEAT AND VAPOR THROUGH COMPOSITE
PERM-SELECTIVE MEMBRANES UNDER SIMULATED CONDITIONS

1. Introduction

One of the major problems encountered in the use of protective clothing is the thermal control of the man wearing the clothing. Depending on the rate of physical activity, his heat output may vary from a few hundred to over 3000 Btu/hr. Under normal conditions the body control mechanism maintains the body temperature within acceptable limits. Heat is lost from the body to the surroundings by convection to the air, by radiation, and by evaporation from the skin surface of water produced by sweating. Except in very low ambient temperatures, high rates of heat removal require the sweating mechanism. However, sweating can only produce a cooling effect when the water can evaporate from the skin surface. When the gas next to the skin surface is saturated with water vapor, additional evaporation will not occur. Thus, a man enclosed in protective clothing which contains an impermeable membrane to conserve the life support gases and to protect him from a hostile environment would not be able to depend upon the normal body temperature control mechanisms. The air next to his body surface would soon become saturated and additional evaporation of the sweat on his skin surface would not occur. Unless artificial means of heat removal were used, the body temperature would soon exceed safe limits even at medium rates of metabolic output.

Two passive thermal control systems for use in composite clothing have been proposed by the Advanced Projects Division, U.S. Army Natick Laboratories.* The objectives of this investigation were to test the design
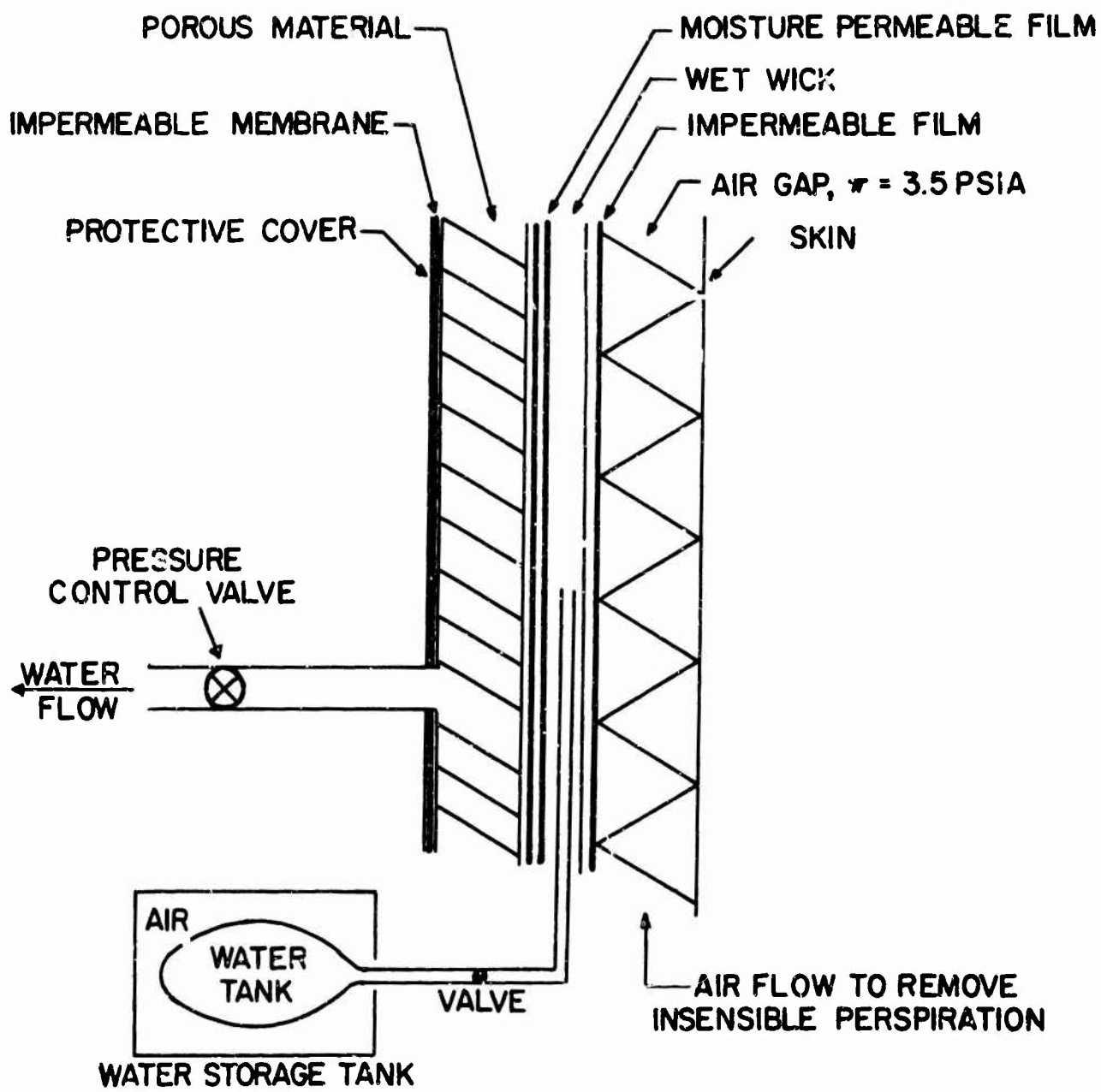
*"Preliminary Study of Two Passive Thermal Control Systems Using Permeable Membranes," Report No. 2, U.S. Army Natick Laboratories, 12 August 1965.

concept of one of these proposed systems(System B), to measure the rates of heat and mass(water) flow through the clothing under various conditions, and to study the temperature control possible on a simulated body surface for various rates of heat output.

The essential components of System B(Figure 1) include the following: The skin would be separated from an impermeable membrane by a narrow air gap controlled by a spacing material. The air gap would allow for some circulation of the gas next to the skin and would contain the life support gas at the required pressure. The impermeable membrane would keep the life support gas from escaping and would be covered and in contact with a wet wick which would itself be covered by a permeable membrane. The permeable membrane would be separated from an outer impermeable membrane by a porous vapor space. For operation in a vacuum environment, such as in space, the vapor space would vent to the surroundings through a pressure control valve. For operation in a hostile atmosphere, the atmospheric gas could be circulated through the vapor space. The man would be protected from this hostile gas by the impermeable membrane. In either case cooling would be obtained by the controlled vaporization of water from the wet wick and the diffusion of the water into the vapor space.

A variation in the composite clothing system for use at atmospheric pressure would be to eliminate the outer impermeable membrane and to allow the wet wick to come into direct contact with the atmosphere. Vaporization of water from the wick would then be directly to the atmosphere.

The major emphasis in this investigation was on tests conducted at reduced pressures. The equipment was designed primarily for this purpose.

