NSL 65-87-3
SEPTEMBER 1965

TECHNOLOGY STUDY OF PASSIVE CONTROL OF HUMIDITY IN SPACE SUITS

BY
ARNOLD P. SHLOSINGER, WILTON WOO,
CONSTANTINO CAFARO AND EMIL W. BENTILLA

PREPARED UNDER CONTRACT NO. NAS 2-2102
BY

NORTHROP CORPORATION
NORTHROP SPACE LABORATORIES
3401 WEST BROADWAY
HAWTHORNE, CALIFORNIA

for the

AMES RESEARCH CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NSL 65-87-3
SEPTEMBER 1965

TECHNOLOGY STUDY OF PASSIVE CONTROL OF HUMIDITY IN SPACE SUITS

BY
ARNOLD P. SHLOSINGER, WILTON WOO,
CONSTANTINO CAFARO AND EMIL W. BENTILLA

PREPARED UNDER CONTRACT NO. NAS 2-2102
BY
NORTHROP CORPORATION
NORTHROP SPACE LABORATORIES
3401 WEST BROADWAY
HAWTHORNE, CALIFORNIA

for the

AMES RESEARCH CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF TABLES

TECHNOLOGY STUDY OF PASSIVE CONTROL OF HUMIDITY IN SPACE SUITS

By A. P. Shlosinger, W. Woo,
C. Cafaro and E. W. Bentilla

SUMMARY

Investigations were performed to establish feasibility and develop basic techniques for control of humidity, emitted by the human body in a space suit, without the use of forced gas flow. These investigations used analytical and experimental techniques. Results of the analytical investigations have been reported previously, Reference 1, under this contract and are briefly summarized in this report. Results of the experimental investigations and their correlation with the analytical results are presented in this report. Two basic techniques for passive humidity control were investigated: (a) Condensation of water vapor from a stagnant pressurization gas in the space suit on wicks cooled below the required dew point, and retention or transport of the liquid condensate by wicks, and (b) Adsorption of the water vapor by desiccants. Performance data for cooled wicks and desiccants for this application are presented.

Concepts for integration of passive humidity control techniques, with present concepts of liquid cooled suits are presented. A concept for simplification of liquid loop cooled space suit automatic temperature control, required for adaptions to metabolic heat rate variations, is suggested.

Theoretical investigations of the use of heat sinks, integral with and distributed over the space suit shell, for body temperature control were performed under this contract. Feasibility and problem areas were discussed in a previous report, Reference 2. Concepts for integration of integral heat sink temperature control techniques with passive humidity control are presented and a brief summary of Reference 2 is included for reader convenience.

INTRODUCTION

The purpose of the study program covered by this report was to investigate feasibility and develop techniques for passive control of humidity in space suits, which use liquid loop cooling or heat sinks integral with and distributed over the space suit shell, for sensible heat control.

In the gas-ventilated, first generation, space suits, resulting essentially from adaption of aircraft full pressure suits to space flight requirements, humidity control was inherent in the use of a ventilating gas. In fact, much of the heat removal from the human skin resulted in these suits from evaporation of sweat.

The use of liquid loop cooling separated the function of sensible cooling of the skin from the water vapor removal function. Liquid loop cooling does permit removal of high body heat rates as sensible heat and sweating can be minimized. However, the liquid loop has no inherent ability for humidity control.

There is, however, still emission of water vapor from the human skin, even when sensible eccrine sweating is suppressed by high rates of sensible heat removal. Present concepts of liquid-cooled suits provide for removal of this water vapor by ventilating gas. Gas flow rates are much smaller than in gas-cooled suits, but a liquid and a gas loop are required.

The objective of the study program was to eliminate the need for thi gas loop and provide removal of body moisture by passive diffusion of water vapor from the skin to loci of disposal, to explore methods to passively condense or adsorb water vapor and to recover or dispose the condensed liquid.

The results of a theoretical study on water vapor diffusion in a binary mixture of water vapor and oxygen were previously reported in Reference 1 and a brief summary is included in this report. Further theoretical and experimental investigations, performed to show feasibility and develop techniques for application to a space suit, are then described.

Under the same contract an investigation of the feasibility of the use of heat sink materials, integrated in the suit wall, for body temperature control has been performed (Reference 2). Potential heat sink materials considered are organic materials of suitable melting point and heats of fusion which by phase change are capable of absorbing and storing body heat. It was recognized that this technique would be practical for only limited mission durations in certain specific applications.

However, within the limitations established, integration of heat sink temperature control with passive humidity control and open type breathing atmosphere control leads to a concept of a suit system without power demand or moving parts, useful for short extravehicular activities.

PASSIVE HUMIDITY CONTROL IN SPACE SUITS

In present liquid loop cooled space suits a gas loop provides humidity control, breathing atmosphere regeneration and suit pressurization. Lower power demand, reduced system complexity and improved control of body temperature were expected to result from a system in which water vapor, emitted or evaporating from the skin, passively diffuses through a stagnant pressurization gas towards either wick surfaces cooled below the dew point temperature of the water vapor-oxygen mixture or toward desiccant surfaces distributed in proximity to the skin throughout the space suit interior.

Diffusion of a component gas in a binary mixture of gases is an effect resulting from concentration gradients, with temperature gradient effects playing a minor part. The effect is not gravity dependent, hence applicable under zero G or lunar G.

The feasibility of the use of the diffusion process for humidity control of space suits was established by an analytical review. The results of this study were summarized and published in Reference 1. This report presents an analytical study of molecular diffusion, mass transfer within an adsorption bed, and condensation on a cooled wick, as they apply to space suit concepts.

A theoretical analysis of diffusion coefficients indicated that the rate of water vapor diffusion across a gap between the skin and the water vapor removal devices would make passive water vapor diffusion entirely feasible. The thermal diffusion coefficient was found to have no significant effect in space suit applications. It also became apparent that the capabilities of the passive vapor diffusion techniques may permit relaxation of the zero eccrine sweating requirement imposed on liquid cooled suit design. This requirement resulted from the desire to reduce ventilating gas flow rates and related power penalty to the minimum, but it has also caused a difficult automatic control problem under variations of metabolic heat emission.

Two concepts of water vapor removal devices or "Moisture Sinks" were considered. Desiccants have the potential of adsorbing, condensing and retaining water. The desiccants were assumed to be retained in many small porous or screen material bags distributed over the undergarment and cooled by the liquid loop coolant flow provided for sensible body cooling. A capillary material, such as a wick, when cooled by embedded coolant tubes, will condense water vapor and by capillary action retain the liquid condensate. With certain arrangements it is also capable of transporting the liquid condensate to locations of storage or disposal.

Application of design criteria derived in Reference 1 to analysis of desiccant bed performance in a space suit indicated applicability for only limited periods of time. Vapor adsorption rate diminishes, as desiccant bed saturation progresses with operating time. This requires desiccant beds designed for the highest expected sweat rate and for adsorption capacities as they will exist at the end of a mission when the desiccant is already partly saturated. High weight penalties must be expected for mission duration of the order of several hours. Weight of the desiccant in a 0.6 cm thick layer of one square meter face area, as was assumed in deriving analytical desiccant performance data in Reference 1, would be about 4.5 kg.

The concept of condensation of water vapor on wicks, cooled below the desired dew point is much more promising. Wick weights in the order of only several hundred grams per suit are expected. Condensed perspiration water can be collected and retained by wicks having water retention capacities between 5 and 10 times their dry weight. Wicks can transfer liquid water to locations of disposal, such as water evaporators, where the condensed water can be used as refrigerant boiling to space vacuum.

An analysis of water vapor removal by a wick cooled below the dew point, across an oxygen-water vapor filled gap, was performed and is presented in Appendix E of Reference 1. This analysis resulted in an expression requiring experimentally derived input data and a numerical computer solution. It was concluded that experimentation with an arrangement simulating the physical conditions in the space suit was the direct and most practical method of determining cooled wick system performance.

Experimental Investigations of Cooled Wick System Performance

Experimental arrangement. - The requirements for an experimental arrangement to simulate humidity control of a man-suit system are:

1. Provide simulation of a sweating skin.
2. Provide control and information of water vapor pressure at the simulated skin.

3. Provide for the installation of various test arrangements of cooled wicks.

4. Provide a method of adjusting the width of a gap between the simulated skin and the cooled wick from approximately 5 mm to 20 mm.

5. Provide for the collection, retention and quantitative measurement of the amount of simulated sweat condensed by the cooled wick.

An apparatus was designed and built to satisfy these requirements. This experimental apparatus is shown in Figures 1 and 2.† The basic material for the apparatus is clear plexiglass. A pressed copper fiber material* was used to simulate the sweating skin. Figure 3 shows the simulated skin (vapor source) section of the apparatus. A metallic copper felt was selected for simulating a sweating skin because of its high thermal conductivity which minimized lateral temperature gradients. Thermocouples soldered to the copper felt provided temperature and water vapor partial pressure information. The copper felt was maintained in a water soaked condition; and because of good heat transfer from the copper fibers to the water, it was reasonably safe to assume saturation at the temperature of the metal at the face of the copper felt. The copper felt selected has high water permeability and provides a thermally conductive, vapor and liquid permeable metallic matrix for the water. A sheet of highly capillary textile wick was put in close contact with the back side of the copper felt. This capillary wicking provided even distribution and capillary retention of liquid water. The copper felt surface was maintained wetted. In a facing down position, the wetted surface did not drip. This surface provided a good simulation of a sweat wetted skin without sweat runoff. An immersible tape heater located on the water side of the wick provided control of temperature and vapor pressure on the moist frontal face of the copper feltmetal (Figure 4). The wick and cooling coils were fastened to a plexiglass disc opposed to the simulated skin and suspended on a laboratory jack from the top of the apparatus. As shown in the schematic, Figure 1, the gap width was adjustable by turning the jack adjustment knob. The total pressure in the experiment area was controlled by placing the experimental apparatus in a vacuum bell jar and lowering the pressure in the bell jar to the desired level. Water at a controlled temperature was circulated

---

* "Feltmetal" made by Huyck Metals Department of the Huyck Equipment Company, Milford, Connecticut.

† Referenced figures have been grouped as the final entry in this report (pages 39 - 73).

in a cooling coil and provided cooling to the wick. The flow rate and temperatures in and out of the apparatus were recorded. The wick temperature was controlled by the coolant temperature which ultimately controlled the water vapor pressure at the face of the wick. The complete test arrangement is shown in Figures 5 and 6.

There were two vapor condensing and water collection schemes used. The first of these consisted of a tubular HITCO Refrasil wick sleeve Series N 0.95 centimeters wide with a 0.635 centimeter outer diameter Tygon (polyvinyl chloride) tube threaded through the center of the wick sleeving. The tube-Refrasil wick assembly was then mounted on a wire screen in a spiral pattern as shown in Figure 7. At each end of the Refrasil wick, and on the opposite side of the wire screening, two pouches of fibrous Refrasil batting were used as water storage cavities. The batting was within the plastic housing, and the wick sleeving end was routed into the batting. The pouches each contained approximately 25 grams of Refrasil batting. The purpose of the pouches was to store the moisture picked up and transported to the pouches by the Refrasil sleeving. Coolant water was circulated through the Tygon tubing during the test and cooled the wick to provide heat removal as required by the moisture condensing on the wick. A few test runs were made with a variation of this arrangement, that is without the wick pouches.

The second arrangement worked in a similar manner (Figures 8 and 9). The coolant was circulated through a coil of copper tubing 0.635 centimeter outer diameter, that was soldered onto a copper wire screen. On the side of the screen opposite the coolant tubes, a piece of Refrasil cloth was sewn onto the copper wire screen. The copper screen minimized lateral temperature gradients in the Refrasil cloth. Refrasil batting was used to hold the liquid condensed on the Refrasil cloth. For this water collection system, 30 grams of Refrasil batting were located on the coolant tube side of the wire screen in such a way that they were in contact with the Refrasil cloth through the openings in the screen.

Test procedure. - In order to either demonstrate the absence of significant gravity effects or obtain boundary values on the magnitude of error caused by earth laboratory testing relative to zero G performance, tests were performed with the simulated sweating skin either below or above the chilled wick (Figure 10). These tests were performed at 0.238 and 0.340 atmospheres (3.5 and 5 psia) pressure. Normal atmospheric air at these reduced pressures was used with the exception of one verification test, performed in an oxygen atmosphere at 0.238 atm. The data obtained by this test were compared with data from an identical test performance in

0.238 atm. air. The assumption made on theoretical grounds that no significant error in results would be caused by performing the experiments in air rather than in oxygen was confirmed by this test. Table 1 lists the test runs and the conditions under which they were performed.

The procedure followed in performance of the tests with the simulated sweating skin below the cooled wick was as follows:

1. The water reservoir at the lower portion of the test apparatus was filled to the point where the top of the Feltmetal was moist.
2. The vapor condensing and water retention assembly was installed above the Feltmetal and the desired gap width adjustment and the cooling coil connections at the "quick disconnect" joints made.
3. The circulation of chilled water was started.
4. The pressure in the bell jar and apparatus was lowered to the desired value.
5. The temperature of the Feltmetal (simulated skin temperature) and the wick coolant inlet temperature were adjusted and stabilized. The run was then continued for a period of approximately one hour to obtain initial wetting of the cooled wick. The pressure was then increased to 14.7 psia, and the cooled wick vapor condensing and water retention assembly was weighed.
6. After the initial weighing, the cooled wick assembly was installed and the pressure reduced to the test pressure required.
7. Data taking was started from this initial point for the ensuing test period.
8. The test was concluded by increasing the pressure to 14.7 psia and making a final weighing of the water collection assembly.

For tests on a water removal concept utilizing only Refrasil sleeving, whose capacity to retain water is limited, several weighings were made at half hour intervals until two close consecutive weight readings indicated that the full capacity of the sleeving had been utilized.

The test procedure in the case of the tests with the water vapor source above the chilled wick required some development testing to insure

TABLE I

DIFFUSION ACROSS GAPS TO COOLED WICKS TEST RUN SUMMARY

RUN NO.	SOURCE SYSTEM		SINK(1) SYSTEM CONFIG.	TYPE GAS IN GAP	GAP TOTAL PRESSURE, atm.	GAP WIDTH, cm	REMARKS
	SOURCE ABOVE SINK	SOURCE BELOW SINK					
1		x	A	Air	0.340	0.917	Test Development Run
2		x	A	Air	0.340	2.540	Test Development Run
3		x	B	Air	0.340	———	Test Development Run
4		x	A	Air	0.340	1.27	Test Development Run
5		x	A	Air	0.340	1.45	Test Development Run
6		x	A	Air	0.340	0.635	Data Taking Run
7		x	A	Air	0.340	1.905	Data Taking Run
8		x	A	Air	0.340	1.27	Data Taking Run
9		x	A	Air	0.238	0.635	Data Taking Run
10		x	A	Air	0.238	1.905	Data Taking Run
11		x	A	Air	0.238	1.27	Data Taking Run
12		x	A	Air	0.340	0.317	Possibility of Incorrect Gap Width
13		x	A	Air	0.238	0.317	Possibility of Incorrect Gap Width
14		x	A	O_2	0.238	1.905	Data Taking Run
15	x		A	Air	0.238	1.905	Data Taking Run
16	x		A	Air	0.238	1.27	Data Taking Run
17	x		A	Air	0.238	1.27	Data Taking Run
18	x		A	Air	0.238	1.588	Possibility of Dry Source
19	x		A	Air	0.238	1.588	Data Taking Run
20	x		A	Air	0.340	1.905	Data Taking Run
21	x		A	Air	0.340	1.27	Data Taking Run
22	x		A	Air	0.340	0.635	Data Taking Run
23	x		A	Air	0.238	0.635	Dripping From Source May Have Occured

TABLE I (Continued)

DIFFUSION ACROSS GAPS TO COOLED WICKS TEST RUN SUMMARY

RUN NO.	SOURCE SYSTEM		SINK(1) SYSTEM CONFIG.	TYPE GAS IN GAP	GAP TOTAL PRESSURE, atm.	GAP WIDTH, cm	REMARKS
	SOURCE ABOVE SINK	SOURCE BELOW SINK					
24	x		A	Air	0.238	0.635	Data Taking Run
25	x		A	Air	0.340	1.270	Possibility of Dry Source
26		x	B	Air	0.340	0.635	Moisture Condensing on Wire Screen
27		x	C	Air	0.340	1.905	Incomplete Run
28		x	C	Air	0.340	1.270	Incomplete Run
29		x	C	Air	0.340	0.635	Data Taking Run
30		x	C	Air	0.340	1.270	Data Taking Run
31		x	C	Air	0.238	0.635	Data Taking Run
32		x	C	Air	0.340	1.905	Data Taking Run
33		x	C	Air	0.238	1.270	Data Taking Run
34		x	C	Air	0.238	1.905	Data Taking Run
35		x	D	Air	0.238	1.905	Data Taking Run
36		x	D	Air	0.238	1.270	Data Taking Run
37		x	D	Air	0.238	0.635	Data Taking Run

NOTES:

(1) SINK CONFIGURATIONS:

A - Refrasil sheet backed by copper cooling coil and 30 gms Refrasil batt.

B - .954 cm wide 160 cm long, Refrasil sleeving, over .635 cm ODTygon cooling coil. 50 gms Refrasil batt at ends of wick. Wire screen at face of wick.

C - .954 cm wide 240 cm long, Refrasil sleeving, over cooling coil of .317 cm ODTygon.

D - .954 cm wide 240 cm long, Refrasil sleeving over cooling coil of .317 cm ODTygon. 50 gms Refrasil batt pouches at ends of wick.

reliability of the results. The water supply had to be adjusted such that there would be neither dripping from, nor drying out of, the simulated skin surface.

The following procedure was used: As Figures 5 and 10 show, the test arrangement includes provisions to supply measured quantities of water to the wick on the back side of the Feltmetal. The sweating skin simulating section of the test apparatus was placed in a downfacing position in the vacuum bell jar, supported such as to permit visual inspection of the metal (sweating skin) surface. Water was slowly added until the felt wick was soaked and drops of water just started to form on the simulated skin surface. The pressure was then lowered to 0.238 atm. and returned to one atm. This was done because of an observed increase in Feltmetal permeability resulting from vacuum, probably because of outgassing of the capillaries. The test apparatus was then fully assembled and data taking tests performed, following the procedure outlined before. For test runs 1 through 15, 17 through 19 and 25 through 37 the vapor diffusion rate was relatively small and no addition of water during a test run was required. This was verified at the end of each test run by inspection of the Feltmetal surface. If this surface was not wet after completion of a test run, then the data obtained were not considered valid and the run repeated with addition of water during the run. The vapor condensing rates of runs 16 and 20 through 24, which used a smaller gap, were high. Water addition to the simulated skin surface was required to insure a moist surface for the entire duration of the run. This required determination of a water addition rate which would provide a wet simulated skin surface, yet would not cause dripping.

The approach taken was to make the rate of water addition somewhat smaller than the evaporation rate. The deficit in water supply would be compensated from water stored in the felt wick. The water vapor diffusion rate was first estimated on the basis of analytical data (Reference 1). Trial and error development testing was then used to determine the water addition rates required for each of the various data taking runs.

Two criteria were used for a correct water addition rate. Criterion one was, that after completion of a test run, the amount of vapor condensed and collected in the cooled wick assembly, as determined by weighing, must be larger than the water added to the sweating skin assembly. As a no drip condition, prior to water addition, had been established at the beginning of each test run by the methods described above and the addition of water was at a steady rate, this is evidence that dripping could not have occurred during the test.

The second criterion was that after completion of a test run the Feltmetal surface must still be wet. This was required to assure that the data taken reflected the performance of the vapor diffusion-cooled wick system and were not biased by the available supply of water vapor. The validity of this approach was verified by repetition of several of the initial data taking test runs. As shown on Figure 11 repeatability was good, indicating the reliability of data derived by this procedure.

Test results. - The experimental investigations had the purpose of providing performance data of various concepts of cooled-wick passive humidity control. The data were then used to generate performance curves. Where applicable, the experimental data were compared with the results of the theoretical diffusion analysis previously performed and reported in Reference 1.

Figure 11 is based on data from test runs made with the test apparatus in a position where the simulated skin (water vapor source) was above the cooled wick water vapor collection assembly. Water vapor diffusion took place in a downward direction. Fixed values of temperatures of the simulated skin and the cooled wick were the basis of the curve. Where the measured temperature data showed minor fluctuations during the experiment, temperatures were averaged. The data points, based on test data as shown in the figure resulted in the dashed lines on the curve. The solid line in the curve represents the value of water vapor diffusion across the gap, derived by the analytical methods of Reference 1. The water vapor removal system concept used in this test was the cooled sheet of Refrasil wick described under "Experimental Arrangement" and shown in Figures 8 and 9.

Figure 12 is based on data derived similar to Figure 11 with the exception that the test apparatus was in a position with the simulated sweating skin below the chilled wick. The cooled sheet of Refrasil (Figures 8 and 9) was used again. Water vapor diffusion was upward. Both figures show good agreement of test data points with the analytical curves. This is an indication that the vapor diffusion across the gap is the limiting factor. The capacity of the test models for condensation and liquid retention is apparently in excess of the vapor emitted and diffused across the gap.

Figures 11 and 12 show the results of tests performed under identical conditions, except that Figure 11 shows performance with diffusion in a downward direction while Figure 12 shows performance with diffusion upward. Contrary to what should be expected from theoretical considerations, performance with diffusion downward is higher than with diffusion upward, Convection currents, whether resulting from temperature gradients or from water vapor-air density differences would be caused by the warm simulated skin and source of water vapor being below, rather than above, the cooled wick. Therefore, convection must be ruled out as the explanation.

Whenever results of experimental investigations are contrary to theory, the suspicion of experimental error is justified. In this case, there was suspicion of liquid water dripping from the wet Feltmetal to the vapor condensing and collecting assembly. Tests were therefore repeated, taking special care to eliminate any possibility of water excess. As the dual test points on the curve of Figure 11 show, repeatability of the tests was very good. It is unlikely that an error would be duplicated this closely.

The maximum difference in results between the two positions of the test apparatus is in the order of 30% at the minimum gap width, and decreases with increasing gap. The lower of the two vapor rates is still more than adequate for space suit passive humidity control. A satisfactory explanation for this deviation from theoretical prediction is at present not available, but should be the subject of future investigations.

Figure 13 shows performance of a test setup shown in Figure 7. This is the arrangement where a Tygon cooling coil was threaded through a tubular Refrasil wick sleeve described under "Experimental Arrangement". The data of Figure 13 are based on the use of the cooled tubular wick with attached Refrasil fiber-filled pouches for water storage. The test was performed at 0. 340 atmospheres and with diffusion in an upward direction. Fairly good agreement with the analytical curves was shown.

Figure 14 shows results with the test arrangement where the Refrasil fiber-filled pouches were deleted. This test was also performed at 0. 340 atmospheres. Accumulated moisture is plotted versus time for three different gap widths. The water vapor source (simulated skin) was below and diffusion was in an upward direction. The curves, while starting as straight lines as should be expected, flattened out as the wick becomes saturated with moisture. As the actual rate of condensation itself is not dependent on the saturation of the wick, it is assumed that when the wick became saturated to capacity some back-dripping or "raining" from the wick, back to the water vapor source, occurred.

Figure 15 shows a similar test performed at 0. 238 atmospheres. At the lower total pressure in the gap, rate of water vapor transfer increases as was predicted by the analysis. The same phenomenon of the flattening out of the curve, when the wick apparently reaches the limits of its water retention capacity, can be observed.

As mentioned previously, the tests were performed with air, based on analytical prediction that the binary diffusion of water vapor in an oxygen environment is essentially identical to that in a nitrogen environment (Reference 1). The use of air simplified performance of experiments. Using pure oxygen required some special precautions to avoid hazards of running undiluted oxygen through the vacuum pump. In order to provide experimental verification for the analytical predictions, one run was performed with pure oxygen and a resulting test point is shown in Figure 12. The experiment confirmed the analytical prediction that no significant difference would be caused by performance of the experiments with air.

Evaluation of Wick Materials

Application of existing and commercially available fibrous textile materials to cooled wick passive humidity control requires information on behavior and performance data of potentially suitable materials. A review of vendors' data and the literature did not provide the type of data required.

In order to gain a basic insight into the mechanism by which wicks perform, an analysis of condensation and mass transfer within a porous wick was performed. This analysis is presented in Reference 1. It became apparent that, because of the randomness of the wick fibers and the assumptions which would be the basis of a mathematical model, an empirical approach was needed to obtain useful working data on wicks. The purpose of the experimental program, reported on in this section, was therefore to experimentally examine wicks which had potential applicability to space suit passive humidity control.

