DEVELOPMENT OF
A PORTABLE LIFE SUPPORT SYSTEM
AND
EMERGENCY LIFE SUPPORT PACK

FINAL REPORT

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DEVELOPMENT OF
A PORTABLE LIFE SUPPORT SYSTEM
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EMERGENCY LIFE SUPPORT PACK

FINAL REPORT

13 JUNE 1970

Contract No. NAS 9-8135
National Aeronautics and Space Administration
Manned Spacecraft Center

LITTON SYSTEMS, INC.
APPLIED TECHNOLOGY DIVISION
Space Sciences Center
Beverly Hills, California

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ABSTRACT

This final report on the performance of Contract NAS 9-8135 covers the period from July 1968, when the work was initiated and December 1969 when the final series of tests was completed.

The original contract was for the design and fabrication of a feasibility model of a breathing bag life support system for extravehicular activity. This program was satisfactorily completed in April 1969. In the same month the contract was extended and redirected by NASA to include the design and construction of a prototype emergency life support system. The prototype suit was delivered to NASA in December 1969.

INTRODUCTION

The overall program for Contract NAS 9-8135 was performed in two stages. For the simplification of this final report the work done under the original contract, the design and construction of a feasibility model of a breathing bag life support system for extravehicular activity, will be called Stage I, and the work of the extended and redirected contract covering the design and construction of a prototype emergency life support system will be called Stage II.

STAGE I

DESIGN AND CONSTRUCTION OF A FEASIBILITY MODEL BREATHING BAG LIFE SUPPORT SYSTEM

GENERAL

In accordance with Exhibit A of the original Contract the first part of this development program (Stage I), was divided into two phases of 4 months and 5 months duration respectively. Phase I, in two parts, was concerned with:

a. The design and fabrication of a breathing vest to be compatible with a state-of-the-art soft suit

b. A determination of the general packaging arrangement for the PLSS.

Phase II saw the final design, construction and test of a feasibility model consisting of breathing vest and back pack PLSS complete with connectors to allow external water and gas supply. The back pack was provided to NASA for the purpose of testing the breathing vest system in the GFE suit. It was not a deliverable item under the contract.

The back pack, proprietary to Litton, is characterized by an open loop gas flow system, a gas operated pump for water cooling, a lightweight non-clogging sublimator, and front-mounted controls for air and temperature. The breathing vest developed under this contract, used in conjunction with the Litton PLSS minimizes oxygen storage requirements. At average metabolic rates up to 2000 BTU/hr the two low pressure bottles provide 27 minutes of breathing gas for a total system filled weight, including breathing vest, of

30.5 lb. If high pressure O_2 bottles are substituted, operating time is extended to 4 hours with a weight penalty of only 9 lb.

The total life support system was satisfactorily demonstrated to NASA in March 1969, in vacuum and under both simulated and real metabolic heat loads.

PHASE I

PART A - BREATHING VEST

The first task of the program was to design a breathing vest compatible with a soft suit representative of those in current use by NASA. To this end an immediate request was made for a state-of-the-art ILC suit, sized to fit Dan Curtis, to be provided as GFE. Other items requested as GFE, as part of the cooling system and its interface with the suit were:

- Litton pneumatic pulse pumps (3)
- Liquid coolant garment with head covering (1)
- Suit outflow valve, 3.7 ±0.2 psig (1)

Pending delivery of these items a preliminary design for a breathing vest was completed. The design allowed for testing in both hard and soft suits.

In the meantime, the original breathing vest was prepared for tests with the Litton Mk II suit. A Beckman LB-1 Medical Gas Analyzer was used to measure inspired CO_2. Fittings were made to interface with the normal helmet vent line of the Mk II suit, and the Beckman Gas Analyzer. Preliminary subject tests with this equipment configuration showed that at a metabolic rate of approximately 1200 BTU/hr and an inlet gas flow rate to the vest of 1-1/4 cfm, the inspired CO_2 level was essentially zero (<2 mm Hg).

The prototype breathing vest designed under this contract is in the form of a double-walled vest that is slipped on over the head. It is made of lightweight silicone coated nylon (1.1 weight). Adjustable shoulder straps are provided for sizing purposes and a crotch strap for positioning and securing. A slot is provided in the mid-torso area for the passage of liquid coolant garment lines. The total weight of the breathing vest, including breathing port, entry port, and straps is 0.5 lb.

Prior to the first planned series of tests modification of the Mk II suit was completed with the attachment of the liquid coolant garment connector (GFE), and the installation of a Carleton regulator at the suit exhaust to maintain constant suit pressure. The Beckman LB-1 Analyzer was used to sample and measure the CO_2 content of the exhaust.

The determination of the subject metabolic rate (MR) was based upon the percent CO_2 content of the exhaust gas after taking into account the gas expansion from 3.7 psig to atmospheric pressure. The relationship between MR and CO_2 content of the exhaust, as derived from the nomogram on page 185, Bioastronautics Data Handbook, 1964 is:

$$MR = 620 \times CO_2\ (\%)\ BTU/hr$$

The above equation assumes an input gas flow into the suit of 1-1/4 cfm at a pressure of 3.7 psig.

Tests at 3.7 psig were performed with two subjects (D. Curtis and E. Lindsten) using the Mk II suit with an input ventilation rate of 1-1/4 cfm. CO_2 measurement was taken by the Beckman LB-1 Gas Analyzer at atmospheric pressure. Inspired CO_2 was sampled orally using a SCUBA mouthpiece. The method of sampling is described in Appendix A.

TEST REPORT - BREATHING VEST PERFORMANCE

The following data were taken in the Mk II suit at 3.7 psig using a Sanborn Recorder to obtain a permanent record of the results.

Subject: D. Curtis
Date: July 23, 1968
Test Condition: Standing
Inspired CO_2: 2 mm
Exhaust CO_2: 1.25%, MR = BTU/hr
Test Condition: Walking on horizontal treadmill at 2 mi/hr for 2 minutes
Inspired CO_2: 15 to 20 mm
Test Condition: Stopped walking
Inspired CO_2: 6 mm
Exhaust CO_2: 3.4%, MR = 2100 BTU/hr.

During the above test, the subject was not aware of any breathing restriction or pressure exerted by the vest on the torso. The exhaust CO_2 trace was also very constant indicating that subject's breathing was not affecting the gas flow conditions through the suit. The higher-than-desired inspired CO_2 readings during walking seemed to be caused by the difficulty in maintaining a proper relationship between the subject oral/nasal region and the breathing vest output. This was confirmed when the inspired CO_2 immediately dropped to an acceptable value upon termination of walking.

At the conclusion of the above test the CO_2 sampling line was moved to a point within the breathing vest to test for CO_2 back-streaming. None was measured in spite of the absence of a check valve at the vest outlet.

Test Condition: Continuation of previous test after 3 min elapsed time and with subject still standing. Subject turned head away from inlet gas flow to obtain inspired CO_2 readings under adverse conditions. MR = 1200 BTU/hr
Inspired CO_2: 15 - 20 mm
Test Condition: Subject in prone position

Inspired CO_2: 3 mm

Subject experienced no difficulty in breathing in prone position.

Subject: E. Lindsten
Date: August 2, 1968
Test Condition: Standing
Inspired CO_2: 1.5 mm
Exhaust CO_2: 1%, MR = 620 BTU/hr
Test Condition: Walking at 2 mi/hr for 1-1/2 minutes
Inspired CO_2: 15 mm (walking)
7 mm (stopped walking)
Exhaust CO_2: 2% = 1320 BTU/hr.

The test was terminated after 1-1/2 minutes because subject reported that his chin kept knocking into the input flow duct from the breathing vest as he walked which prevented him from remaining in a favorable relationship to the duct. His recommendation that the duct be shaped to curve past his chin was acted upon for the next test.

A test was performed on the AiResearch pressure relief valve No. 800278-6-1 to check for icing. See Appendix B for test report.

Two of the three GFE pulse pumps were modified to improve their performance. The major change was an increase in the size of the rubber ball check valve from 0.375 in. dia to 0.437 in. dia. This change is recommended on all previously delivered pulse pumps to prevent the 0.375 ball from seat sticking as has been occurring on occasion.

A second modification entailed covering the two air exhaust holes in the pump body proper and the air relief hole in the accumulator with loose weave nylon to prevent membrane rupture if either pump or accumulator membrane should be excessively pressurized. One unit was returned to NASA for evaluation following a 50-hr test.

The use of automatic flow sensing and regulating devices as related to the inlet flow of gas to breathing vest was also investigated at this time. The LARU tilt valve (sometimes called an "Air-Saver" demand valve) as designed by C.J. Lambertsen was considered and then rejected because of unavoidably excessive breathing impedance at high MR.

The only possibility that appeared worthy of future study was some form of automatically controlled upstream valve on the inlet air supply to the breathing vest. If such a valve could be controlled by the subject MR then some gas economy for the open-loop breathing system could be realized. Sensing the subject MR, however, presented a problem.

The possibility was considered of obtaining the subject's MR as an electrical output from a portable infrared CO_2 analyzer, since such a unit, designed specifically for use as a space suit CO_2 sensor, was known to be under development by Beckman Instruments. The degree of their success might make this a feasible approach at some future date.

A second possibility seemed to exist for sensing MR. This was to measure the Δt across the suit liquid coolant garment (LCG). At constant MR and transport water flow the temperature rise across LCG should be directly proportional to MR. The problem here, however, is that the body exhibits considerable thermal inertia by virtue of its mass. The subject need for increased ventilation is considerably more rapid than the rise in MR as derived from the inlet and outlet temperature of the LCG. The subject would, therefore, find himself starving for fresh air if he suddenly began exercising.

The approach to inlet gas control that was followed for the remainder of the program was as originally proposed. A fixed flow of approximately 1-1/4 cfm was used at the inlet to the breathing vest, the option to increase this flow by manually opening a control valve being left to the subject. At low MR, the excess flow allows greater latitude in the relationship of the oral/nasal region to the breathing vest output while maintaining a low value of inspired CO_2.

For the second series of tests the duct from the breathing vest to the oral/nasal region was redesigned to avoid chin interference and consequent high inspired CO_2 values. Figure 1 illustrates the nature of the interference and the action taken to avoid it. However, with the forward-curving duct, while chin interference was entirely eliminated, the problem of high inspired CO_2 readings persisted. The velocity of the air from the vest on compression was such that much of it escaped vest-to-lung exchange.

The next stage in duct design was to recurve the outlet toward the mouth and nose as shown in Figure 2. A test with this configuration provided the first real verification that the breathing vest principle is operational at high metabolic rates. The results of this test in the Mk II suit, using an air flow of 1-1/4 cfm at 3.7 psig, are as follows:

Subject: E. Lindsten
Date: September 4, 1968
Test Conditions: Standing
Inspired CO_2: 0 mm
Exhaust CO_2: 1.1% = 680 BTU/hr
Test Conditions: Walking level at 1 mi/hr for 7 minutes
Inspired CO_2: 0 mm
Exhaust CO_2: 3% = 1860 BTU/hr
Test Conditions: Walking level at 1.2 mi/hr for 6 minutes
Inspired CO_2: 0 mm
Exhaust CO_2: 3.2% = 1984 BTU/hr

The subject had no difficulty maintaining the above metabolic rates and felt he could have continued for an extended period of time. The subject also stated that there was no sensation of either chest pressure or breathing restriction.

At an MR of 1800 BTU/hr subject was instructed to turn his head to the side (away from the inlet duct). The inspired CO_2 level immediately rose

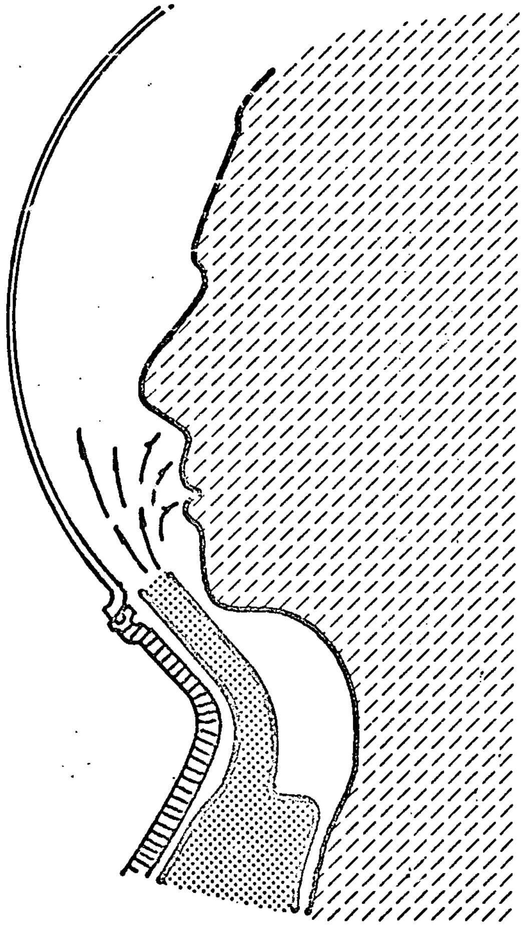


Figure 1. Duct Redesign to Avoid Chin Interference

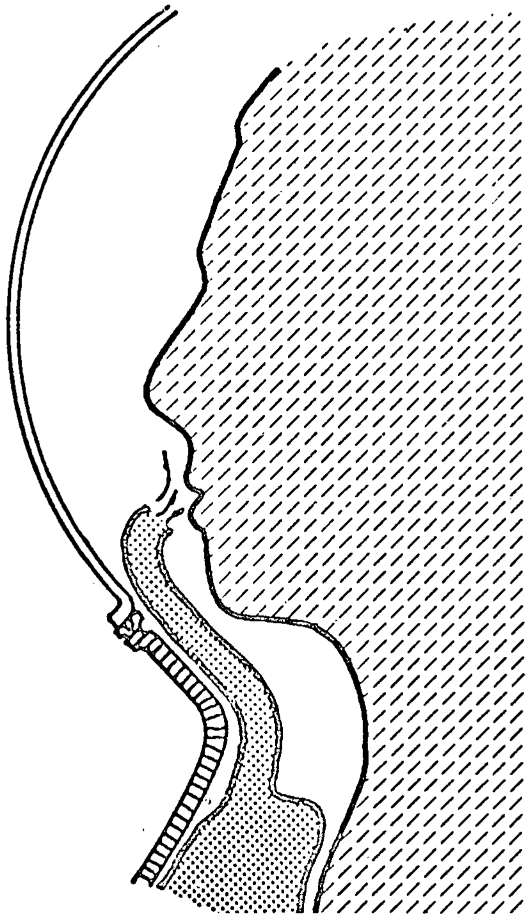


Figure 2. Recurved Duct Design

to 30 mm. After reestablishing the 0 mm inspired CO_2 condition, the subject was then instructed to breathe through his nose rather than his mouth. Although inspired CO_2 could not be directly measured for this condition (sampling tube still located at mouth), the subject said he could feel a CO_2 buildup. He also said he could feel some of the inlet air flow missing his nostrils.

The conclusion drawn from the above test was that as long as the subject breathes through his mouth and is facing forward in the suit, then an inlet air flow of 1-1/4 cfm is adequate at an MR up to 2000 BTU/hr. Any deviation from the above two conditions requires a considerable increase in air flow, negating the advantage derived from using the breathing vest. The above two restrictions may be tolerable if the vest is only to be used in an emergency condition as a means of reducing the amount of purge oxygen required. The two restrictions are considered to be intolerable, however, if the vest is to be employed as a gas saver in a non-emergency condition.

At this stage Litton devised a system whereby adequate vest-to-lung exchange was assured while allowing the subject complete freedom of head position. It was in the form of a light half-mask resting on the bridge of the nose and cheeks that acted as a collector of incoming air and a deflector of expired air. This concept was declared unacceptable by NASA.

With the delivery to Litton of the GFE soft suit, it was prepared for breathing tests. Although the subject found the suit very constrictive, the vest worked well and adequate air was available on demand from a duct of cross section 2-1/2 in. by 3/4 in. Some problems were encountered with the suit connectors, in particular the LCG water connector which was extremely difficult to close. The first test with this suit was terminated because of a water line disconnection inside the suit.

The problems were resolved and a successful series of tests was performed using 1-1/4 cfm air flow and a suit pressure of 3.7 psig. The test reports are as follows:

Subject: R. Rocco
Weight: 145 lb
Height: 5 ft 8 in.
Date: October 3, 1968
Test Conditions: Standing
Inspired CO_2: 0 mm
Exhaust CO_2: 1% = 620 BTU/hr
Test Conditions: Walking level at 1 mi/hr for 6 minutes
Exhaust CO_2: 2.5% = 1550 BTU/hr (constant at 2.5% over the final 3 minutes)

Subject experienced no difficulty in breathing or maintaining the above rates. The test was terminated as it was obvious that 2000 BTU/hr was not going to be reached at the above walking rate.

Test Conditions: Prone (3.7 psig)
Exhaust CO_2: 1.1% = 680 BTU/hr
Inspired CO_2: 0 mm

Subject again experienced no difficulties except that occasionally he could feel the vest inflating against his chest. After some experimenting, he found that his chin occasionally pinched off the inlet duct to the helmet, causing vest inflation. This same effect was subsequently found to be duplicated in a standing position.

Test Conditions: Walking level at 1.4 mi/hr for 4-1/2 minutes
Exhaust CO_2: 3.2% = 2000 BTU/hr (expired CO_2 constant for 2 minutes)
Inspired CO_2: 3 mm max.

At the end of the 4-1/2 minute period, subject inspired CO_2 as monitored suddenly increased to 10 mm which terminated test. It was subsequently found that subject had leaned his chin against the inlet duct restricting flow. It was decided then to repeat the above test.

Test Conditions:	Walking at 1/4 mi/hr in soft suit at 3.7 psig with inlet air flow to suit of 1-1/4 cfm
Extent of Test:	8 minutes with a constant expired CO_2 level for 4 minutes.
Exhaust CO_2:	3.2% = 2000 BTU/hr
Inspired CO_2:	4 mm (max)

The main conclusions drawn from the above test were that the breathing vest is compatible with the soft suit as well as the hard suit and the use of the vest permits much lower inlet flow rates to the suit than would otherwise be required at an MR of 2000 BTU/hr with a maximum restriction on inspired CO_2 level of 7.6 mm.

A problem of chin and inlet duct interference still persisted, however. This was aggravated in the soft suit because the space between the subject's chin and the helmet neck ring is considerably more restricted than in the hard suit.

To obviate the difficulty the duct was once more redesigned. The air is conducted to the oral/nasal region via two curved branches that circumvent the chin entirely (see Figure 3).

As an aid in determining optimum duct size and shape Litton devised and constructed the system illustrated in Figure 4. This test tool provides a simple method for measuring the percentage of air that will exchange between breathing vest and lungs during inspiration as a function of duct configuration. It will be shown that, once this exchange fraction has been determined, an inspired CO_2 value can readily be obtained.

The system allows the direct measurement of the exchange fraction by measuring the CO_2 concentration at the exhaust lines from the manikin's head. Before the measurement is made, the exhaust flow to the suction pump is set equal to the inlet flow through the breathing vest duct to be evaluated. The inlet gas, containing a small quantity of CO_2, is used to set the CO_2 analyzer (Beckman LB-1) to the full scale (100). The meter will then read

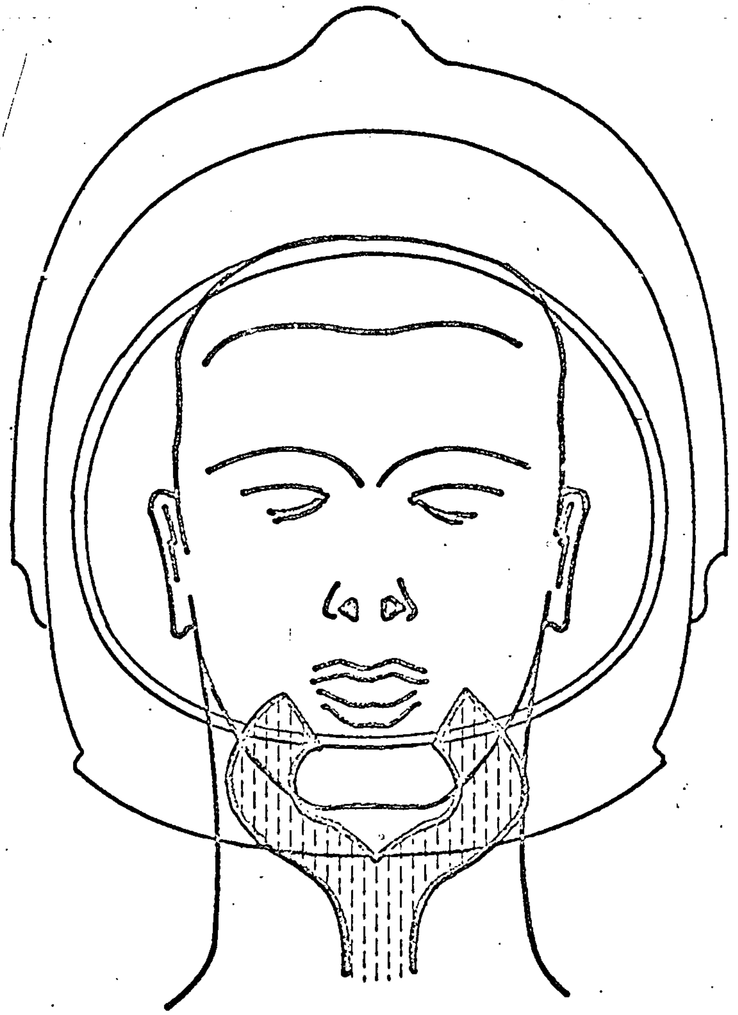


Figure 3. Branched Duct Design

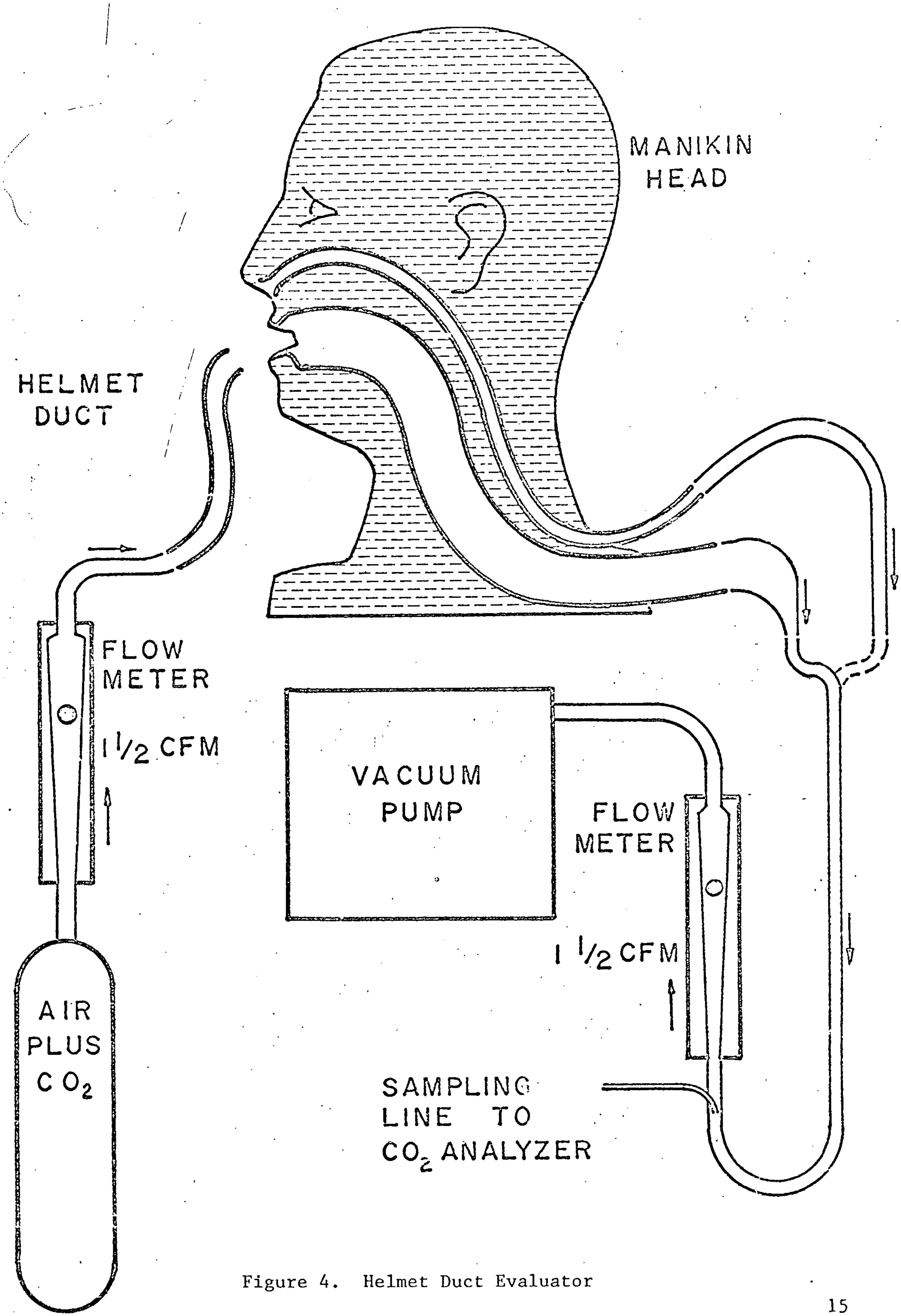


Figure 4. Helmet Duct Evaluator

directly in percentage of the duct gas that enters the oral/nasal cavities (it was independently determined that the LB-1 scale is directly proportional to CO_2 concentration for small values of CO_2). As is shown in Figure 4, the oral and nasal cavities are brought out of the manikin's head separately for independent evaluation.