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POROUS MATERIAL

MOISTURE PERMEABLE FILM

WET WICK

IMPERMEABLE MEMBRANE

IMPERMEABLE FILM

AIR GAP, π = 3.5 PSIA

PROTECTIVE COVER

SKIN

PRESSURE
CONTROL VALVE

WATER
FLOW

AIR

WATER
TANK

VALVE

AIR FLOW TO REMOVE
INSENSIBLE PERSPIRATION

WATER STORAGE TANK

HEAT REGULATION BY EVAPORATION COOLING
SYSTEM B

Figure 1

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However, some tests were also carried out at atmospheric pressure. In these atmospheric tests the outer impermeable membrane was eliminated and the water vaporized directly into the atmosphere. Both forced and natural convection were used. Forced convection was obtained by blowing air across the outer surface of the clothing.

2. Experimental Equipment

A schematic diagram of the equipment used in this investigation is shown in Figure 2. The equipment(Figures 3, 4, and 5) consisted of a test chamber, two vacuum pumps, two vapor traps, a motor-operated control valve, vacuum or pressure measuring instruments, temperature control and measuring instruments, and various small valves and piping.

The test chamber consisted of an annular space formed by two concentric brass pipes. Each pipe was sealed off at one end by being welded to a disc or head and welded to a flange at the other end. The flanges were bolted together with a gasket between them to form the test chamber. The outer pipe was a standard 16-inch pipe and the inner pipe was a standard 8-inch pipe. An asbestos cement or transite pipe was mounted over the inner pipe and served as the simulated skin surface. The temperature drop through the transite pipe, measured with a differential thermocouple, was used as the basis for calculating the rate of heat flow. The asbestos cement pipe was divided into three sections to reduce longitudinal heat transfer. The center section was one foot long and served as the test section. The total surface area of the transite was 3.8 square feet. Eleven thermocouples were installed to the surface. Each thermocouple consisted of three junctions connected parallel.
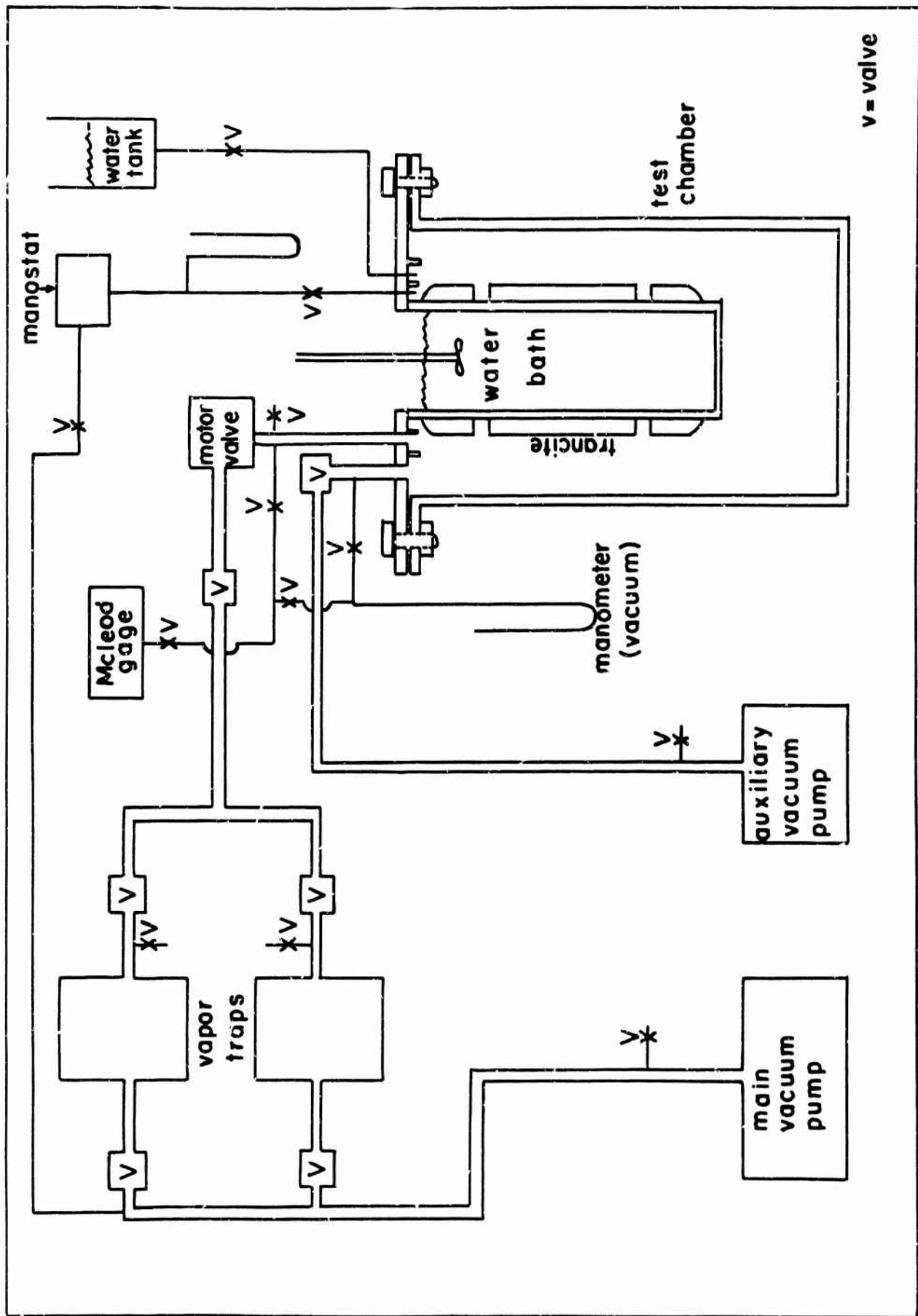
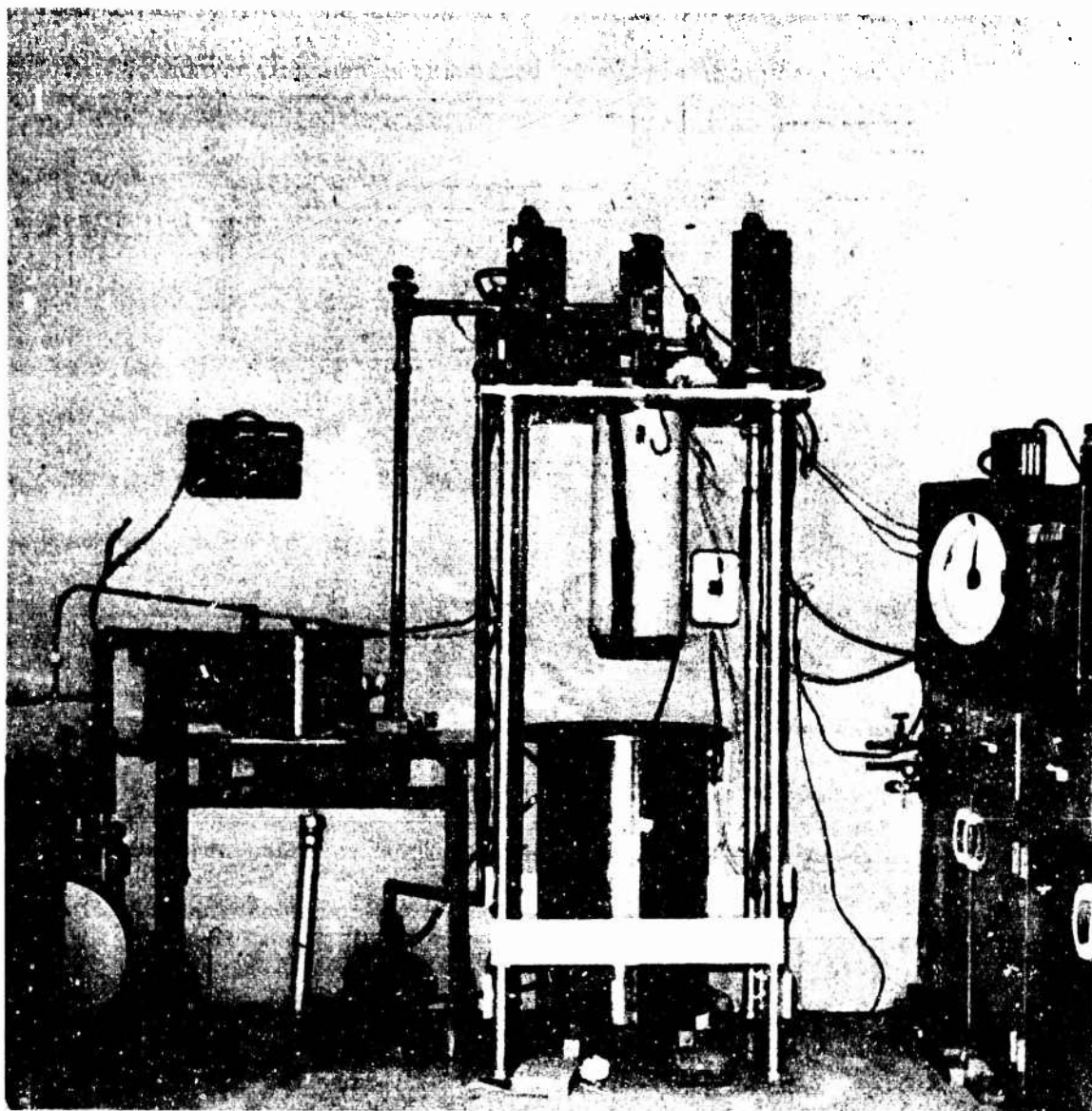Figure 2. Diagram of Experimental Equipment