Criteria for wick selection. - For application to a space suit, the ideal wicking material should have the following characteristics:

1. Ability to wet with water.

2. High water retention.

3. Ability to lift water against the pull of gravity.

4. High transport capability under zero gravity conditions.

5. Low dry density.

6. Easily dried.

7. Repeated wet-dry cycles without deteriorating.

8. Ability to perform under conditions found in space suits (low pressure, oxygen-water vapor, moderate temperature environment).

9. No emission of dusts or vapors which could be irritating to the astronaut. (Direct contact of the wick with the skin is not envisioned.)

Selection of wicks for testing. - The initial step of this study phase was to contact sixteen companies whose product areas were related to wick materials. Technical information which could be of assistance in the selection of candidate materials was requested. Seven companies furnished data and/or samples of wicking materials.

From the data and preliminary test observations on the samples obtained, several candidate materials were selected for further testing (see Table II). Of the criteria listed for wick selection, dry density, water retention, lift capability and horizontal transport capability were determined by quantitative tests. The remaining properties were qualitatively evaluated.

Dry density and water retention tests. - Samples of the candidate wick materials were weighed on a Christian Becker analytical balance. They were weighed in the as received, wet by wicking action, soaked by submersion in distilled water and oven dried conditions. Materials which were not able to lift water by capillary action could not be weighed in the "wet by wicking action" condition. The submersion soaked wick samples were allowed to drip drain at room conditions for exactly one minute prior to weighing. Oven drying was accomplished in an oven at 100°C over a two hour drying period. Using the data obtained, percentage relationships were computed. These data together with the test data are presented in Table III.

It can be seen that the felts together with Refrasil batt exhibited the highest water retention capabilities of 400 to 1200%. The Refrasil sleevings, the glass web tape and the asbestos tape retained 60 to 120% of their, as received weight.

TABLE II
SIZE AND SOURCE OF WICK MATERIALS TESTED FOR WATER RETENTION CAPABILITY

Wick Sample No.	Wick Description		As Received Condition Sample Size, cm	
	Company	Designation	Cross-Sectional Area	Length
1	HITCO Gardena, California	Refrasil Series N .954 cm Sleeving	1.143 x .1017	25.4
2		Refrasil Series N .635 cm Sleeving	.762 x .1143	25.4
3		Refrasil UB-100 Batt	10.15 x .635	10.15
4	Atlas Asbestoes N. Wales, Penna.	1.27 cm Glasweb Tape Style 2021	1.22 x .508	15.25
5	Taylor Instruments Rochester, New York	Cotton 97P15	.711 x .178	10.15
6	H. K. Porter Charlotte, N. Carolina	Asbestoes #160 Comm. Grade 2.54 cm Woven Tape	2.54 x .1588	12.7
7		Data Sheet #6 Felt Mdse 51018	.953 x .635	7.62
8	American Felt Company Glenville, Connecticut	Dacron 62 DA 11	1.27 x .635	17.5
9		Polypropylene 62 PO 38	1.27 x .635	16.8
10		Nylon 62 NY 13	1.27 x .635	16.5
11	Western Felt Works Chicago, Illinois	Arnel 4.8 WAR-250-1	1.27 x .635	5.08
12		Orlon 9.5 WO-130-1	1.59 x .476	5.08
13		Fortrel 6 WF-250-1	1.27 x .635	5.08
14		Rayon 8.6 WR-125-3	1.27 x .238	5.08

TABLE III

TEST SUMMARY OF WATER RETENTION CAPABILITY OF WICK MATERIALS

Wick Simple No. (See Table II)	Weight, gms				As Received Density, gms/cm^3	Wt. Increase of as Rec'd Wick when Wet by Wicking Action, Percent	Wt. Increase of as Rec'd Wick when Soaked, Percent
	As Received Condition	Wet by Wicking Action	Soaked in Distilled Water	Oven Dried			
1	2.360	3.260	3.930	2.180	0.800	38	66
2	1.550	2.150	2.690	1.425	0.702	38	74
3	2.724	26.714	27.200	2.420	0.0417	883	900
4	8.040	12.090	12.910	-----	0.852	50	61
5	0.449	1.590	1.785	0.449	0.351	253	297
6	4.786	-----	10.477	4.600	0.933	---	120
7	1.094	-----	5.853	0.950	0.237	---	436
8	0.885	-----	7.408	0.883	0.0660	---	736
9	2.383	9.020	13.459	2.378	0.176	279	464
10	1.347	-----	9.585	1.324	0.101	---	610
11	0.544	4.166	4.367	0.528	0.133	665	702
12	0.496	2.985	3.595	0.488	0.128	503	862
13	0.604	-----	4.522	0.600	0.148	---	648
14	0.190	-----	2.546	0.172	0.124	---	1240

Lift tests. - The ability to climb against the pull of gravity was one of the wick selection criteria tested. Lift tests were conducted, measuring lift as a function of time.

Initial tests revealed the difficulty of observing the level of the water in the wick. Several dyes were tried but were found to influence the lift capability of the wicks. In order to minimize this effect, the water was not dyed. Small marks with a water soluble ink were made on the wick at measured intervals. The ink marks were smeared and then erased as the water level passed each mark.

It was further necessary to minimize evaporation losses from the wick by maintaining a high humidity environment around the wick. Data taking tests were therefore performed with the wicks enclosed in glass or plastic tubes to provide a high humidity environment.

The testing consisted of recording the time required for the water level to reach the previously marked intervals. A schematic of the test setup is shown on Figure 16. The results of these test runs are shown on Figures 17 and 18 as lift height versus time. It is interesting to note that the maximum lift capability of the two Refrasil sleevings was never determined. When these wicks had lifted to a height of 230 cm, the ceiling height of the laboratory stopped further testing.

For four materials which showed the greatest vertical lift, the mass flow rate of water versus lift height was calculated by use of the water retention capability data for these wicks when wetted by wicking action. The mass water lift and the mass flow rates on a wick cross section unit area basis are plotted in Figures 19 and 20. It can be seen from these figures that the wicks which are made of fiberglass and Refrasil exhibit the greatest vertical lift capability.

The data derived from these lift tests, performed in an earth laboratory under one G, can be used to approximate performance under, for example, 1/6 G conditions. Maximum static lift in a wick results from the balance between capillary force and weight of the liquid column. Attainable static lift under 1/6 G can therefore be safely assumed to be 6 times that under conditions on earth.

This will not be equally correct for the time rate of attaining a given lift height in a wick or for the mass flow rate versus lift relationship. While static head reduces proportionally to change in weight of the fluid column, flow pressure drop does not. However it is believed that only a minor error is introduced by this method for approximation of lift time or flow rate, whenever a lift in the order of 10 cm or more, under earth G, is required. The much higher mass flow rates in horizontal wicks, discussed in the following paragraph, are an indication that flow resistance represents only a very small fraction of a static head of ten or more centimeters.

Mass flow of water in horizontal wicks. - Purpose of this series of tests was to determine mass flow rates of water attainable by various wick materials in a horizontal position, without any lift. These tests are considered the best possible earth laboratory simulation of performance of wicks under zero G. Initially, an inverted "U" test arrangement, using a small amount of lift from the water source to the horizontal section of the wick, and a small vertical drop at the exit of the horizontal section was tried. It could not be reliably determined whether the two vertical sections compensated for each other. It was found difficult to determine and maintain an exact constant water level at the source. Surface effects caused the water at the outside surface of the wick to be higher than the level in the container. No satisfactory method of removing water at the exit vertical drop of the horizontal test section could be found. Making this section longer than the vertical lift section would cause flow but introduced an error in the measurements by causing a siphoning effect.

A test arrangement was finally developed which eliminated the need for a lift at the water supply end of the wick. A completely horizontal wick was used (Figures 21 and 22). One end of the wick was supplied by letting water drip on it in excess of the amount carried by the wick. The oversupply dripped off and was collected in a graduated cylinder. The difference between the measured supply and the collected and measured excess was the amount transported by the horizontal wick.

The other end of the horizontal wick was attached to a metal strip. The strip was heated causing water to be evaporated from the end of the wick. The dryness of this end of the wick was checked by using water soluble ink. If the ink did not smear, it was safe to consider the wick to be dry.

As with the vertical lift tests, the test section was enclosed in a glass tube to provide a high humidity environment and minimize evaporation loss. Water transported as a function of time was recorded. These data were then used to obtain a rate of water transport. The resulting rates are shown on Table IV. On a per unit cross section basis, the Refrasil sleeving samples of .635 cm and .954 cm exhibited the highest performance.

TABLE IV

HORIZONTAL WICK PERFORMANCE

Wick Description	Wick Cross Sectional Flow Area, cm^2	Water Flow (1) Rate Through Wick, cm^3/min	Water Flow (1) Rate Through Cross Section Unit Area of Wick, $cm^3/min - cm^2$
HITCO Refrasil Series N 0.954 cm Sleeving	0.116	0.440	3.789
HITCO Refrasil Series N 0.635 cm Sleeving	0.087	0.680	7.807
American Felt. Co. Polypropylene 62 PO 38	0.918	0.600	0.654
Atlas Co. 1.27 cm Glasweb Tape Style 2021	0.620	0.600	0.968

NOTES:

(1) Wick test length was 30 cm.

Reference 5 has discussed the problem of repeatability of wick material performance data. This problem was also observed in this study. In some of the horizontal tests, there were some discrepancies in the results of repeated tests. Since the objective of this study was to make a survey to find wicking materials which are potentially suitable for space suit passive humidity control, the problem of repeatability was not further pursued.

Qualitative evaluation of criteria. - All the materials tested were wettable with water. There was some indication that wick performance was affected by long exposures to the atmosphere in the laboratory. In an area such as Los Angeles where, as a result of heavy automobile traffic and large scale petroleum refining, oily aerosols are known to be contained in the atmosphere, it is possible that deposits from the atmosphere could cause performance deterioration. On these samples performance was apparently restored by washing in alcohol and vacuum drying.

Further observations will be required to determine whether special handling and "Clean Room" conditions are required for the handling of these wicks.

Small samples of these wicks were repeatedly handled with bare hands without any significant skin reactions. Handling of the Refrasil fiber batt and the Glassweb tape did temporarily cause a slight itching of the skin. None of the passive humidity control concepts considered envisions wicks in direct contact with the skin. This would be basically objectionable for reason of loading of the wick with electrolytes and organics from sweat. But further investigations on behavior and effects of the various materials in regard to breakdown of fibers, dusting and effects of such dust on the skin are required.

It was possible to quick dry the materials tested at 100°C without apparent deterioration, with the exception of the American Felt Company polyproplyene. This material hardened and lost its wicking characteristics when exposed to this temperature. Room temperature drying or a combination of reduced temperature and pressure would be required to dry this material. The Refrasil sleeving material tended to have low mechanical strength when wet.

The ability of these materials to withstand the environmental conditions to be encountered in a space suit application, such as the combination of low pressure O_2, impurities in the suit and recycling were not studied. These were, however, recognized as problems requiring study.

Evaluation of Water Adsorption for Use in a Space Suit

Application of existing and commercially available desiccants to space suit passive humidity control requires information on behavior and data on performance of desiccants, exposed to a stagnant gas-vapor mixture. A review of vendor data and the literature showed that data in existence applied predominantly to desiccant performance under conditions of forced flow.

In order to obtain a preliminary evaluation of the suitability of using desiccants for passive humidity control in a space suit, an analytical study of mass transfer in an adsorption bed was performed. The results of this analysis are a set of parametric curves on desiccant performance in a stagnant gas-vapor mixture which has been presented in Appendix D of Reference 1. Vendors' data and desiccant properties data obtained from a review of publications were used in this analysis. Certain simplifying assumptions were required for an analytical solution, and as a result of the type of assumptions made, the curves presented in Reference 1 represent the upper boundary values of desiccant bed performance. Using these curves to estimate adsorption bed performance will result in data for the maximum theoretically possible performance of an adsorption bed, at the stipulated conditions.

Experimental investigations. - The objective of these experiments was to verify the analytically derived parametric curves of adsorption bed performance presented in Reference 1. Assumptions for the analysis were that the gas-vapor mixture entered one face of a flat desiccant bed by diffusion and without forced flow. An isothermal desiccant bed was assumed. Silica Gel (Grace-Davison Chemical, Grade 05) and Molecular Sieve type $4A^o$ (Union Carbide Corporation Linde Division, .318 cm pellets) were the desiccants selected.

The experimental arrangement is shown in Figures 23 and 24. A vacuum bell jar was used to contain a controlled gas-vapor mixture. The test was performed in an air-water vapor atmosphere at 0.238 and 0.340 atmospheres pressure. Previous analysis and a verification experiment described in this report under "Passive Humidity Control in Space Suits" have indicated that no significant error would be caused by the use of air in place of oxygen in diffusion experiments.

Humidity was supplied to the bell jar atmosphere by a dish of water heated by an electric immersion heater. Power supply to this heater through a "Variac" permitted control of evaporating rate. A small battery-operated fan provided air circulation within the bell jar for the purpose of equalization of the bell jar atmosphere. However, the relatively high walls of the desiccant pan essentially maintained the stipulated stagnant atmosphere condition at the face of the desiccant bed.

The bed surface temperature was measured by a thermocouple buried beneath the top layer of desiccant and was checked to determine if the bed was isothermal. The sensor of an Abrax Instrument Corporation electric hygrometer was placed as near to the desiccant surface as practical to measure relative humidity at the bed face. Average condition of the bell jar atmosphere was measured with a hair hygrometer (Durotherm) and thermocouple. Chamber pressure was read on a vacuum gage. Desiccant bed weight was read from a direct reading spring platform scale (Hanson Model 1440 Dietetic). The readings were taken at fixed time intervals and are presented in Figures 25, 26 and 27.

Test data interpretation. - The tests were performed under different atmosphere pressures and for two different desiccants. It was not possible to exactly duplicate test conditions, other than pressure, for various test runs. Deviations in "Water Adsorbed" and rate of adsorption (i.e. the slope of the curves) can be observed when comparing Figures 25 and 27. The lower values for "Water Adsorbed" and the smaller rate of adsorption in Figure 27 are primarily ascribed to lower vapor diffusion at the higher pressure (0.340 atm), with the lower relative humidity at the bed face considered of secondary importance.

In order to permit comparison of test results with the parametric curves derived in Reference 1 by analytical techniques, test results were analytically converted into parametric form. The analysis used certain material property data provided by the vendors of these materials.

For Silica Gel:

bed porosity ϕ = 31%
bulk density ρ_E = 0.721 gms/cm^3

For Molecular Sieves:

bed porosity ϕ = 40.5%
bulk density ρ_E = 0.721 gms/cm^3

Maximum amount of water vapor, w, used in the analysis can be read from the curves, Figures 28 or 29, which were also derived from vendors' data.

A sample calculation is presented in order to demonstrate the analytical approach used.

The following test data were read from Figure 27: The test chamber pressure P_T was 0.340 atmospheres. The desiccant (Silica Gel) adsorbed 3.9 gms of water over a time period, t, of 40 minutes (2400 seconds). Air temperature $T_c = 298^oK$. The relative humidity at the bed face was $(RH)_c = 32.5\%$. Relative humidity at the hair hygrometer, $(RH)_s = 61.5\%$. The bed face area, A_{face}, was 292 cm^2. The bed face temperature was 305.2^oK. The water concentration,

$$C_w = (RH)_c (C_w) \text{ saturated at } T_c$$

where,

$$(C_w) \text{ saturated at } T_c = \frac{P_{w,\,s}}{R\ T_c}$$

$P_{w,\,s}$ is the partial pressure of water vapor at saturation temperature.

$$(C_w) \text{saturated at } T_s = \frac{0.03125 \text{ atm}}{82.057 \dfrac{cm^3 \text{ atm}}{\text{mole } ^oK} 298^oK}$$

$$= 1.272 \times 10^{-6} \frac{\text{moles}}{cm^3}$$

then,

$$C_w = (.325) \left(1.272 \times 10^{-6} \frac{\text{moles}}{cm^3}\right) \left(18 \frac{\text{gms}}{\text{mole}}\right)$$

$$= .748 \times 10^{-5} \text{ gm}/cm^3.$$

At the bed temperature of 305.2^oK and partial pressure of water vapor at saturation, $P_{w,\,s}$, for gas temperature, $T_c = 298^oK$, the water content as a percent of activated weight, w_s, can be found on Figure 29 where 41.5% is w_s maximum possible. At a bed face relative humidity $(RH)_c = 32.5\%$, a correction factor, C_{RH}, for w_s can be obtained from Figure 29. The maximum weight of water vapor that can be adsorbed in 100 gms of dry desiccant, w, is:

$$w = w_s C_{RH}$$

$$= (41.5)(.505)$$

$$= 20.96 \text{ gms}$$

The equilibrium constant, E, is,

$$E = \frac{C_w}{(w/100)\,\rho_E}$$

$$= \frac{.748 \times 10^{-5} \text{ gms/cm}^3}{\left(\frac{20.96}{100}\right)(.721 \text{ gms/cm}^3)}$$

$$= 4.947 \times 10^{-5}$$

The weight of water adsorbed, $\bar{C}*$, is

$$\bar{C}* = \frac{\Delta W}{W_i / \rho_E}$$

where W_i is the initial dry weight of adsorber

$$\bar{C}* = \frac{\frac{3.9 \text{ gms}}{257 \text{ gms}}}{.721 \text{ gms/cm}^3} = .01095 \text{ gms/cm}^3$$

The adsorption efficiency, Q, is

$$Q = \frac{\bar{C}* E}{C_w (1 + E)}$$

$$= \frac{(0.01095 \text{ gms/cm}^3)(4.947 \times 10^{-5})}{(0.748 \times 10^{-5} \text{ gms/cm}^3)(1 + .00004947)}$$

$$= 0.0725$$

The time parameter, θ, is expressed in the following relationship

$$\theta = \frac{D_{eff} Et}{4L^2 (1 + E)}$$

where $$D_{eff} = D_{12}\emptyset \left[1 - 1/3 \ (1 - \emptyset)\right]$$ from Reference 1.

For a gas temperature of 25.0°C in 0.340 atmospheres of air, the diffusion coefficient, D_{12}, may be obtained from Figure A-3 of Reference 1.

$$D_{12} = 0.790 \text{ cm}^2/\text{sec.}$$

then,

$$D_{eff} = (.790)\ (.31) \left[1 - 1/3 \quad (1 - .31)\right]$$
$$= 0.1886 \text{ cm}^2/\text{sec.}$$

While Figure A-3 of Reference 1 is for water in an oxygen environment, Figure A-1 of the same Reference shows that at one atmosphere pressure, the difference between the primary diffusion coefficients for water vapor in an oxygen environment is essentially the same as for a nitrogen environment. It would be expected that the difference between an oxygen environment and an air environment would not be significant. The bed depth, L, was determined from the bulk density, ρ_E, the measured bed face area, A_{face}, and the initial dry weight, W_i, of adsorber.

$$L = \frac{W_i}{\rho_E \ A_{face}}$$

where $$A_{face} = 292 \text{ cm}^2,$$

then $$L = \frac{257 \text{ gms}}{(.721 \text{ gms/cm}^3)\ (292 \text{ cm}^2)}$$

$$= 1.22 \text{ cm}$$

The time parameter is,

$$\emptyset = \frac{D_{12}\ D_{eff}\ Et}{4L^2\ (1 + E)}$$

$$= \frac{\left(0.1886 \frac{\text{cm}^2}{\text{sec}}\right)\ (4.947 \times 10^{-5})\ (2,400 \text{ sec})}{(4)\ (1.22 \text{ cm})^2\ (1 + 4.947 \times 10^{-5})}$$

$$= 0.00377$$

The flux parameter, F, may be found from the following relationship:

$$F = \frac{J_w L (1 - x)}{D_{eff}}$$

The mole fraction of water vapor in gas, x, is determined from the following relationship:

$$x = \frac{(RH)_c \; P_{w,\,s \text{ at } T_c}}{P_T}$$

$$= \frac{(.325)\;(.03125)}{.340}$$

$$= 0.0299$$

The instantaneous flux of water vapor into the bed, J_w, is the slope of the curve of Figure 27, divided by the bed face area.

$$J_w = \frac{.000583 \text{ gms/sec.}}{292 \text{ cm}^2}$$

$$= 2.00 \times 10^{-6} \frac{\text{gms}}{\text{sec-cm}^2}$$

The flux parameter is

$$F = \frac{J_w \; L\,(1 - x)}{D_{eff}\; C_w}$$

$$= \frac{\left(2.00 \times 10^{-6} \frac{\text{gms}}{\text{sec-cm}^2}\right)(1.22 \text{ cm})\;(1 - .0299)}{\left(0.1886 \frac{\text{cm}^2}{\text{sec}}\right)\left(0.748 \times 10^{-5} \frac{\text{gms}}{\text{cm}^3}\right)}$$

$$= 1.67$$

$$\frac{F}{2} = 0.835$$

In a similar manner, the remaining test data points can be reduced to the parametric form. These points are presented in Figure 30. The analytically derived (see Reference 1) parametric curves are compared to the test data on this curve, It can be seen that there is a discrepancy between the analytical curves and the test points. The test points show a lower performance.

The primary unknown in the analysis is the assumed geometrical relationship between the bed particles. This geometrical relationship is reflected in the constants used in obtaining the effective diffusion coefficient, D_{eff},

$$D_{eff} = D_{12}\emptyset \left[1 - \frac{1}{3} \quad (1 - \emptyset) \right] .$$

Knowing that this relationship presents a theoretical maximum, the test data can be used to establish empirical constants for the geometrical relationships and a revised effective diffusion coefficient. By a trial and error procedure, the constant 1/3 was revised to unity to obtain a better fit between the test data and the analytical curves. This yields

$$\begin{aligned} D_{eff} &= D_{12}\emptyset \left[1 - 1 \quad (1 - \emptyset) \right] \\ &= D_{12}\emptyset^2 \end{aligned}$$

Using the revised constants for D_{eff}, Figure 31 shows a good fit between the analytical and the test data for the Adsorption Efficiency curve and an imporved fit for the Flux Parameter curve.

INTEGRATION OF PASSIVE HUMIDITY CONTROL CONCEPTS WITH SPACE SUIT TEMPERATURE CONTROL

The first generation of space suits as exemplified by Mercury, Gemini and gas cooled Apollo suits resulted from modification of aircraft full pressure suits. Body temperature control in these suits is by ventilating gas. Limitation of gas flow rates, dictated by considerations of power penalty, suit pressure drop and mobility, severely limit the sensible heat removal capabilities of this approach. For example, at metabolic rates in the range of 300 kcal per hour, as much as 85% of the body heat may be removed as latent heat of evaporated sweat (Reference 3).

The high sweat rates experienced in ventilated suits are undesirable. Deep body temperatures near the upper limit of the permissible range, dehydration and loss of electrolytes are some of the disadvantage of this approach. However, suit ventilation provides control of temperature and humidity, and provides adaption of the heat removal rate to variations in metabolic heat rate by the natural thermo-regulatory body function of variations in sweat rate.

Heat transport by circulating liquids has been shown to provide much improved sensible heat removal capabilities. Even at high metabolic heat rates, sweating can be reduced to near the insensible level of body moisture emission. In present advanced concepts of liquid cooled suits, sweating is minimized and ventilating gas at a rate of approximately .142 m^3/min (5 ft^3/min) is provided for humidity control.

However, the need for both, a cooled liquid loop and a circulating gas loop, adds complexity to the suit-backpack system; and a difficult control problem results from the need to closely adjust sensible heat removal rate to metabolic heat production.

Initially the intent of this study on passive humidity control was to eliminate the need for the ventilating gas used to control humidity in liquid cooled suits. The theoretical and experimental studies, reported in the preceding sections, have however shown the capabilities of the water vapor diffusion system of passive humidity control to be in the range of 1000 grams/hr-m^2 (Figures 11 and 12). This is far in excess of the water vapor removal rates of approximately 200 grams per hour required in such suits.

This permits approaches to integrated temperature and humidity control, with the potential of simplifying automatic control requirements by permitting sweat rates similar to those in comfortable Earth environments.

For convenience of presentation, the following discussion of applications of passive humidity control to space suits is divided into the areas of:

"Minimum Sweat Rate Liquid Cooled Suits"

"Normal Sweat Rate Liquid Cooled Suits"

"Integration of Heat Sink (Fusible Material) and Moisture Sink Concepts for Space Suit Environmental Control"

Minimum Sweat Rate Liquid Cooled Suits

Passive humidity control in this type of suit shall only substitute for the ventilating gas flow provided in present liquid loop cooled suits for humidity control.

For purpose of discussion, it is assumed that under any variation of metabolic heat rate enough body heat will be removed as sensible heat by the liquid loop cooling system to essentially limit body moisture emission to the insensible level.