If X is the fraction of gas leaving the duct that enters the oral/nasal cavities (as measured from the model), then the inspired CO_2 (as measured at the oral/nasal region of a subject in a pressure suit) can be expressed as follows:

$$\text{Inspired } CO_2 = K \quad (1 - X) \text{ mm} \tag{1}$$

Where K is the concentration of background CO_2 expressed in millimeters. K is also a function of the pressure P_0 and the ratio of the subject CO_2 production rate, S, and the average flow to the helmet, T.

$$K = \frac{S}{T} P_0 \text{ mm} \tag{2}$$

Where P_0 is the total system pressure expressed in millimeters.

Substituting in Equation (1) for K gives the relation:

$$\text{Inspired } CO_2 = P_0 \ (1 - X) \ \frac{S}{T} \text{ mm} \tag{3}$$

Assuming an average flow to the helmet of 1.25 acfm and a CO_2 production rate of 0.05 scfm (corresponding to an MR of 2000 BTU/hr), at one atmosphere operating pressure (P_0 = 760 mm) Equation (2) becomes

$$\text{Inspired } CO_2 = 30.5 \ (1 - X) \text{ mm}$$

For the inspired CO_2 to be less than 7.6 mm requires that the fraction X be greater than 0.75, or no more than 24% of the inlet gas can be allowed to miss the oral/nasal cavities.

Equation (3) is useful as it shows the relationship of subject inspired CO_2 to the average helmet flow rate, T, as modified by the fraction (1 - X).

Doubling T, for example, will halve the value of inspired CO_2, all other factors being equal. An increase of T can also be used to compensate for a low value of gas exchange fraction, X. For example, if the vest/helmet duct were completely ineffective (X = 0) then T would have to be at least 5 acfm for the inspired CO_2 to be less than 7.6 mm.

First results indicated that the enlarged duct exit should be about 1/2 inch from the manikin mouth opening, with the duct directed at the mouth for X to be equal to 0.75. The same duct position gave a fraction X of 0.5 using manikin nasal breathing. From Equation (1), this fraction will result in an inspired CO_2 of 16 mm if a subject were used. The subject, of course, would be required to breathe through his nose at an MR of 2000 BTU/hr which is difficult even under a shirtsleeve environment.

The branched inlet duct (Figure 3) was investigated on the Helmet Duct Evaluation. It was again found that in order to obtain an X factor of 0.75 (inspired CO_2 equal to 7.6 mm) the duct exit was required to be no more than 1/2 in. from the oral/nasal region. It was also determined, using Equation 3, that the X factor can be reduced to 0.5 if the input flow is doubled (2-1/2 cfm). The manikin was again used to test this relationship and it was found that the distance between the oral/nasal region and the duct exit could be increased to approximately one inch for an inspired CO_2 of 7.6 mm.

DESIGN REVIEW

A design review and post-award conference was held at Litton's Beverly Hills facility on November 7, 1968. During this review Mr. Joe McMann, MSC Technical Monitor, was used as a test subject for an evaluation of the breathing vest. Using the breathing vest and branched inlet duct as designed for the Gemini suit, he became the first subject to test the system in the Litton EVA suit. The test lasted approximately 10 minutes with the subject walking at 1.3 miles per hour on a treadmill. The maximum observed metabolic rate was 1240 BTU/hr and the inspired CO_2 varied between virtually 0 mm to about

15 mm depending upon the relationship of the oral/nasal region to the duct exit. The high CO_2 value was obtained by the subject turning his head as far as possible from the duct opening.

Interrogation after the test revealed that the subject was not aware of any interface problems involving the vest proper. He was aware of the duct exit sometimes contacting his chin but did not feel that this interference presented any difficulties. He also stated that he was aware of the inlet air flow contacting the oral/nasal region during inhalation but again without discomfort.

The test was terminated before reaching 2000 BTU/hr as it was suddenly realized that exit flow of gas from the suit had decreased. The inlet gas flow had not changed and it was reasoned that the vest must be restricting the flow through the outlet connector. As this condition could lead to overpressurizing the suit, the test was terminated. It was apparent from this test that entrance to the suit exhaust line must not be in a position that can be blocked by the breathing vest.

PART B - LIFE SUPPORT SYSTEM

Concurrent with the development of the breathing vest a preliminary design for the portable life support system was prepared. The design for the water storage container was completed and submitted to a contractor for fabrication. The storage envelope measures 5 in. by 11-1/2 in. and is designed to hold 7 pounds of water in a collapsible bladder. A perforated tube located on the axis of the container is used for water exhaust.

It was determined that the controls for LCG temperature and O_2 flow would be chest operated.

A schematic diagram of the Litton Portable Life Support System is shown in Figure 5.

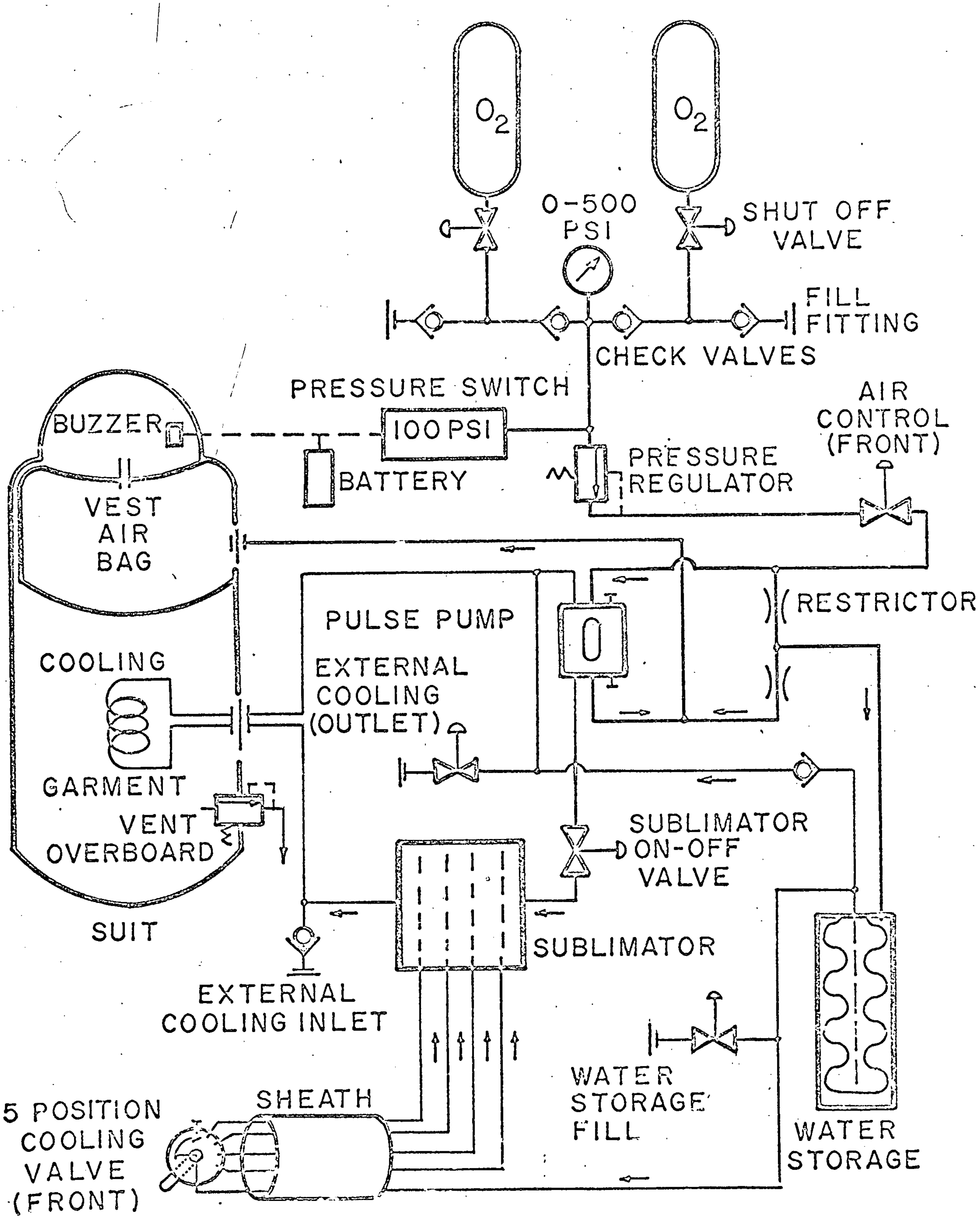


Figure 5. Schematic Diagram of Litton PLSS

The oxygen bottles used are low pressure bottles (400 psi) allowing a total operation time of 24 minutes at a suit pressure of 3.7 psia and a flow rate of 1-1/4 cfm. Lightweight, high pressure bottles (3500 psi) of the same size could be substituted to allow a 4-hour uninterrupted test.

A 100 psi pressure switch is used to inform the subject to switch to the second oxygen bottle and thus leave an emergency reserve of 6 minutes. If high pressure bottles are used then the pressure switch would be set for 900 psi giving 30 minutes of emergency reserve.

Fill fittings are provided for individual refilling of the oxygen bottles. The fittings can also be used as an oxygen inlet from a high pressure umbilical line as a means of supplying breathing gas to the subject. Alternatively, a low pressure umbilical line can be connected directly into the normal suit connector.

The air flow control, which is operated from the front of the suit, has 3 positions, giving the following flows: (1) off, (2) 1-1/4 cfm. (3) 2-1/2 cfm. The middle flow setting of 1-1/4 cfm will normally be used.

Bypassing the air flow section of the pulse pump are two series connected restrictors that serve as both an air bypass and a means of providing a slight positive pressure (over suit pressure) to the water reservoir. The positive water pressure is required for proper pulse pump operation.

The only other major innovations of this life support system are the sublimator and the means for thermal control. The sublimator is a lightweight, plastic foam covered unit described later. The means for thermal control are different from the more conventional approach to subject cooling. In the approach illustrated, the sublimator is divided into four separate sublimation zones that are independently fed by four lines as selected by a miniature control valve brought to the suit front together with the air flow valve. Controlling the feed water to the sublimator, rather than the amount of cooling water bypassing the heat exchanger portion of the sublimator, allows the use of a very small diameter lines and a much smaller control valve than is normally required by bypass control. These features result in a considerable reduction in the size of the front control box and the overall size of the control lines connecting the control box with the backpack.

A packaging layout of the life support system is illustrated in Figure 6. The case dimensions will be 6 in. deep by 17.3 in. wide by 19.5 in. high. The system was planned to include all aspects of a portable life support system (except communications) and to provide 7000 BTU of cooling. When used in conjunction with the breathing vest and with a suit pressure of 3.7 psig, the two low pressure gas bottles will provide 27 minutes of breathing gas. If high pressure bottles (3500 psi) are substituted, then the system will provide four hours of oxygen at average MR's up to 2000 BTU/hr.

The case is of unitized construction with a door opening at the bottom for inspection and maintenance of the functional portions of the life support system including the pulse pump, the air inlet regulator, the inlet to the water reservoir and the sublimator.

Provision for a communication unit has been provided for in the space between the two oxygen bottles and the top of the reservoir (7.3 lb storage). This space has the dimensions of 6 in. x 5-1/2 in. x 1-1/2 in.

PHASE II

PLSS - CONSTRUCTION AND TEST

At the completion of Phase I and determination of the final PLSS packaging arrangement, orders were placed for all hardware items and work commenced on the construction of the back pack shell. This was made of fiberglass laid up on a mandrel to a thickness of 0.15 in. Because the strength and weight of this shell greatly exceeded what was necessary (it weighed approximately 8 lb), a second shell was made with a fiberglass thickness of only 0.070 in. and a total weight of 4.4 lb

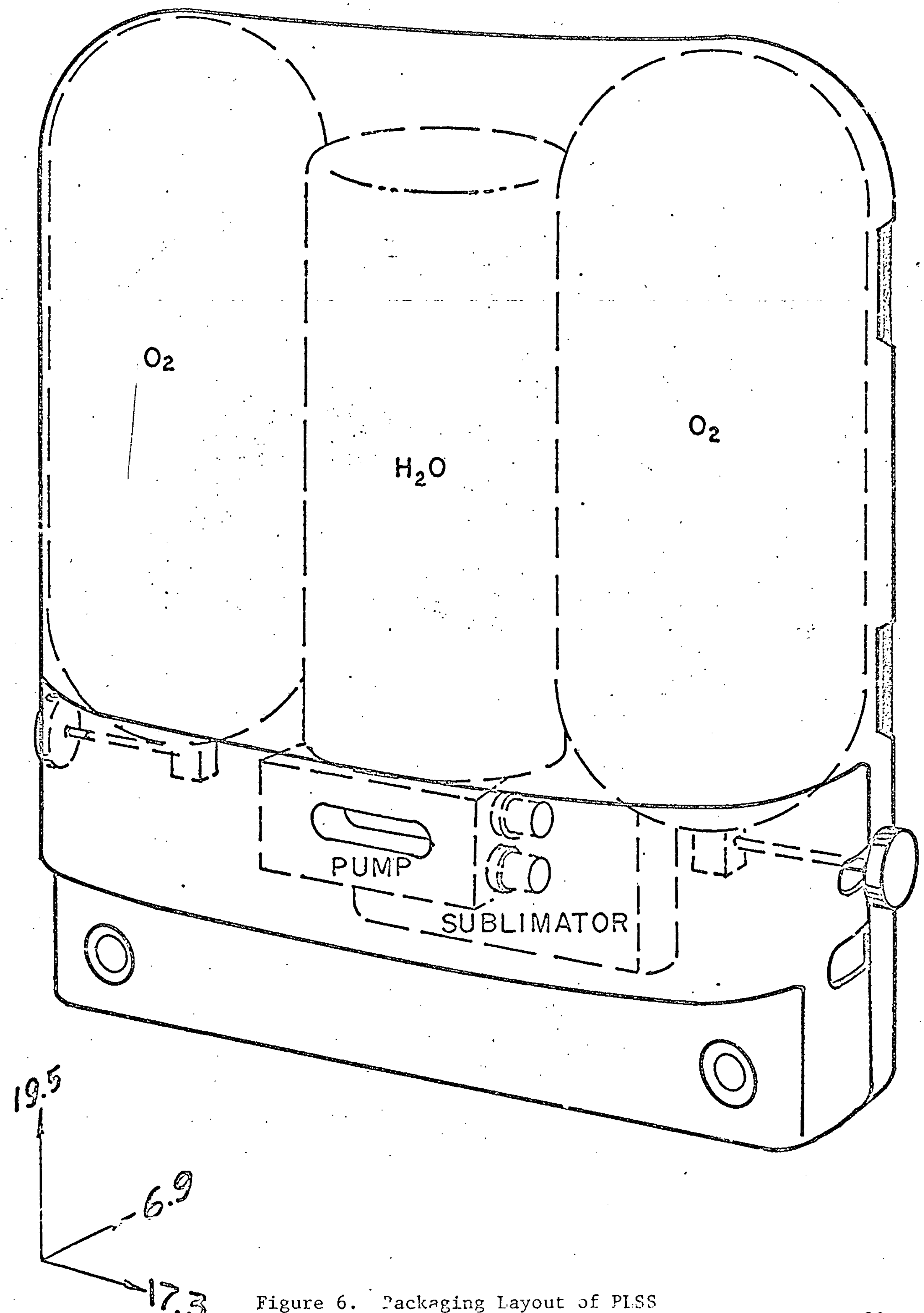


Figure 6. Packaging Layout of PLSS

With the exception of the hardware mentioned above, which included low pressure O_2 bottles, control valves and regulator, the remainder of the components were made in-house.

A lightweight, single-stage regulator (Smith's No. H826 weighing 3/4 lb including gauge) was purchased for use as the pressure reducing mechanism between the pressure bottle and the pulse pump inlet. Because the flow characteristics of the regulator as a function of inlet pressure were not readily available, it was measured by use of the test facility shown in Figure 7. After connecting together the necessary hardware, the pressure vessel was filled to 400 psi with oxygen and then allowed to exhaust through the regulator with an outlet pressure, as set by the throttle valve, of approximately 7 psi. The measured bottle pressure, outlet flow, and outlet pressure are shown in Figure 8 as a function of time. While the performance of the regulator could be improved upon, the constancy of flow and outlet pressure as a function of inlet pressure were deemed adequate.

It should be emphasized that the bottle discharge time of 3-1/2 minutes was at an exhaust flow of 1-1/4 standard cfm. If the same bottle were used in conjunction with a suit operating at 3.7 psia then the time per bottle for the same volumetric flow to the suit is extended to 14 minutes per bottle or 28 minutes for the two bottles that will be provided in the delivered life support system. If the initial storage pressure were then increased to 3500 psi (as is eventually planned), as operating time of four hours is permitted. See Table C-1 in Appendix C.

Water Storage Container. This was a 5 in. dia stainless steel off-the-shelf canister. The cover, siphon tube and bladder were made by Litton.

Sublimator/Heat Exchanger. Under Article VIII of the Contract Schedule the Government was to furnish a PLSS sublimator. Because of the unavailability of this item, Litton's proprietary sublimator/heat exchanger was used. While operating on the self-regulating principle of state-of-the-art sublimators the Litton System differs in construction and mode of operation, resulting