v = valve

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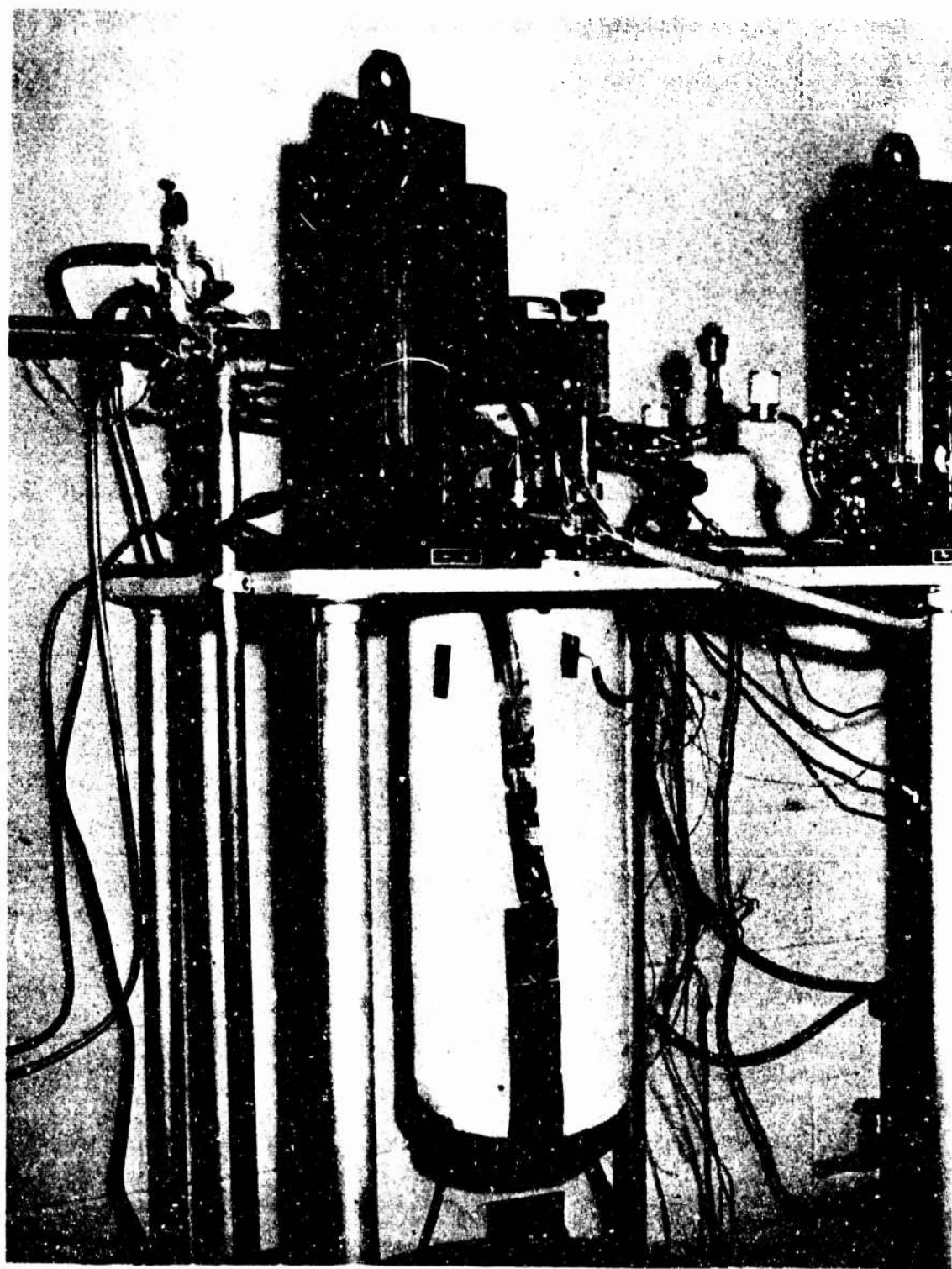Figure 3