In the concept of direct conduction body cooling presently considered as most promising (Reference 3), tubes through which a liquid coolant circulates are brought in direct contact with the skin for sensible cooling by an elastic porous or net type undergarment. Passive humidity control devices, either cooled wicks or desiccant bags, can be attached to this undergarment (Figure 32).

Choice of technique of passive humidity control will depend on the mission for which the suit is designed. Desiccants, such as silica gel or molecular sieves in porous bags, will be suitable for short mission duration. Reuse of the suit will require either replacement of the desiccant bags or regeneration of the desiccant in the thermal undergarment by heat or heat and vacuum. Cooled wicks, with the retention of the liquid water in the suit in wick filled containers or pouches distributed throughout the suit, will apply to extended missions (Figure 33). The water can be recovered by squeezing out the wick filled pouches. This will also prepare the suit for reuse. Because of the limited amounts of moisture generated by man under the assumed minimum sweat conditions, a system which evaporates condensed perspiration to space vacuum in unnecessary. At the high rate of sensible heat removal, water production of a man would not exceed approximately 1000 grams for an 8 hour mission, which can be retained by approximately 100 to 150 grams of dry wick.

Weight penalty and regenerating methods for desiccants are apparent disadvantages when compared with cooled wicks. Desiccants may have a place for specific applications where their ability to adsorb water at temperatures above the saturation temperature (dew point) of a gas vapor mixture outweighs their shortcomings relative to cooled wicks.

None of the techniques of humidity control, passive or by ventilating gas, will be able to guarantee that, under certain operating conditions, condensation will not take place on the coolant tubes contacting the skin. It seems unavoidable that at times, the dew point in the gas layer closest to the skin will be higher than the sensible cooling tube temperature and that tubes and undergarment will become moist with condensed perspiration. This is not detrimental to suit operation. This moisture will re-evaporate and collect on cooled wicks (or be adsorbed by desiccants).

It will not lead to any accumulation of liquid moisture. As long as the temperature of the wicks is lower than the dew point of the gas layer near the skin, water vapor will diffuse away from the skin and toward the wicks.

The dew point attainable by the use of cooled wicks depends on the temperature to which the wick is cooled. Ideally, the temperature of the cooled wicks should be low enough to reduce the dew point in close proximity to the skin to below the temperature of the sensible cooling tubes. Wick coolant temperatures, much lower than the temperature of the sensible body cooling fluid, would be required. This may not be practical, especially at the higher metabolic heat rates, when coolant temperatures as low as 5°C may be required for sensible heat removal (Reference 3). Liquid coolant at two different temperatures could be supplied to the thermal suit undergarment from the same water evaporator-heat exchanger by the use of a standard temperature control bypass circuit for the sensible cooling fluid and operation of the water boiler at a constant and low temperature. Desiccants also require heat removal but can be adequately cooled by the sensible cooling fluid.

Normal Sweat Rate Liquid Cooled Suits

The "Minimum Sweat Rate Liquid Cooled Suit" concept, attractive as it appears from considerations of minimum body water loss and physiological comfort, suffers from a serious shortcoming. To stay within the principle of the concept for a wide range of metabolic heat rates, close matching of coolant temperature and metabolic rate by an automatic control system is required. Figure 34 (reproduced from Reference 3) shows the narrow band of acceptable skin temperatures which must be maintained to prevent either sweating or shivering of the astronaut. Allowing for differences in individuals, this control band may need further narrowing. The requirement that body temperature must be maintained below the sensible sweating threshold eliminates this most important thermo-regulatory function of the body. The automatic control system is required to substitute for this inherent body function. Considering the outstanding capability of the body thermoregulatory system to maintain body temperature within a narrow range and the absence of a suitable physiological indicator of metabolic rate which could be readily sensed for automatic control purposes, there arises a question as to the practicability of the "Minimum Sweat Rate Liquid Cooled Suit" concept.

With techniques of passive humidity control capable of removing considerable rates of evaporated sweat without additional power penalty, it will be possible to rely in liquid cooled suits to a higher degree on evaporation of sweat for body temperature control. This would not lead to the extreme sweat rates seen in ventilated suits. Rather, thermo-regulatory body functions similar to those in a comfortable Earth environment shall be achieved.

This approach eliminates the need for close automatic matching of body heat rate and coolant temperature. For example, an increase in physical activity would result in some temporary sweating, just as it would in an earth environment designed for sedentary activities. Evaporation of sweat will temporarily provide body temperature control. A person in an Earth environment who is required to perform a physical task resulting in increased heat production, might remove his coat to change the sensible heat removal rate. In a similar manner, readjustment of the cooling rate to accommodate the higher activity level will be required in a space suit. Sweating will then be reestablished at the same level it was before the higher activity. After completion of the physical effort, cooling of the body will occur and similar to that which occurs in everyday Earth activities, temporary coolness may be experienced until reduction in cooling rate is provided by either manual or automatic control.

Geometrical arrangements of suit thermal control systems using this approach could be similar to those of the previously discussed "Minimum Sweat Rate" suits. Higher capacity passive humidity control will be provided. Sensible cooling could be by contact with the skin.

Modifications of this design concept can be envisioned. A moderately effective, thermally insulating separation layer between coolant tubes and skin will, by increasing the temperature gradient between skin and coolant, permit lower coolant temperatures for effective cooled wick type humidity control with a single temperature coolant supply (Figure 35).

Cooled wicks could also be used in an arrangement where they are spaced away from the astronaut's skin by a net type spacer of fiber of low thermal conductance (Figure 36). This concept is similar to a suit liquid cooling concept described in Reference 4, except that no humidity control gas loop would be provided. Cooled wick surfaces serve both as heat sink and as humidity control surfaces. Use of the spacer permits low coolant temperatures for most effective humidity control. Sensible cooling rates attainable with this arrangement are, however, lower than with conductive body cooling.

With the "Normal Sweat Rate" thermal control concept, more moisture will be emitted than with the "Minimum Sweat Rate" concept. Latent heat fractions similar to those occurring in air-conditioned Earth environments are expected. An average latent heat fraction of 50%, or of 250 kcal/hour at a metabolic rate of 500 kcal/hr is considered as a conservatively high estimate. This will result in a production of 3470 gm of water during an 8 hour mission. For missions of such extended duration and high activity level, as for instance lunar surface research expeditions, retention and later recovery of perspiration water may be less desirable than its use as an evaporative coolant.

Various techniques to use perspiration water as an evaporant coolant are conceivable. All will require venting of the evaporated water to space vacuum. With present suit-back pack system concepts, perspiration water would be transferred from the wicks, where it is condensed, to the back pack, and evaporated to space in the evaporator-heat exchanger used to cool the circulating liquid coolant. Wicking action can accomplish this with no difficulty under zero G conditions. Under positive G, some of the water from the lower part of the body and extremities must be lifted to the back pack. At one G (on earth), an accumulated wick cross section in the order of 100 cm^2 would be required. Reduced lunar gravity reduces this figure to a range of 20 cm^2 to 40 cm^2.

Systems can be conceived where evaporation of perspiration water takes place at several locations of the suit and provides cooling of the circulating liquid coolant or direct cooling of the skin. Several penetrations of the suit pressure shell or one penetration, but a relatively large collecting tube, will be required for venting of the low pressure and density water vapor. These approaches seem complex and less promising than transferring the liquid water to the back pack.

Integration of Heat Sink (Fusible Material) and Moisture Sink Concepts for Space Suit Environmental Control

Present concepts of liquid cooled space suits rely for removal of sensible metabolic heat on conductive and/or radiative heat transfer from the human skin to a solid surface which is cooled by a circulating liquid.

The desire for simplification of space suit thermal control systems has led to a concept of body temperature control where the solid surface to which metabolic heat is rejected is temperature controlled by a stationary and passive "heat sink material" rather than by a circulating coolant.

The concept of the heat sink space suit is similar to that of a liquid cooled suit, except that the heat emitted by the man is not transported to the back pack. Instead, the heat is stored in close proximity to the skin in a material, fusible at a suitable temperature and distributed in flexible sealed pockets over the inner suit surface (Figure 37). Adequate thermal storage capacity, at a temperature compatible with the comfort requirements of man, must be provided for the duration of the mission. Materials which have a high heat of fusion while undergoing a solid to liquid phase change at temperatures suitable for human body temperature control, were selected as having a good potential for application as space suit heat sink materials.

Investigations were performed under this contract with the purpose to analytically determine feasibility and operating time limitations of various physical arrangements and design concepts. The results of these investigations were published in Reference 2. In this report the performance of materials with melting points below the desirable skin temperature of man and with heats of fusion near or above 50 kilocalories/kg has been evaluated.

Feasibility of the concept, for applications where limitations of operating time are acceptable, was established. The formation of a low thermal conductivity melt layer, rather than the mass of available heat sink material, was identified as the limiting factor.

Integration of passive humidity control with the use of heat sink type temperature control leads to a concept of a very simple and essentially passive space suit system. To reduce system complexity further, the use of fresh oxygen breathing in an "open" system is suggested. It is recognized that this is a most uneconomical way to use oxygen. However the concept would be practical only for special extravehicular missions of short duration, where simplicity of a system may be the prime consideration. Envisioned are missions such as minor extravehicular orbital repair work or transfer of personnel between shelters on the lunar surface, not connected by environmentally controlled passages. The deletion of mechanical devices would eliminate pre-mission checkout prior to suit use, and the use of the suit would become somewhat analogous to putting on an overcoat for going outdoors on Earth. The requirement for such a suit would be that it can provide body temperature control and life support for a limited period of time, maybe for 30 minutes, or at most one hour.

A possible suit concept would use fusible materials contained in flexible plastic bags in direct contact with the skin for sensible cooling. Humidity control would be provided by the use of a desiccant or a cooled wick. The concept is similar to that of a liquid-cooled suit, except that the fusible material phase change substitutes for heat removal by a circulating liquid. A fusible material of lower melting point can be used for cooling of desiccant bags or as low-temperature core of water vapor condensation wicks. Trade-offs between the use of predominantly sensible cooling, or reliance on evaporation of sweat for body temperature control, are possible. Reference 2 emphasizes that one of the major problems in the application of fusible material heat sinks to space suit temperature control is adaptation of heat removal to variations in metabolic rate. It is probable that a suit designed for high water vapor removal and allowing normal sweat evaporation rates will, by taking advantage of the natural thermo-regulatory body functions, be more practical than the "Minimum Sweat Rate" concept.

A modification of the concept described in the preceding paragraph and shown in Figure 36 for liquid cooled suits, using phase change cooling by a low-temperature fusible material (e.g., tetradecane $C_{14}H_{30}$ with a melting point of $5^{\circ}C$) is promising. The fusible material will be retained in flexible, impermeable containers, surrounded by a wicking material and spaced away from the skin by a net-type textile undergarment. Both sensible cooling and latent heat removal will be performed by these devices. Sensible cooling of the skin will be predominantly by radiation from the skin, with some conduction through the net-type undergarment. Water condensed will be retained by the wick which will have adequate water retention capacity for short duration use. Regeneration would be by first drying and subsequent cooling of the undergarment. For high use rate, two or three thermal undergarments may be available for each pressure suit system to permit ample regeneration time.

CONCLUSIONS

The theoretical and experimental efforts which are described in this report demonstrate the feasibility of and provide basic technology for passive humidity control in space suits.

The experimental program essentially substantiated most of the theoretical findings described in an earlier report prepared under the same contract (Reference 1). Tests on a variety of wick materials indicated that wicks of glass fibers and Refrasil provide superior performance for space suit passive humidity control applications. This applies to water transport capability in a horizontal plane (simulated zero G) as well as to vertical water lift capability. The performance of these wick materials indicates that lifting of condensed sweat to a back pack for the purpose of re-evaporation to vacuum is feasible under zero or lunar G. The high water retention capacity of fibrous Refrasil batts indicates that retention of condensed water in the space suit is equally feasible.

An experimental program resulted in empirical constants for desiccant bed geometry, providing improved applicability of the analytically derived expressions of Reference 1 to the conditions in a space suit.

The experimental findings confirmed the conclusions of the theoretical analysis of Reference 1 that the applicability of desiccants is limited by high weight penalty and by difficult regeneration procedures. Desiccants may, however, be useful in specific applications where the advantage of operation at temperatures higher than the required dew point is significant.

A number of concepts for integration of passive humidity control systems with present concepts of liquid-cooled suits show promise that simpler and more nearly passive suit temperature and humidity control systems can be designed. Notably, the high capacity for water vapor removal of the cooled wick passive humidity control concept, combined with the absence of a power penalty for water vapor control, permits relaxation of the zero eccrine sweating requirement for close matching of metabolic and sensible heat removal rate presently required in liquid-cooled suits.

The feasibility of the use of heat sink materials, which by solid-liquid phase change provide temperature control, has been explored under this contract and has been reported previously in Reference 2. Ability of heat sinks of organic materials with suitable melt points, such as paraffins, to provide sensible heat control for time periods of 30 minutes to one hour has been shown. Integration with passive humidity control, using heat sink materials to control the temperature of cooled humidity control wicks or of desiccants promises applicability to special purpose suits. These suits may be useful for one-half to one hour extravehicular activity, such as minor repair activities and transfer of personnel between shelters on the lunar surface not connected by environmentally controlled passages. Fresh oxygen breathing in an "open" system is considered a possibility for short time missions, which would permit short duration life support without mechanical devices.

REFERENCES

1. Peterson, J. A., Cafaro, C., Shlosinger, A. P., Sterrett, K. F., Analytical Review of Passive Mass Transfer of Water Vapor in a Space Suit, Northrop Space Laboratories Report No. NSL 65-87-1, May 1965.

2. Shlosinger, A. P. and Woo, W., Feasibility Study of Integral Heat Sink Space Suit Concepts, Northrop Space Laboratories Report No. NSL 65-87-2, May 1965.

3. Anonymous, Study of the Thermal Processes for Man-in-Space, Airesearch Manufacturing Company, NASA CR-216, April 1965.

4. Felder, J. W., Jr., and Shlosinger, A. P., Research on Methods for Thermal Transport in a Space Workers Garment, AMRL-TDR-63-90, November 1963.

5. Ginwala, K., Blatt, T. A., and Bilger, R. W., Engineering Study of Vapor Cycle Cooling Components for Space Vehicles, AF Flight Dynamics Laboratory, ASD, ASD-TDR-63-582, September 1963.

6. Anonymous, Linde Molecular Sieves, Union Carbide Corporation, Linde Division, San Francisco, California, Sales Brochure.

7. Anonymous, Davison Granular Silica Gels, W. R. Grace & Company, Davison Chemical Division, Baltimore, Maryland, Technical Bulletin #303.

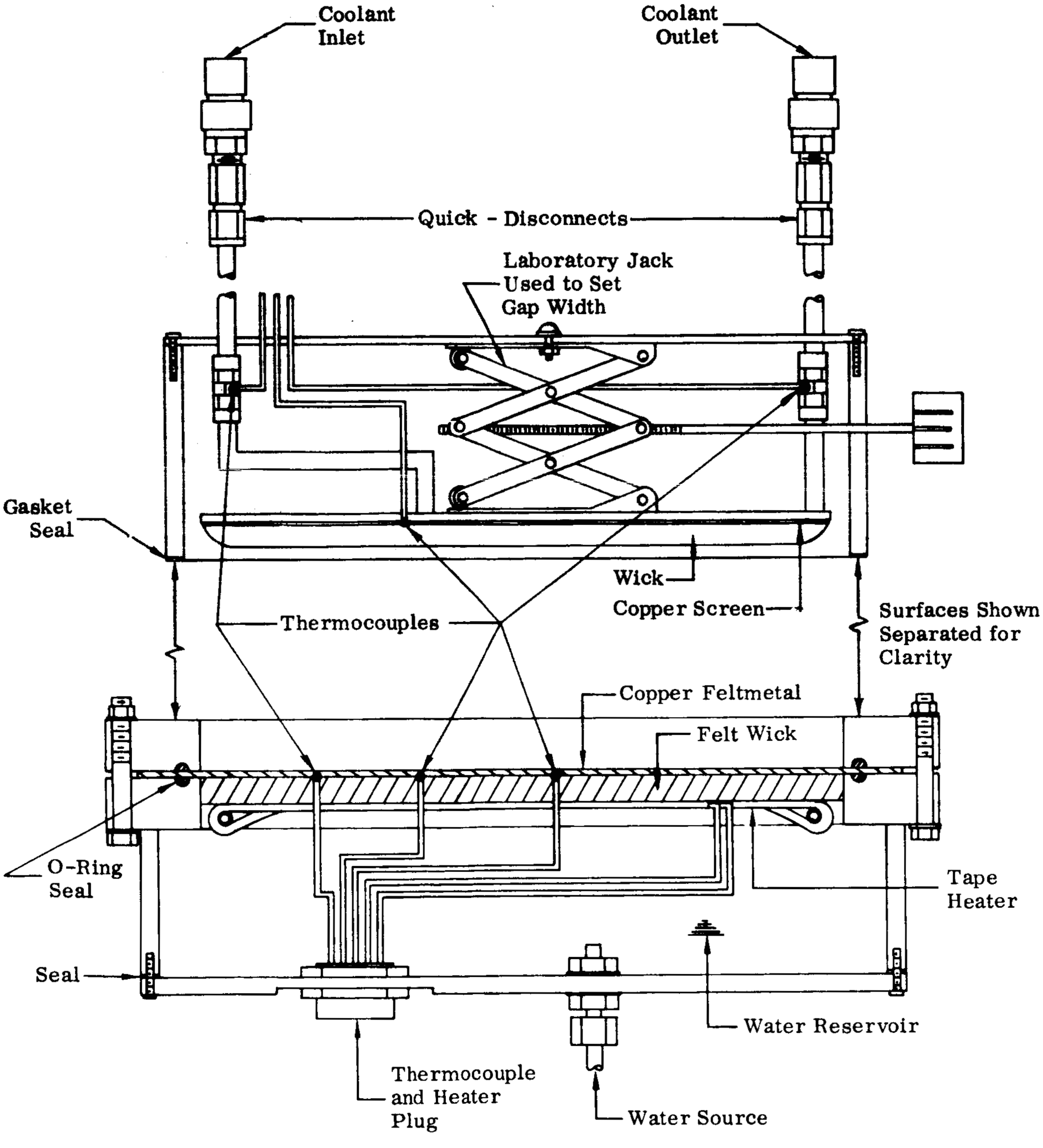


FIGURE 1 SCHEMATIC OF EXPERIMENTAL APPARATUS FOR DETERMINING WATER VAPOR CONDENSING AND COLLECTING SYSTEM PERFORMANCE

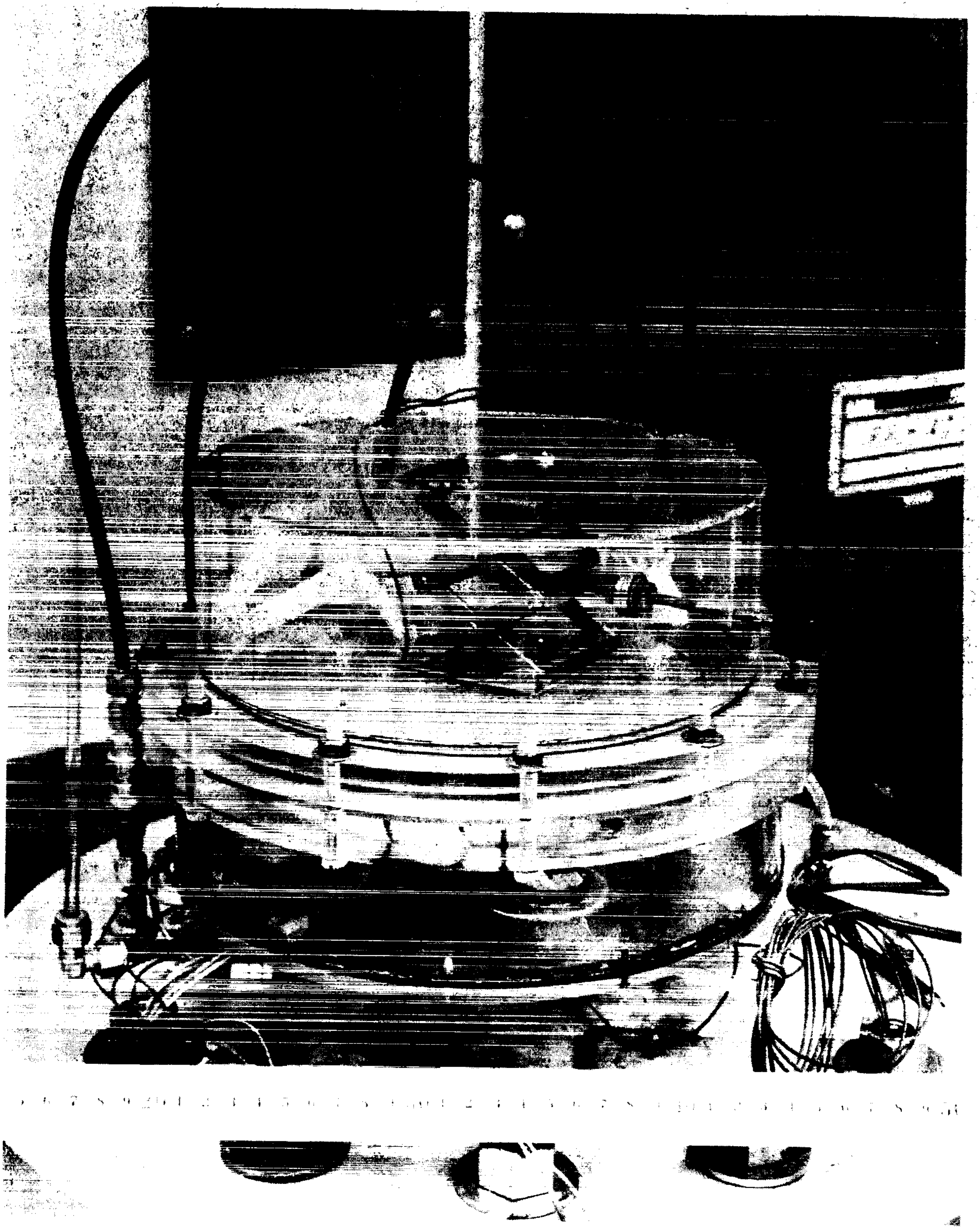


FIGURE 2 TEST APPARATUS FOR SIMULATION OF PASSIVE HUMIDITY CONTROL BY A COOLED WICK, FULLY ASSEMBLED ON BASE PLATE OF VACUUM BELL JAR, IN POSITION WITH SIMULATED SKIN (VAPOR SOURCE) FACING UP.

Copper Feltmetal Providing Simulation of a Sweating Human Skin

FIGURE 3 SIMULATED SKIN (VAPOR SOURCE) SECTION OF TEST APPARATUS

FIGURE 4 VIEW OF BACK OF SIMULATED SKIN (VAPOR SOURCE) SHOWING TAPE HEATER.