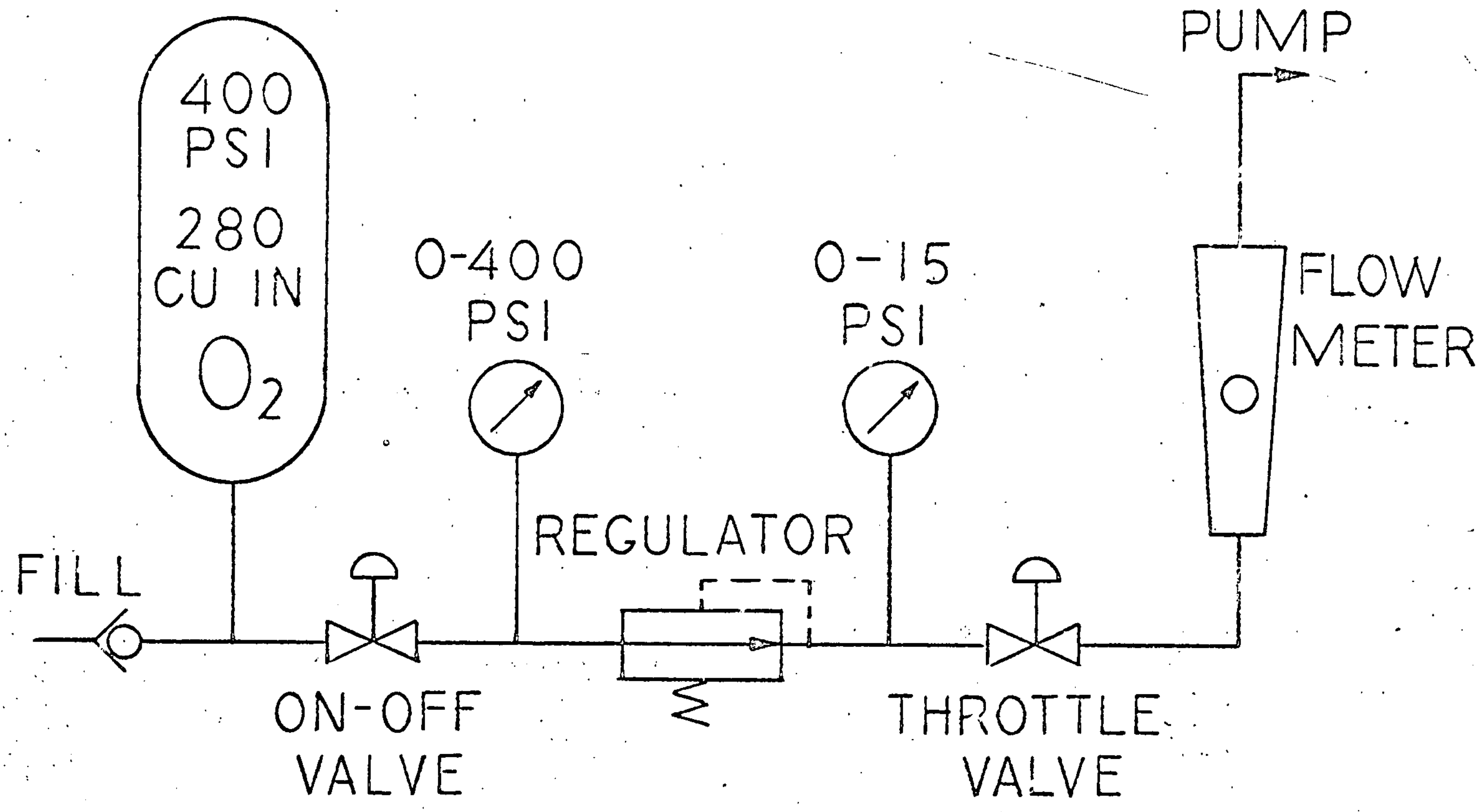


Figure 7. Regulator Test Facility

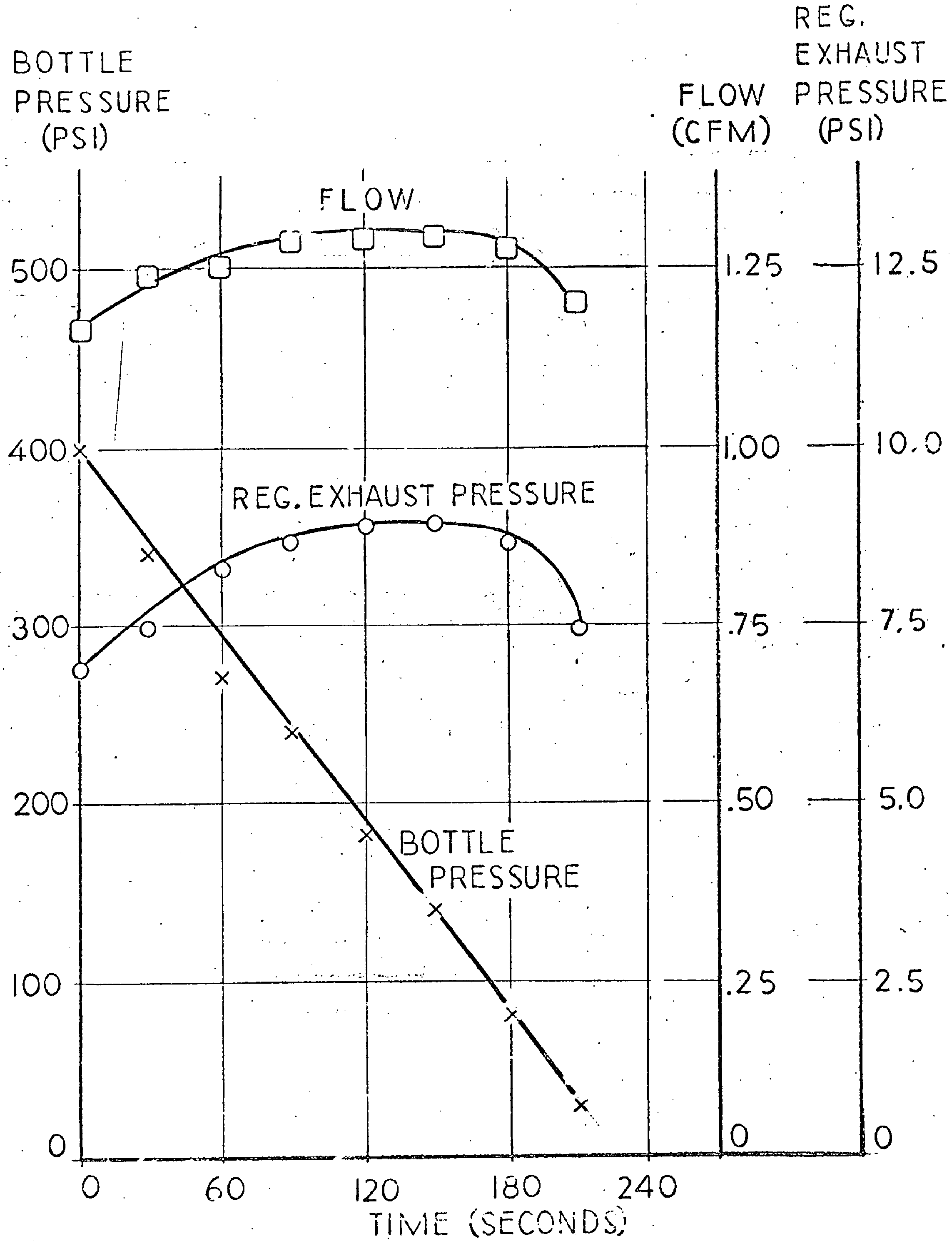


Figure 8. Regulator Flow Characteristics

in a unit that, for the same heat load, is much lighter and smaller. The problem of system degradation through the accumulation of solid residue in the porous metal structure is avoided in the Litton system by separating the sublimation region from the water distribution and flow control region.

Separation is accomplished by the technique illustrated in Figure 9. Feedwater at the suit pressure is initially channeled along a pressure pad distributor/flow controller. The distributor consists of a layer of teflon felt sandwich between an adjustable pressure pad and a metal base.

The feedwater is allowed to seep through the teflon felt throughout the lengths of the pressure pads into the sublimator zones A and B. The water spreads in a thin sheet over the metal surface of the heat exchanger and any water leaving the surface into the open-cell foam covering immediately freezes, preventing further water migration into the foam. The net result is that the water is initially forced to spread more or less uniformly over the surface of the heat exchanger. As the surface temperature of the heat exchanger drops to 32°F by virtue of water evaporation, the water freezes in contact with the surface until the ice front reaches the teflon water feed pads. Water flow stops as soon as the external surface of the pads is frozen and commences again as regions of ice sublimate away. As there are many regions operating in parallel, the net result is a uniform flow of feed-water that varies in direct proportion to the heat input.

The important feature in the above operation is that the major sublimation zone is over the open surface of the heat exchanger and removed from the more critical teflon felt pads. Only a tiny portion of the total sublimation occurs at the pads and, as this takes place on the external surface, any residue that is left does not influence the flow of feedwater through the pads. Feedwater should be of a reasonable purity such as the commercial grade Arrowhead Puritas distilled water (solid residue 1.5 ppm).

The heat exchanger required as the heat source for the sublimator is an integral portion of the thermal control unit. It is the function of this unit to transfer heat from a liquid or gas coolant loop to sublimator.

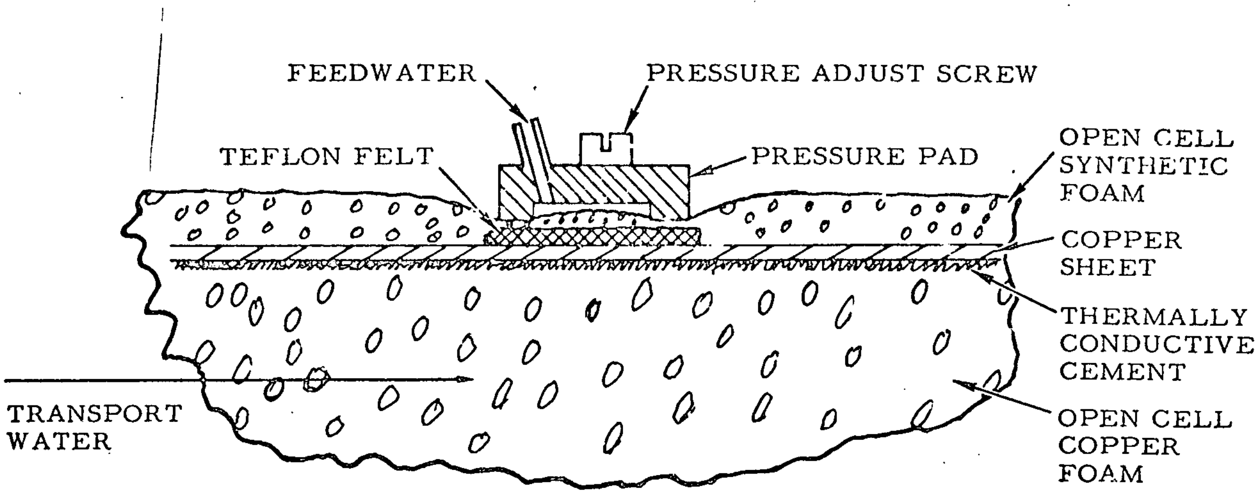


Figure 9. Sublimator Construction

The essential component of the exchanger is a porous copper sheet arranged in such a way that the coolant fluid (either gas or liquid) is forced to pass laterally through the sheet. The labyrinthine course forced on the fluid produces turbulent flow even at low flow rates resulting in high heat transfer between the fluid and the metal. Temperature drops within the metal are kept to a minimum by use of copper and also by providing a very short thermal path from the foam to the sublimator. On the other hand, the interconnecting cells are open enough to allow a relatively low water pressure drop. At 4 lb/min water flow the pressure drop across the unit is 0.25 psi (one third the pressure drop in existing systems). The Litton sublimator/heat exchanger is shown in Figure 10.

Water Pump. The pump used for water circulation is one of the pulse pulps developed for NASA. Three of these pumps were provided by NASA as GFE for this program with all three being modified by Litton to improve their performance. The modifications were:

- An increase in the diameter of the rubber check balls from 0.375 in. to 0.437 in. to obviate the problem of seat sticking which had occurred on occasion. This change was recommended to be made on all pulse pumps already delivered to NASA.
- The two air exhaust holes in the pump body proper and the air relief hole in the accumulator were covered with loose weave nylon to prevent membrane rupture if either pump or accumulator membrane are excessively pressurized. One unit underwent a 50-hour test and was returned to NASA for evaluation.
- Neoprene rubber was substituted for hypalon to increase elasticity.

Supporting Frame. The supporting frame upon which all the components are mounted is an anodized aluminum weldment.

Remote Control Unit. This chest-mounted unit has two rotary valves, one to control air flow, and a 5-position valve for varying inlet water temperature to the LCG by applying zone control to the sublimator. Because

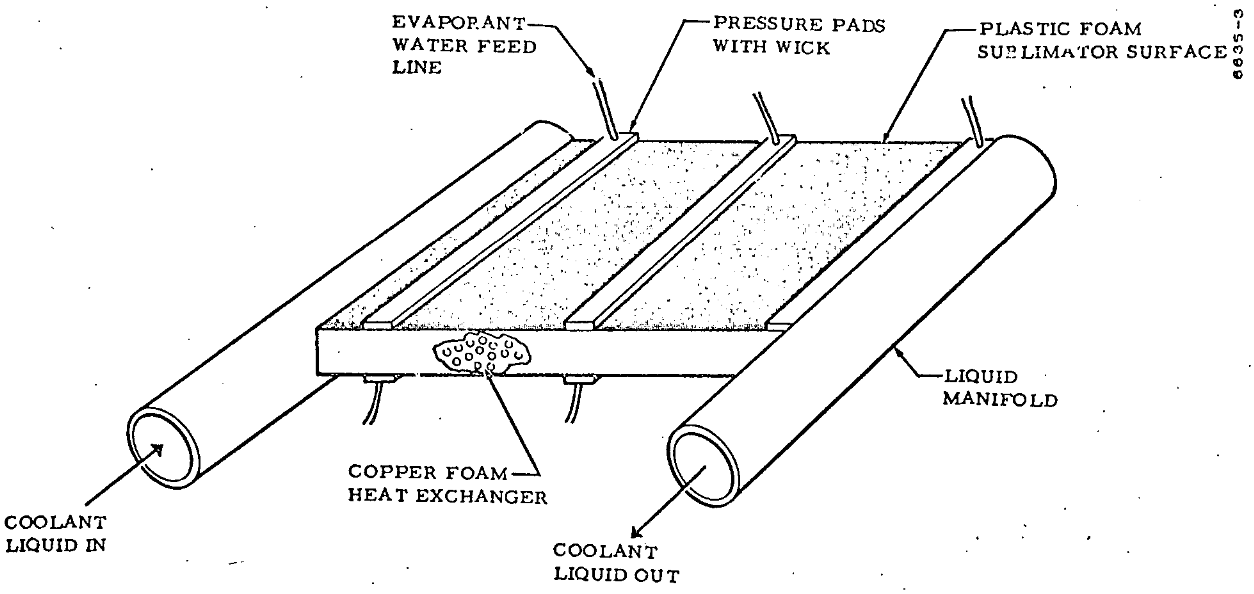


Figure 10. Sublimator/Heat Exchanger

of the very low feedwater flow rate the tubes from the remote control to the PLSS are of very small bore that allows the temperature control line bundle to have a diameter of less than 1/4 in. The air/oxygen feed line is also of small diameter, again because of the low flow rates involved.

Final System Arrangement. A review of the system schematic resulted in the elimination of the on-off valve located between the pulse pump and the sublimator. This valve was intended to be closed during external coolant supply to prevent flow to the sublimator but it was realized that the water check valves in the pulse pump perform this function, making the shutoff valve unnecessary. Later, two further items were eliminated from the system; the check valve previously located in the water storage to LCG line, and a water inlet fill valve.

The check valve was tentatively eliminated as it was deemed unnecessary to the protection of water purity in the storage unit. The use of distilled water in both the LCG and sublimator sections should preclude the need of the check valve, especially as the sublimator that will be used is insensitive to clogging.

The elimination of the check valve made automatic the elimination of the water fill valve. As this valve is now paralleled by the valve previously designated "External Cooling (outlet)," the two functions can now be combined in a single unit designated "External Cooling and Outlet and Fill."

Two-Stage Regulator. A superior two-stage regulator was substituted for the single-stage regulator of the original system.

Figure 11 illustrates a performance comparison of the new two-stage regulator unit with the single-stage unit. The method used in evaluating the two units was as shown in Figure 7.

As can be seen from the curves the output of the two-stage unit is essentially independent of the input pressure. Besides providing a more uniform flow to the breathing vest, the two-stage unit actually allows a

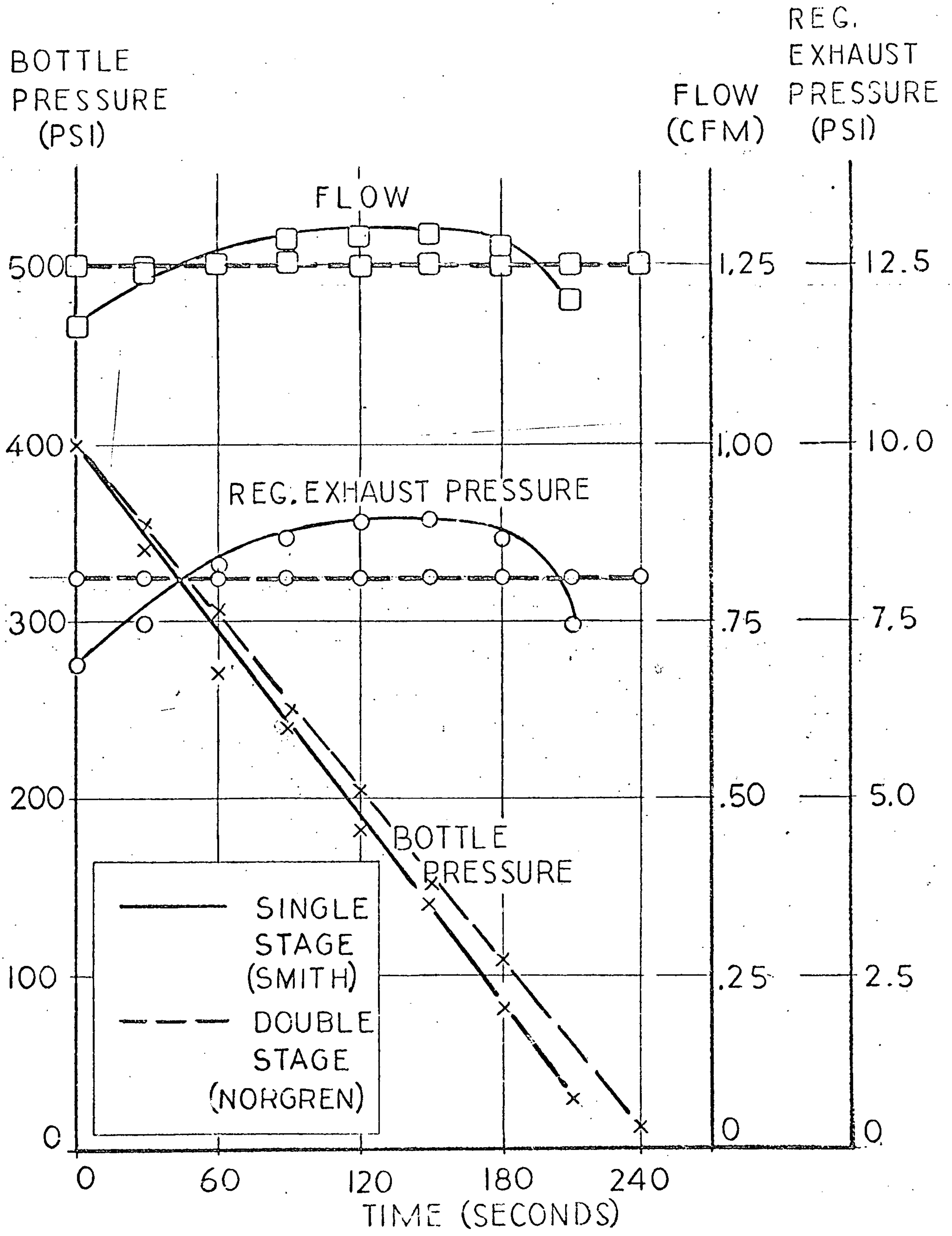


Figure 11. Regulator Flow Characteristics

13 percent increase in operation time by virtue of the constancy of flow. Additional features are that the two-stage unit is self-venting, eliminating any downstream pressure buildup problem, and it weighs less than its single-stage counterpart (0.48 lb versus 0.57 lb).

The revised schematic diagram is shown in Figure 12. Final assembly of the prototype PLSS (Figure 13) was completed in the seventh month of the program.

The dry weight of the unit, including shoulder straps, remote control unit and breathing vest is 22.8 lb. The filled weight of the 7000 BTU system is then estimated to be 30.5 lb (7 lb water and 0.7 lb oxygen).

As shown in the photograph, the two oxygen control valves are brought out to the base of the PLSS, allowing the crewman to easily switch bottles when cued by a tone alarm. The alarm indicates to the crewman that his first bottle now serves as the system emergency reserve should the second bottle for some reason fail. When the second bottle is exhausted to one fourth of its original value the alarm will again activate, indicating to the crewman that he has entered the final quarter of his mission and should return to his base.

Alternatively, the crewman can open both control valves at the beginning of a mission and use the first tone alarm as an indication that his mission time is 3/4 completed. This approach is considered somewhat less attractive because it eliminates the emergency reserve feature as described above. The second approach has the advantage, however, of eliminating the requirement for the crewman to open a valve on the PLSS during the mission.

Except for the two oxygen valves, control of the PLSS is completely accomplished by use of the chest mounted remote control unit attached to the end of a two foot, flexible extension line. The remote unit contains two control valves allowing two oxygen flow levels and five thermal control levels.

The PLSS is provided with a fiberglass enclosure with a removable bottom panel for easy accessibility to the system components. The two large holes