Complete apparatus with outer pipe removed

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Figure 4
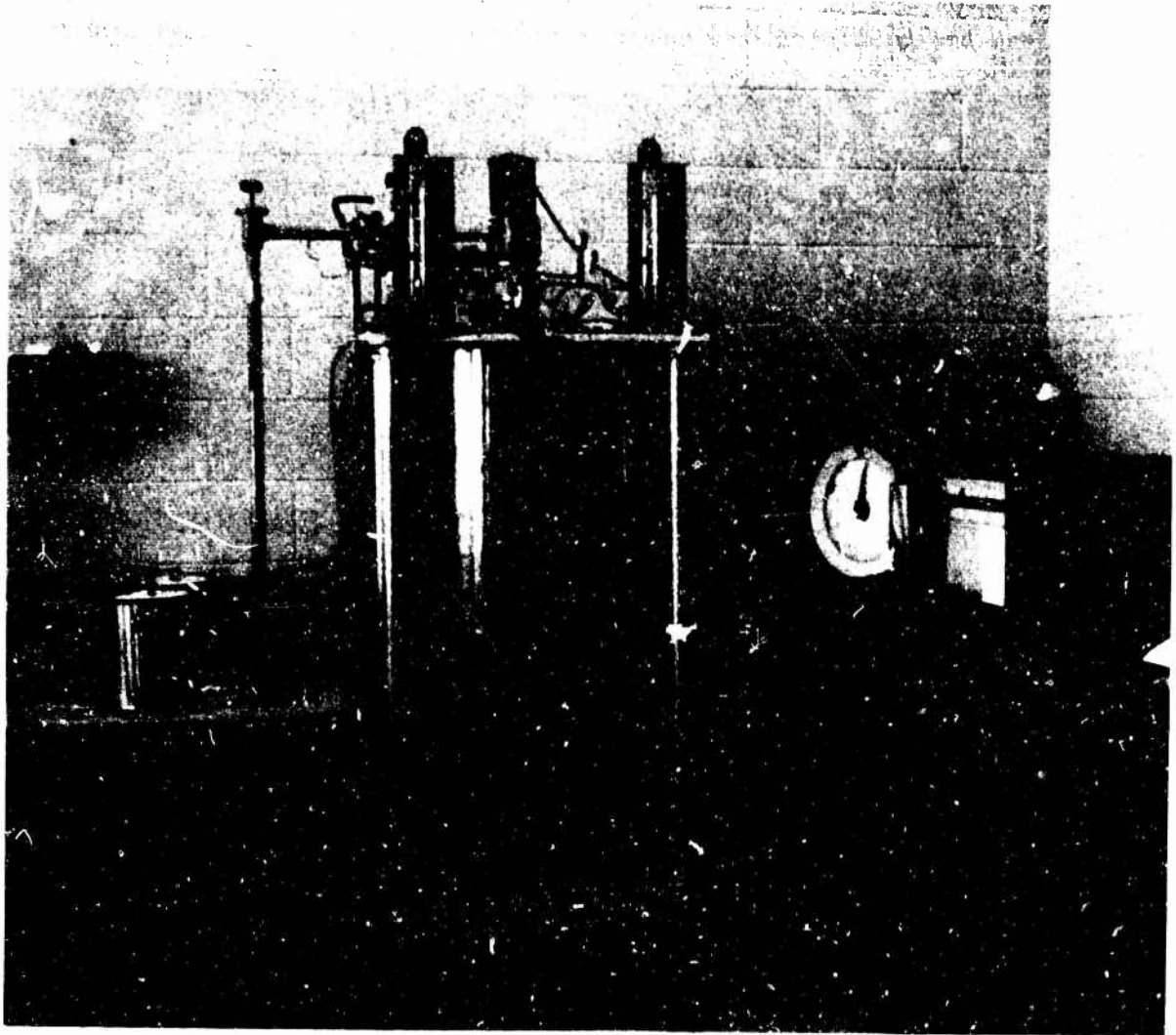
Inner pipe and measuring devices

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Figure 5

Assembled System

Heat was supplied by an electrically heated hot water bath inside the inner pipe. The water temperature for most tests was controlled by a mercury-in-glass thermoregulator.

The motor-operated valve in the vacuum line from the vapor space controlled the pressure in that space and the rate of water vaporization from the wet wick. It was operated by a potentiometric thermoregulator. In an actual operation the pressure control valve would be activated by the skin temperature, but for steady state tests it was found that more uniform operations resulted when the valve was activated by one of the wick thermocouples. In several temperature control tests, however, the control valve was activated by the simulated skin temperature.

Two other potentiometers were used to measure temperatures. One, a 24-point Honeywell-temperature recorder, was used to record the electro-motive force from all thermocouple junctions in the system. The other potentiometer was a two-pen Mosely-strip chart recorder. Generally, one pen was used to measure the temperature of the other surface of the transite (simulated skin temperature) and the other to measure the temperature drop through the asbestos cement from which the rate of heat flow was calculated. However, by using a thermocouple selector switch, it was possible to use the more sensitive strip chart recorder to measure and record other key temperatures. Full-scale range on the strip chart recorder was adjustable. Generally, it was used with full scale set at 1 or 2 millivolts. At maximum sensitivity each division on the chart was less than $0.5^\circ F$ and it was possible to estimate temperatures to approximately $0.1^\circ F$.

The simulated clothing systems were mounted over the transite skin

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simulator. The impermeable membrane was cemented and clamped to projections
on the flange and to the lower portion of the inner pipe. The outer brass
pipe served as the outer impermeable membrane. Figures 3 and 4 show the
equipment with the outer pipe dismantled and the impermeable membrane in place
over the transite. Atmospheric tests were conducted with the outer pipe
dismantled and removed. Figure 5 shows the equipment assembled with the outer
pipe bolted in place, as it was for the reduced pressure tests.

3. Description of Clothing Systems Tested

Suit No. 1 consisted of a polyethylene-saran spacing material
mounted over the transite skin simulator so as to form an air gap. The
polyethylene-saran spacer was 0.285 inches thick and weighed 33 ounces per
square yard. A white rubberized fabric was mounted on the outside of the
spacer and attached by cement to the tor flange and to the lower portions of
the inner brass pipe. The joints on the rubberized fabric were made leak
tight and it thus became an impermeable membrane separating the air gap from
the remainder of the system. The water distribution was obtained by 12 feet
of 1/16-inch teflon tubing coiled outside the rubberized fabric. The teflon
tubing was punched by a needle about every two inches. The wick consisted
of a single layer of absorbent paper toweling covered by a single layer of
woven nylon. The wick was covered by a tightly fitting layer of leather
which served as the moisture permeable membrane. The entire system was then
wound tightly with nylon tape so that it would withstand the 3.5 psi pressure
differential between the air gap and the vapor space.