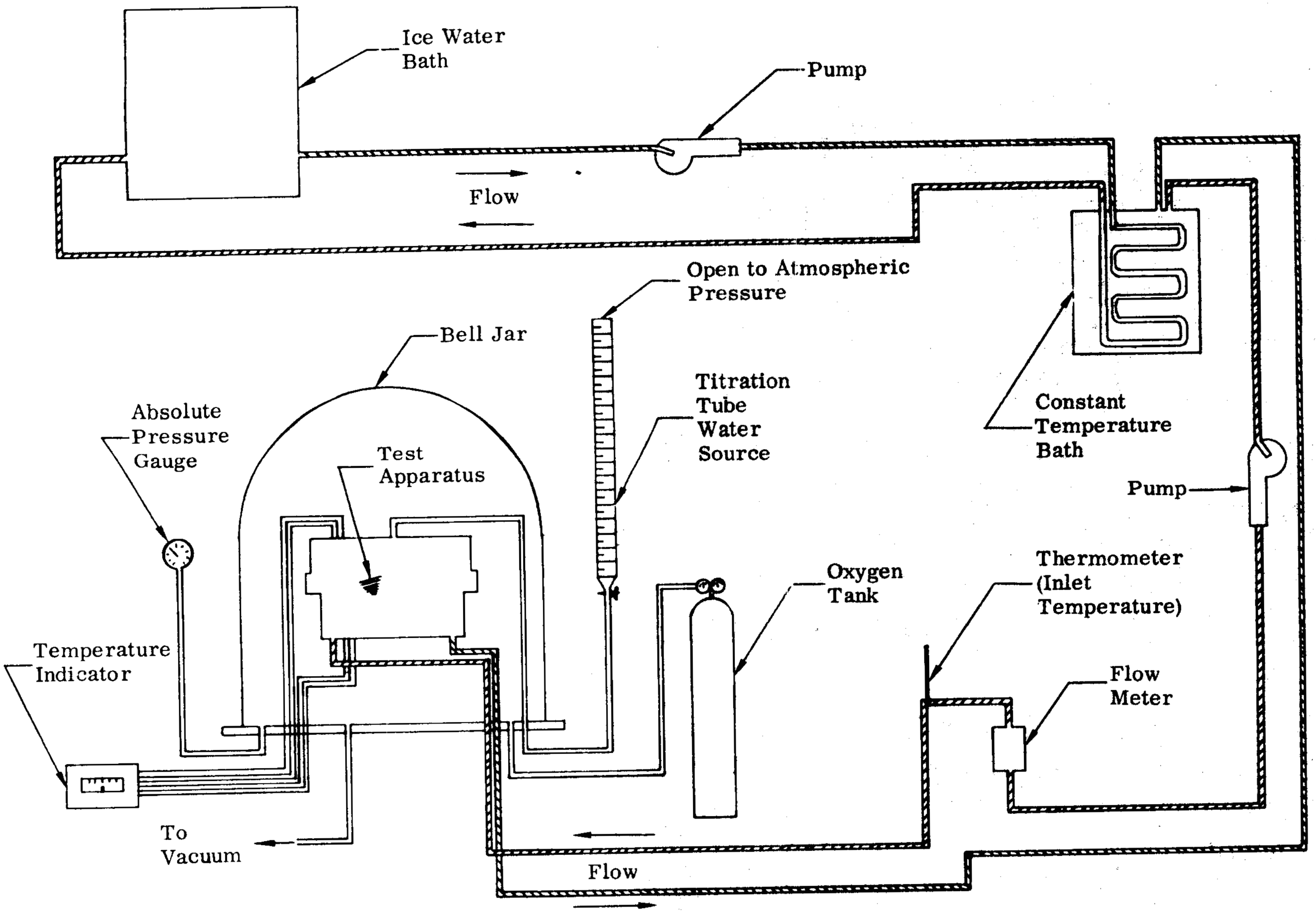


FIGURE 5 SCHEMATIC OF EXPERIMENTAL SET UP FOR DETERMINING WATER VAPOR CONDENSING AND COLLECTING SYSTEM PERFORMANCE.

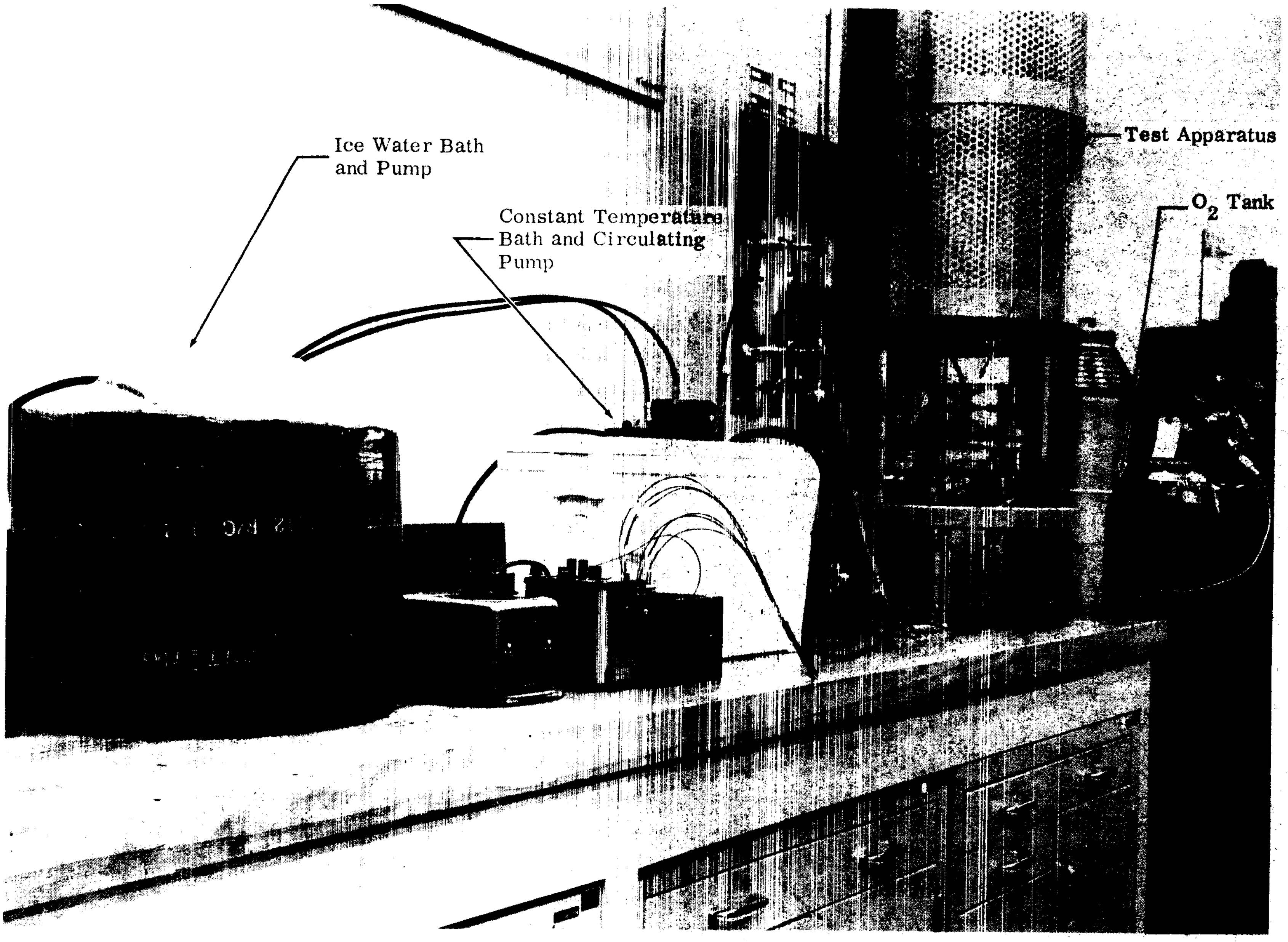


FIGURE 6 VIEW OF TEST ARRANGEMENT

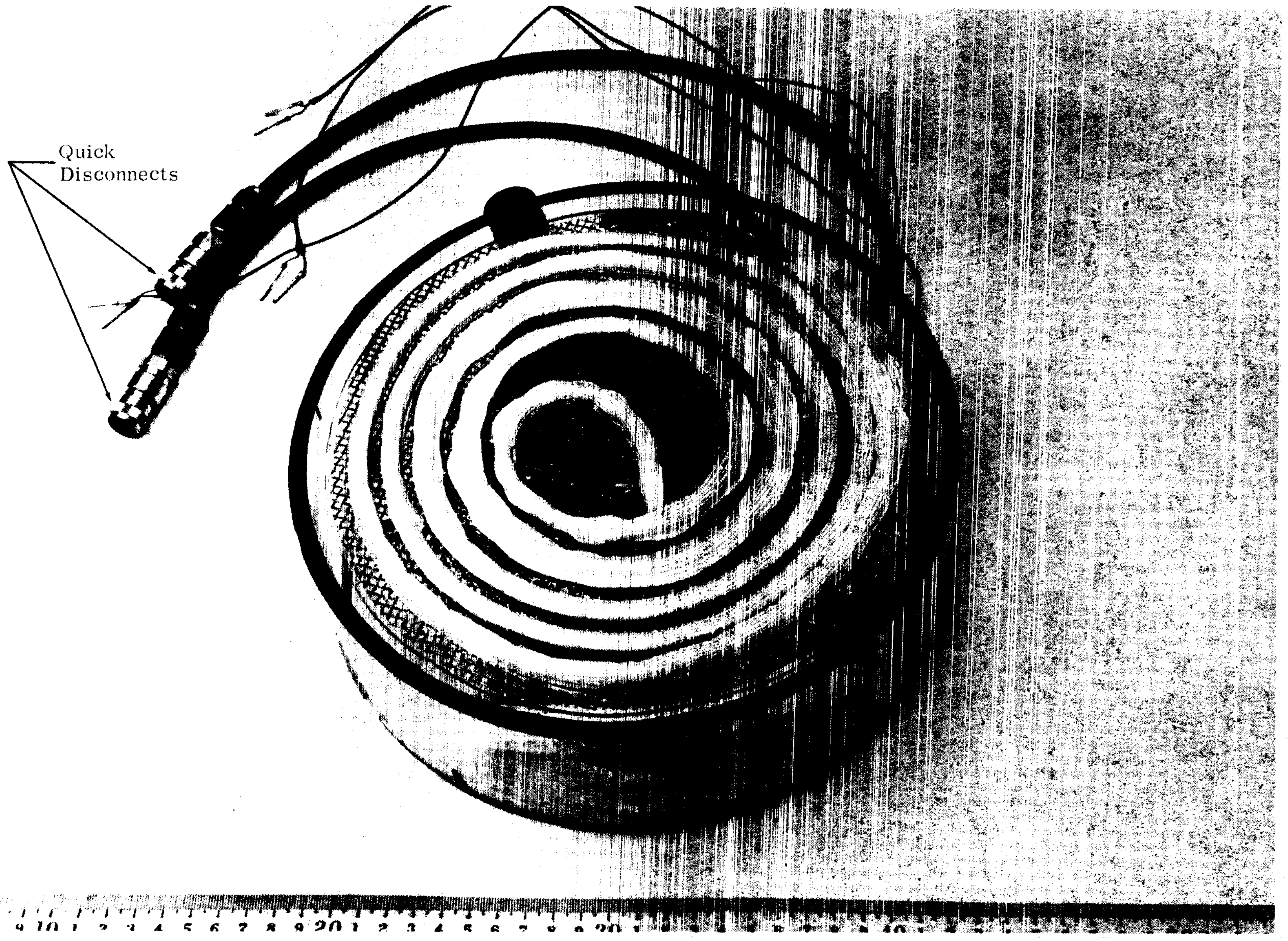


FIGURE 7 VIEW OF TUBULAR COOLED WICK VAPOR CONDENSING AND COLLECTING ASSEMBLY.

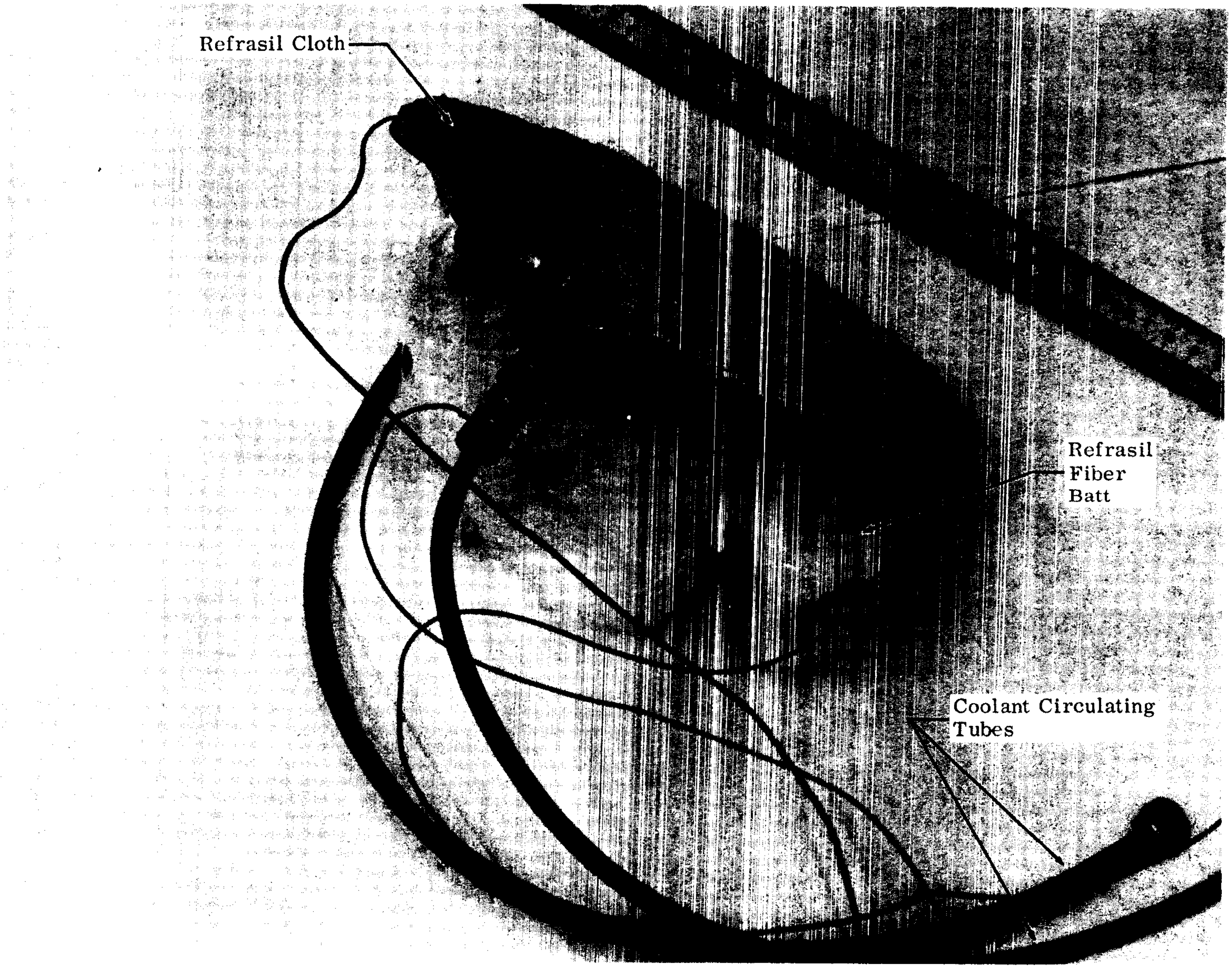


FIGURE 8 VIEW OF COOLED REFRASIL CLOTH VAPOR CONDENSING ASSEMBLY. FIBROUS REFRASIL BATT IS USED FOR WATER RETENTION.

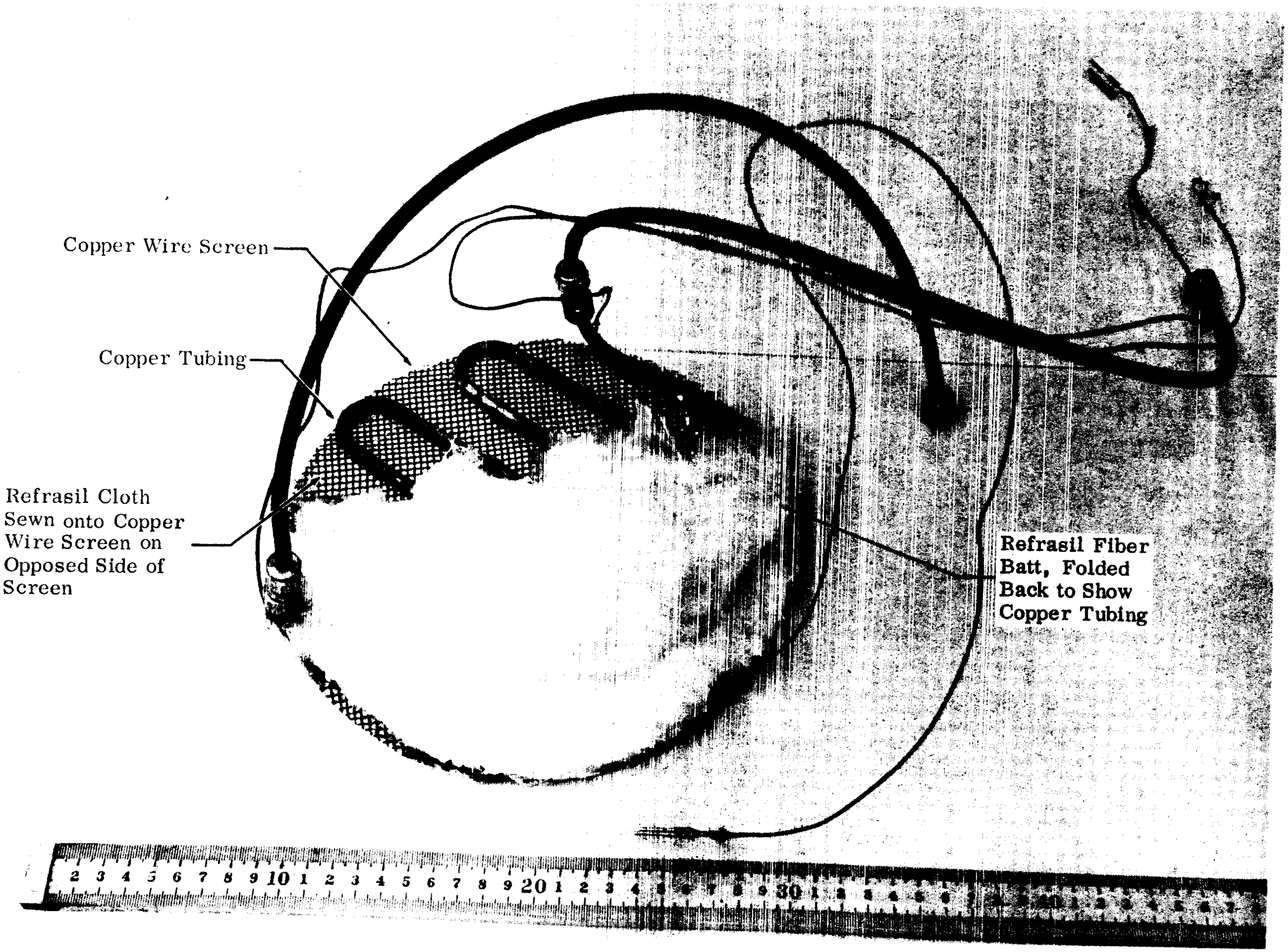
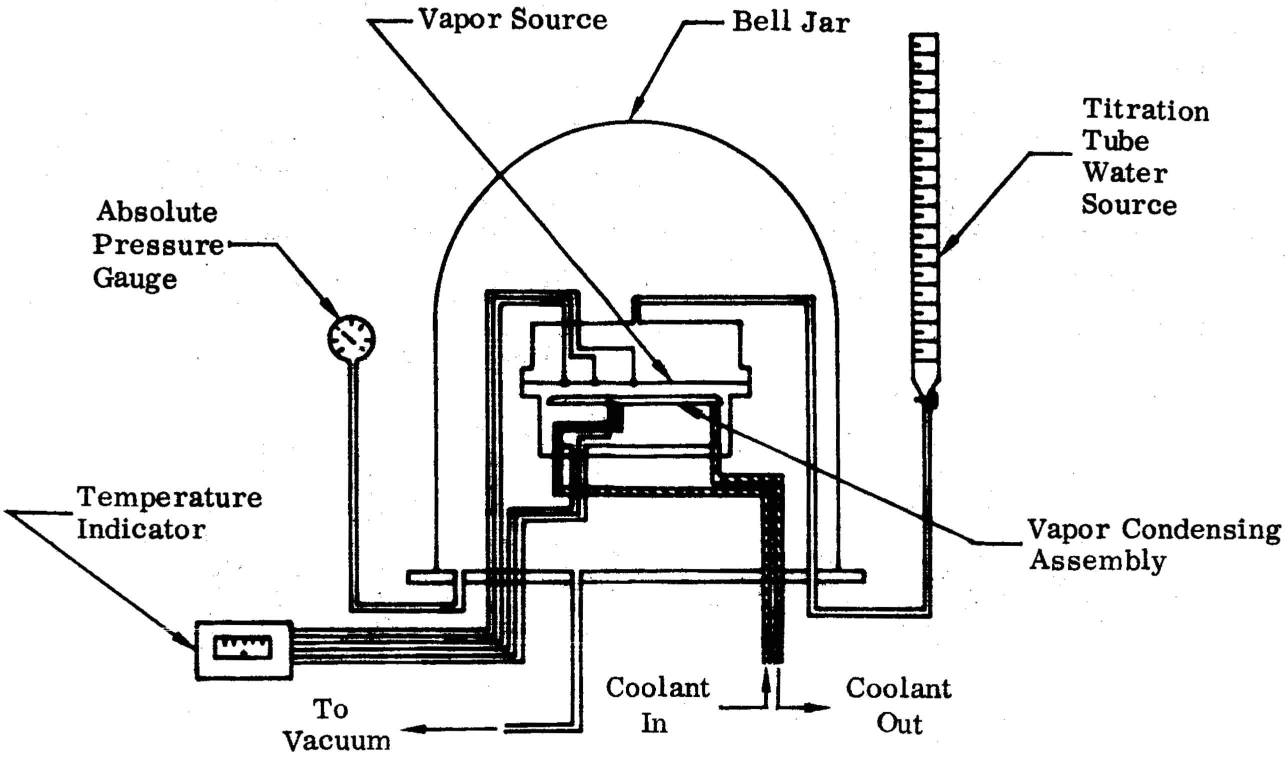
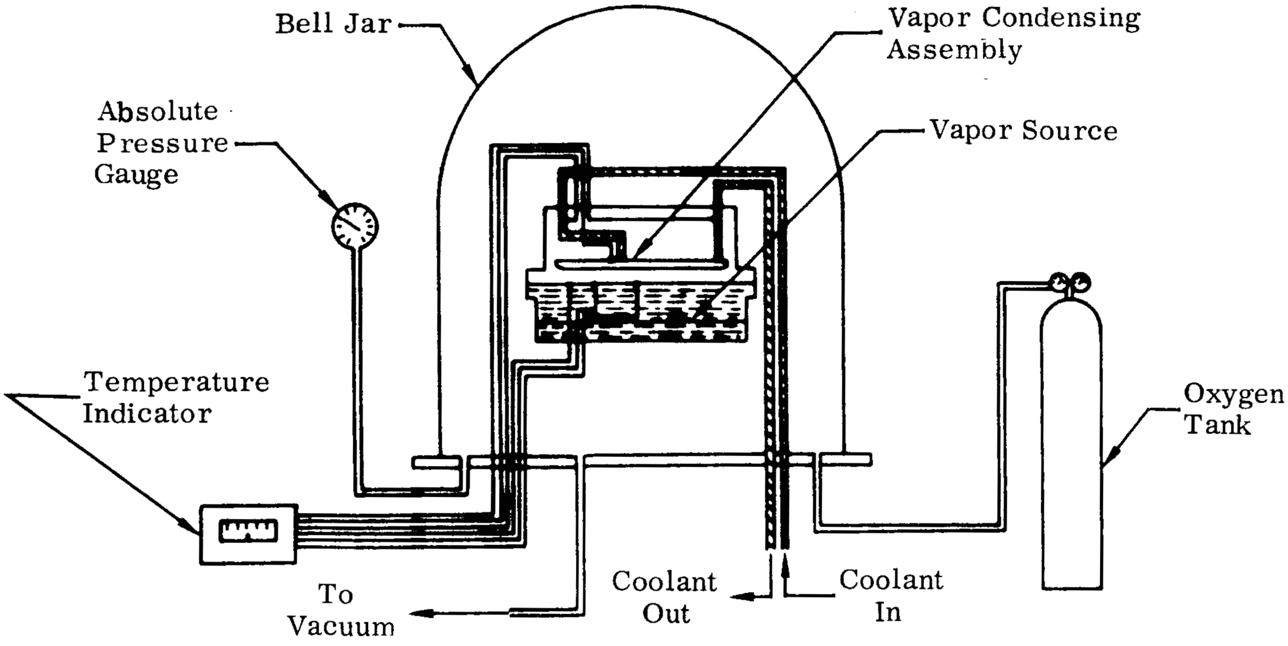


FIGURE 9 VIEW OF COOLED REFRASIL CLOTH VAPOR CONDENSING ASSEMBLY.



Water Vapor Source Above Vapor Condensing Assembly (Diffusion Downward)



Water Vapor Source Below Vapor Condensing Assembly (Diffusion Upward)

FIGURE 10 SCHEMATIC OF TEST APPARATUS FOR DETERMINING WATER VAPOR CONDENSING AND COLLECTING SYSTEM PERFORMANCE, INSTALLED IN BELL JAR.