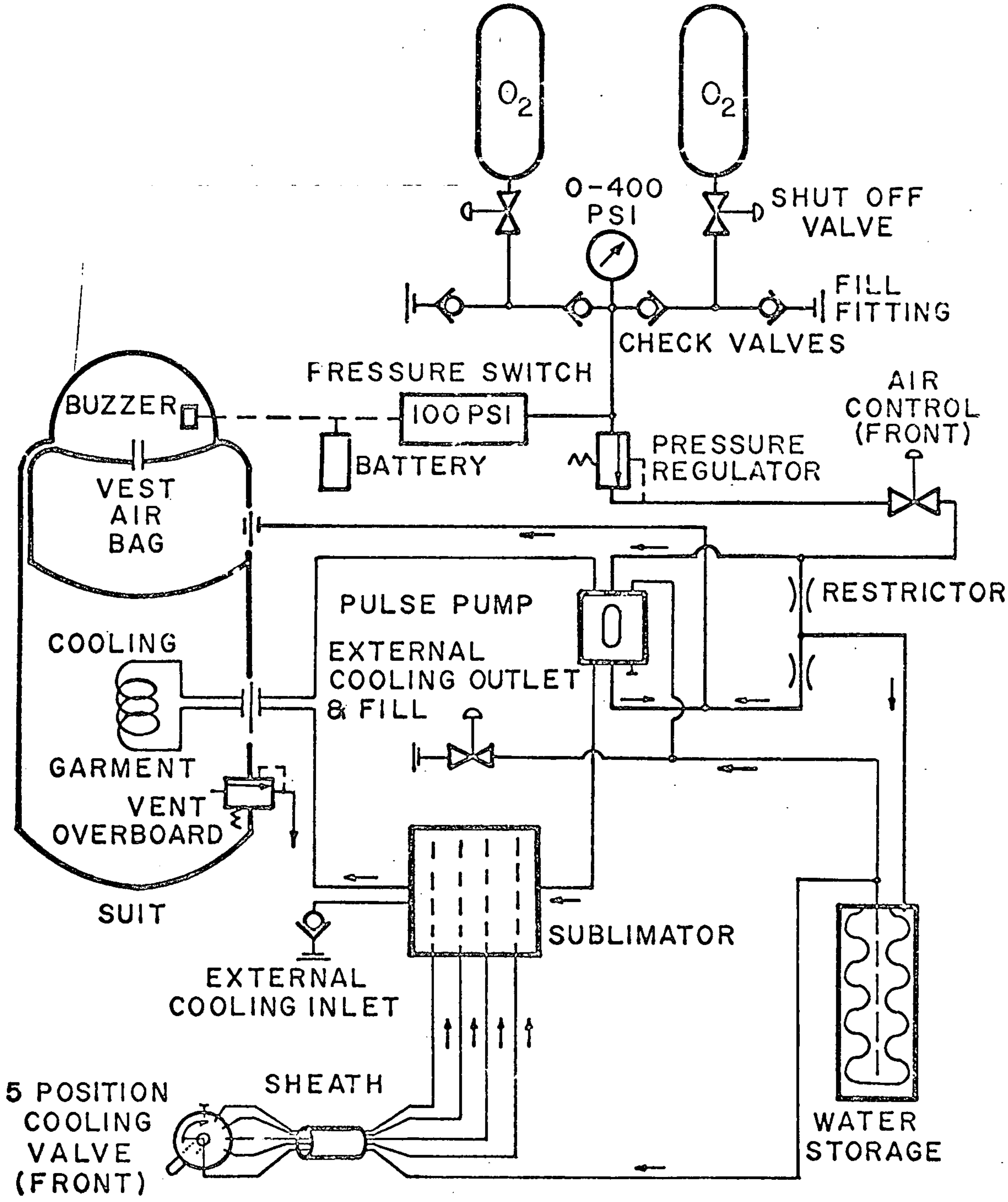


Figure 12. Revised Schematic Diagram

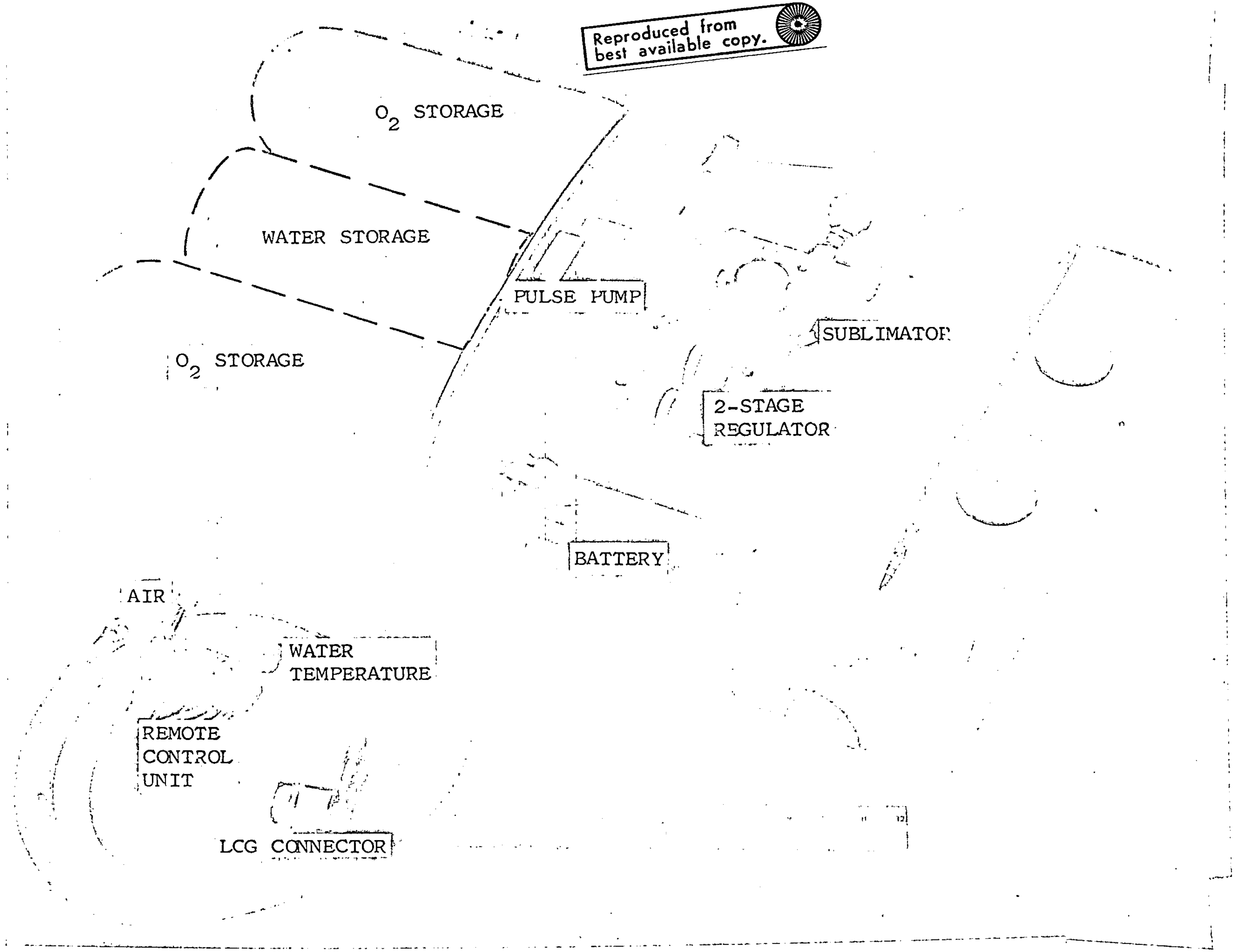


Figure 13. PLSS Package Assembly

in the panel are primarily for sublimator exhaust venting but are also used to allow the high pressure oxygen gauge to be visible. System water and oxygen filling through the designated fittings can be accomplished with the panel either in place or removed.

TESTING

During the last two months of the program the major effort was expended in debugging and testing the back pack under vacuum conditions using simulated metabolic heat loads. All goals were essentially met with the exception of the thermal loop suit inlet and outlet temperatures at an MR of 2000 BTU/hr. The inlet temperature at the MR was measured to be 55°F instead of the desired 48°F, indicating that the heat transfer coefficient of the sublimator unit is not as great as expected. It was not possible to construct the sublimator as originally designed. The original design called for 6 percent density Emerson and Cuming, Inc. open cell copper foam as the heat exchanger element. Emerson and Cuming no longer produce this material and at their suggestion the Metallurgical Division of General Electric was contacted. For some reason, not clear, G.E. does not have the capability of producing 6 percent density open cell foam but can produce 3 percent density. At G.E.'s suggestion the 3 percent density material was obtained and then compressed by a factor of 2 to obtain 6 percent density.

The sublimator constructed of the compressed material was found to be inferior when compared with results from the original unit that used the uncompressed material. After eliminating several other possible causes, the thermal conductivity of the compressed copper foam was compared with the uncompressed material of equal density. As suspected, the two materials were not thermally equivalent, with the compressed material having a conductivity of about half that of the uncompressed material.

The test indicated that compression actually reduced the conductivity of the foam on a unit thickness basis (the heat transfer coefficient remained constant). In retrospect this is reasonable, as compression does not alter the thermal path lengths in the foam but only distorts the cells.

After considerable phone communication with both G.E. and Emerson and Cuming in an attempt to obtain the original foam or equivalent, it was finally decided to abandon the foam concept in favor of an in-house, machined, all aluminum, fin construction.

Static Testing in Vacuum Chamber. Figure 14 illustrates the test apparatus used for evaluating the life support system. Except for the remote control unit which was extended to permit control from outside the Litton space chamber, the PLSS was completely contained in vacuo. Passthroughs were made in the chamber wall allowing control, air supply and exhaust, and liquid coolant water.

The coolant water, as recirculated by the internal pump of the PLSS, was connected by 3/8 inch diameter Poly-Flo lines to an air trap, a heating source, a standard liquid coolant garment (using standard LCG connectors) and a liquid flow meter. The product of the temperature differential, Δt (^{o}F), as measured at the liquid input and output connections of the PLSS, and the water flow, $\dot{W}$ (lb/hr), was used to determine the heat input, $\dot{Q}$ (BTU/hr), to the system. The heat input (simulated metabolic loading) was supplied by a hot plate attached to a coil of copper tubing through which the liquid circulated.

The liquid loop trap, as shown in Figure 14, was added to allow the removal of any air that occasionally is contained in the system after filling the PLSS water storage bladder. More stringent filling procedures than the one employed would, of course, eliminate the need of the trap.

Air to the PLSS, as shown in Figure 14, was supplied on a continuous basis using the laboratory air supply. The two storage bottles contained in the pack could also be used, but this would entail frequent refilling. Either of the O_2 inlet fill fittings (see Figure 12) can be used to connect the source of air to the system.

Exhaust air that normally would provide inlet air to the suit breathing vest was brought out by a separate line through the chamber walls. A vacuum

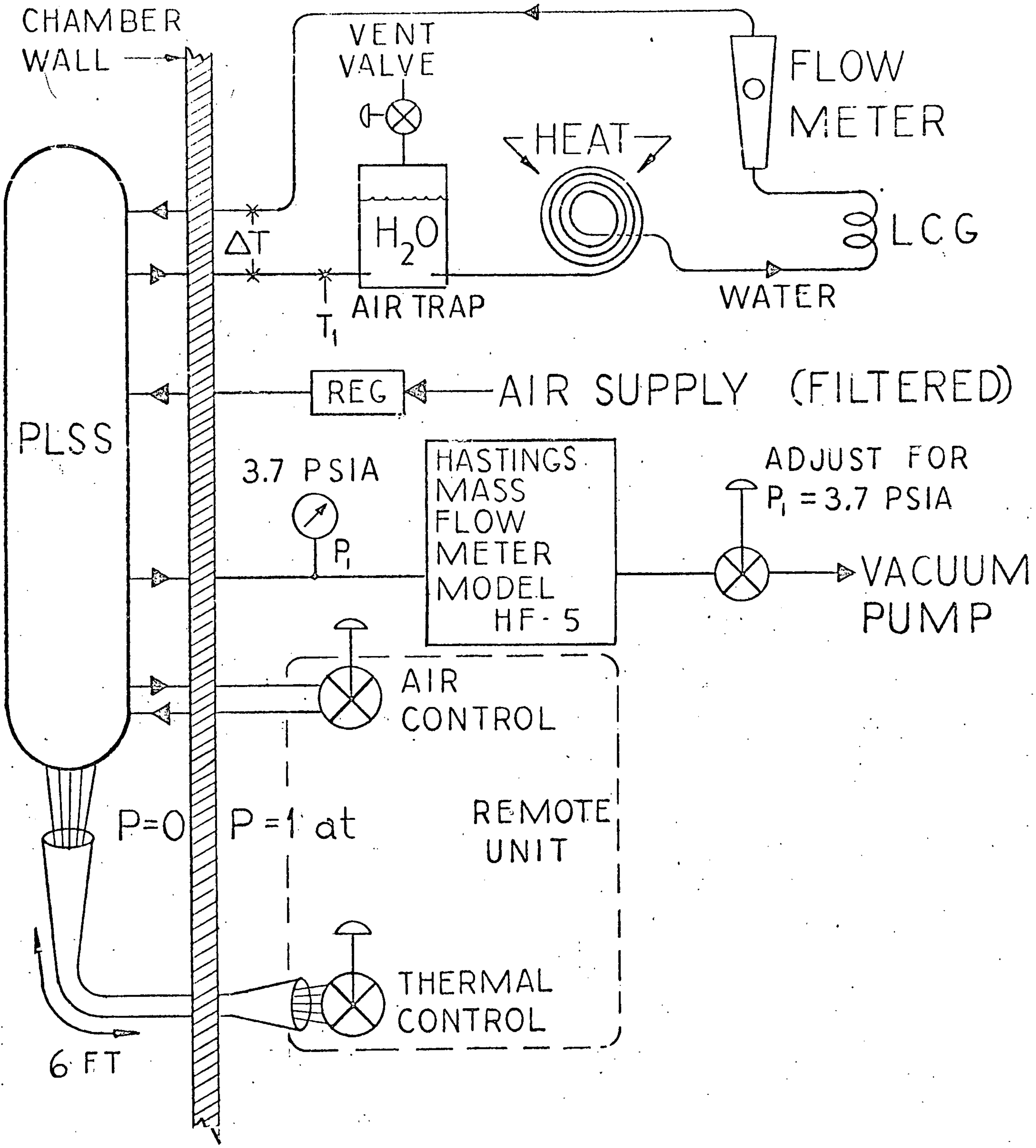


Figure 14. PLSS Test Apparatus

pump was used to maintain the output of this line (as measured by the pressure gauge, P_1) at 3.7 psia with the actual flow of gas as determined by a Hastings mass flow meter. Separate pumping facilities were used for the PLSS exhaust air so as to avoid overloading the main pumps of the space chamber.

After leak testing the system, the output gas flow was set for 1-1/4 cfm at 3.7 psia (1.68 lb/hr) using the Hastings mass flow meter and checking with a rotameter. This flow measurement was made for the normal position of the remote control unit with its full-open position giving about 2-1/2 cfm.

A test run was then conducted using air from the system's 400 psi storage bottles. It was verified from this test that the flow of 1-1/4 cfm at 3.7 psia had been realized as the two bottles took an extrapolated time of 28 minutes (30 minute goal) to be exhausted.

The pulse pump for circulating coolant water was then placed in operation at a water storage pressure of 2 psi above suit pressure (5.7 psia). After setting the pressure rise across the pump for 6 psi at a flow of 240 lb/hr by means of a line restrictor, the restrictor was removed allowing an LCG (with suit connector) to be substituted.

System tests have primarily involved sublimator performance at varying heat loads and remote control settings.

The initial thermal test consisted of adding 1200 BTU/hr of heat to the unit at a flow of 240 lb/hr and measuring the equilibrium water temperature. Initial results were as follows:

Date: January 31, 1969
$\dot{Q}$ = 1200 BTU/hr
$\dot{W}$ = 240 lb/hr

Remote Control Position	LCG Inlet Temperature
1	73°F
1+2	61°F
1+2+3	58°F
1+2+3+4	56°F

Date: February 5, 1969 (increased sublimator feedwater flow)

$\dot{Q}$ = 1200 BTU/hr

$\dot{W}$ = 240 lb/hr

Remote Control Position	LCG Inlet Temperature and Test Duration
1	68°F (10 min)
1+2	53°F (25 min)
1+2+3	48°F (10 min)
1	68°F (30 min)
0	(Climbing fast)
1	70°F (10 min)
1+2+3	47°F (40 min)
Increase power to 2160 BTU/hr	
1+2+3	61°F (20 min)

Figure 15 shows the results from a sustained heat load of 2000 BTU/hr starting with a filled water storage unit (7.3 lb). As explained previously, the heat transfer coefficient of the sublimator is not as high as desired, resulting in an inlet LCG temperature of 55°F rather than the desired 48°F. In addition, the unit did show a slow degradation as a function of time indicating that the teflon felt in the water distributor portion of the sublimator was changing its impedance. This was assumed to be because the water loop had not been adequately purged after assembly and some large particle contaminants had been left in the system. Figure 16 indicates the validity of this assumption. For this test the system was initially flushed with commercial grade distilled water. The results indicated an essentially constant inlet temperature to the LCG of 58°F for a period of 3-1/2 hours at a heat load of 2000 BTU/hr.

One feature of the Litton sublimator that has not been previously stressed is that the teflon felt strips can be replaced in a matter of minutes should they become plugged. It is a simple matter, therefore, to reactivate the unit.

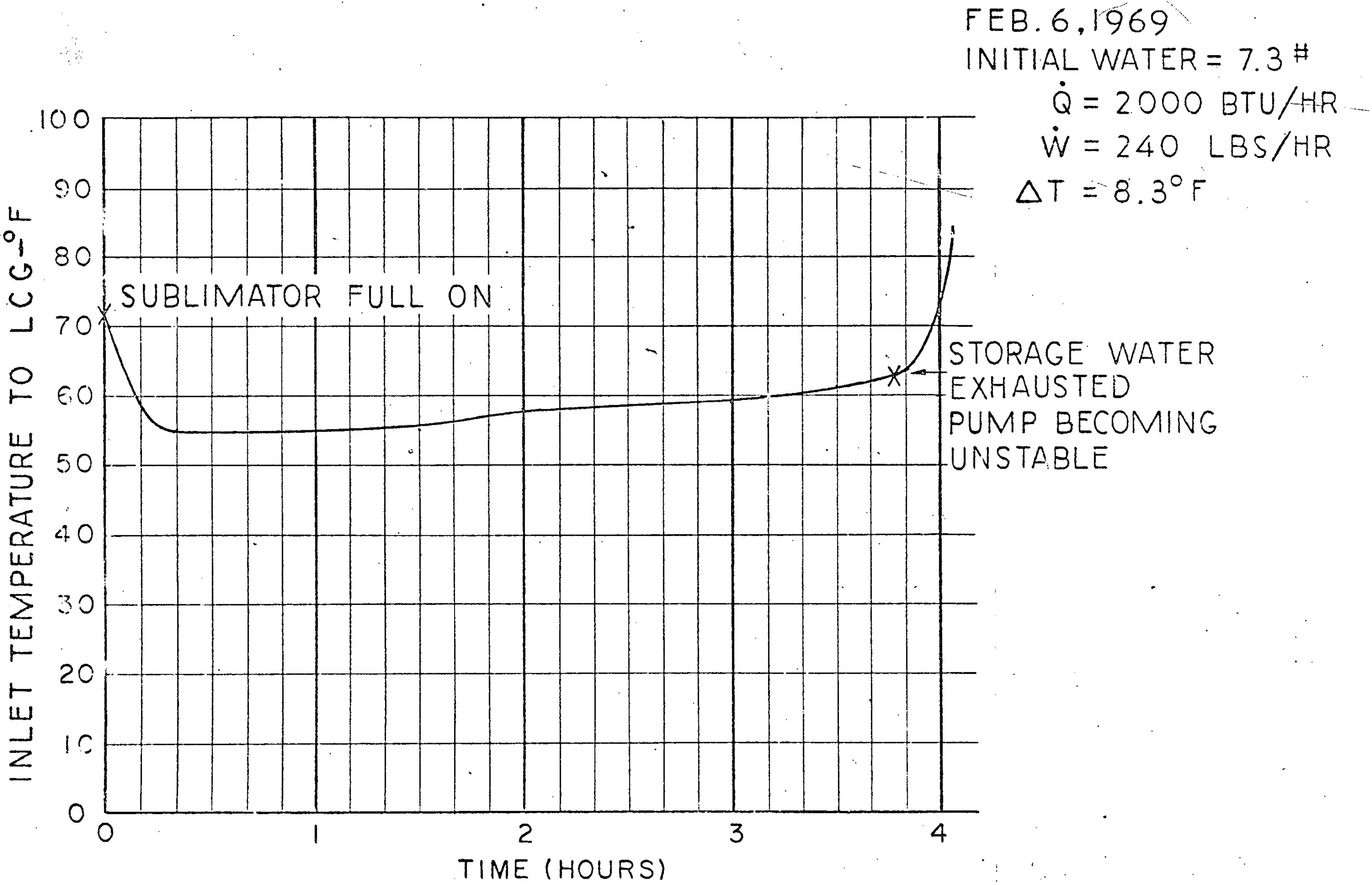
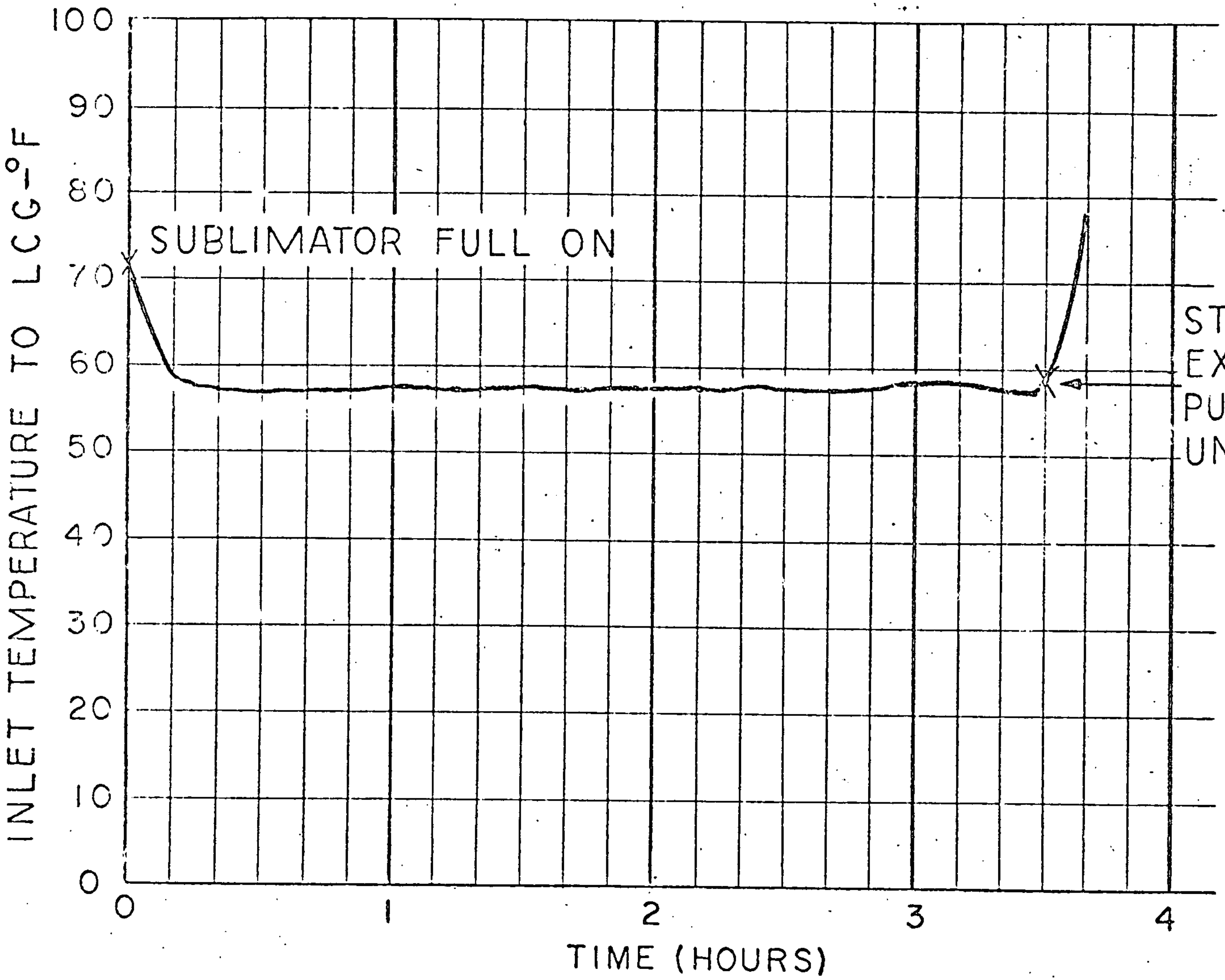


Figure 15. LCG Inlet Temperature at Constant Heat Load



SUBLIMATOR FULL ON

STORAGE WATER EXHAUSTED
PUMP BECOMING UNSTABLE

FEB.11,1969
INITIAL WATER = 7.3#
$\dot{Q}$ = 2000 BTU/HR
$\dot{W}$ = 240 LBS/HR
ΔT = 8.3°F

Figure 16. LCG Inlet Temperature at Constant Heat Load

An important result obtained from Figure 16 is the storage water exhaustion point at approximately 3 hours and 45 minutes after activating the system. Based on the measured heat load of 2000 BTU/hr and using 1000 BTU/lb as the heat of vaporization of the 7.3 lb of storage water gives an estimated operation time of 3 hours and 39 minutes. The estimated and measured results are, therefore, in very close agreement.

The system response time of approximately 10 minutes (see initial portion of graph) is assumed to be primarily the result of the large thermal inertia of the hot plate used to supply heat to the system.

Testing with PLSS in Vacuum Chamber and Subject at One Atmosphere. Testing progressed to the application of actual metabolic heat loads to the PLSS with a pressure differential of one atmosphere. With the PLSS only in a vacuum the air and water lines were led out of the vacuum chamber and attached to an A-6L suit and LCG worn by a subject equipped with the breathing vest.

The test arrangement is shown in Figure 17. The first test was conducted on February 11, 1969, with Dan Curtis as the subject. A second test took place on the following day with the NASA Technical Monitor, Joe McMann, as the subject.

Using a treadmill to produce the desired metabolic rate, both subjects were exercised at a sustained MR of approximately 2000 BTU/hr (7-1/2 minutes and 12 minutes duration). Throughout both tests the breathing vest maintained an inspired CO_2 level less than 4 mm at an average ventilation rate to the helmet of 1-1/4 acfm.

The subjects were able to select the number of sublimator feed lines and thus the degree of cooling. At the maximum MR both subjects demanded maximum cooling with subject McMann achieving an inlet LCG temperature of 52^{o}F at test termination.

Both tests were considered highly successful with all subsystems of the PLSS performing to expectations.