Suit No. 2 consisted of a layer of cotton shirting mounted over

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the transite skin simulator. The air gap was formed by a layer of 0.10-inch polyethylene-saran spacer which was in contact with the cotton shirting. The impermeable membrane and water distribution system used were the same as in Suit No. 1. The wick was formed by six layers of cotton shirting covered by the layer of woven nylon. The wick was then covered by a layer of leather which was tightly wound with nylon tape as in Suit No. 1.

Suit No. 3 was similar to Suit No. 2 except that the cotton shirting wick was replaced by a nylon felt wick(approximately 0.1 inch thick) and the leather layer was eliminated. Thus, Suit No. 2 and Suit No. 3 contained the identical air gap spacing material.

Suit No. 4 consisted of a layer of cotton shirting mounted over the transite skin simulator. The spacing material and, thus, the air gap were eliminated. The impermeable membrane was mounted over the layer of cotton shirting and was in contact with it. The water distribution system was the same as that used in the previous suits. The 0.1-inch-thick nylon felt wick covered the impermeable membrane. The outer surface of the wick was exposed to the air.

Suit No. 5 was identical to Suit No. 4 except that the nylon felt wick was replaced by a wick consisting of two layers of cotton toweling and the layer of nylon shirting.

Suit No. 6 did not contain a wick. The wick of Suit No. 5 was removed, leaving the impermeable membrane in contact with the atmosphere.

Suit No. 7 consisted of a layer of cotton shirting mounted over the transite skin simulator and covered by a rubber impermeable membrane, as was the case in Suits 4, 5 and 6. A single sheet of nylon parachute cloth

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(Rip-Stop 11 ounce OG106) was placed over the rubber membrane. The nylon was covered with a single sheet of carbon-treated polyurethane-nylon cloth (polyurethane foam/nylon tricot laminate, impregnated with activated charcoal sprayed on nylon tricot side with a fluoro-chemical, 7.5 oz/sq. yd.). The carbon-treated side was in contact with the nylon parachute cloth.

In all clothing systems, several thermocouples were installed in the clothing for measuring the temperature at various points. Thermocouples were attached to the outside surface of the impermeable membrane and to the outside surface of the clothing system. The thermocouples attached to the membrane were also in contact with the wick(for those systems in which a wick was used) and were considered the wick thermocouple.

Suit numbers 1, 2 and 3 were tested both under reduced and under atmospheric pressure. Suit numbers 4, 5, 6 and 7 were tested only at atmospheric pressure.

All materials used in the construction of the clothing systems were supplied by the U.S. Army Natick Laboratories.

4. Operating Procedure, Reduced Pressure Tests

Before conducting any experimental tests, the system was leak tested, both between the entire system and the atmosphere, and between the air gap and vapor space.

The following procedure was used in carrying out a test:
The water bath heater and stirrer were turned on and the bath was heated to the desired temperature. The vapor space and air gap were slowly evacuated, with a bypass valve between the two open so that the pressures would be equalized.

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When the pressure reached 180 mm of Hg(3.5 psi), the bypass valve was closed and full vacuum was applied to the vapor space. The air gap pressure was maintained at approximately 180 mm of Hg for most tests. Originally, a manostat was planned for pressure control of the air gap. However, the glass manostat broke and it was found that manual control of the pressure was not difficult as the air gap pressure changed very slowly. Ice was put into one of the vapor traps. The main vacuum pump was a ballast pump which could handle up to 25 mm of Hg partial pressure of vapor, but the pumping speed was increased if some of the vapor was condensed and separated before the pump. In three of the runs where very high pumping speeds were required, dry ice and acetone were used in the traps. The controller operating the automatic control valve was set at the estimated wick temperature required and water was allowed to flow into the wick. Sufficient water was added so that the six wick thermocouples were nearly the same. The water vaporized from the wick and cooled it very rapidly. The simulated surface temperature also cooled rapidly. When the wick temperature reached its set point, the motor valve closed and vaporization stopped. The temperatures then started to rise until the control valve reopened. The temperature set point for the valve was adjusted until the simulated skin temperature was maintained at the desired value. After conditions in the system had been constant for approximately 30 minutes, the temperatures were recorded and the run ended.

5. Operating Procedure, Atmospheric Pressure Tests

For the atmospheric pressure test, the outer pipe was removed, exposing the clothing surface to the air. The bath heater was controlled by

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the potentiometric thermoregulator which was activated by a simulated skin thermo-couple.

In carrying out a test, the bath heater and stirrer were turned on and the simulated skin temperature controller set at the desired value. Water was added to the wick in these runs in which a wet wick was desired. In tests made with Suits 1, 2 or 3, the air gap pressure was controlled at 3.5 psig. Forced convection was obtained from a large fan placed under the equipment. The air velocity during the forced convection runs varied from 5.2 to 7.9 ft./sec., using an anemometer for measurement.

6. Calculated Heat Flow Rate

The experimental rate of heat flow was determined from the temper-ature drop across the transite. The rate of heat flow through the transite is given by:

$$\frac{q_t}{A} = \frac{k_t \, \Delta t}{L} \tag{1}$$

where

q_t = heat transfer through the transite
A = area, sq. ft.
k = thermal conductivity of transite,
     $5.5(Btu \times in)/(hr. \times sq. ft. \times {}^\circ F)$
L = thickness of transite, 0.4 inches
Δt = temperature difference between inner and outer surface, ${}^\circ F$

The theoretical rate of heat flow through the air gap from the simulated sking surface was calculated and compared with the experimentally measured rate through the transite. Heat, leaving the simulated skin surface,

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will be transferred through the air gap spacer to the inside wick surface by radiation, conduction and by natural convection. The total heat transferred across the air gap will be conducted through the wick where it will be removed by vaporization of the water from the outer wick surface. Thus:

$$q_w = q_R + q_c + q_{NC} \tag{2}$$

where

q_w = heat transferred through wick
q_R = radiant heat transfer
q_c = conductive heat transfer
q_{NC} = heat transfer due to natural convection

In these calculations it was assumed that convection in the spacing material would be negligible, and that the temperature drop through the wick will be small and the wick temperature would be uniform.

The rate of energy transfer by radiation from the simulated skin surface to the wet wick may be approximated by:

$$q_{R/A} = 0.173 \, \mathcal{E} \left[\left(\frac{Ts}{100} \right)^4 - \left(\frac{Tw}{100} \right)^4 \right] \tag{3}$$

where

$\mathcal{E}$ = emissivity of skin surface
Ts = simulated skin temperature, $^{\circ}$R
Tw = wick temperature, $^{\circ}$R

In using equation (3), it was assumed that the wet wick behaved as a black body and the skin surface as a grey body. The emissivity was assumed to be 0.95. The air gap size has no effect on the rate of radiation.