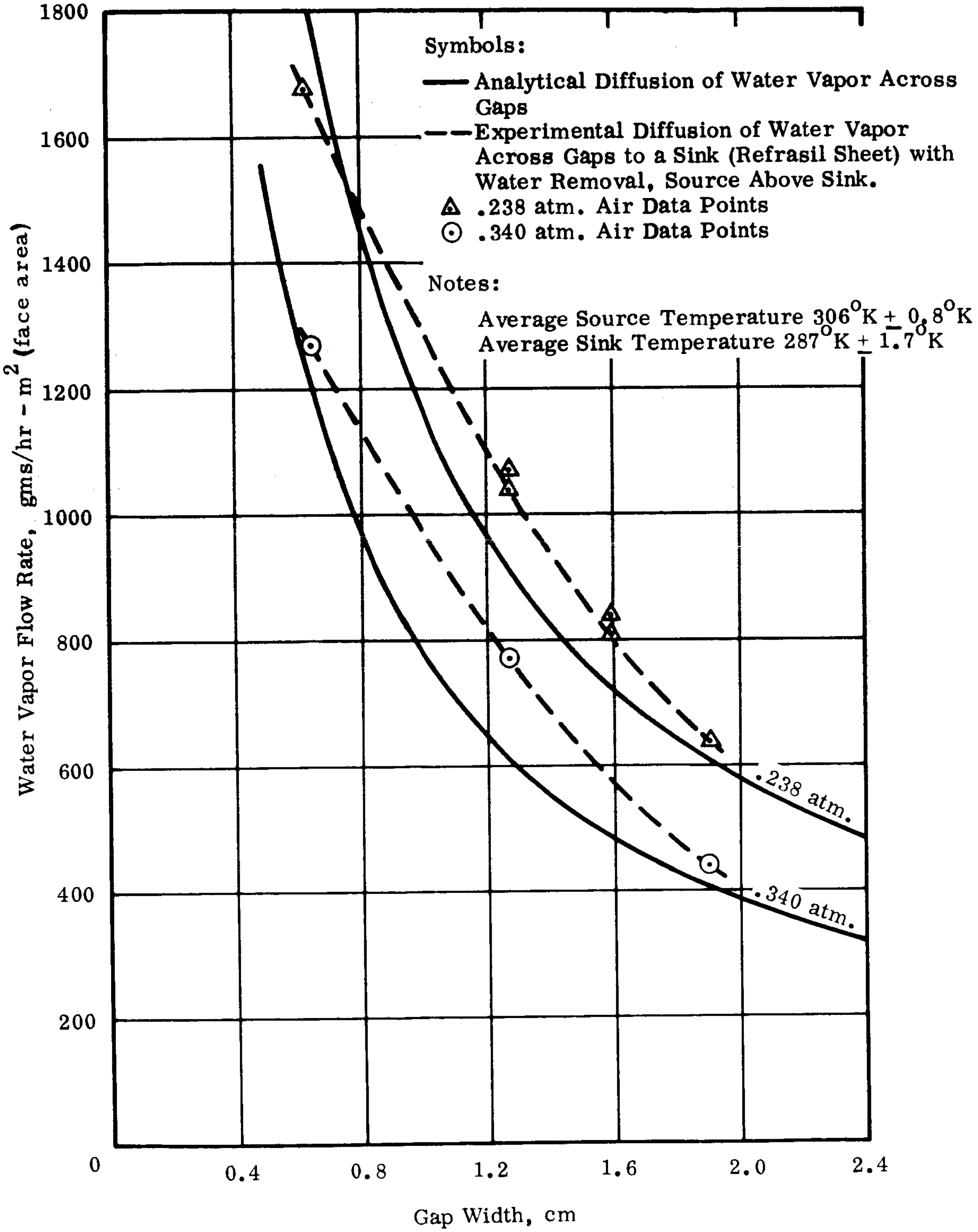


FIGURE 11 WATER VAPOR CONDENSING AND COLLECTING SYSTEM PERFORMANCE VS. GAP WIDTH, COOLED REFRASIL SHEET WITH WATER RETENTION BY REFRASIL BATT, 0.238 AND 0.340 ATMOSPHERES PRESSURE, VAPOR DIFFUSION DOWNWARD.

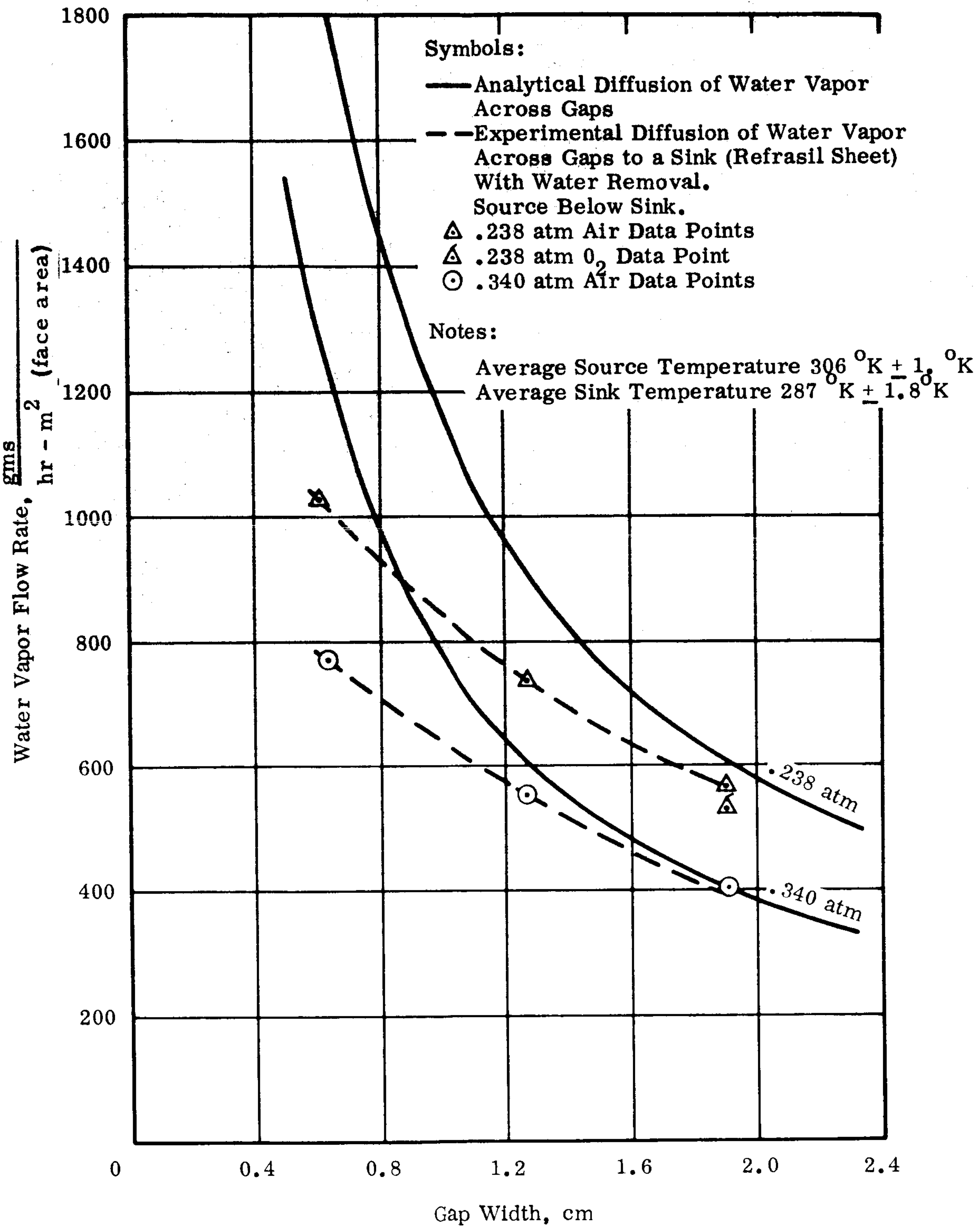


FIGURE 12 WATER VAPOR CONDENSING AND COLLECTING SYSTEM PERFORMANCE VS GAP WIDTH, COOLED REFRASIL SHEET WITH WATER RETENTION BY REFRASIL BATT, 0.238 AND 0.340 ATMOSPHERES PRESSURE, VAPOR DIFFUSION UPWARD.

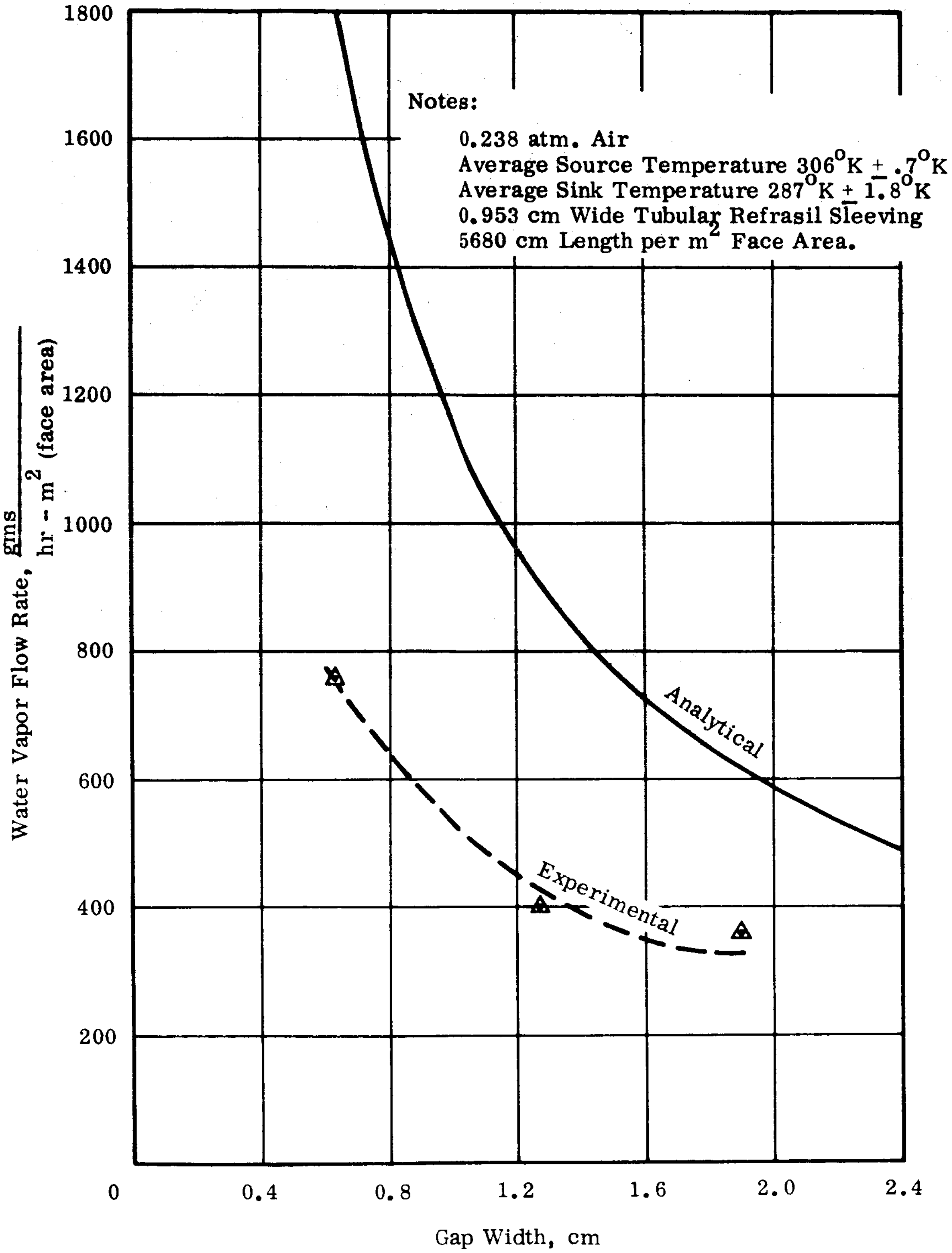


FIGURE 13 WATER VAPOR CONDENSING AND COLLECTING SYSTEM PERFORMANCE VS. GAP WIDTH, COOLED REFRASIL TUBULAR WICK WITH WATER REMOVAL BY REFRASIL BATT POUCHES AT ENDS OF TUBULAR WICK, 0.238 ATMOSPHERES PRESSURE, VAPOR DIFFUSION UPWARD.

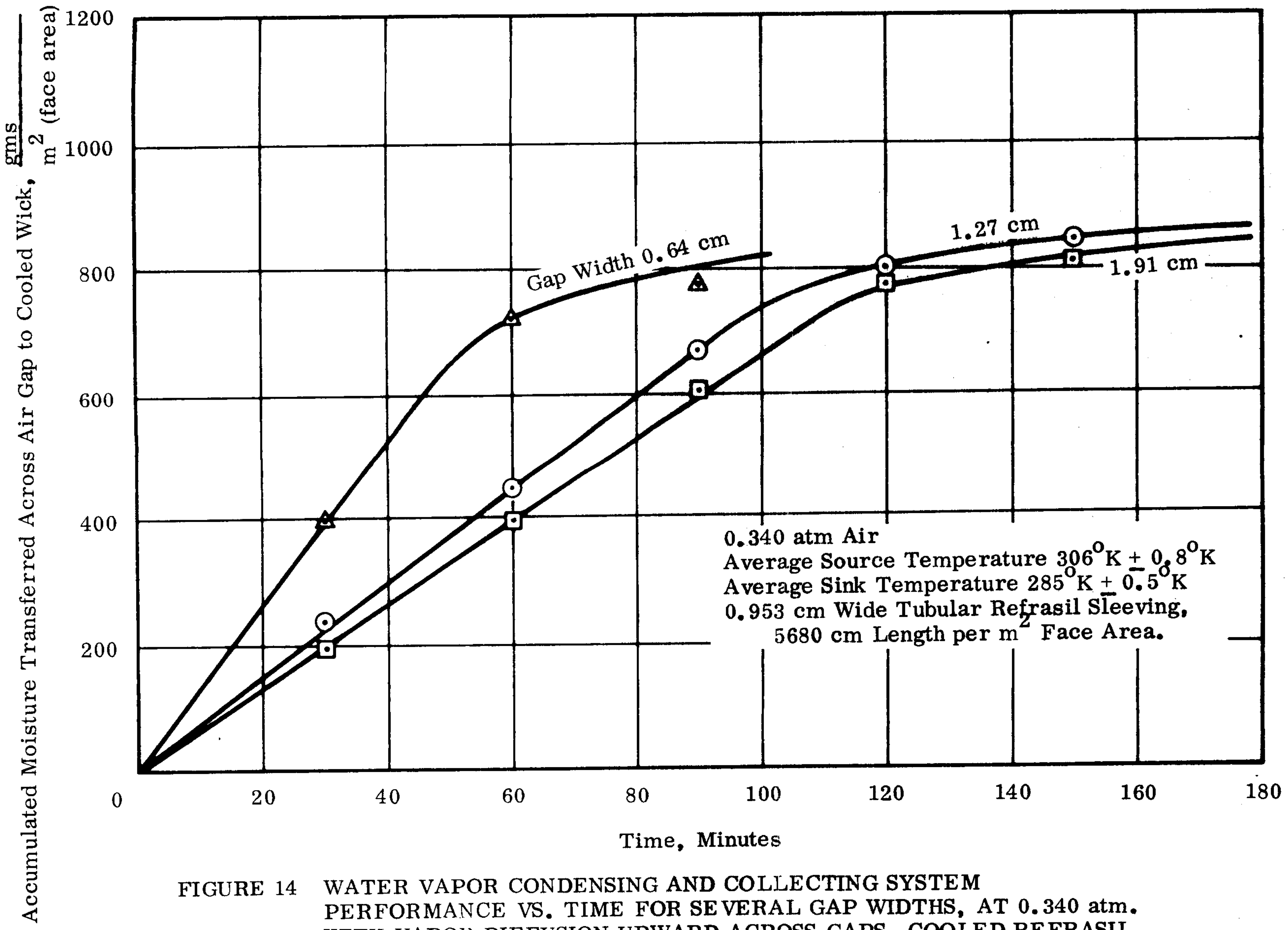


FIGURE 14 WATER VAPOR CONDENSING AND COLLECTING SYSTEM PERFORMANCE VS. TIME FOR SEVERAL GAP WIDTHS, AT 0.340 atm. WITH VAPOR DIFFUSION UPWARD ACROSS GAPS, COOLED REFRASIL TUBULAR WICK FOR VAPOR CONDENSATION, WATER RETAINED IN WICK.

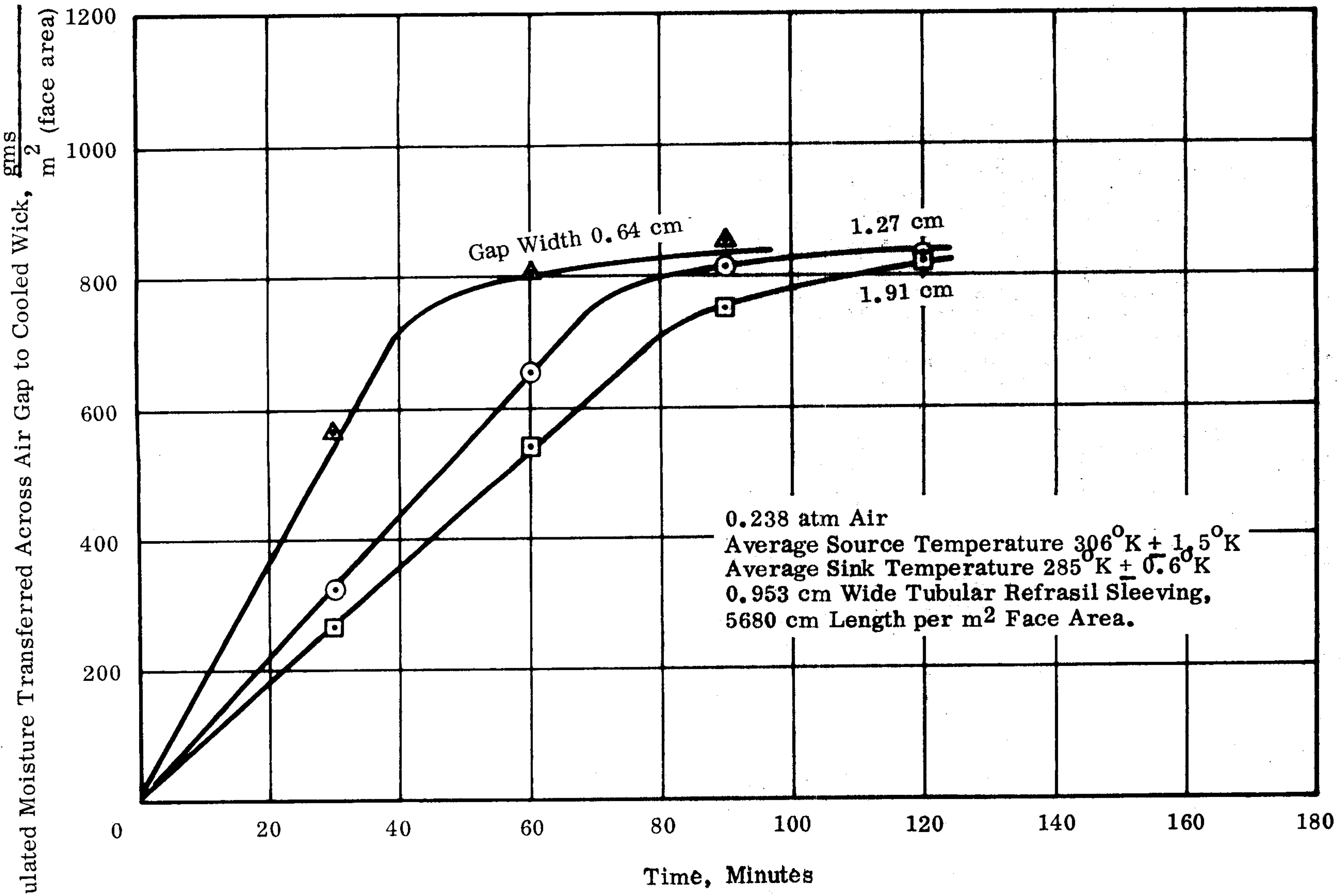


FIGURE 15 WATER VAPOR CONDENSING AND COLLECTING SYSTEM PERFORMANCE VS. TIME FOR SEVERAL GAP WIDTHS, AT 0.238 atm. WITH VAPOR DIFFUSION UPWARD ACROSS GAPS, COOLED REFRASIL TUBULAR WICK FOR VAPOR CONDENSATION, WATER RETAINED IN WICK.

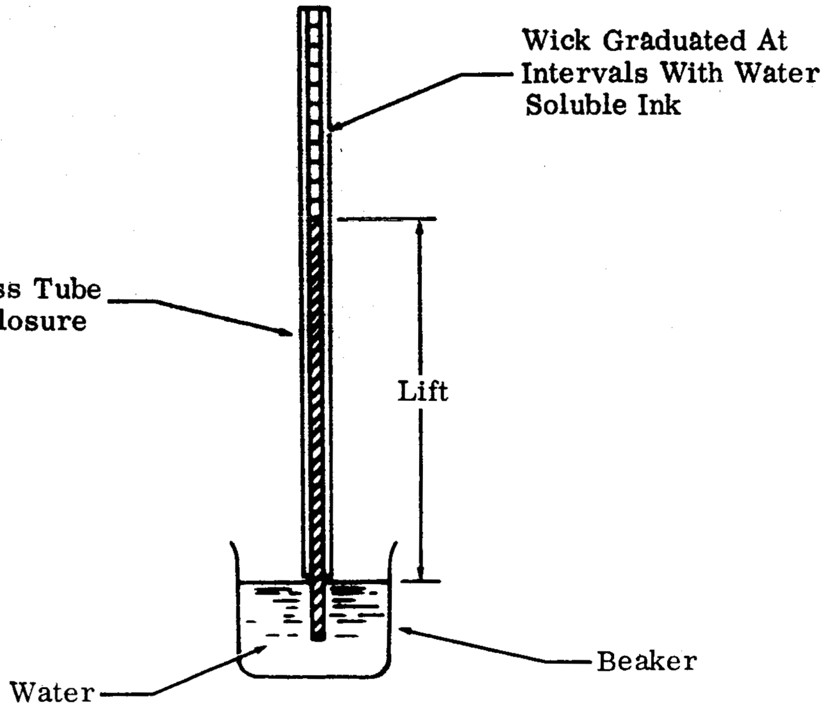


FIGURE 16 SCHEMATIC OF TEST ARRANGEMENT TO TEST THE LIFT CAPABILITY OF WICKS.