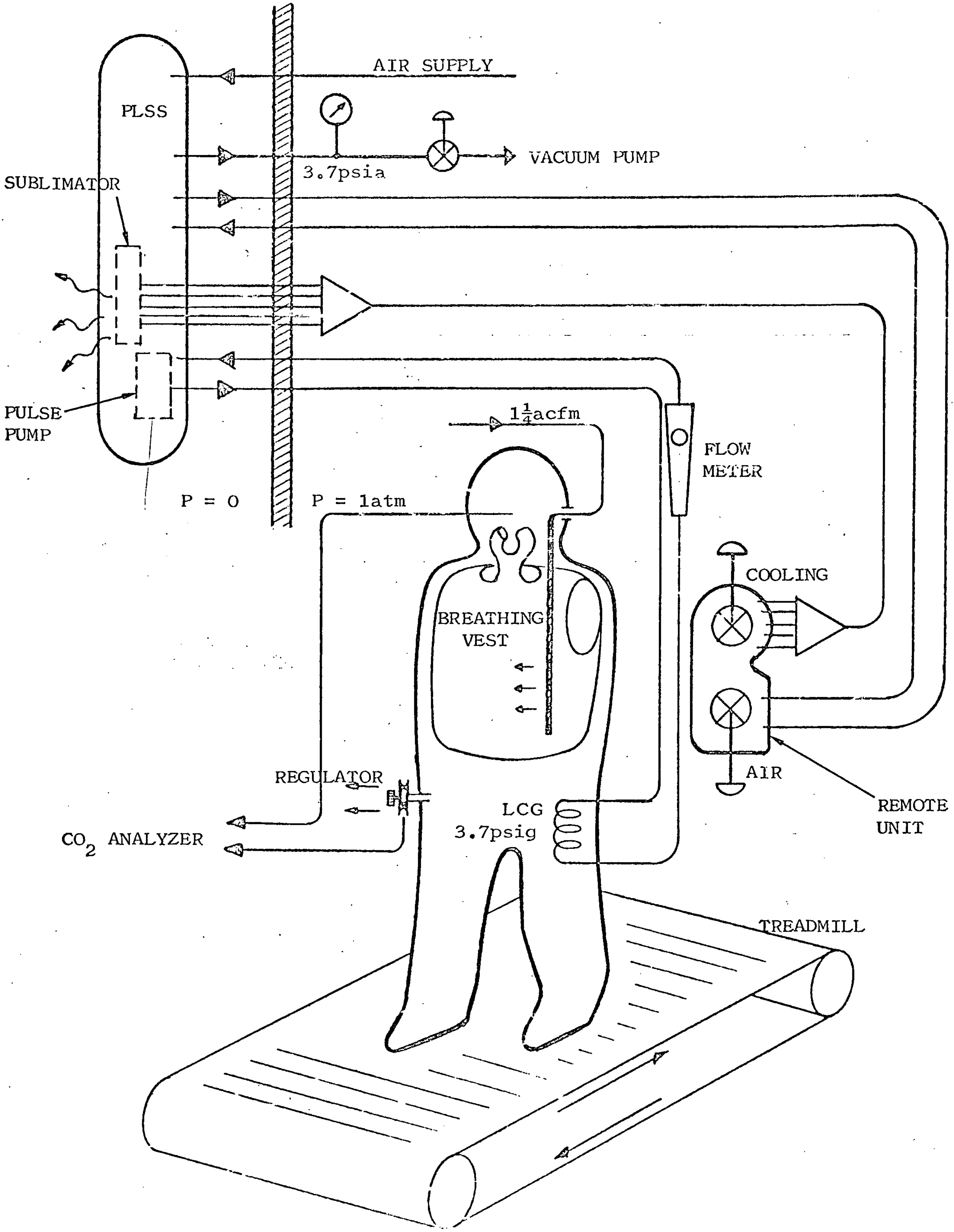


Figure 17. Diagram of PLSS Arrangement for Manned Testing

Body cooling for the test duration was adequate for both subjects although a test continuation would probably have necessitated additional cooling. Because neither test employed the LCG head shroud some head sweating and slight visor fogging were experienced. Neither subject felt any indication of chest pressure or oxygen starvation. The only adverse criticism was that the helmet duct impaired a clear view of the chest area of the suit when the head was bent forward.

Figures 18 and 19 show a reproduction of the strip chart obtained from both tests showing the subject's LCG inlet temperature together with inspired CO_2 as a function of time and metabolic rate.

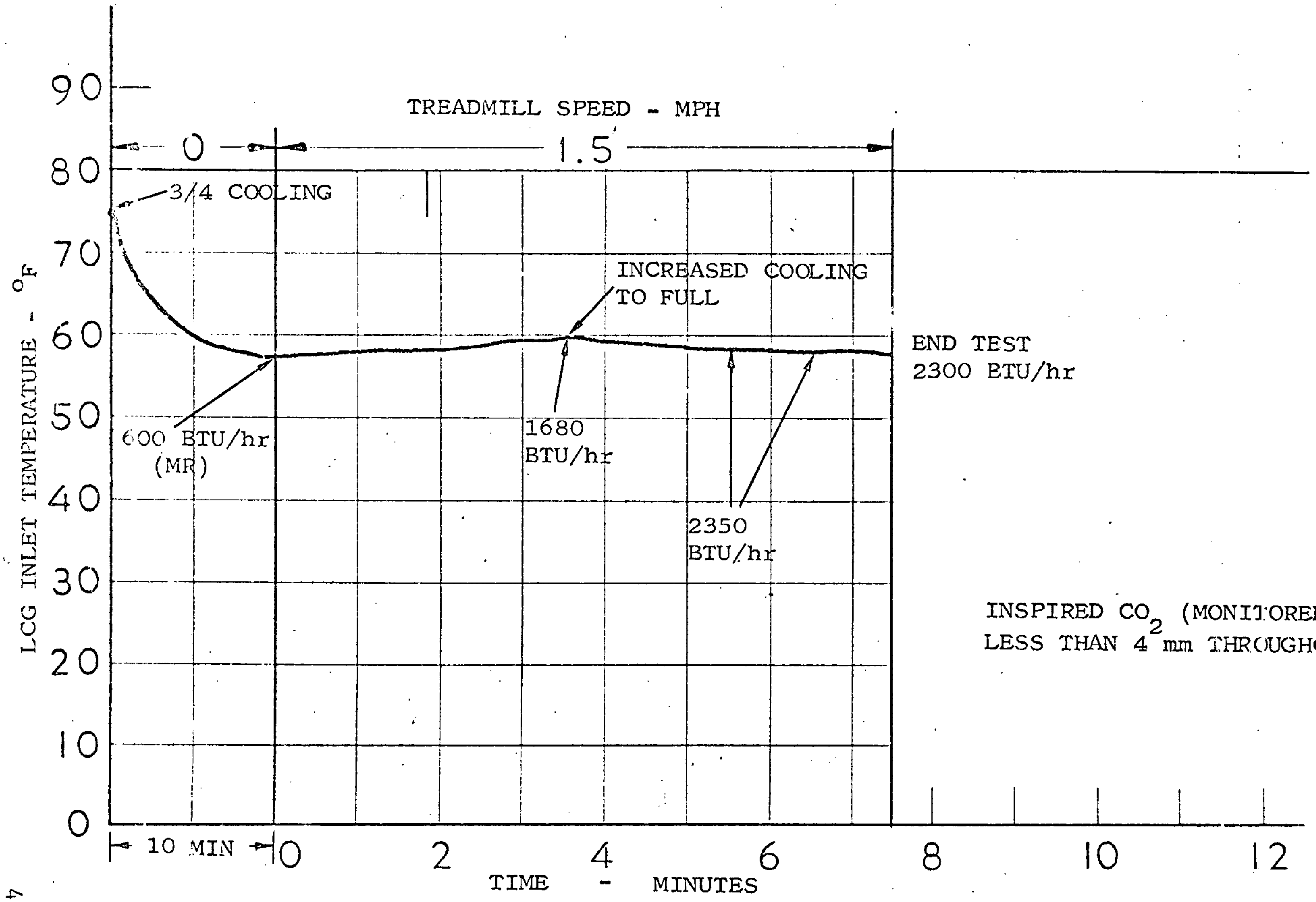
As a final test on the sublimator the unit was purposely subjected to a condition resulting in freezing the transport water section. The purpose of this test was to determine (1) if the transport water could be frozen and (2) whether the water expansion in freezing would result in sublimator damage (leakage).

Using a simulated metabolic heat source (Figure 14), a 2000 BTU/hr load was imposed on the sublimator resulting in a high feedwater flow (2 lb/hr). Liquid circulation, heat, and feedwater were then simultaneously interrupted.

The result was a complete freezing of the transport water in the heat exchanger portion of the sublimator. This result is hardly surprising because the metal portion of the sublimator had already been established at or below $32^{\circ}F$ and at 2000 BTU/hr there is a considerable ice layer already formed at the sublimator surface. On the other hand the amount of water (at $55^{\circ}F$) contained in the heat exchanger portion is approximately 1/10 pound. To cool this quantity of water to a frozen state requires the removal of only 16 BTU of heat.

After establishing that the transport water had frozen, the unit was permitted to thaw out. The following day the unit was again placed in operation without any apparent damage including leakage.

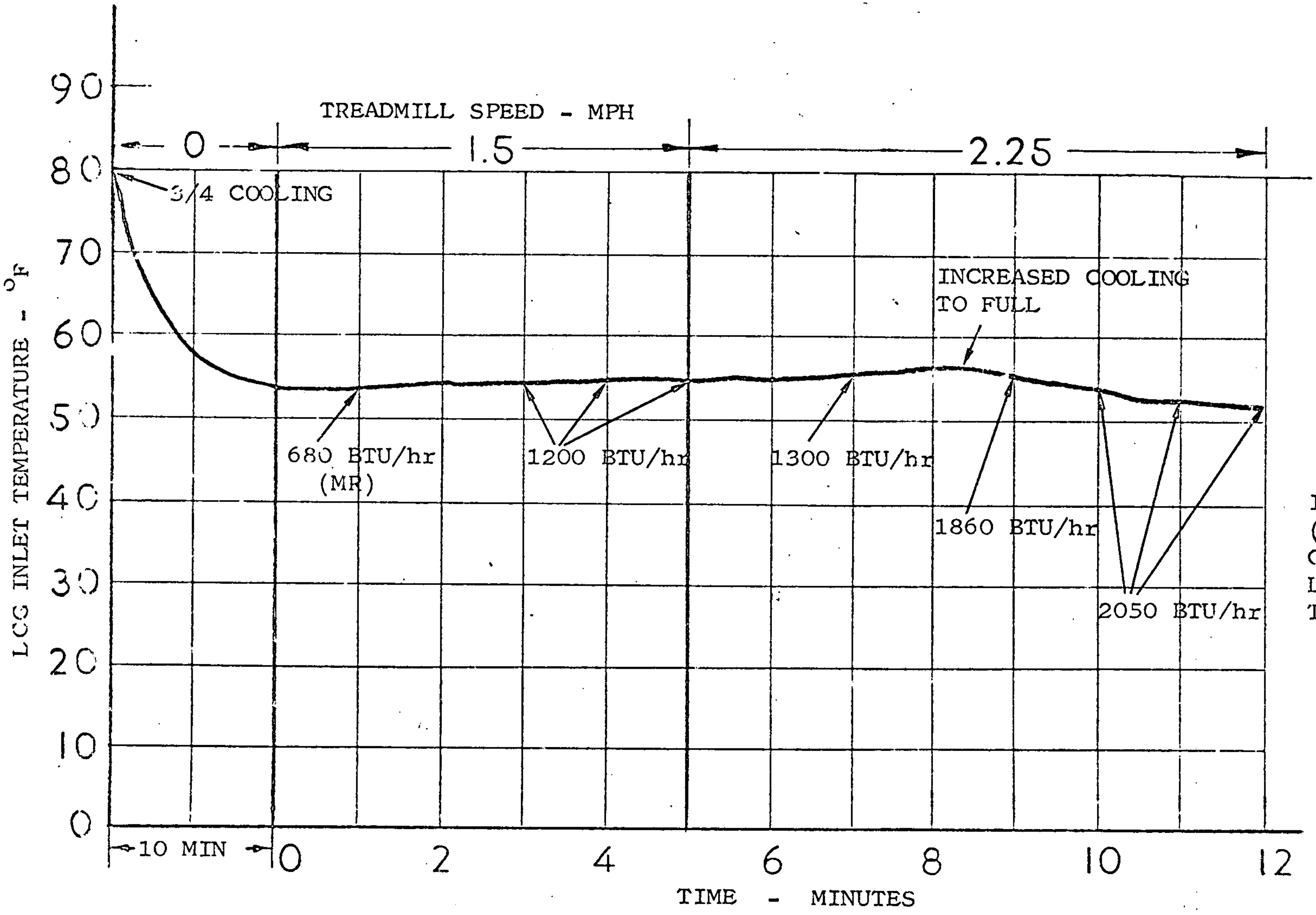
DATE - Feb 11, 1969
TEST DIRECTOR - Robert Rocco
SUBJECT - D. Curtis
SUIT PRESSURE - 3.0 psig
AIR FLOW - $1\frac{1}{4}$ acfm
COOLANT FLOW - 240 lb/hr



INSPIRED CO_2 (MONITORED CONTINUOUSLY) LESS THAN 4 mm THROUGHOUT TEST

Figure 18. PLSS Test with A6-L Suit (1)

DATE - Feb,12, 1969
TEST DIRECTOR - Robert Rocco
SUBJECT - J. McMann
SUIT PRESSURE - 3.0 psig
AIR FLOW - $1\frac{1}{4}$ acfm
COOLANT FLOW - 240 lb/hr



INSPIRED CO_2
(MONITORED
CONTINUOUSLY)
LESS THAN 3 mm
THROUGHOUT TEST

Figure 19. PLSS Test with A6-L (2)

NEW SUBLIMATOR

The new sublimator to replace the foamed metal was designed and made. Although it was not the original intention to incorporate it into the deliverable PLSS, this was accomplished at the last moment at the request of NASA.

In its construction aluminum is used instead of copper for the structure, and the copper foam heat exchanger is replaced by a machined aluminum unit containing an array of fins.

The unit has been assembled by dip-brazing which has resulted in a strong and yet very light (1 lb) assembly. Preliminary test (use of crushed ice to produce a structural temperature of 32°F) has resulted in a heat transfer coefficient (HTC) of 225 BTU/hr/°F/ft^2 as compared with half this value for the older unit. The present dimensions of the sublimator call for a nominal HTC of 220 BTU/hr/°F/ft^2 for an inlet temperature of 48^c; therefore, the new unit should be more than adequate.

BREATHING VEST - CONSTRUCTION AND TEST

The prototype breathing vest with branched helmet duct, that was designed to interface with the Gemini suit, was tested with the A6-L (GFE) suit received from NASA-MSC. The suit, with Dan Curtis as the subject, was pressurized to 3 psi.

Interfacing difficulties were experienced in the helmet area because the A6-L neck ring and helmet geometry are considerably different from the Gemini suit.

A new helmet duct was made, therefore, to interface with the A6-L. The configuration is similar to that shown in Figure 3 except that it conforms to the face rather than the suit. This approach allows the duct to interface with any suit, and provides the very important feature of allowing the duct to pivot at its point of attachment to the suit so that the duct exit will follow the oral/nasal region as the head is turned from side to side. Duct performance was also considerably improved by continuing the duct past the oral/nasal region, providing fresh breathing air in a manner similar to a breathing mask, while avoiding the objection to fastening something to the face.

In examining the duct, two small plastic deflectors will be found within the duct just preceding the opening to the oral/nasal region. The purpose of the deflectors is to provide a slight downward direction of the gas flow at the exhaust point to avoid any possibility of the exhaust gas flow causing eye irritation. The design proved successful, and it was this duct that was used for both subject tests involving the A6-L suit. A mandrel was made to the new design and a transparent duct of lesser wall thickness was made for attachment to the end item breathing vest (Figure 20). The reduced thickness allows the duct to be easily deflected by the head for either side-to-side or up-and-down motion.

The A6-L suit was tested in the emergency vent mode under conditions similar to those for the Gemini suit test (6 acfm to the helmet at an MR of 1000 BTU/hr). The subject (D. Curtis) observed that there was a perceptible decrease in torso cooling when the vest was worn. It appears that some of the helmet exhaust air passes between the vest and the suit wall during the emergency vent mode and thereby reduces torso cooling by sweat evaporation.

Figure 21 illustrates a possible vest modification to eliminate the above-mentioned problem. In this configuration a neck flap terminating in a Velcro band would be attached to the vest. Before donning the helmet the Velcro band would be attached to a mating Velcro band located just below the suit neck ring. Gas exhausting from the helmet would then be forced to completely pass between the vest and the man.

SUIT VENTILATION SYSTEM

As requested during the design review, a series of tests was performed to determine any conflict between the breathing vest and the normal suit

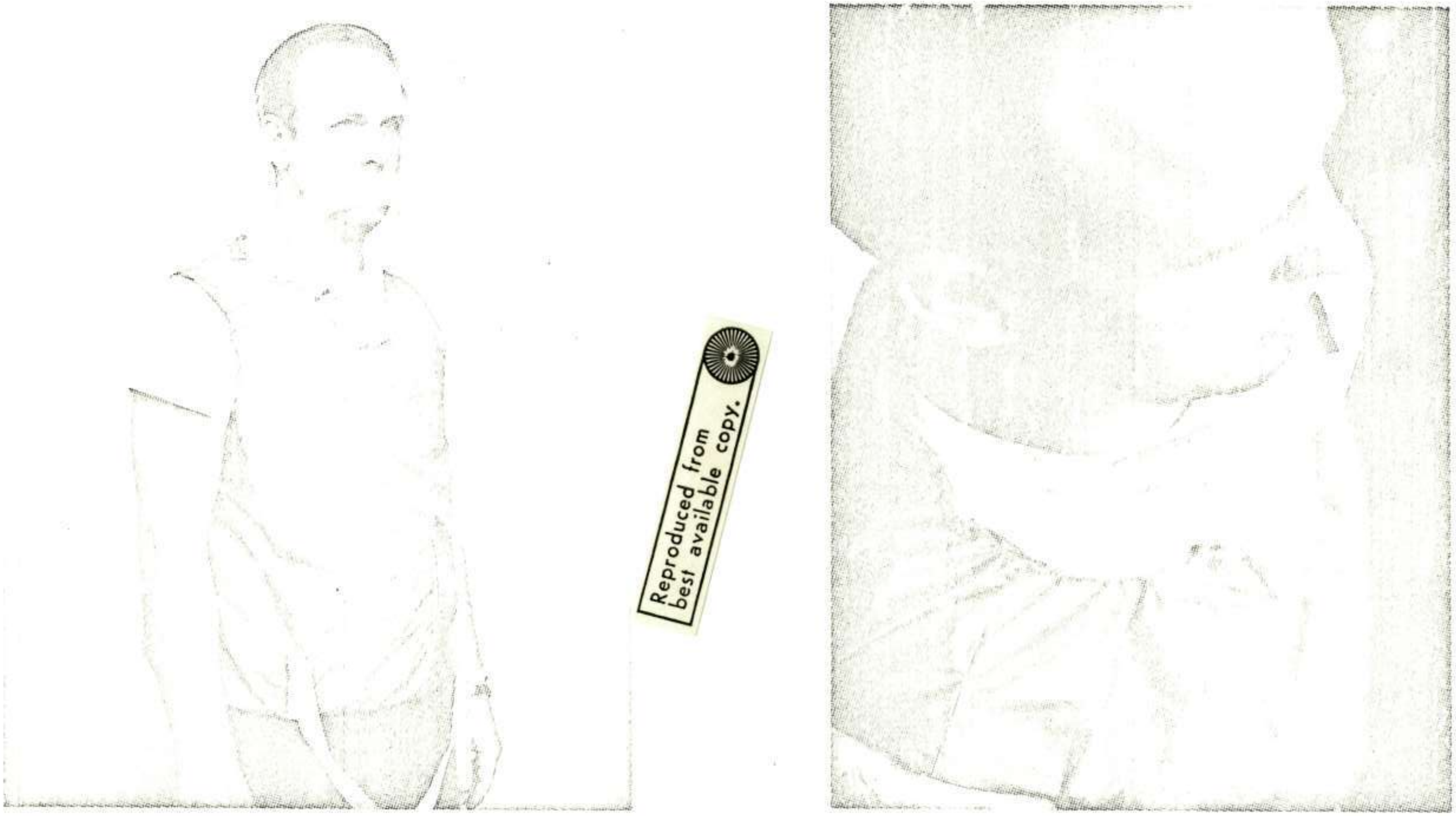


Figure 20. Breathing Vest and Duct

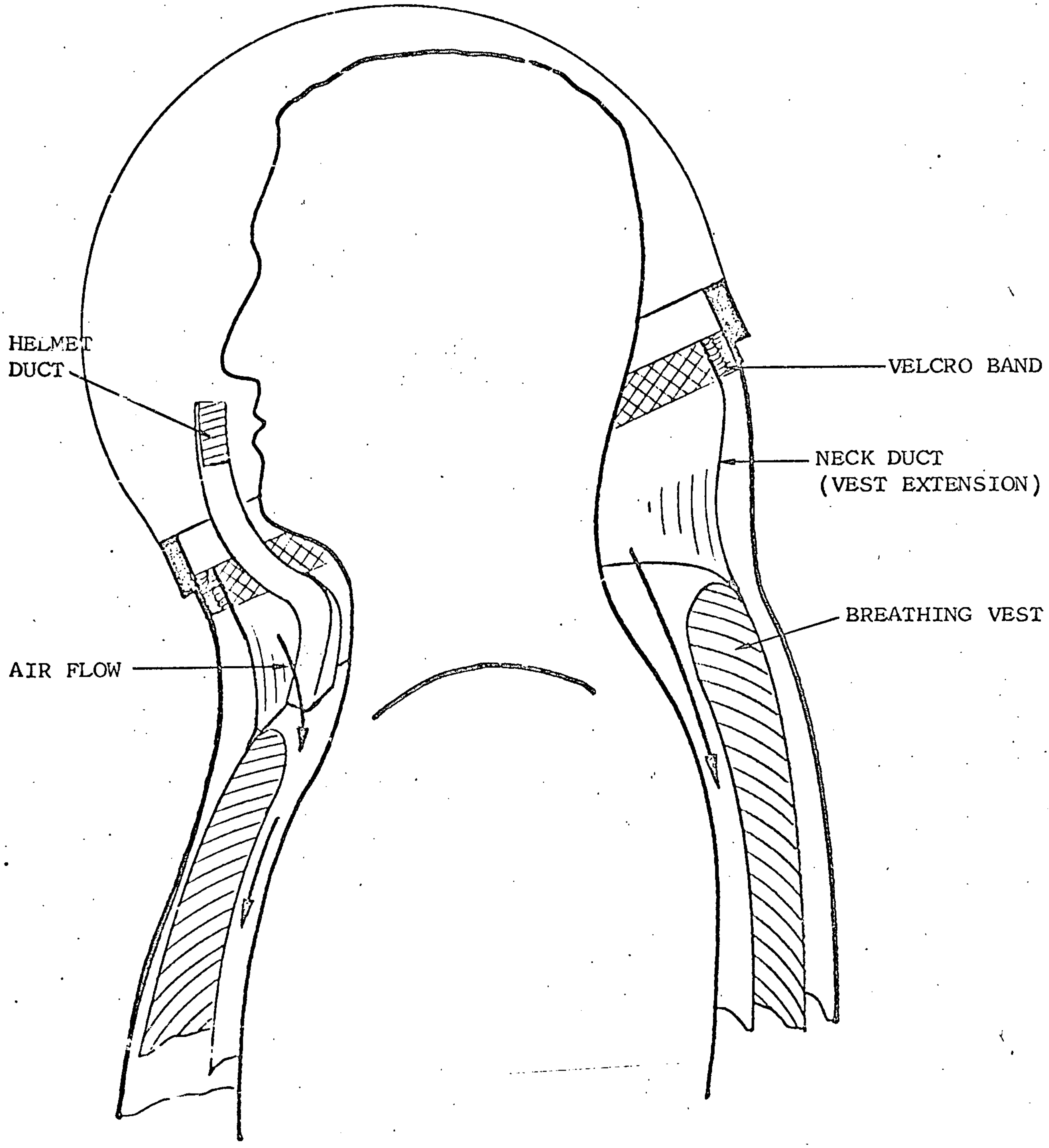


Figure 21. Breathing Vest with Neck Duct for Torso Ventilation

ventilation system. These tests consisted of subject operation of the Gemini suit (Figure 22) using 6 cfm oxygen flow to the helmet with and without the wearing of the breathing vest. The LCG was worn during the tests but no cooling flow was provided.