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Conduction through the spacer material may be calcu'ated by:

$$q_{c/A} = \frac{km(Ts - Tw)}{L} \qquad (4)$$

where

km = thermal conductivity of spacer(Btu x inch)/(hr. x sq. ft. x $^\circ$F)
L = thickness in inches

Two different spacer materials were used. The first, used only in Suit No. 1, was a 0.285-inch-thick polyethylene-saran spacer, and the second, used in Suit numbers 2 and 3, was a 0.10-inch-thick polyethylene-saran spacer. The thermal conductivities of both spacing materials were determined and supplied by the U.S. Army Natick Laboratories. These were 0.27279 for the 0.285 inch spacer and 0.29196 (Btu x inch)/(hr. x sq. ft. x $^\circ$F) for the 0.10 inch spacer. In calculations for Suits 2 and 3, the thickness of the cotton shirting of 0.01 inch was added to the spacer thickness.

Suits 4, 5, 6, and 7 did not contain an air gap and no attempt was made to calculate theoretically the heat flow rate attained in tests with these systems.

7. Results of Reduced Pressure Tests

The results of the reduced pressure tests are summarized in Table I. Both the calculated and experimentally measured heat flow rates are listed for each of the three clothing systems tested. Also listed for each run are the simulated skin temperature, t_s, the wick temperature, t_w, the condition of the wick and the air gap pressure. Figure 6 shows the calculated and experimentally

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TABLE I

SUMMARY OF REDUCED PRESSURE TESTS

RUN NO.	SUIT NO.	t_s °F	t_w °F	WICK	AIR GAP PRES mm. Hg	COOLING RATE, Btu/(hr x sq ft) Measured	COOLING RATE, Btu/(hr x sq ft) Calculated
4	1	118.2	110.9	dry	0	18	---
6	1	91.5	80.0	wet	180	33	22
7	1	90.0	64.0	wet	173	48	52.5
8	1	90.9	52.0	wet	174	69	67.5
9	1	91.2	65.4	wet	187	41	45
10	1	91.1	73.4	wet	186	24	34
11	1	95.3	63.4	wet	177	54	54
12	1	95.5	81.8	wet	180	37.5	25
13	1	91.0	86.3	dry	0	13	---
14	1	90.9	85.5	dry	180	16	11
15	2	92.0	91.6	dry	0	6.5	---
16	2	91.0	77.4	wet	180	54	50
17	2	91.0	68.5	wet	180	71	82
18	2	91.6	61.5	wet	180	115	108
19	2	116.0	113.3	dry	180	23.5	14.5
20	2	104.0	102.3	dry	180	12	8
21	2	91.5	80.5	wet	180	39	39
22	2	103.0	87.3	wet	180	60	60
23	2	95.7	79.3	wet	180	56	62
24	2	91.2	46.5	wet	180	159	161
25	2	95.8	44.5	wet	180	172	189
26	2	91.4	40.0	wet	180	182	184
30	3	118.4	114.0	dry	180	24	17
31	3	103.0	91.4	wet	180	64.5	42
32	3	90.8	80.7	wet	200	46	39
33	3	92.0	71.2	wet	190	79.5	72
34	3	90.9	65.8	wet	185	110	92

$t_s = 91\ °F$

EXPERIMENTAL

Reduced Pressure
● Suit No. 1
■ Suit No. 2
▲ Suit No. 3

Atm. Pressure
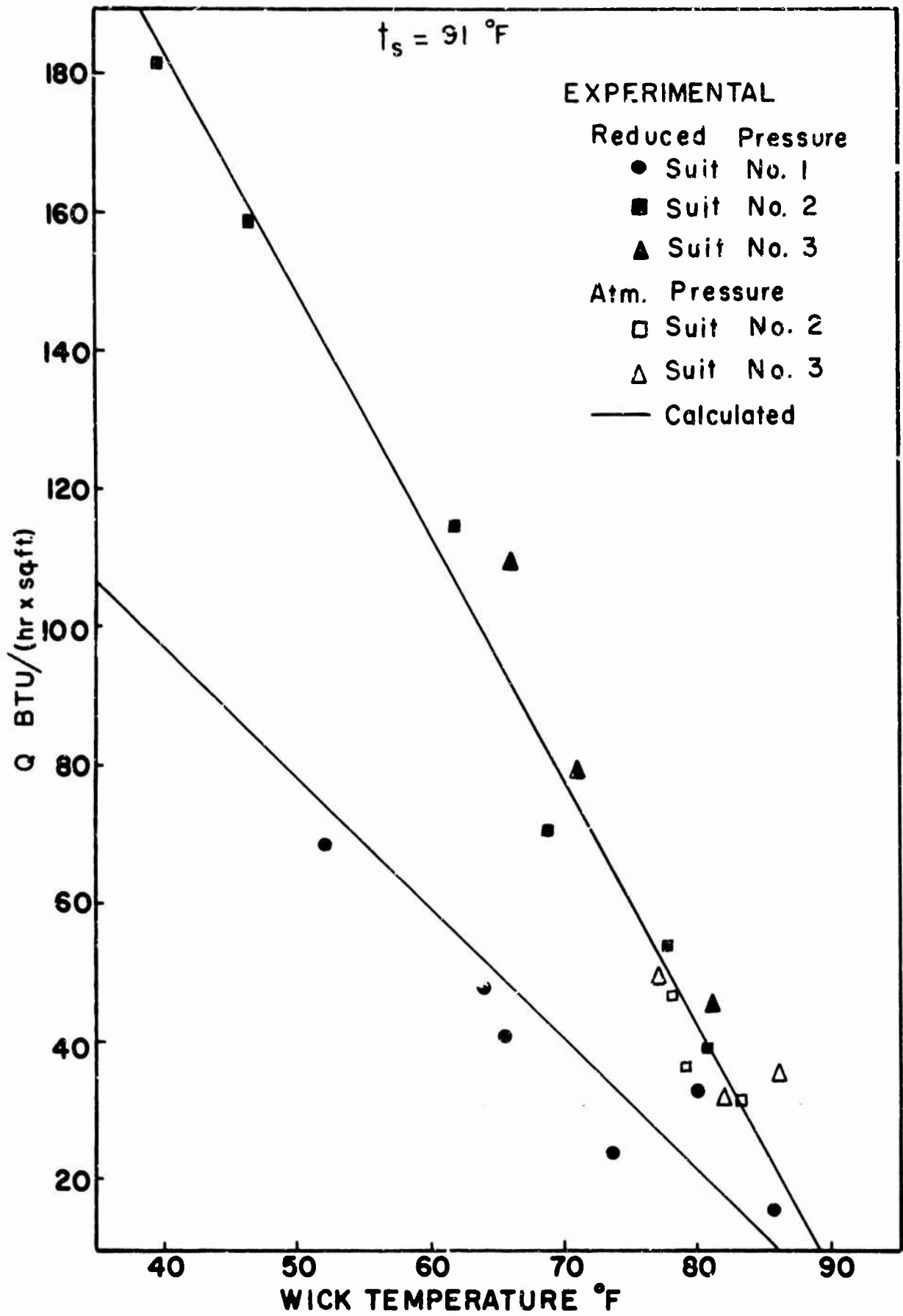□ Suit No. 2
△ Suit No. 3
— Calculated

Fig. 6   HEAT FLOW RATE

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measured cooling rates for a simulated skin temperature of 91°F as a function of wick temperature.