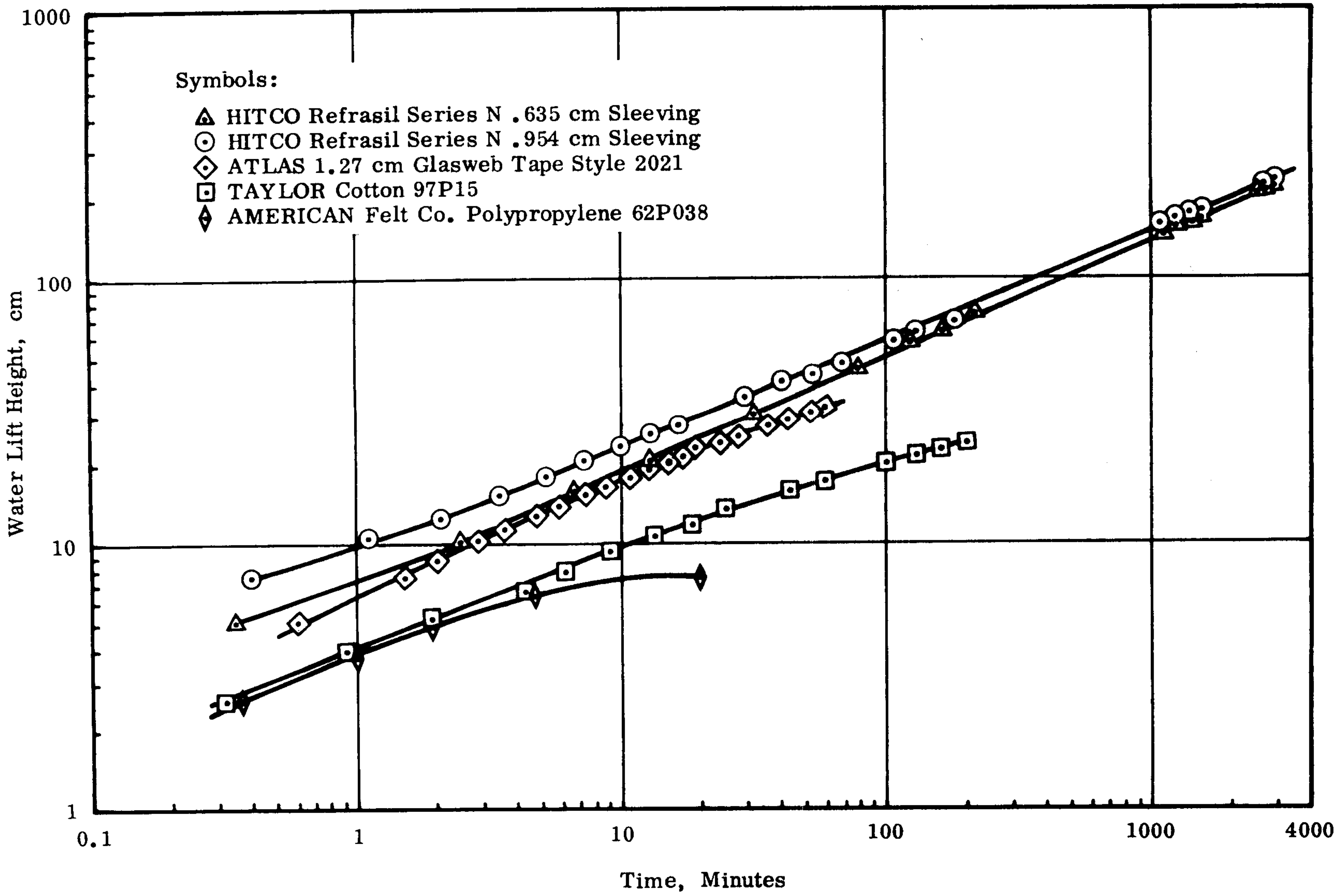


FIGURE 17 WATER LIFT HEIGHT IN WICK MATERIALS AS A FUNCTION OF TIME

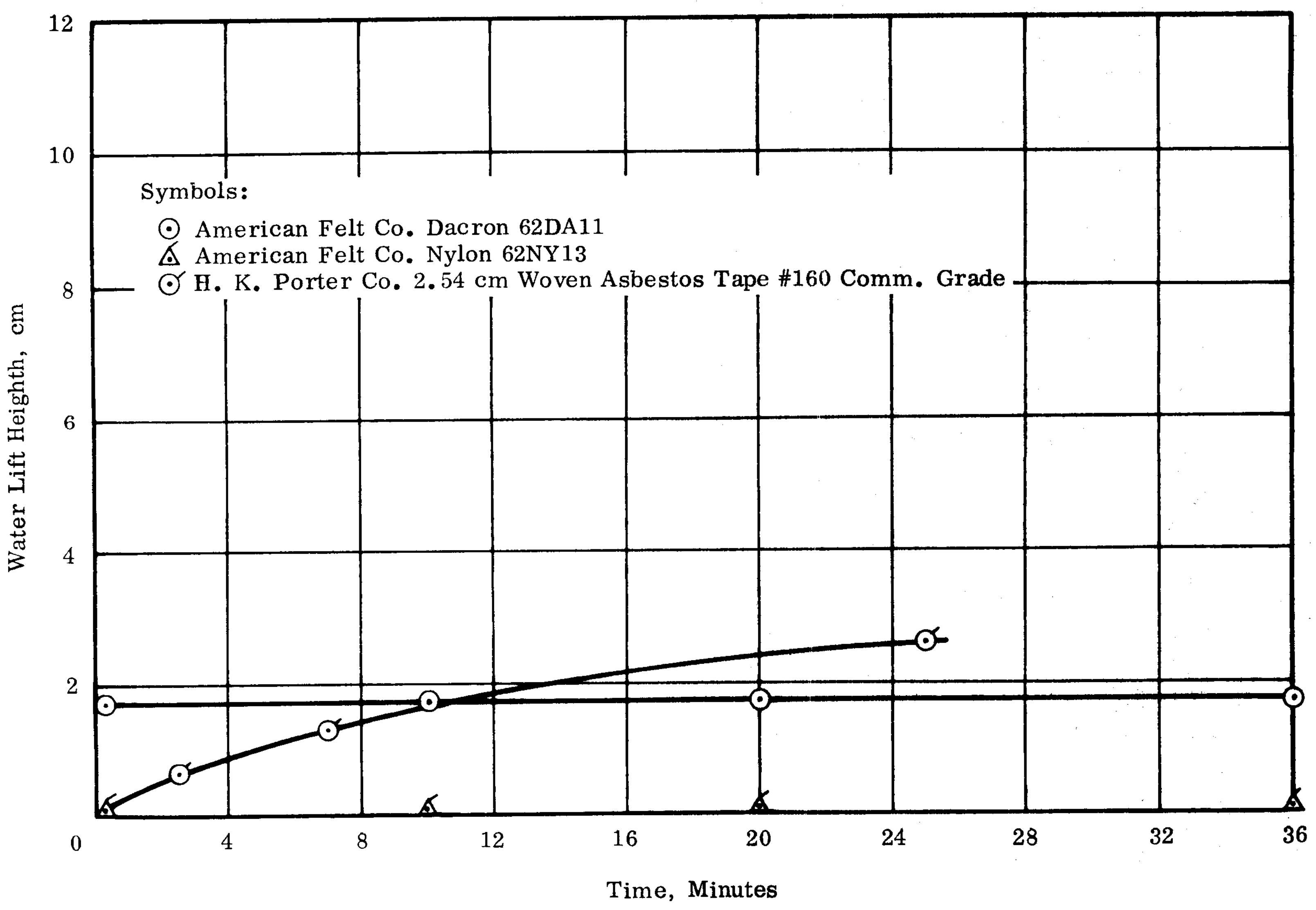


FIGURE 18 WATER LIFT HEIGHT IN WICK MATERIALS AS A FUNCTION OF TIME

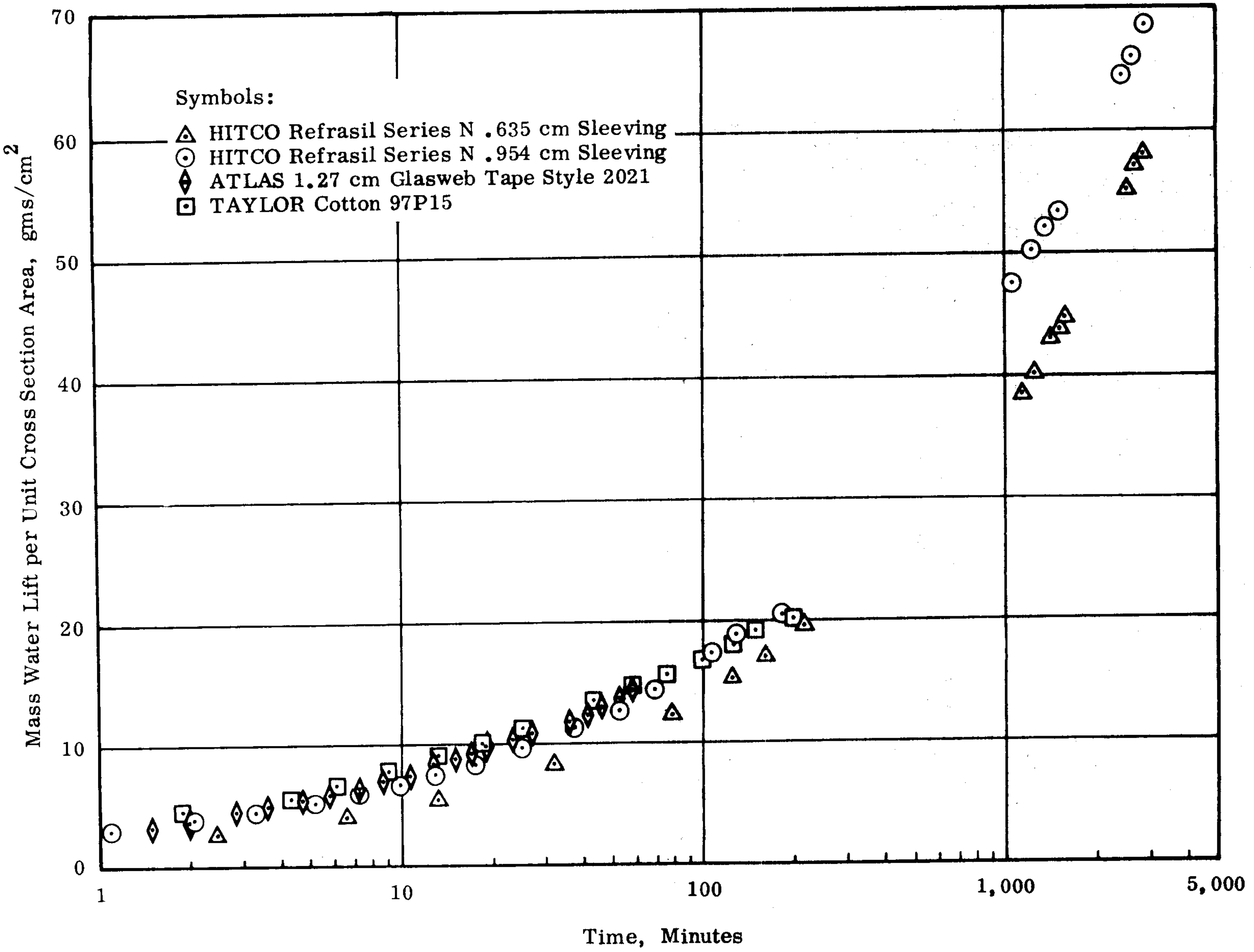


FIGURE 19 MASS WATER LIFT PER UNIT CROSS SECTION AREA IN WICK MATERIALS AS A FUNCTION OF TIME.

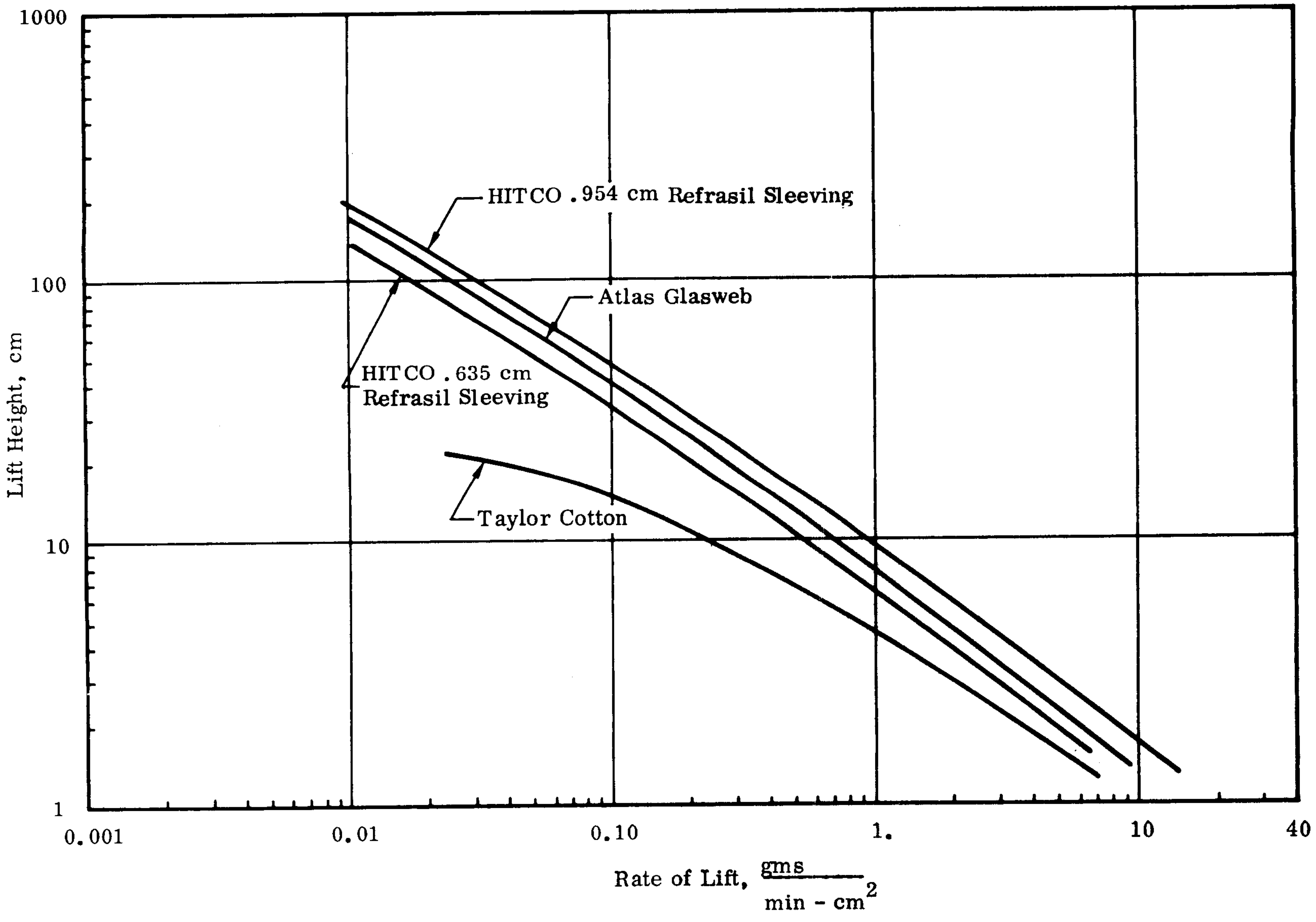


FIGURE 20 WICK LIFT RATE PER UNIT CROSS SECTIONED AREA AS A FUNCTION OF LIFT HEIGHT FOR WATER.

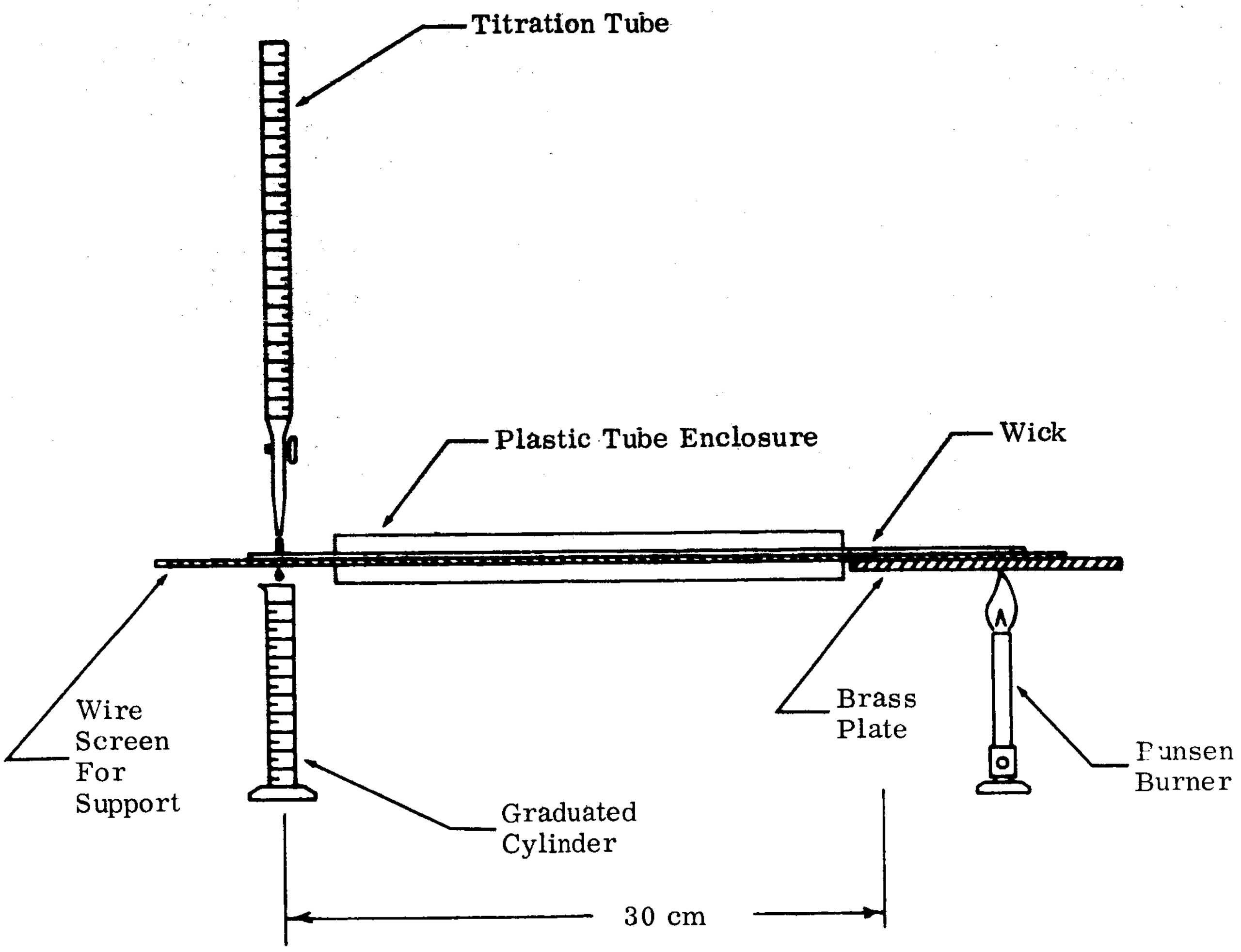


FIGURE 21 SCHEMATIC OF TEST ARRANGEMENT FOR MEASUREMENT OF CAPILLARY FLOW IN HORIZONTAL WICKS (ZERO G SIMULATION).

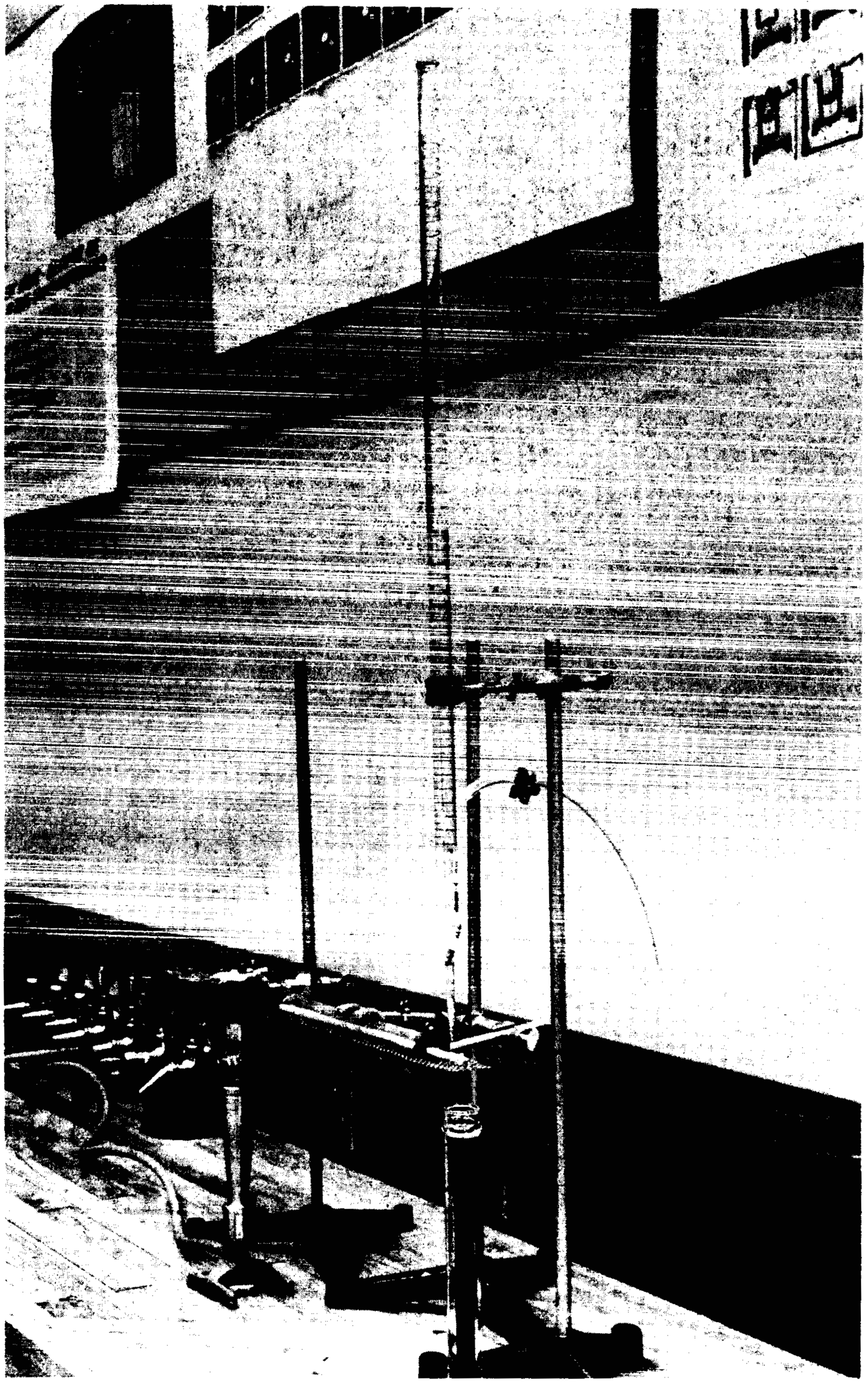


FIGURE 22 VIEW OF TEST ARRANGEMENT FOR MEASUREMENT OF CAPILLARY FLOW OF WATER IN HORIZONTAL WICKS (ZERO G SIMULATION).

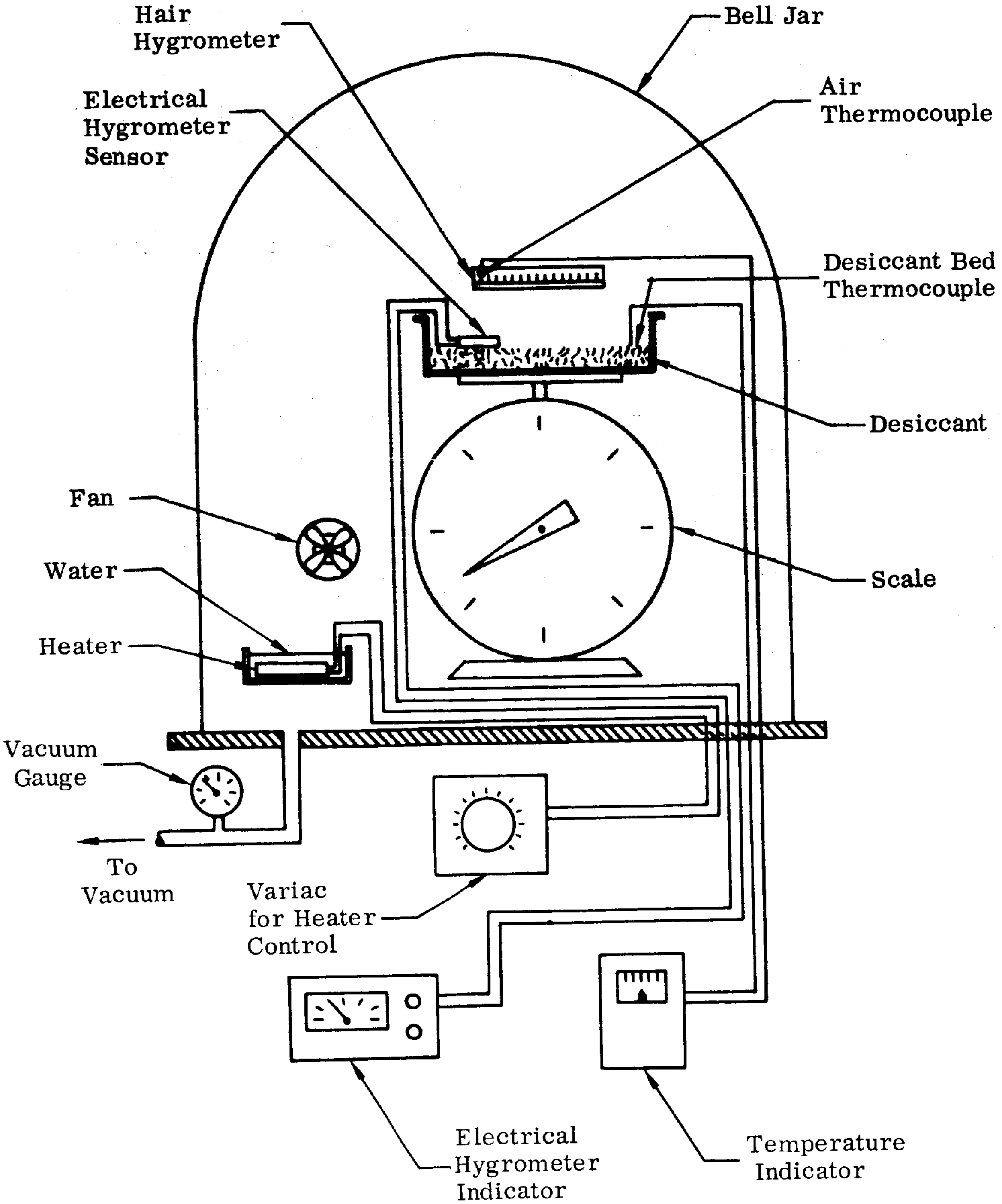


FIGURE 23 SCHEMATIC OF EXPERIMENT ARRANGEMENT FOR MEASUREMENT OF DESICCANT BED PERFORMANCE.