At a suit pressure of 3.7 psig the subject was required to perform a task (consisting of arm motion) which established an MR of approximately 100 BTU/hr. The MR was determined by CO_2 sampling of the suit exhaust gas. The previously established criterion of 620 BTU/hr, equivalent to a 1 percent CO_2 at a suit inlet flow of 1-1/4 cfm, was modified in this test because of the increased inlet flow conditions. A direct extrapolation was used resulting in a 1 percent CO_2 reading, equivalent to 3000 BTU/hr. The tests were, therefore, conducted at a CO_2 level of 0.33 percent in the exhaust, resulting in a computed MR of 1000 BTU/hr.

Figure 21 also shows that a hygrometer was used during the tests to measure the relative humidity of suit exhaust gases. It was hoped that the use of this instrument would establish quantitatively any difference in ventilation resulting from the presence of the breathing vest. It was reasoned that the presence of the vest could prevent ventilation gas from passing over the surface of the torso. This would result in a loss of evaporative cooling which would be indicated by a lower relative humidity reading. In operation, however, the measured values of relative humidity (and thus the difference) were too small to be accurately determined.

With the suit pressurized at 3.7 psig and a 6 cfm flow to the helmet of the Gemini suit, the subject was required to perform a 10-minute task, first with the breathing vest and then without it. The subject felt slightly more comfortable in the chest area without the vest. The gas flow leaving the helmet normally passes over the chest before exiting the suit at the exhaust port. The presence of the vest, however, forced the flow to pass between the vest and the suit wall preventing some evaporative cooling from the body in this region.

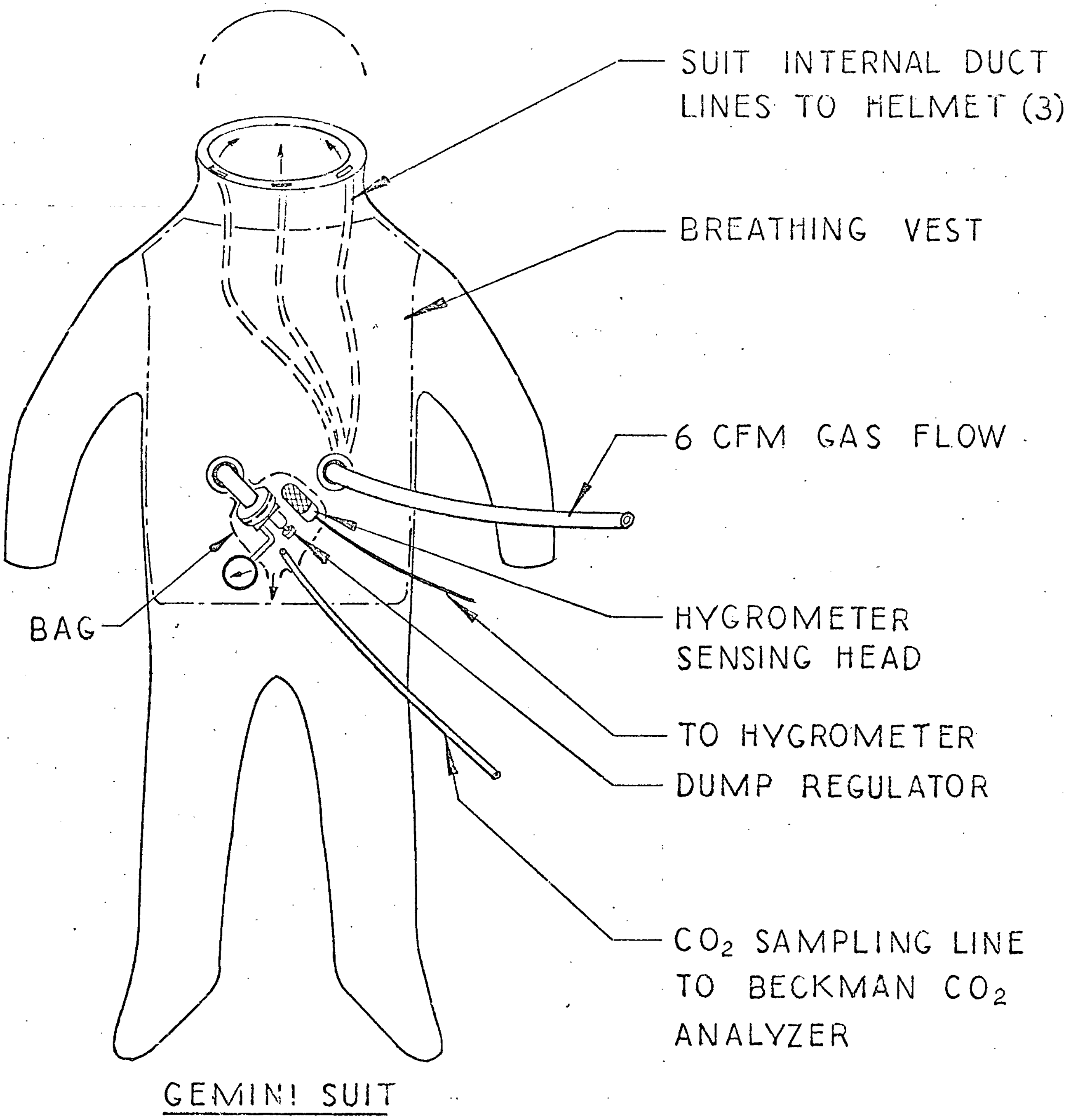


Figure 22. Suit Ventilation/Breathing Vest Test

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Figure 23 depicts a relatively simple modification to the vest and suit that should completely eliminate the above problem if it appears significant. For this solution a circular hole would be cut in the vest in the region adjacent to the suit exhaust port. The outside of the hole (away from the body) would then be lined with Velcro with a corresponding ring of Velcro attached to the suit surrounding the exhaust port. After suit donning and before pressurizing, the crewman would press the suit material to his body in this region allowing an attachment of the two Velcro surfaces. The gas flow would now be forced to pass over the body surface before exiting the suit. This modification would also ensure that the exhaust port can never be covered over by the vest.

ENGINEERING CHANGE PROPOSAL

On June 13, 1968, an ECP (ECP-1) was received, resulting in a program change of scope. The effect of the ECP was to expand the original Task 2, allowing the determination of the feasibility of controlling hand sweating by extending the LCG into the palmar area. For this test a nylon slipover glove was modified as shown in Figure 24, allowing the circulation of cooling water into the hand area.

It was first determined that a tight-fitting Gemini overglove did not in any way restrict the flow of liquid through the 1/16 in. ID, 1/32 in. wall, polyurethane tubing. This test was performed for both fist-clenched conditions and tightly gripping a wrench handle. It was also determined that the subject was not aware of the tubing and, therefore, its presence did not in any way degrade the performance of the Gemini glove.

The ability of the glove to cool the hand was tested by having the subject wear the modified nylon glove on his right hand and an unmodified glove on his left hand. Gemini gloves were then donned on both hands. A 50°F coolant flow (0.15 lb/min) was established through the modified glove and a 10-minute task of raising and lowering both arms and clenching and unclenching the fists was then imposed on the subject.

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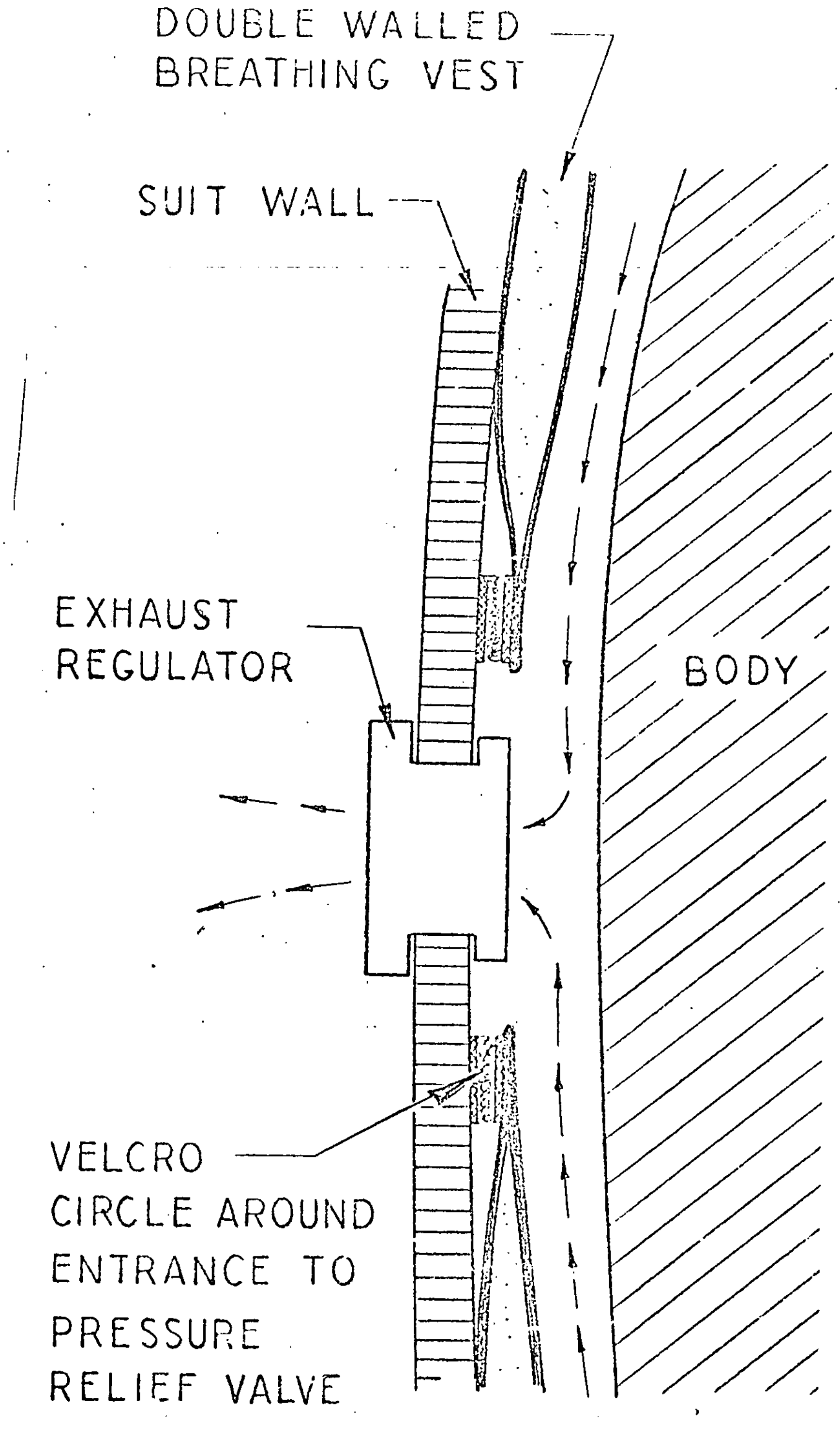

Figure 23. Breathing Vest at Exhaust Regulator

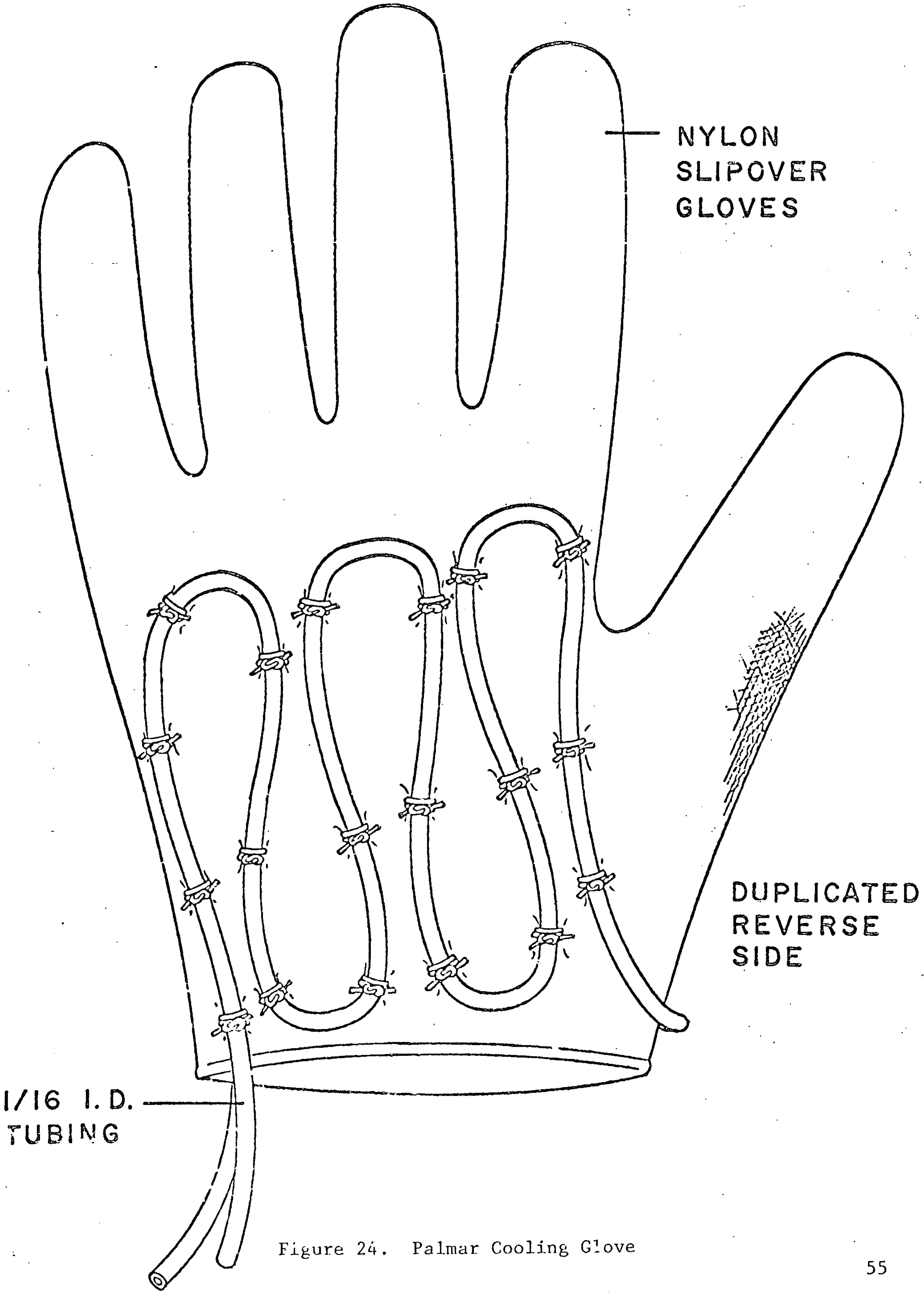

Figure 24. Palmar Cooling Glove

It was quickly apparent to the subject that his right hand was considerably cooler and more comfortable than his left hand. In addition, his right hand felt uniformly cool, and not, as might be expected, subject to any localized cold sensation in the region of the tubing. After 10 minutes of exercise the two palmar areas were examined. The left hand showed a pronounced layer of sweat while the right hand was uniformly cool and dry.

It is concluded that extending the LCG into the palmar area represents a significant improvement in crewman cooling. The modified glove, as a permanent extension of the LCG, is seen as a better alternative than the approach requiring some form of liquid connectors.

STAGE II

DESIGN AND CONSTRUCTION OF A PROTOTYPE EMERGENCY LIFE SUPPORT PACK (ELSP)

GENERAL

In April 1969 Contract NAS 9-8135 was extended and redirected by NASA-MSC to provide for the design and construction of a prototype emergency life support system. In accordance with the change notice issued as a result of Contract Amendment No. 35, the new designator for the deliverable end item is Emergency Life Support Pack (ELSP). This terminology replaces the formerly used PLSS.

Major system parameters were that the unit be capable of supplying both oxygen and cooling for 45 minutes at a metabolic rate of 2000 BTU/hr.

The first few weeks of the Stage II effort were devoted primarily to a review of the program with the program Technical Monitor, Joe McMann of NASA-MSC, to establish as many guidelines as possible. The early concept of a back pack was abandoned in favor of a chest-mounted suit. This complete reorientation resulted in a greatly simplified design in which long connector lines from back pack to suit could be eliminated and all controls mounted on the case for direct access.

The total system comprised a number of different areas of development, namely:

- Pulse pump
- Thermal control unit
- Pressure bottles
- Sublimator

- Packaging configurations
- Water storage
- Breathing vest and duct
- Testing

The progress of each of these will be discussed separately.

PULSE PUMP

Pump Body

During development the barrel of the original pulse pump was machined from polycarbonate for several reasons, not the least of which was the advantage to be derived from being able to observe the internal mechanism in operation - the pulsations of the bladders and neoprene check valves and the shuttle action of the polycarbonate ball. However, since basic pump design and performance had been verified to a point where observation was no longer necessary it was decided to make the new pump body of aluminum, assembled by dip brazing. This construction is not only lighter and stronger but, with the exception of the internal bladders and check balls, will be nonflammable.

The drawings of a completely redesigned gas/liquid pump were released for fabrication in May 1969. While functionally the same as the plastic-bodied pumps made for NASA-MSC, the redesigned pump's dip brazed all-aluminum body is smaller and more compact and has lower external connectors. All aluminum parts were given a hard anodized coating to protect the base metal from corrosion. During later evaluation testing of the assembled prototype an unforeseen problem developed when abrasion of the bladder surfaces became apparent throughout their length after from ten to fifteen hours of operation. As this type of wear had never occurred with the polycarbonate pumps it was reasoned that the cause must be a rubbing contact with the chamber walls, because, microscopically, anodizing presents a highly irregular hard surface of aluminum oxide that is highly abrasive.

To overcome the problem it was planned to coat the inner walls of the pump barrels with teflon but consultation with establishments specializing in such techniques revealed that this would be an extremely difficult, if not impossible, operation. The alternative was to install an inner liner of thin-wall plastic tubing or to coat the inside pump barrel surfaces with a liquid plastic. After some experimentation on the adhesion properties of various liquid plastics to an anodized surface, a clear polyurethane was chosen. Satisfactory coating was achieved by pouring the polyurethane over the surfaces to be coated and allowing the excess to run off. After an overnight air cure to harden the polyurethane the pump was assembled. Thereafter it ran without trouble (1850 hours).

In accordance with suggestions made by the technical monitor at the program design review, certain modifications were made to the pulse pump drawings. These included a modification to the check ball cage, a method of keying the inlet portion of the pump body to the pump housing, nyloc insets on the shuttle ball adjustment screw and an alteration to the inlet end of the pump. An assembly drawing incorporating these changes was sent to the technical monitor.

Pump Bladders

It was realized that the neoprene rubber used for the bladders was changing its shape due to absorption of water when exposed to this environment. Therefore, the field of material selection for the pump bladders was reviewed.

Tests conducted at Litton showed that the neoprene selected for bladder material will absorb approximately 40 percent by weight when soaked in water for 48 hours. The strength of the material, however, did not appear to be affected. A dimensional growth increase of 15 percent was also noted; it was apparent that an observed degradation in pump performance after a few days of continuous operation could be attributed to this growth.

To rectify the problem three areas of investigation were pursued.

1. Presoaking the neoprene bladders prior to installation
2. Changing to a material that does not absorb water
3. Coating the bladders with a material that isolates the neoprene from the water.

No. 1 appeared to be a workable, but only temporary, solution and was not considered to be a practical long term approach.

Solution No. 2 was attempted using the same Dow Corning air-cured white silicone rubber that was under investigation as a glove material. From its very low water absorption properties this material looked very favorable, but its performance in actual pump operation proved disappointing. The silicone bladders do not have the same toughness as neoprene, and failed repeatedly after 15 to 20 hours of pumping.

Solution No. 3 appeared to be the most promising and an investigation was immediately begun by giving existing bladders a thin protective coating of silicone. Satisfactory protection against water absorption was achieved and dimensional changes were inhibited. An endurance test on the pump using two of the new silicone-coated neoprene bladders ran for a total of 1850 hours before failure. This represents a total of almost 7,000,000 cycles for each bladder. A detailed analysis of the causes of final failure is included in the section on testing.

A dimensional check was made on the bladders when the pump was disassembled for inspection. Measurements were taken of the unstretched bladder lengths and compared with the original figures. If any change at all had occurred it was less than 1/16 in. in the total length.

Two new bladders were installed and the pump reassembled for a record endurance test. For this test the single difference was that a light coating of silicone oil was applied to the surface of the pumping chamber walls and to the teflon rings to discourage abrasion since it was at the point of contact of bladder and teflon rings that the only signs of wear had occurred.

This second test ran for 1750 hours and was terminated not because of failure, but because the pump had to be prepared for delivery to NASA.

Pump Operational Noise

NASA-MSC raised the question of annoyance from pump noise under operational conditions when the ELSP is worn with a suit. The problem arises when the output of the pump is added to the PGA ventilation gas, and is especially objectionable when the ventilation gas is ducted directly to the helmet. In this condition the ventilating duct system acts like a shipboard voice tube in which the exhaust sound of the pump is virtually unattenuated when it reaches the helmet.

After verification of this effect with a Litton hard suit, a breathing vest (as worn by the test subject) was introduced in series with the helmet ventilation following the pump gas output. This procedure had the effect of reducing the noise level of the pump to a barely audible sound.

A second corrective alternative was tried in which the gas output of the pump was first introduced into a buffer chamber with an output restrictor before reaching the helmet ventilation line. The idea behind this approach is to smooth the gas flow by allowing the pulsed output of the pump to build up an average positive pressure in the buffer chamber by means of the pressure drop across the output restrictor. It was found that an essentially smooth flow was produced through the restrictor (undetectable sound to the ear) by allowing a one psi positive pressure in the buffer chamber.