The agreement between the calculated and measured cooling rates was very good. With a simulated skin temperature of 91°F, it was possible to obtain a cooling rate of 182 Btu/(hr. x sq. ft.). For a suit with a total area of 20 square feet, this would be equivalent to a cooling rate of 3640 Btu/hr., which is considerably in excess of the goal of 3000 Btu/hr. Suits No. 2 and 3 gave essentially the same heat flow rates for the same wick and skin temperature. This was as expected since they both contained the same spacing material for the air gap.

A considerable difference in the speed of response and operating characteristics of the three suits was noted. Suit 2 required considerably more water to wet the wick uniformly and responded to temperature change more slowly than did either Suits 1 or 3. Suit 3 required the least water and reacted most rapidly to temperature changes. Suit No. 2 required over 1000 ml. of water to wet the wick uniformly while Suit No. 1 was somewhere between the requirements of the other two. These differences, it is believed, are due to variations in wick construction of the three suits. The multilayer cotton wick of Suit 2 required considerably more water than did the thin paper wick of Suit 1 or the nylon wick of Suit 3. Also, the cotton fibers did not release the water as readily as the nylon wick. With a cotton wick the water is absorbed in the fibers, but with the nylon the water remains on the surface of the fibers.

An interesting phenomenon was noted that shows the difference in behavior of the cotton and nylon wick. When water was first added to the

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system after the wick had been pumped dry. the temperature of the cotton wick increased sharply, before dropping. In some cases the wick temperature increased to above the bath temperature, and in one test the temperature rise was approximately 20°F. This intitial rise in temperature was neglirible or non-existent with the nylon wick. It was assumed that the phenomenon was due to the condensation of the water vapor and its absorption in the cotton fibers.

Two special tests were devised to show the different behavior of the wicks and of the clothing systems. The first was called a "wick response test" and the second, a "speed response test."

The purpose of the "wick response test" was to show the reaction of the system to a fixed quantity of water in the wick. The bath was controlled at 120°F and the system was first evacuated completely to dry out the wick. Air in the gap was controlled at 180 mm of Hg. pressure. Then, exactly 100 ml. of water was added to the wick while continuing to evacuate on the vapor space with the vacuum valve open wide. The response of the system was noted and the results of the tests on the three suits are listed below.

	Suit 1	Suit 2	Suit 3
Maximum Cooling Rate, Btu/(hr. x sq. ft.)	82.5	59.0	190
Lowest skin temperature reached, °F	107	111	89

The intitial skin temperature in each case was approximately 117°F.

The "speed response test" was devised to determine how rapidly the simulated skin temperature could be changed. The test consisted of measuring the time required to reduce the simulated skin temperature from 103°F to 96°F with the bath at 112°F, and also the time required for the skin temperature to

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to return to 103°F after the vacuum valve had been closed. A comparison of the time required by different clothing systems to this standard test would give an indication of their relative response speeds to changing condition. Only Suits No. 2 and No. 3 were subjected to this test. Suit No. 2 changed from 103°F to 96°F in 19 minutes and required 40 minutes for the temperature to return to 103°F. Suit No. 3, on the other hand, only required 4.5 and 22.5 minutes, respectively, for the same tests. This would clearly indicate the superiority of Suit No. 3 in the ability to adjust to rapid changes of conditions, even though the steady state heat flow rates were approximately the same for both.

Several tests were made to study the temperature control that would be possible with the system. Temperature control was obtained by the motor-operated valve in the vacuum line. By opening and closing this vacuum valve, the motor valve was activated and controlled by the wick temperatures. However, for the temperature control runs, the valve was operated by the simulated skin temperature. It was found relatively easy to maintain the skin temperature at a preset value over a wide range of heat flow rates. During one test with Suit No. 3, the skin temperature control was set at 91°F and the heat flow rate was varied from 53 to 150 Btu/(hr. x sq. ft.); the skin temperature did not vary by more than 2°F, and during most of the time the variation was less than 1°F.

The heat flow rates were only slightly dependent on the air gap pressure. A decrease in the air gap pressure resulted in an increase in rate. This is contrary to expectations and it is believed to be due to a variation in the thickness of the gap with the variation in pressure. In a test made with Suit No. 3, the heat flow at a gap pressure of 90 mm of Hg. was 127 Btu/(hr. x sq. ft.). When the pressure was increased to 200 mm of Hg.,

the heat flow decreased to 110 Btu/(hr. x sq. ft.). The effect of pressure on the cooling rates of Suits 1 and 2 was less than that of Suit 3.

8. Results of Atmospheric Pressure Tests

The results of the atmospheric pressure tests are summarized in Table II. The results of tests made with Suits 2 or 3 with a simulated skin temperature of $91^{\circ}F$ are also plotted in Figure 6. In these test results, the calculated heat flow rates agreed reasonably well with the measured rates. In the forced convection tests, there was no significant difference noted in the results when the air velocity was varied between 5.2 and 7.9 ft./sec.

Fairly high rates of heat flow were obtained especially with Suit No. 5. With forced convection, the maximum obtained was 200 Btu/(hr.xsq.ft.). It should be noted that the cooling rate is a function of the air temperature and humidity. No facilities were available for controlling these factors. The tests were made with the air available in the room at the time. Nevertheless, these preliminary results indicate that high cooling rates are possible at atmospheric pressure with a clothing system using a wet wick.