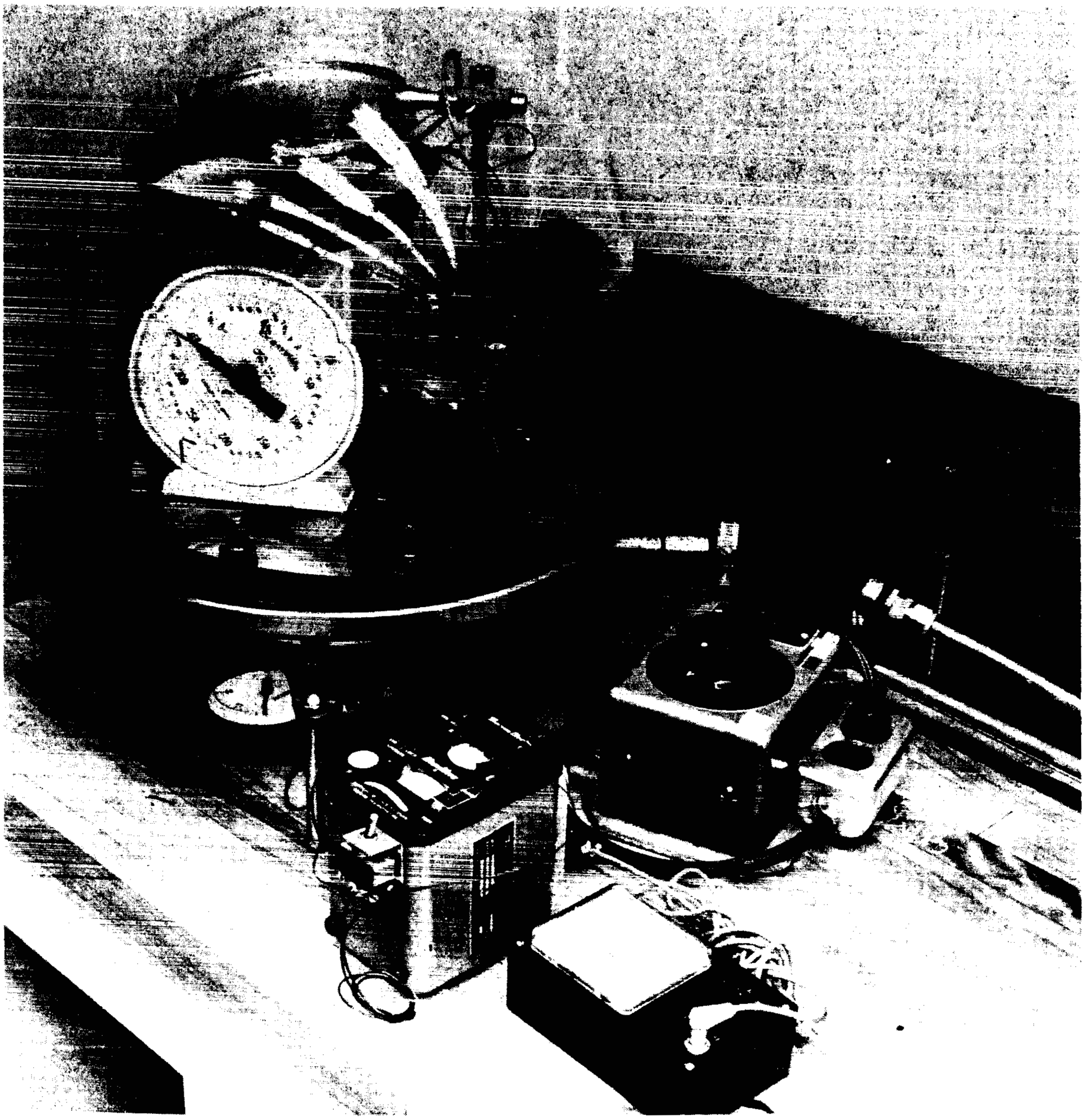


FIGURE 24 VIEW OF EXPERIMENT ARRANGEMENT FOR MEASUREMENTS OF DESICCANT BED PERFORMANCE.

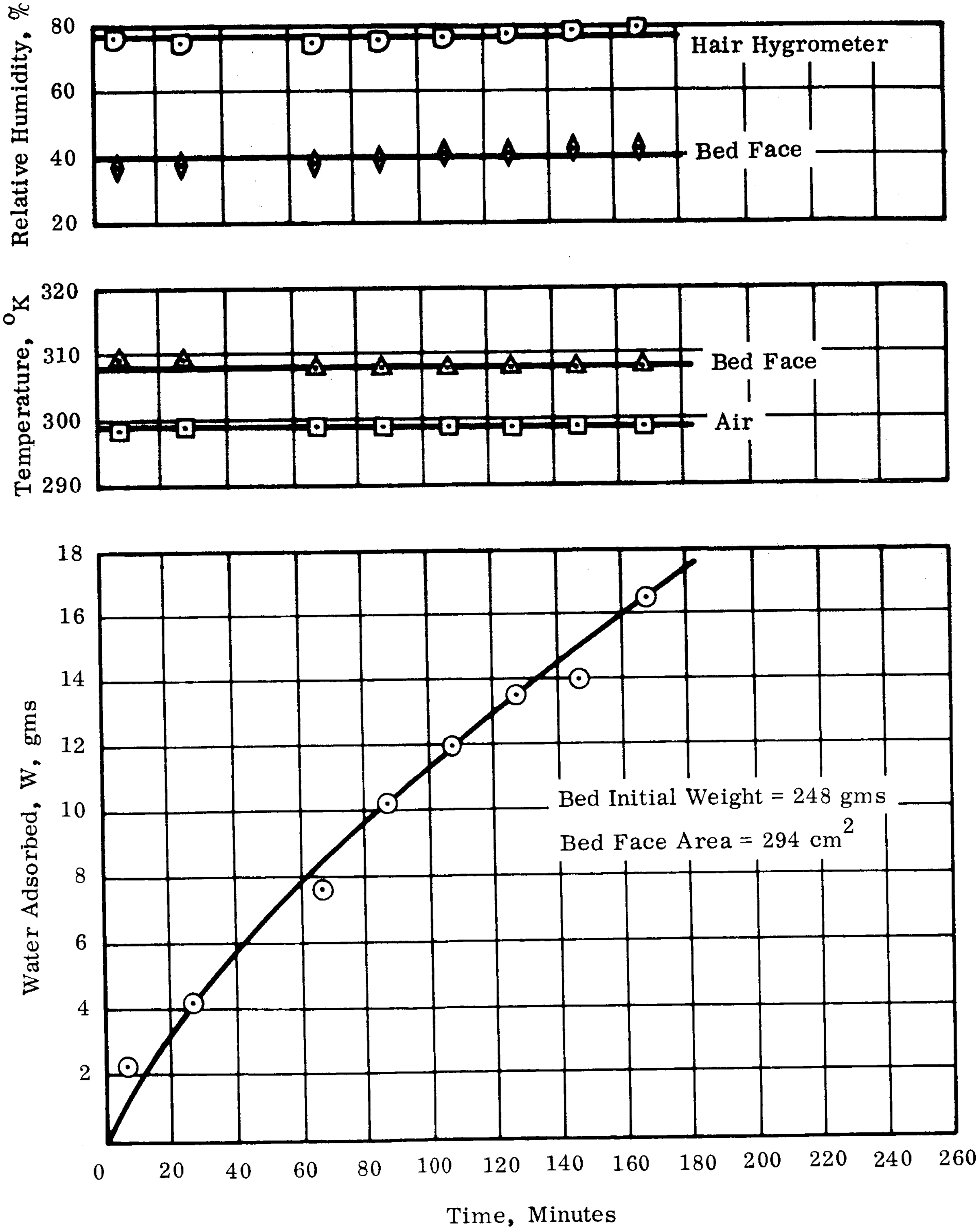


FIGURE 25 ADSORPTION BED PERFORMANCE TEST DATA OF SILICA GEL AT 0.238 ATMOSPHERES PRESSURE.

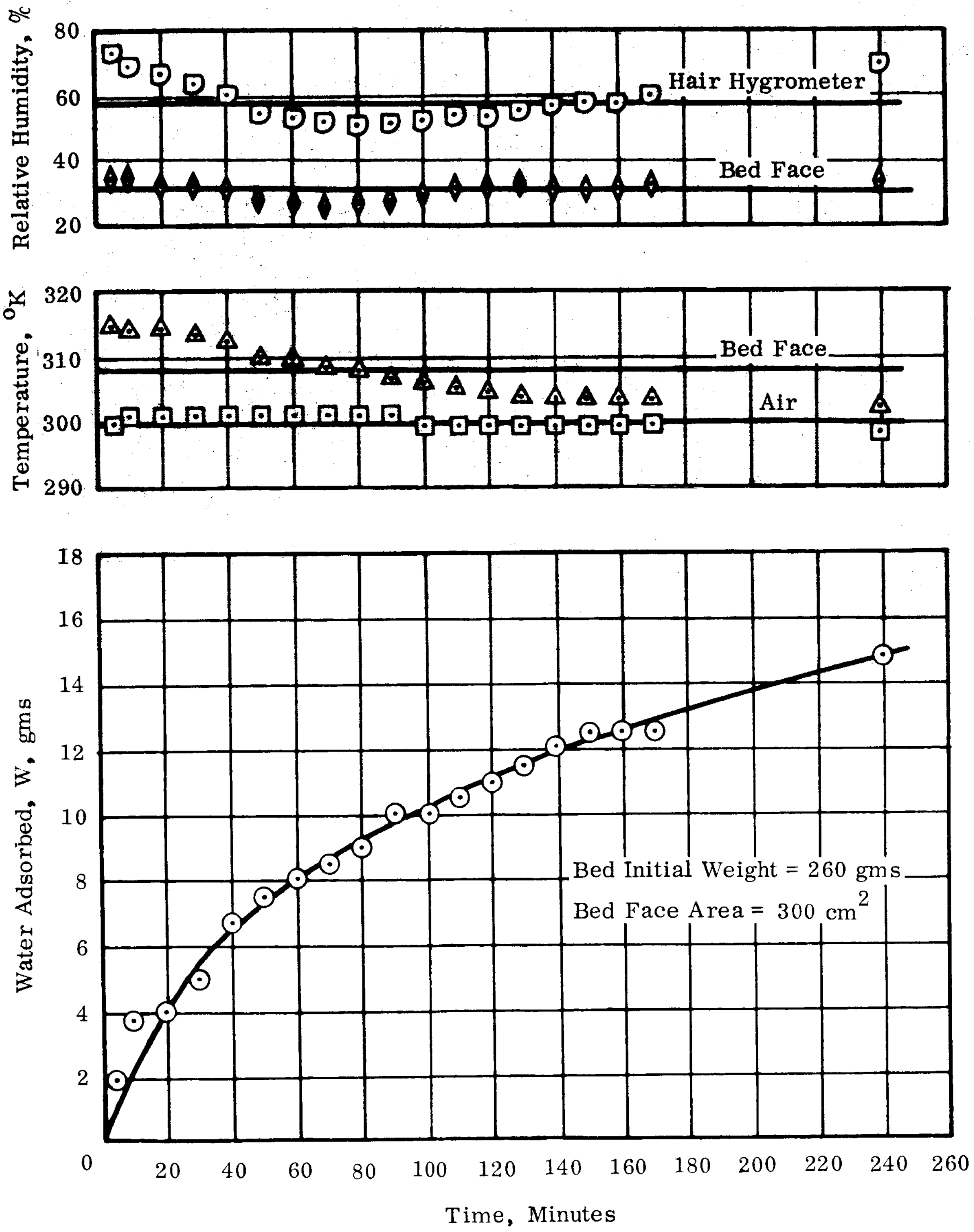


FIGURE 26 ADSORPTION BED PERFORMANCE TEST DATA OF MOLECULAR SIEVES AT 0.340 ATMOSPHERES PRESSURE.

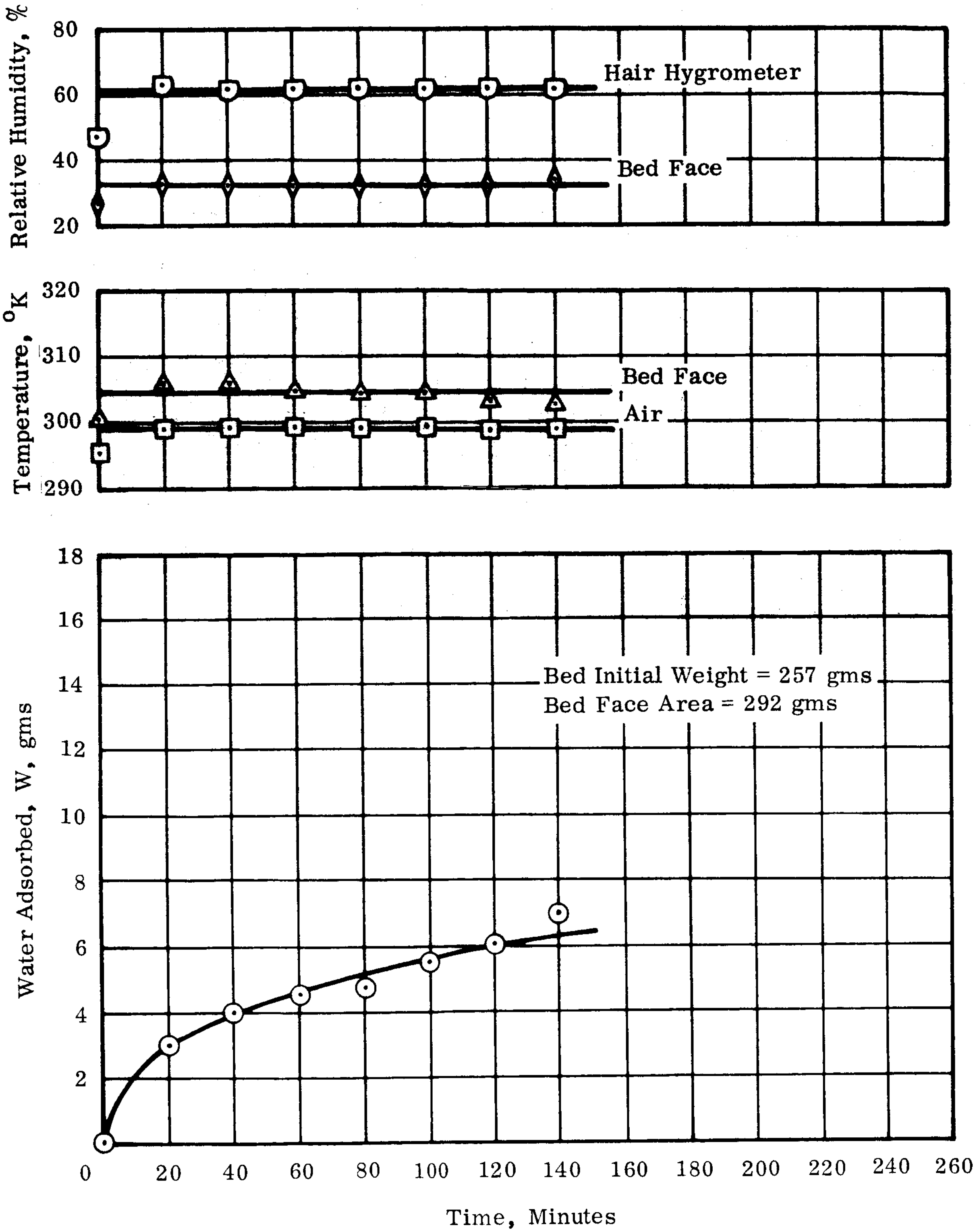


FIGURE 27 ADSORPTION BED PERFORMANCE TEST DATA OF SILICA GEL AT 0.340 ATMOSPHERES PRESSURE.

Notes:

W = Weight of Water Vapor that can be Adsorbed in 100 gms of Dry Adsorbent, gms/gm
Adsorbent is Linde Type 4A° .317 cm pellets from <u>Linde Molecular Sieves</u> Reference 6

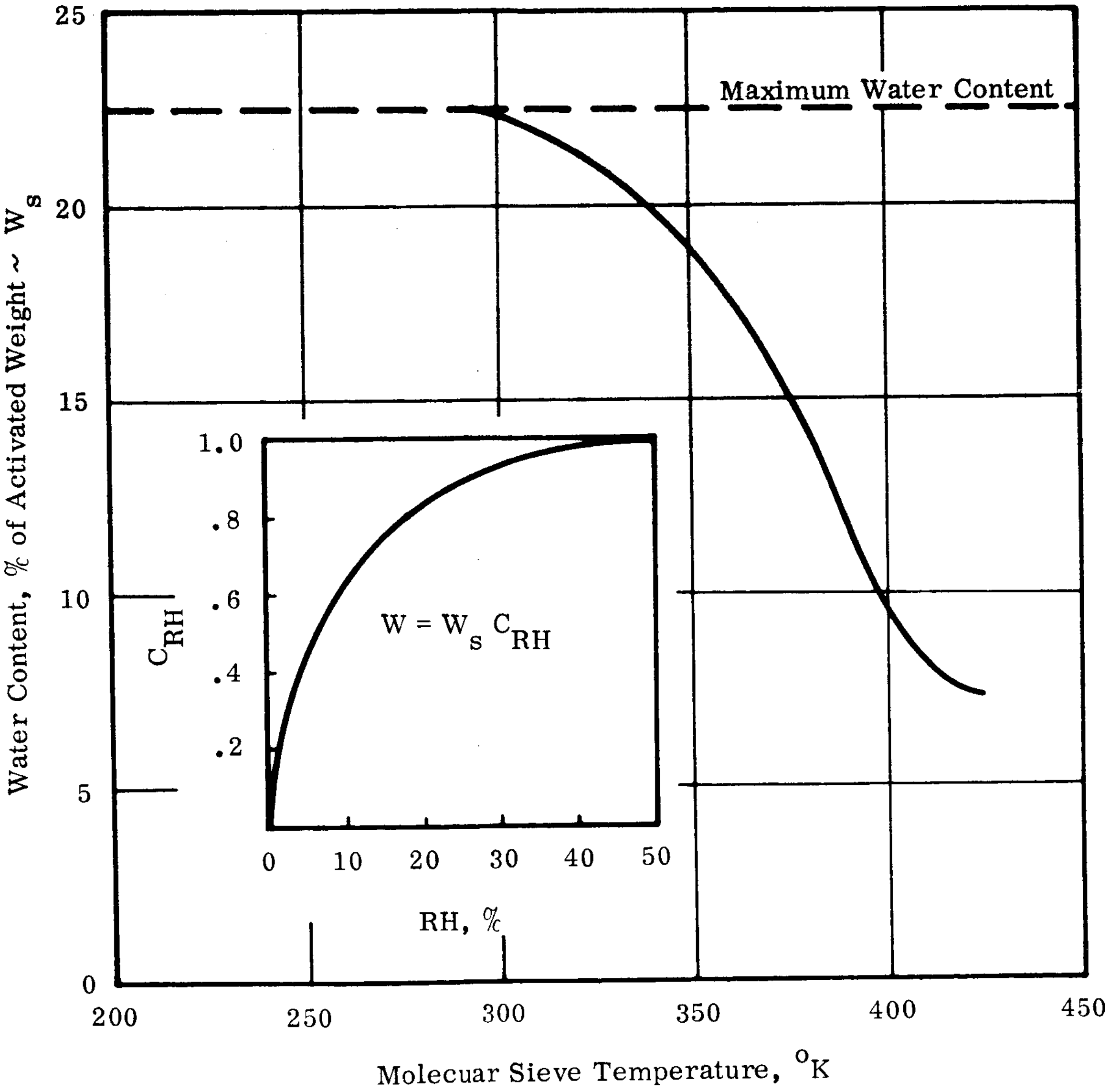
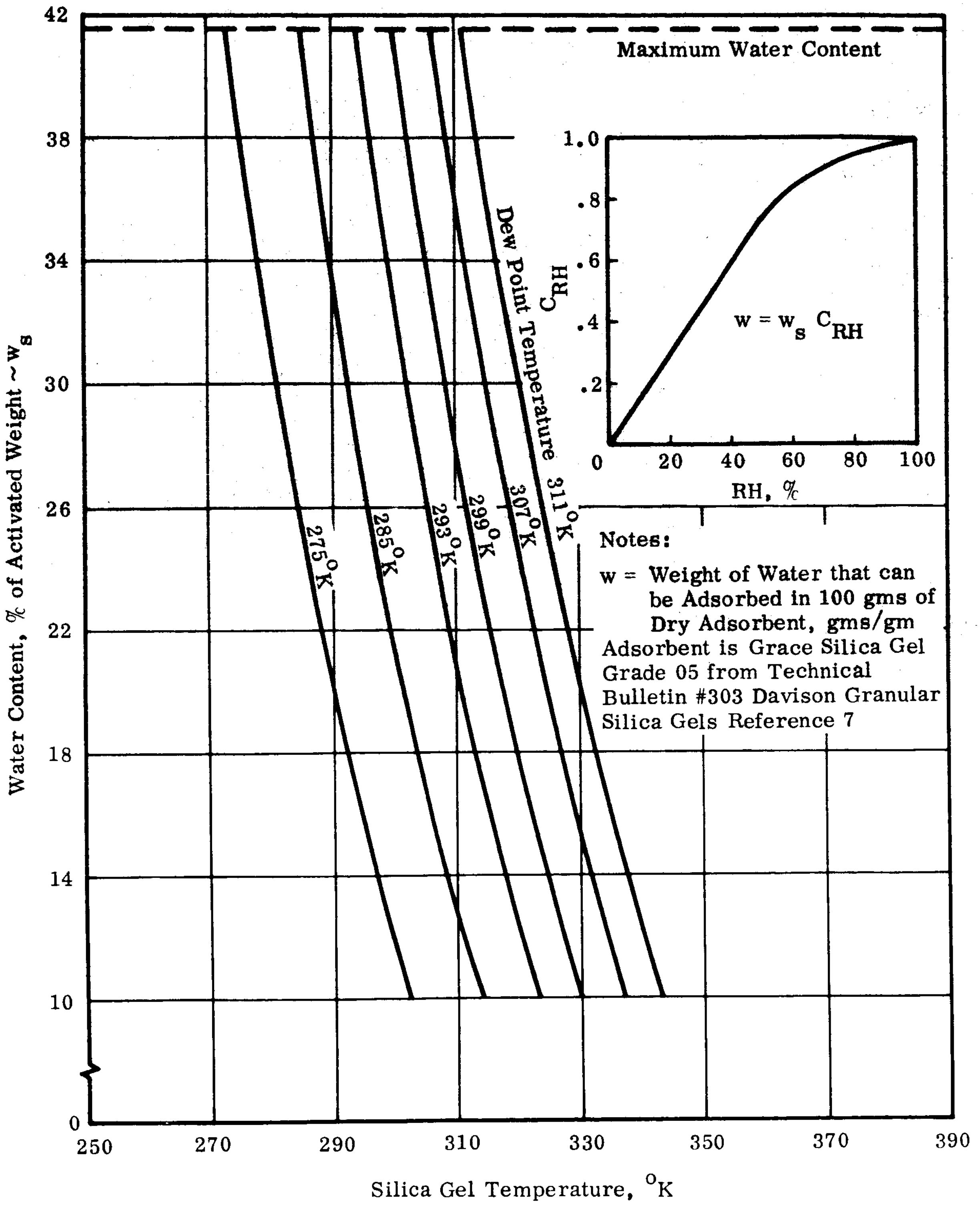


FIGURE 28 WEIGHT OF WATER VAPOR THAT CAN BE ADSORBED IN 100 gms OF DRY MOLECULAR SIEVES AS A FUNCTION OF BED TEMPERATURE AND RELATIVE HUMIDITY.



Notes:

w = Weight of Water that can be Adsorbed in 100 gms of Dry Adsorbent, gms/gm

Adsorbent is Grace Silica Gel Grade 05 from Technical Bulletin #303 Davison Granular Silica Gels Reference 7

FIGURE 29 WEIGHT OF WATER VAPOR THAT CAN BE ADSORBED IN 100 gms OF DRY SILICA GEL AS A FUNCTION OF BED TEMPERATURE AND RELATIVE HUMIDITY.