As shown in Figure 25 the increased gas outlet pressure is reflected back to the accumulator by the accumulator pressure reference line. A one psi increase in gas inlet pressure was also required to compensate for the increased pump exhaust pressure.

THERMAL CONTROL UNIT

Redesign of the thermal control unit began with the plan to make the control continuously variable instead of the stepped operation of the

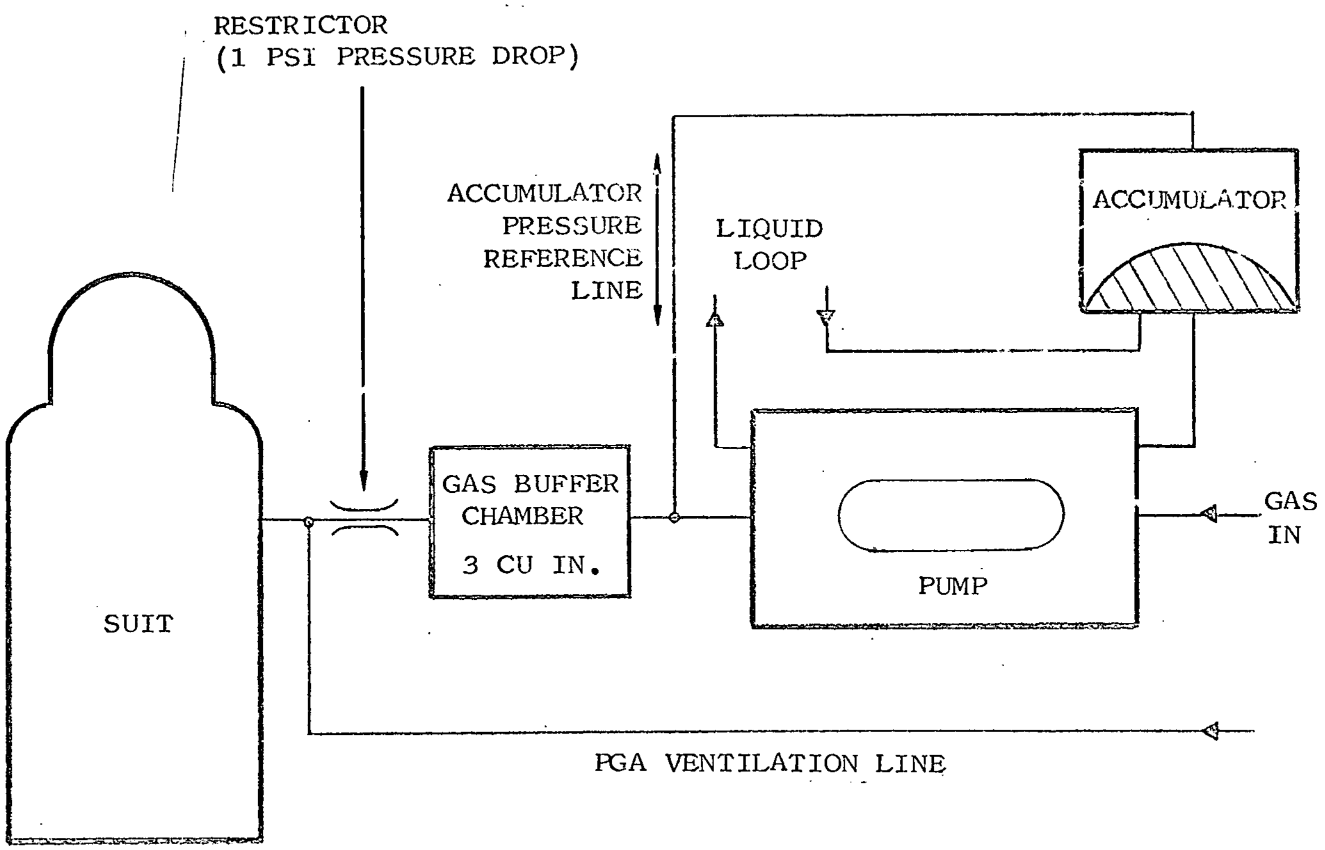

Figure 25. Gas/Liquid Pump Noise Eliminator

control unit on the PLSS delivered at the end of Stage I. The approach was to use a cam-operated compression bar to change the cross-sectional area of the sublimator feedwater line. This system yielded the following advantages:

- Enabled the use of a smaller and lighter valve
- Continuously variable operation
- Improved system reliability by eliminating valve seals.

An engineering model of the new continuously variable water feed valve was made and first tested without coupling to a sublimator. A schematic representation of the valve is shown in Figure 26.

Turning the control knob causes an arm to pivot with a corresponding change of compression on a small diameter, flexible plastic feedwater line. The control is essentially linear and exhibits very little hysteresis as shown in the experimental data sheet (Figure 27). The maximum flow of 45 cc/min corresponds to a maximum sublimator heat absorption capability of 6000 BTU/hr. The actual rate, of course, is dictated by the sublimator self-regulatory mechanism as modified by the impedance of the sublimator distribution system.

Some environmental testing was accomplished on the new continuously variable feedwater control valve. Valve setting repeatability was first determined by setting the valve in an off position for three days (at room temperature conditions) and then reestablishing that the flow characteristics would be essentially unaffected except at maximum flow conditions. It was expected that the slight permanent set taken on by tubing (PVC) as a result of the 3-day closed condition would result in a slightly reduced maximum flow condition.

The test showed that there was a slight deviation in flow at maximum flow conditions (approximately 7 percent). Contrary to prediction, however, the maximum flow had increased slightly instead of decreasing. The extended closed condition of the tubing appeared to have caused a slightly extruded condition with a result that the cross-sectional area had slightly enlarged.

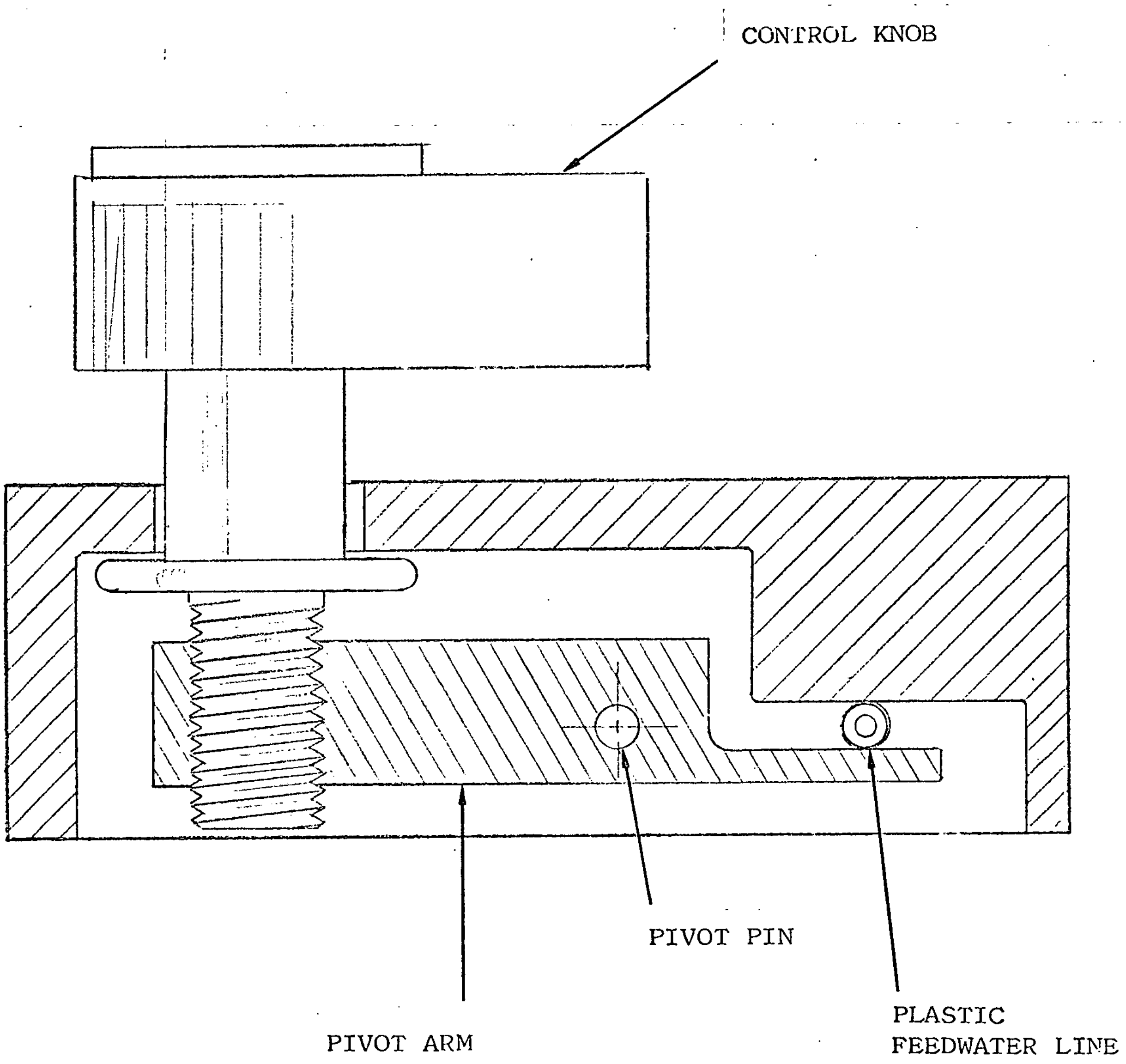

Figure 26. Feedwater Control Valve

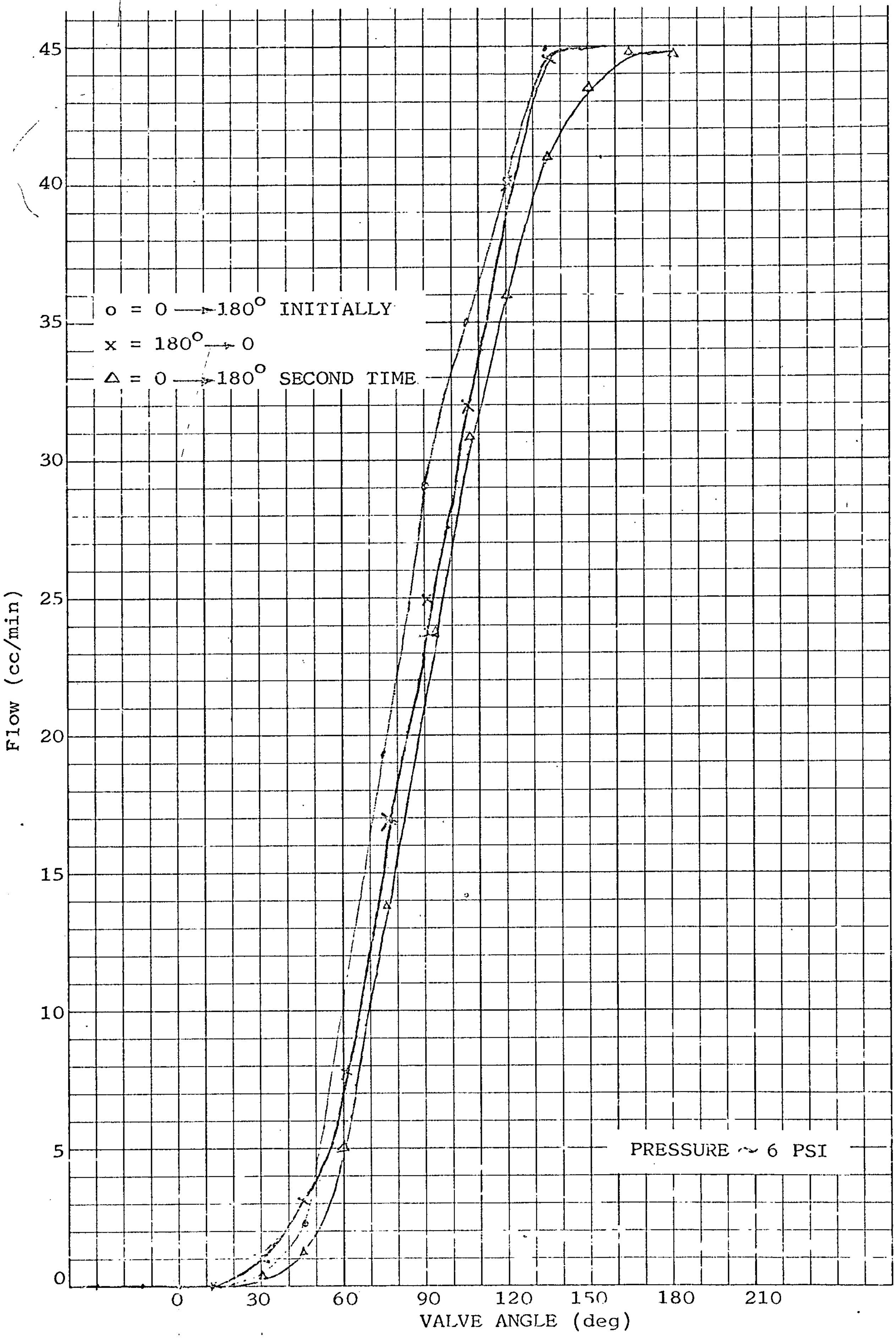

Figure 27. Flow Analysis, Water Intake Valve

A major problem with the polyvinyl-chloride feedwater line did occur, however, when the control valve was subjected to a vacuum (10^{-4}mm) at a temperature of 160°F. After a three-day soak the line was found to have lost some of its flexibility and had taken a semi-permanent set at the control point of the valve, making it unusable for control.

Other line materials were investigated including polyurethane, silicone and Viton. After many hours of testing under vacuum and temperature conditions, silicon was selected for the control valve material. The test consisted of measuring the flow characteristics of the valve using in-house fabricated silicone tubing. After 24 hours of soaking the valve at 160°F and 10^{-5} mm Hg with the valve in a shut-off condition, the flow measurements were repeated with essentially identical results.

SUBLIMATOR

The sublimator for the ELSP was of essentially the same configuration as that in the PLSS delivered at the close of Stage I of the program. It was machined from aluminum and assembled by dip-brazing. To suit the unique packaging arrangement of the ELSP the position of the transport water connectors differed somewhat from the PLSS. Because silicone is considered to be a more acceptable material for space applications than polyurethane, the sublimator cover material was changed from 1/8 in. polyurethane to silicone foam. However, when the silicone foam sheet was delivered from Emerson-Cumings (the only known manufacturer) it was unacceptable because of a preponderance of closed cells.

The material was returned to the supplier and the original choice of polyurethane reverted to.

The fully assembled sublimator was then tested at a heat input of 2500 BTU/hr. The heat transfer coefficient ran about 270 BTU/hr x °F x sq ft, compared with the design goal of 255 BTU/hr x °F x sq ft. Further, hot starts were conducted from an initial temperature of 130°F without problems.

PRESSURE BOTTLES AND REGULATOR

Ardé high pressure bottles were selected for oxygen storage in the ELSP. Because of the long lead time they were ordered at the outset of the program, together with the special inlet port connectors required.

While similar in size to present PEAP bottles (drawing D3703), an important modification was incorporated in the inlet connector fitting. By changing the PEAP fitting to the male portion of a Parker-Hannifin No. 5 Super-Lock tube fitting it was found possible to eliminate a rather bulky adapter fitting. The Parker-Hannifin fitting allows a direct connection between the oxygen bottles and a tubing manifold, thereby eliminating both the weight and bulk of the adapter and a double O-ring adapter seal.

The manifold design is a departure from the PEAP system manifold. Instead of connecting blocks the manifold is welded tube to tube. This approach is considered advantageous since it permits 100 percent weld penetrations, reduces machine time and yields a 30 percent reduction in manifold weight.

Prior to final assembly the manifold, bottles and fittings were tested at 6000 psi using dry nitrogen. The tests were performed by World Research Corporation, and no problems were encountered.

The regulator used on the ELSP system is the same Carleton Control unit that was used on the PEAP system. This regulator is manufacturer set to provide an outlet pressure of 67 psig which is higher than desired for the ELSP system. The ELSP system requires a downstream regulated pressure of about 10 psia and it had been hoped that Carleton Control would be able to simplify a spring in the regulator that would produce the desired change in performance. Apparently it was not as simple as was first thought to modify the regulator. Carleton informed Litton that several thousand dollars and at least three months would be required to make the change.

In looking for an alternative the decision was made to take advantage of the constant flow characteristic of the ELSP system and use a pressure dropping device between the regulator output and the input to the pump. The pressure dropping device could have been an orifice but the hole size for this approach has to be exceedingly tiny to allow a pressure drop of 57 psi (67 - 10 psia) at a required flow. The approach adopted employs a short section of commercially available 27 mil ID stainless steel tube to produce the desired pressure drop. With this approach it is simply a matter of terminating the tube at an appropriate length (about 12 inches).

The employment of the higher regulated pressure, together with the pressure dropping line, resulted in a modification to the basic system schematic (Figure 28). The plan had been to provide an emergency O_2 supply of 2-1/4 cfm controlled by an on-off toggle in conjunction with an orifice. In the revised schematic the orifice is replaced by a second pressure dropping line between the emergency O_2 valve and the regulator output. The flow rates shown represent actual flows when converted to 3.7 psia.

WATER STORAGE

Consideration of a water storage unit design resulted in the decision to use a simple cylinder rather than a more complicated concave/convex shape. The space saving derived from a complex shape did not justify the extent of the additional work involved.

To provide the differential pressure required to maintain feedwater supply the cylindrical neoprene accumulator bladder was encircled by equally spaced elastic bands. When water is introduced to the bladder on filling, the bands expand resulting in a water pressure proportional to the amount of band stretch and, therefore, proportional to the amount of water contained.

Upon delivery from an outside manufacturer the water storage bladder was tested. Filled to a static differential pressure of 2.5 psi the container holds 1.6 lb water.

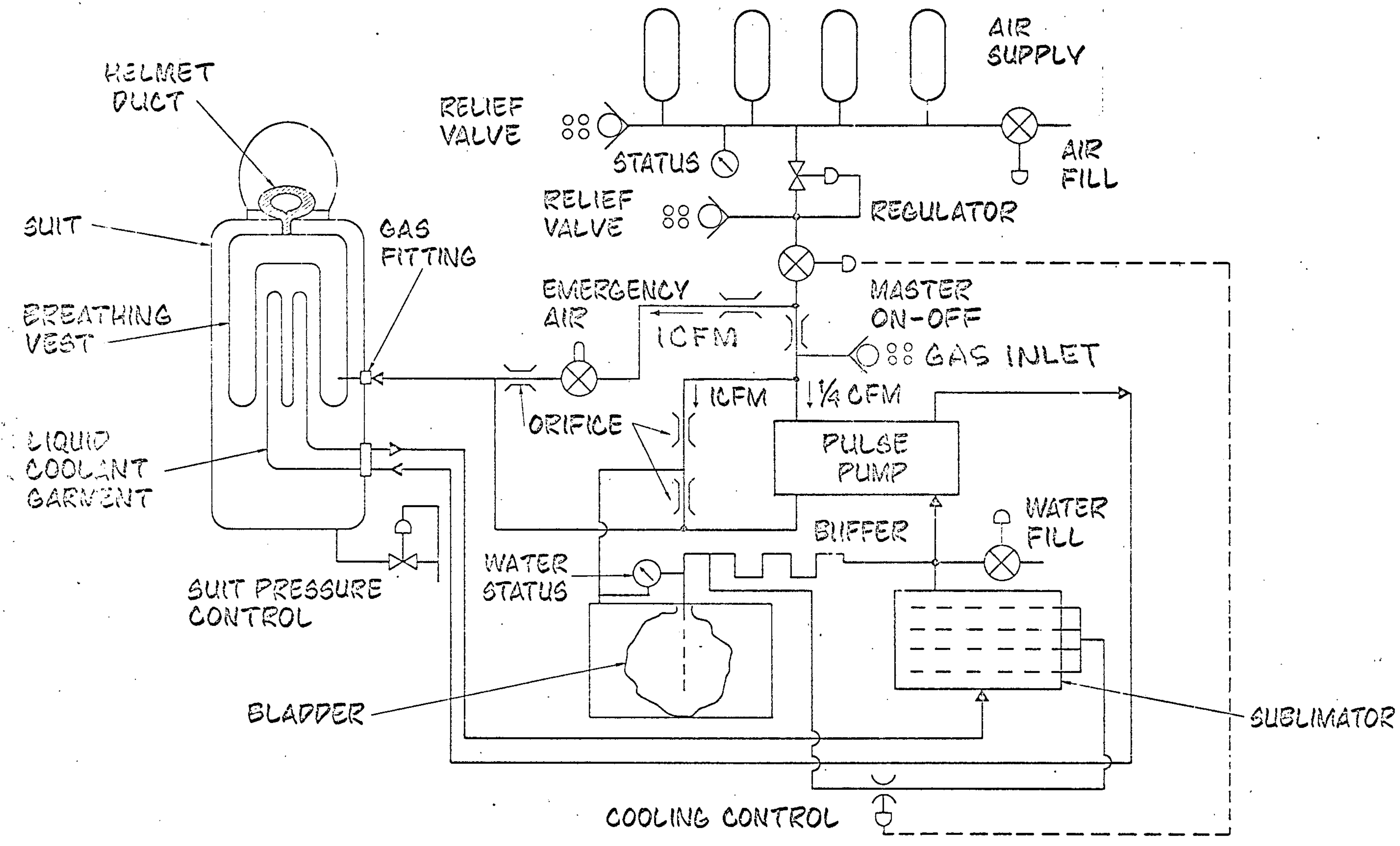

Figure 28. ELSP Schematic - October, 1969

With approximately 0.1 lb water removed the pressure dropped rapidly to about 1 psi. Thereafter the pressure is essentially a linear function of the amount of water left in the container with a residual of about 0.2 lb at zero differential pressure.

A critical test was made of the water storage container to determine the memory qualities of the elastic bands when the container was filled with water. An uncoated neoprene bladder was initially used in a 3/4 filled condition, with the internal water pressure monitored as a function of time. A slow degradation of pressure was experienced as a function of time (one week), indicating that water was reaching the bands and affecting their elastic properties.

A second neoprene bladder was made with the standard internal coating of polyurethane to prevent water penetrating the neoprene. The second bladder indicated essentially zero change after a week's exposure. The polyurethane liner (properly bonded) is used in the final unit.

In the final ELSP assembly water filling is accomplished by first vacuum exhausting the system through a water trap and then pressurizing the trap to 2 psig until flow closes. The system water inlet valve is then closed, thus fixing the filled water system pressure at 2 psig.

WATER STATUS GAUGE

Water status is displayed to the crewman by a small differential pressure gauge mounted beside the oxygen status gauge. The gauge is connected to read the differential pressure existing between the water pressure in the system accumulator and the gas pressure between the accumulator bladder and the container (see Figure 29).