The only difference between Suit No. 4 and Suit No. 5 was in the type of wick used. Suit 4 contained the nylon felt wick while Suit 5 contained a cotton wick. The results with Suit 4 were very unsatisfactory. The nylon wick held very little water and the water content varied considerably during each test. The heat flow rate varied with the water content of the wick and the results were not reproducible. No difficulty was experienced in keeping the cotton wick in Suit No. 5 wet. The heat flow rates were considerably higher than with Suit No. 4 and were consistent and reproducible. The unsatisfactory

TABLE II

SUMMARY OF ATMOSPHERIC TESTS

RUN NO.	SUIT NO.	t_s °F	t_w °F	WICK	AIR TEMP WB	AIR TEMP DB	CONVECTION	HEAT FLOW Btu/hr x ft^2
2	1	117.5	108.8	dry	--	78.3	natural	22.5
27	2	91.2	82.9	wet	71	77.0	natural	31
28	2	90.9	78.2	wet	72.5	79.0	forced	46.5
29	2	91.2	79.1	wet	74.5	84.0	forced	36.5
40	3	91.3	86.0	dry	--	68.0	natural	36.5
41	3	91.0	82	wet	67.8	77.0	natural	32.5
42	3	90.8	76.7	wet	68.5	77.5	forced	50
42A	4	91.0	84.2	wet	67.5	76.5	natural	34
43	4	96.3	87.1	wet	68.5	77.0	natural	26.5
44	4	91.0	79.6	wet	66.5	74.5	forced	59
45	4	91.7	68.6	wet	59.0	75.5	forced	55
46	4	100.4	77.0	wet	61.0	76.5	forced	76.5
47	5	90.5	78.5	wet	63.5	73.5	forced	144
48	5	100.2	83.6	wet	63.5	73.5	forced	200
49	5	91.1	81.9	wet	55.5	71.0	natural	86.5
50	5	100.2	88.2	wet	55.5	71.0	natural	121
51	6	91.5	85.9	---	56.5	75.0	natural	35
52	6	91.1	81.8	---	56.5	75.0	forced	94
53	6	99.3	93.2	---	54.5	73.0	natural	61.5
54	6	100.2	85.9	---	54.0	73.0	forced	147
55	7	99.3	94.5	---	57.0	75.0	natural	46
56	7	101.0	92.2	---	57.0	75.0	forced	58
57	7	91.5	87.7	---	59.5	72.5	natural	29.5
58	7	91.5	86.8	---	59.5	72.5	forced	38

Suits No. 6 and 7 did not contain a wick, for these t_s = membrane temperature.

operation of the nylon wick was surprising since it seemed superior to the cotton wick in the reduced pressure tests.

9. Reliability of Results

The experimental heat flow rates were calculated from the measured temperature drop through the asbestos cement(transite) pipe and the reported thermal conductivity. While the good agreement of the heat flow through the transite and the calculated heat flow through the air gap seemed to indicate that the method used and measurements were reliable, a completely independent check of the results seemed desirable. This was done by making an overall energy balance on the equipment.

The total energy into the system came from the electrical hot water heater and from the water stirrer. The energy out consisted of the heat transferred through the transite pipe and the loss from the water surface and top flange. A wattmeter was installed in an electrical line to the heater. The total heat transferred through the transite pipe could be calculated from the temperature drop measurements since the total surface area of the transite was known. This was 3.8 square feet. The heat loss from the water and top surface was neglected. Only the heat input from the stirrer remained unknown.

A special test was made to determine the rate of energy added to the system from the stirrer. The bath temperature was lowered to slightly below room temperature. Under this condition the direction of the heat flow was from the surroundings into the bath. The stirrer was turned on and the rate of temperature rise was measured when the temperature drop through the transite was zero, indicating no heat flow. The test was repeated with a

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measured energy input into the electrical heater in addition to the stirrer.
From the results of these tests it was possible to calculate the energy input from
the stirrer.

$$q_s = Mc\Delta t_1 \tag{5}$$

$$q_s + q_e = Mc\Delta t_2 \tag{6}$$

where

q_s = energy input of stirrer
q_e = energy input of heater
Mc = heat capacity of system
Δt_1 = rate of temperature rise, stirrer alone .
Δt_2 = rate of temperature rise, stirrer and heater

Dividing equation 5 by 6 gives

$$\frac{q_s}{q_s + q_e} = \frac{t_1}{t_2} \tag{7}$$

From the results of these tests it was found that the stirrer heat input, q_s,
was 50 Btu/hr.

The overall energy balance was applied to several test runs. The
"energy in," which was the sum of the heat added by the stirrer and the electri-
cal heater, was compared to the "energy out," which was the total heat flow
through the transite. The results are given below:

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RUN	ENERGY IN Btu/hr.	ENERGY OUT Btu/hr.	ENERGY OUT / ENERGY IN
6	173	125.5	0.73
7	220	182	0.83
8	340	262	0.77
9	190	156	0.82
10	125	91	0.73
11	220	205	0.93
12	180	143	0.79

Average 0.80

In view of the fact that the heat loss from the top surface of the equipment was neglected, the overall energy balance was considered a very satisfactory check of the measured heat flow through the transite pipe.

10. Conclusions and Recommendations

Passive thermal control with very nigh cooling rates in protective clothing is possible through the use of a wet wick in the clothing.

It is possible with our current state of technical knowledge to design a passive thermal system which will remove heat from a man in a vacuum environment at a rate in excess of 3000 Btu/hr without depending on sweating, and his skin could be maintained relatively dry. Also, it would be possible to control his skin temperature within 1 or 2°F over a wide range of metabolic outputs.

At atmospheric pressure, a man protected against a hostile environment by an impermeable membrane may be cooled by the use of a wet wick. The rate of cooling will depen upon the temperature and humidity of the gas in contact with the wick. Under ordinary conditions of temperature and humidity, preliminary tests indicate that very high cooling rates are possible. Temperature control under natural convection conditions might be difficult to attain,

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but should be relatively easy to attain under forced convection.

It is recommended that:

a. Additional experimental work should be carried out in which various
    wick designs could be studied. For reduced pressure operations, it
    would seem that the desired characteristics can be met by synthetic
    materials which do not tie up relatively large quantities of water in
    the fiber. For atmospheric pressure operation, however, the synthetics
    may not hold enough water to allow stable operation.

b. An actual prototype protective clothing system using a wet wick and
    designed for reduced pressure operation should be constructed and tested
    under actual conditions.

c. A complete study should be undertaken of the use of wet wicks for
    thermal control in protective clothing at atmospheric pressure. The
    present equipment should be redesigned and altered to allow control
    of the air flow rate, temperature, and humidity over a wide range of
    conditions.

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13. ABSTRACT

An experimental study was made of the heat and mass (water vapor) flow rate through several different composite clothing systems. Cooling of a simulated skin surface was obtained through vaporization of water from a wet wick in the clothing system. Tests were conducted at both reduced and at atmospheric pressure.

In the reduced pressure tests, cooling rates as high as 182 Btu/(hr.x sq.ft.) were obtained with a simulated skin temperature of 91°F. Excellent control of the simulated skin temperature at widely varying heat flow rates was possible. Temperature control was obtained by controlling the wick vaporization pressure.

Both forced and natural convection were used in the atmospheric pressure tests. Forced convection was obtained by blowing air from a large fan across the surface of the clothing systems. The air velocity was approximately 7 ft./sec. While the heat flow rate depended somewhat upon the temperature and the humidity of the room air, which were not controlled in these tests, the results indicated that high cooling rates were possible. For a simulated skin temperature of 91°F, cooling rates as high as 200 Btu/(hr. x sq. ft.) for forced convection and 121 Btu/(hr. x sq. ft.) for natural convection were obtained, with room air.

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