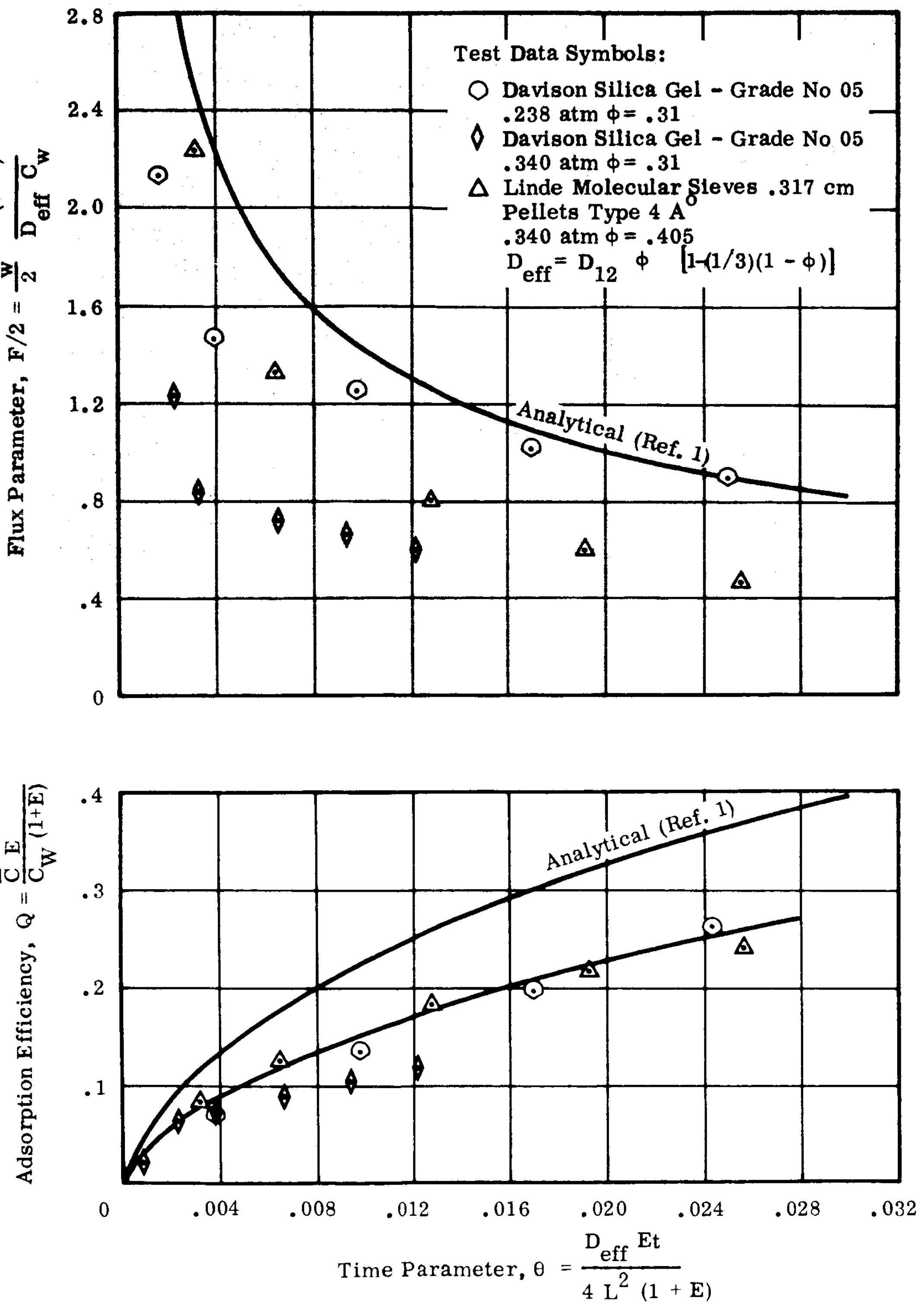


FIGURE 30 COMPARISON BETWEEN ANALYTICAL AND TEST ADSORPTION BED PARAMETERS USING AN EFFECTIVE BED DIFFUSION COEFFICIENT OF $D_{eff} = D_{12}\phi\ [1-(1/3)(1-\phi)]$ FOR TEST DATA

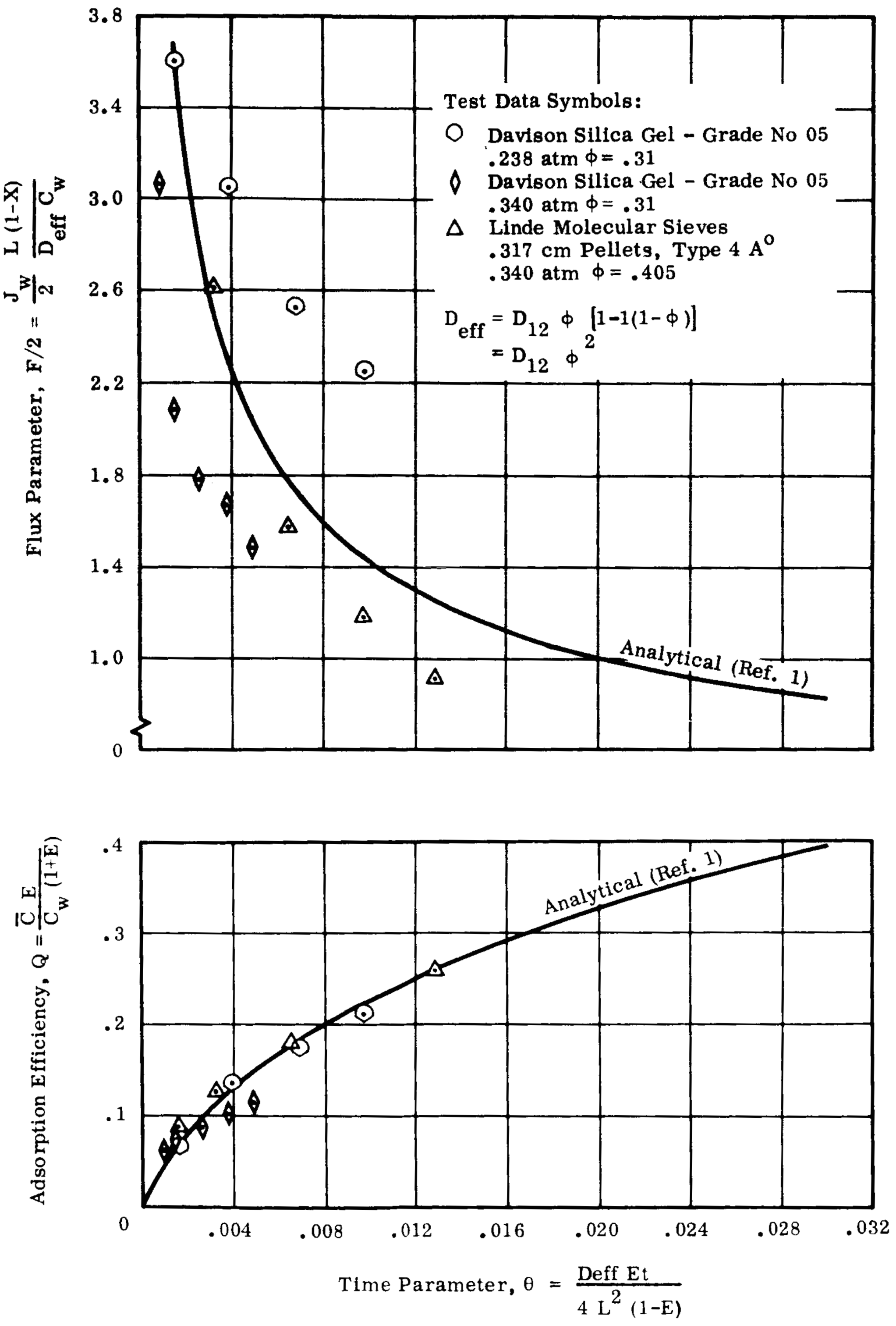


FIGURE 31 COMPARISON BETWEEN ANALYTICAL AND TEST ADSORPTION BED PARAMETERS USING AN EFFECTIVE BED DIFFUSION COEFFICIENT OF $D_{eff} = D_{12}\, \phi^2$ FOR TEST DATA

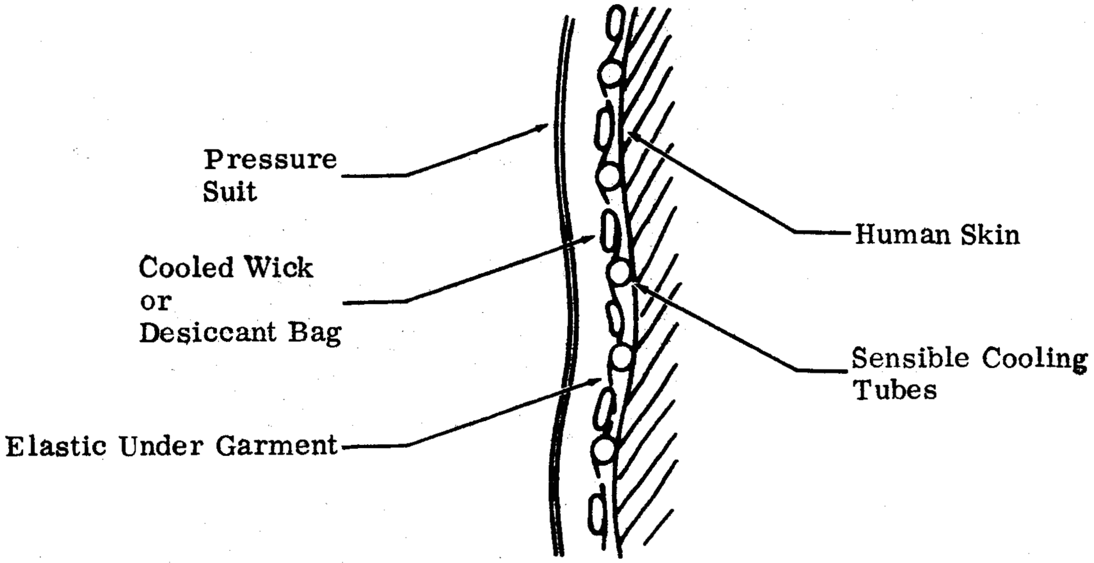


FIGURE 32 PASSIVE HUMIDITY CONTROL DEVICES ADDED TO LIQUID LOOP COOLED SPACE SUIT, USING DIRECT CONTACT BODY COOLING.

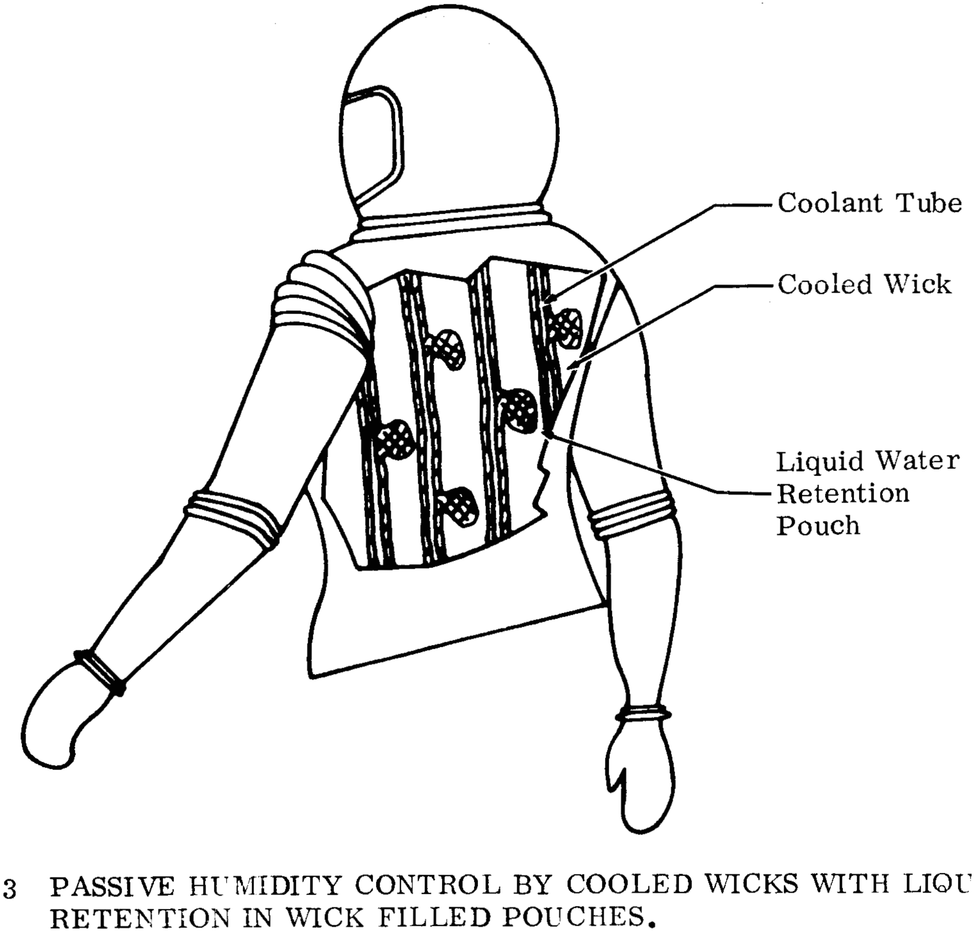


FIGURE 33 PASSIVE HUMIDITY CONTROL BY COOLED WICKS WITH LIQUID WATER RETENTION IN WICK FILLED POUCHES.

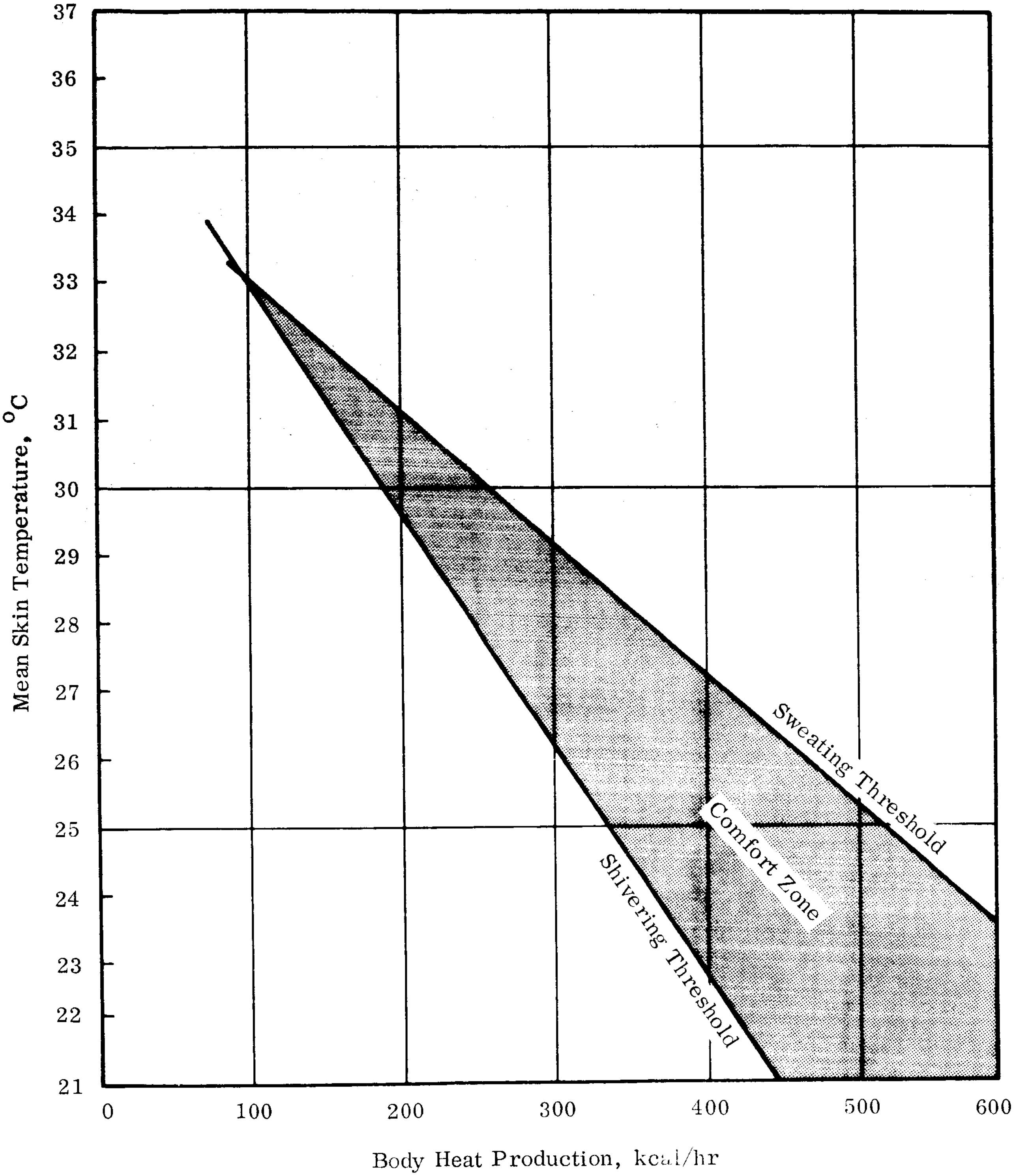


FIGURE 34 MEAN SKIN TEMPERATURE VS. HEAT PRODUCTION CORRELATION FOR COMFORT. (From Reference 3.)

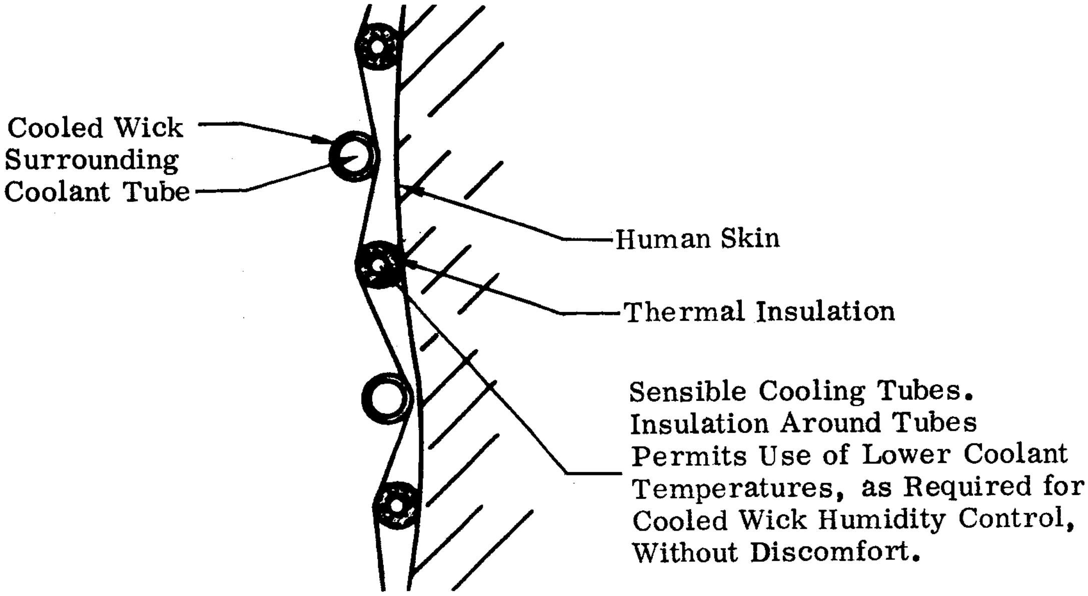


FIGURE 35 CONCEPT OF "NORMAL SWEAT RATE" SPACE SUIT TEMPERATURE AND HUMIDITY CONTROL, USING SINGLE COOLANT AT ONE TEMPERATURE FOR SENSIBLE COOLING AND HUMIDITY CONTROL BY COOLED WICKS.

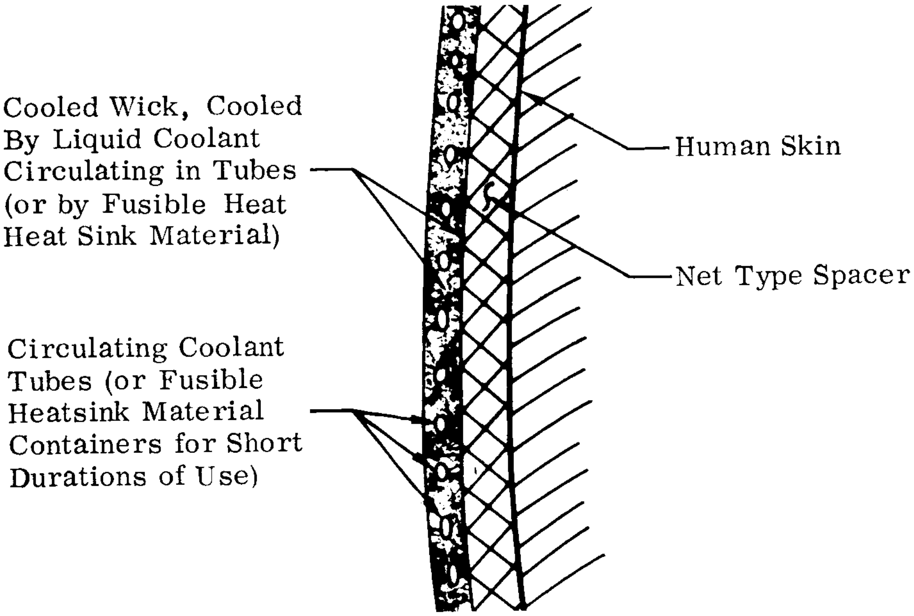


FIGURE 36 THERMAL AND HUMIDITY CONTROL CONCEPT USING COOLED WICK SURFACES FOR HUMIDITY AND FOR SENSIBLE HEAT CONTROL. SENSIBLE HEAT TRANSFER IS PREDOMINANTLY BY RADIATION, WITH LITTLE CONDUCTION, FROM SKIN TO COOLED WICK SURFACE.

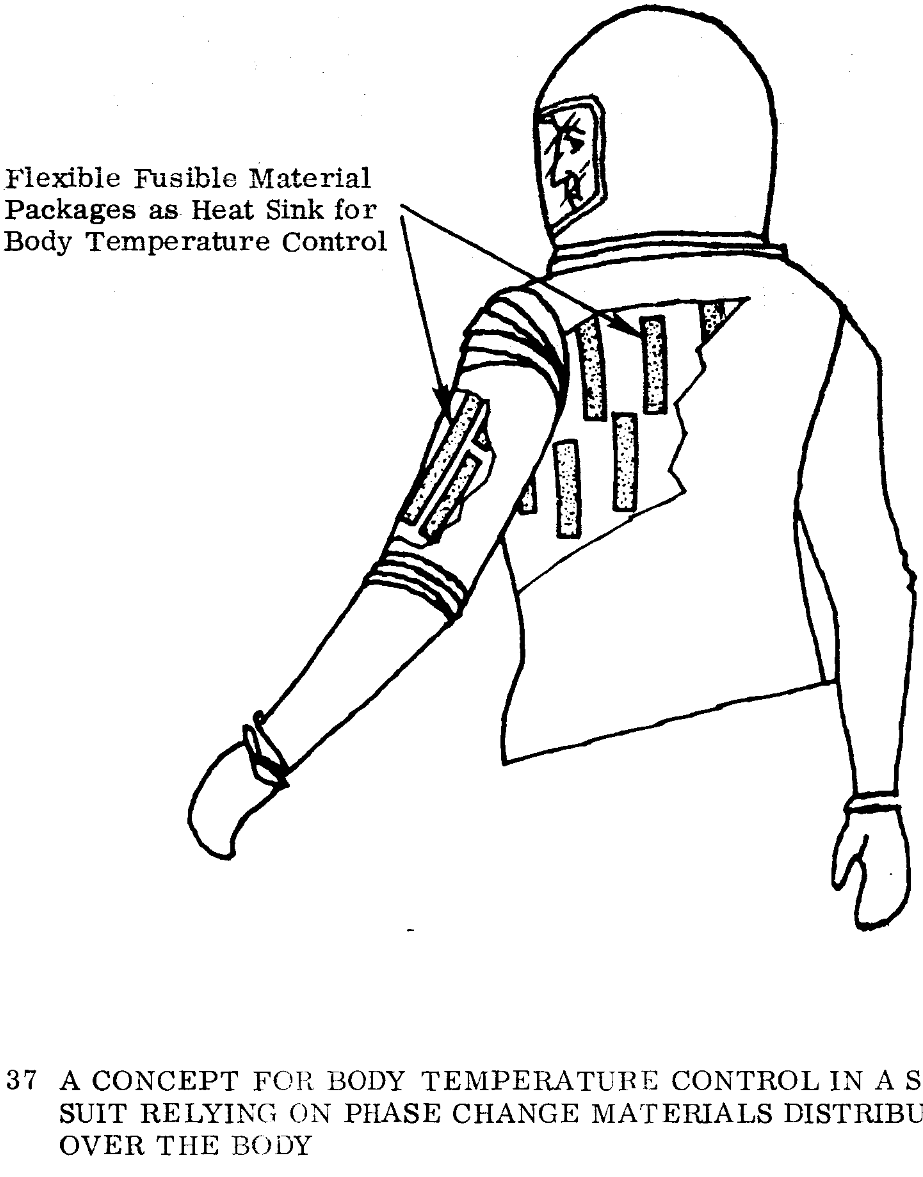


FIGURE 37 A CONCEPT FOR BODY TEMPERATURE CONTROL IN A SPACE SUIT RELYING ON PHASE CHANGE MATERIALS DISTRIBUTED OVER THE BODY