The requirement was for a small size gauge to indicate a differential pressure of 0 to 1.0 psi. A search was made among major pressure gauge manufacturers, (Glassco, Hoke, etc.) for such an item without success. The story received from the gauge manufacturers was that a conventional Bourdon

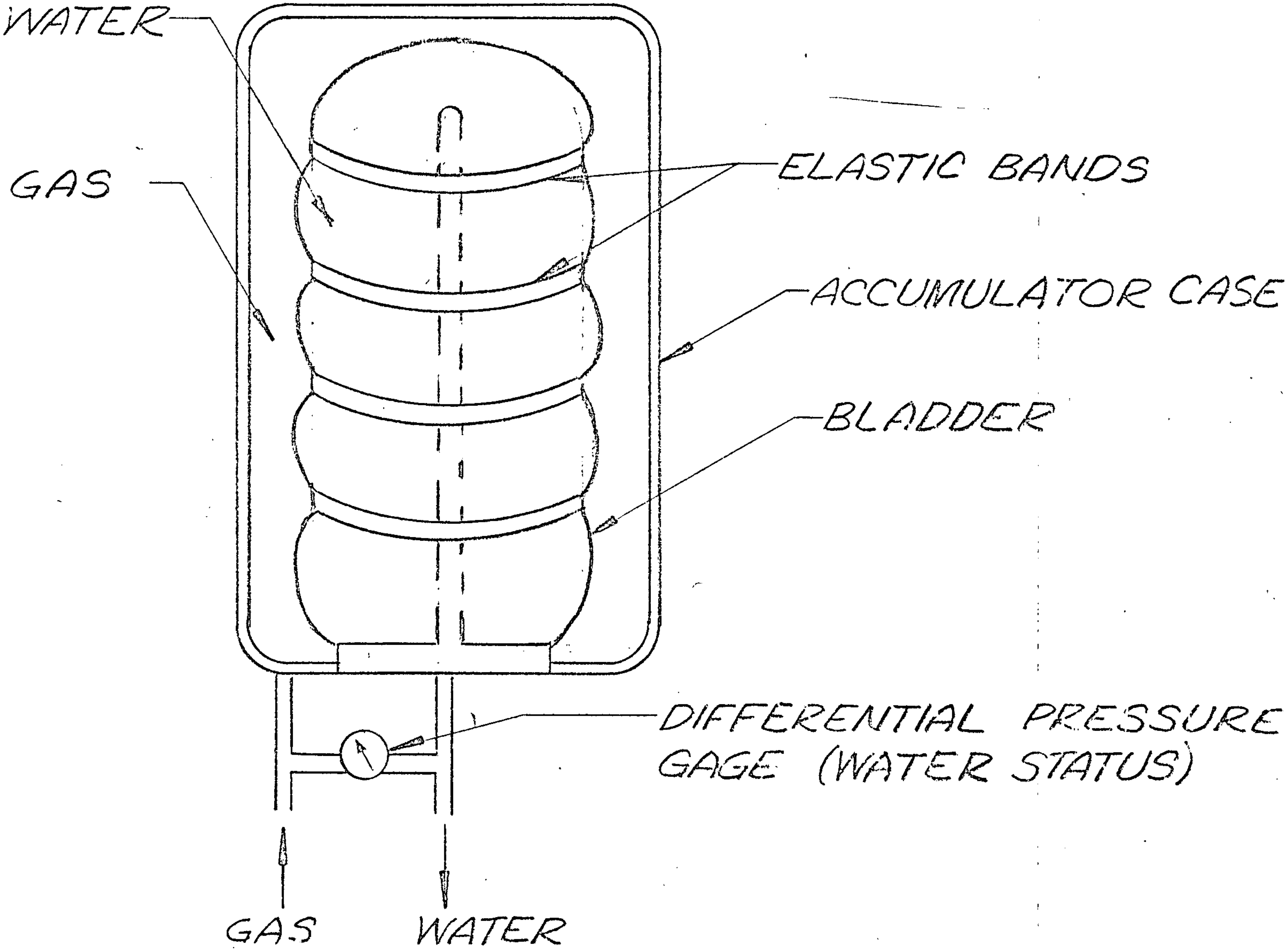

Figure 29. Water Status Subsystem

tube design would not operate in this pressure range and the design would require an aneroid movement. Further, the combination of the differential requirement together with restriction on size meant that the gauge would have to be developed on a best effort basis and would cost at a minimum, several thousand dollars.

The cost, plus the estimated long development time compelled Litton to seek an alternative. Three different designs of water status gauge were evaluated before a satisfactory solution to the problem was achieved. The first design used a Bellofram diaphragm balanced by a spring. The device as proposed is illustrated in Figure 30.

The sketch shows a cross section to illustrate internal construction. The two pressures, P_1 and P_2, are connected to the gauge with P_2 being greater than P_1 (in order that the Bellofram tube be maintained in an inflated condition). The differential pressure, $P_2 - P_1$, times the Bellofram cross sectional area produces a force that is balanced by the expansion of the spring. The system is initially calibrated by adjusting the spring so that the Bellofram is at its maximum (extended) condition when $P_2 - P_1$ is maximum (indicating that the life support water reservoir is full, for example). Under the above conditions the indicating edge of the Bellofram, as seen through the clear plastic tube will coincide with the full mark on the viewing tube. As water is removed from the reservoir, the differential pressure ($P_2 - P_1$) will be reduced causing the indicating edge of the Bellofram to give a continuous indication of the quantity of water remaining in the accumulator.

Because of difficulties encountered in fabricating the small Bellofram required, this design was set aside and the effort redirected.

The second design, shown in Figure 31 had the merit of extreme simplification. In this new approach, a flat, circular black membrane is expanded by the differential pressure across the accumulator bladder. Closely spaced to the membrane surface is a curved, clear plastic disc with a roughened inner surface.

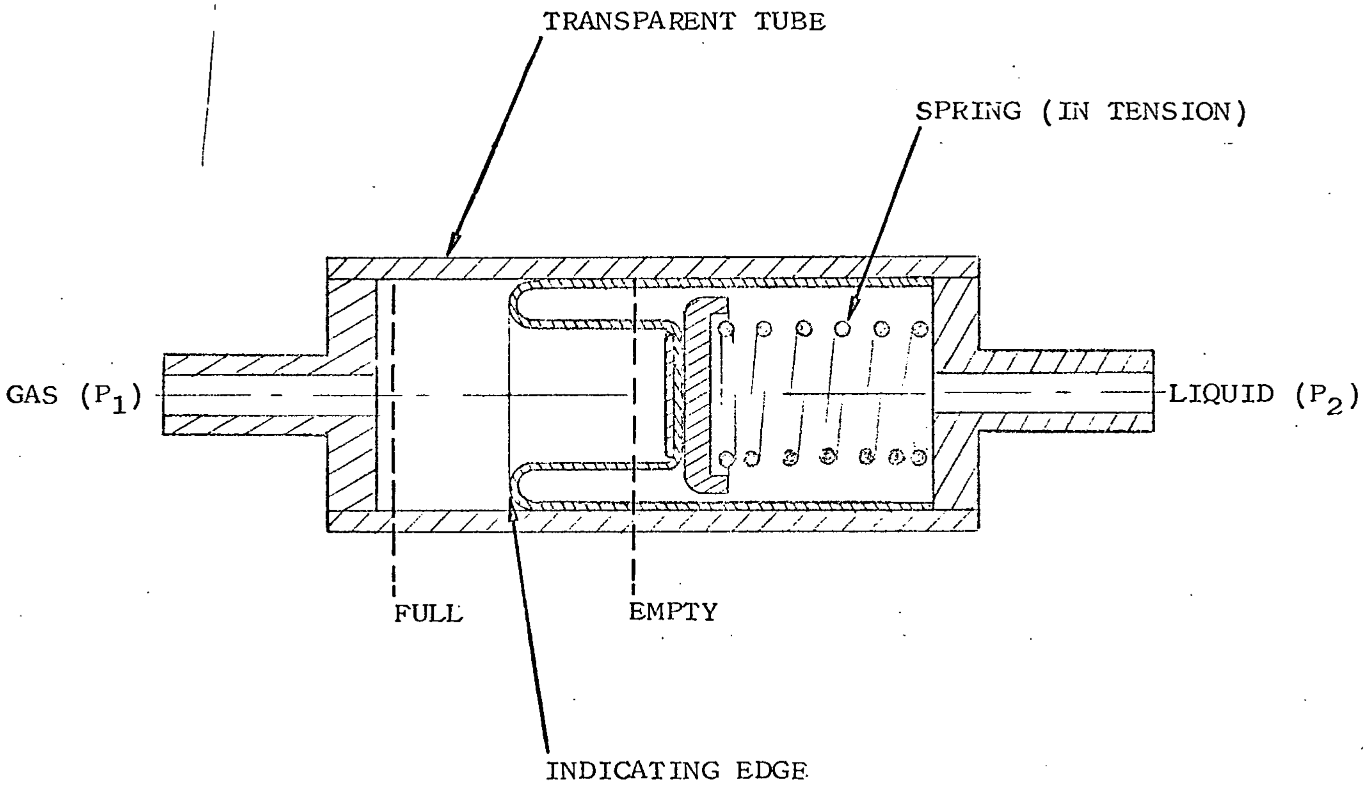

Figure 30. System Water Status Indicator

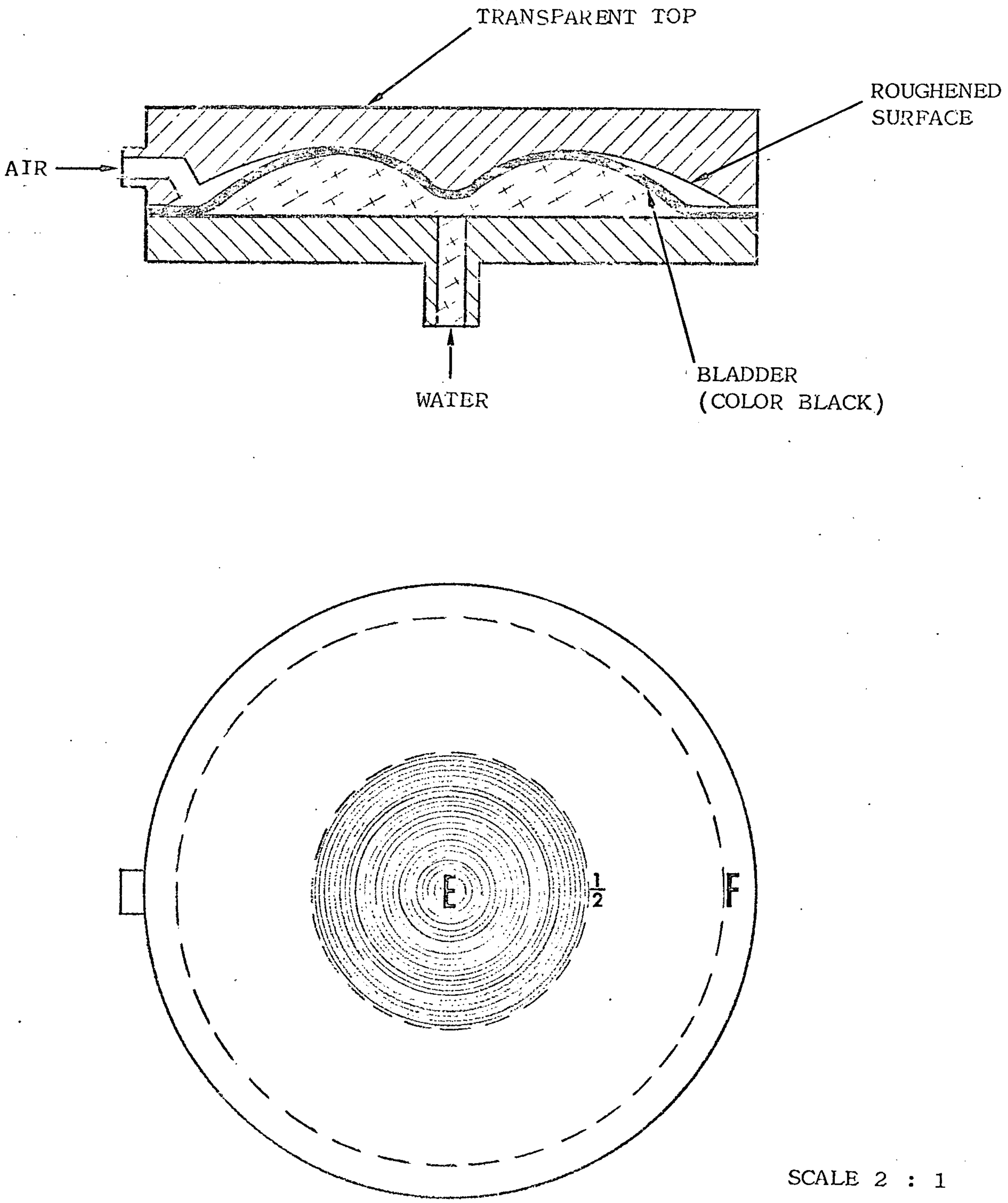

Figure 31. System Water Status Gauge
(Differential Pressure)

In operation, the differential pressure across the system accumulator expands across the black membrane surface against the inner surface of the disc with the result that a black disc (area of contact) is seen when the gauge is viewed from the top. By properly shaping the inner surface, it is possible to make the radius of the disc essentially proportional to differential pressure, and thus proportional to the amount of water stored in the accumulator. The dark area in the drawing is representative of a half-filled status.

This gauge was constructed and tested. While functional, it was judged that in this approach there was insufficient contrast between the membrane contact area and the noncontacted area. A third design was prepared which proved entirely satisfactory.

The improved approach is shown in Figure 32. The gauge consists of a rubber (neoprene) bellows, an internal spring and an external, transparent lexan tube. Spring and bellows tensions are such that when pressure P_2 equals P_1, the bellows is fully extended. When $P_2 - P_1$ equals approximately one pound, the bellows is fully compressed.

This unit was made and installed in the assembled ELSP. Under environmental test its performance was satisfactory and as expected. An unexpected bonus is the slight oscillation of the gauge bellows resulting from small changes in the differential reservoir pressure caused by the pulse pump operation. Not only does the constant motion of the bellows preclude sticking but the small motion gives a visual indication that the pump is functioning.

PACKAGING

Wooden mockups of all major ELSP components (pump, sublimator, water reservoir and four oxygen bottles) were made as a preliminary to evaluating possible packaging configurations. Drawings were made of 5 candidate end item packages and submitted to the NASA-MSC program Technical Monitor for

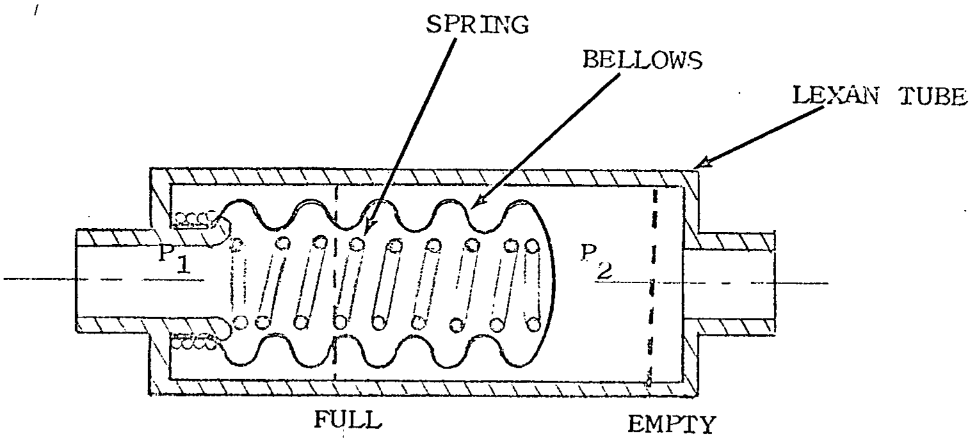

Figure 32. Water Status Gauge

study. Subsequently two additional proposed configurations were devised and the drawings forwarded to NASA. All packaging configurations were for a chest-mounted unit to be attached to the upper and lower D-rings of the A7L suit. The final decision on which of the seven configurations would be selected was to be made at the formal design review.

The first five suggested configurations all used the four bottle (PEAP) system of high pressure oxygen storage. The additional two were prepared at the request of the program Technical Monitor and were based on the concept of a single oxygen storage bottle. The somewhat smaller dimensions yield an approximate 20 percent reduction in volume.

The contention at this time was that a change in configuration affecting the number of bottles would introduce the necessity for a major program modification that should perhaps be delayed until a flight qualified hardware program had been initiated. The major advantage offered by the 4-bottle system was that the PEAP bottles were already qualified for high pressure operation thereby reducing cost and allowing rapid development of a system with the capability of manned chamber testing.

Of the five envelope configurations using four oxygen bottles Litton recommended the adoption of the design illustrated in concept in Figure 33. The advantages of this system were tabulated as follows:

- A split design is used with the oxygen and water located below the suit water and electrical connectors. The remainder of the system is located above the two connectors. This configuration allows for maximum utilization of the suit frontal area while giving the minimum silhouette.
- A feature of this shape is the small channel region between the expendable storage section and the functional elements. This region is provided to permit access to the existing suit electrical connector and water connector while allowing the life support unit to lie flat against the external suit wall.

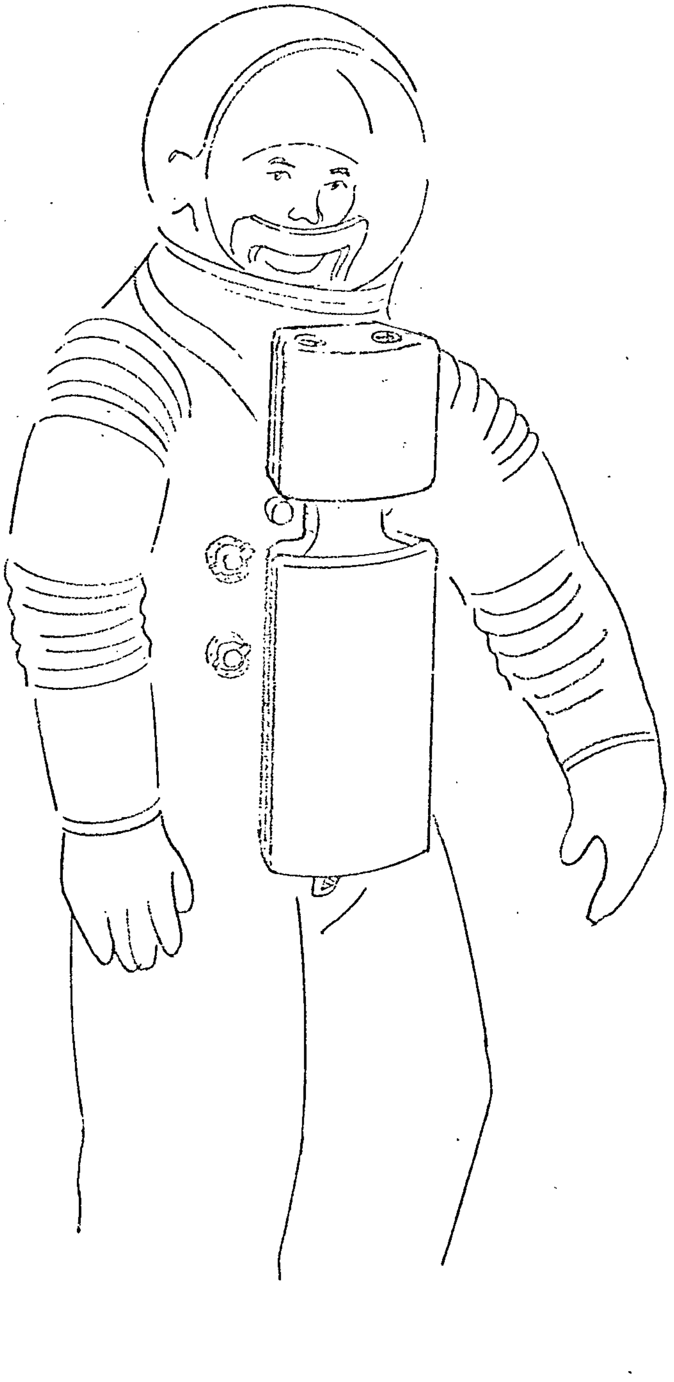

Figure 33. ELSP/Suit Interface

- The four oxygen bottles and single water container are stacked in a pyramid fashion that permits access to the existing suit oxygen connectors.
- High packaging density is provided by incorporating the oxygen regulator in the connecting structure between the two sections of the ELSP.
- The top portion of the package is in the correct position to incorporate the status and control elements of the pack.
- The design lends itself to an expendable package replacement (oxygen and water containers) should this be desired for some future application. The total emergency mission profile planned for the present system, however, is felt to make unwarranted any quick disconnect features for the expendable storage bottles.

BREATHING VEST AND DUCT

Interface Tests

An important series of tests was conducted using a suited subject wearing a duplication of the breathing vest and duct as delivered to NASA in April, 1969 (reference Figure 20). The tests provided valuable information on a weakness of the duct configuration and showed by an independent check that the method that had been used to establish metabolic rate (percent CO_2 in suit exhaust) was accurate (at least for the subject tested).

The tests consisted of a subject (D. Curtis) walking on a treadmill at 1.5 mi/hr while wearing the Litton RX-3 suit. Cooling was provided to the subject by the recirculation of cold water through a Liquid Coolant Garment (LCG), a pulse pump, and a heat exchanger/Freon refrigeration system.

Subject and system were instrumented as follows:

- Subject-inspired CO_2 was measured using a Beckman LB-1 analyzer at a continuous sampling rate of 500 ml/min. A 1/16 in. diameter sampling line was used.

- Percent CO_2 in exhaust gas was monitored through a second 1/16 in. diameter line to the analyzer.
- Water flow ($\dot{W}$) and the temperature rise across the LCG (ΔT) were monitored using a rotameter and thermocouple bridge, respectively.

It was initially established that the duct configuration was not working as well as had been expected. The immediate result was that the subject started to complain that he was not getting enough fresh breathing air above an MR of 1600 BTU/hr. In addition, it was observed that the inspired CO_2 readings were exceeding 7.6 mm at the higher metabolic rates.

After some investigation, it was determined that too much gas was exiting around the sides of the duct opening and missed the subjects oral/nasal region. It had been expected that the two converging gas streams from the two channels of the duct would be directed in a natural manner toward the oral/nasal region upon leaving the duct opening. Some gas, however, was also directed in an up and down direction and thus avoided the oral/nasal region.

One solution tried was to line the opening with plastic foam to provide some channeling of the gas flow as well as offering a soft cushion in case the duct came in contact with the face. The difficulty with this approach was that whenever the oral/nasal region did firmly come in contact with the duct opening, the expired breath would exhaust down the duct channels into the vest and produce a high level of CO_2 during the next breath inspiration.

Figure 34 shows the approach that was taken to solve the above two problems. In this configuration the front side of the duct was cut and shaped as shown with the following results. On inhalation, the breathing-vest air is forced directly at the oral/nasal region by the curved deflectors. On exhalation, however, the opening between the two deflectors allows the breath to leave the oral/nasal region without passing down the duct into the vest. The reason for this is that the vest is always at a slight positive pressure with respect to the helmet (it is continuously being filled by the

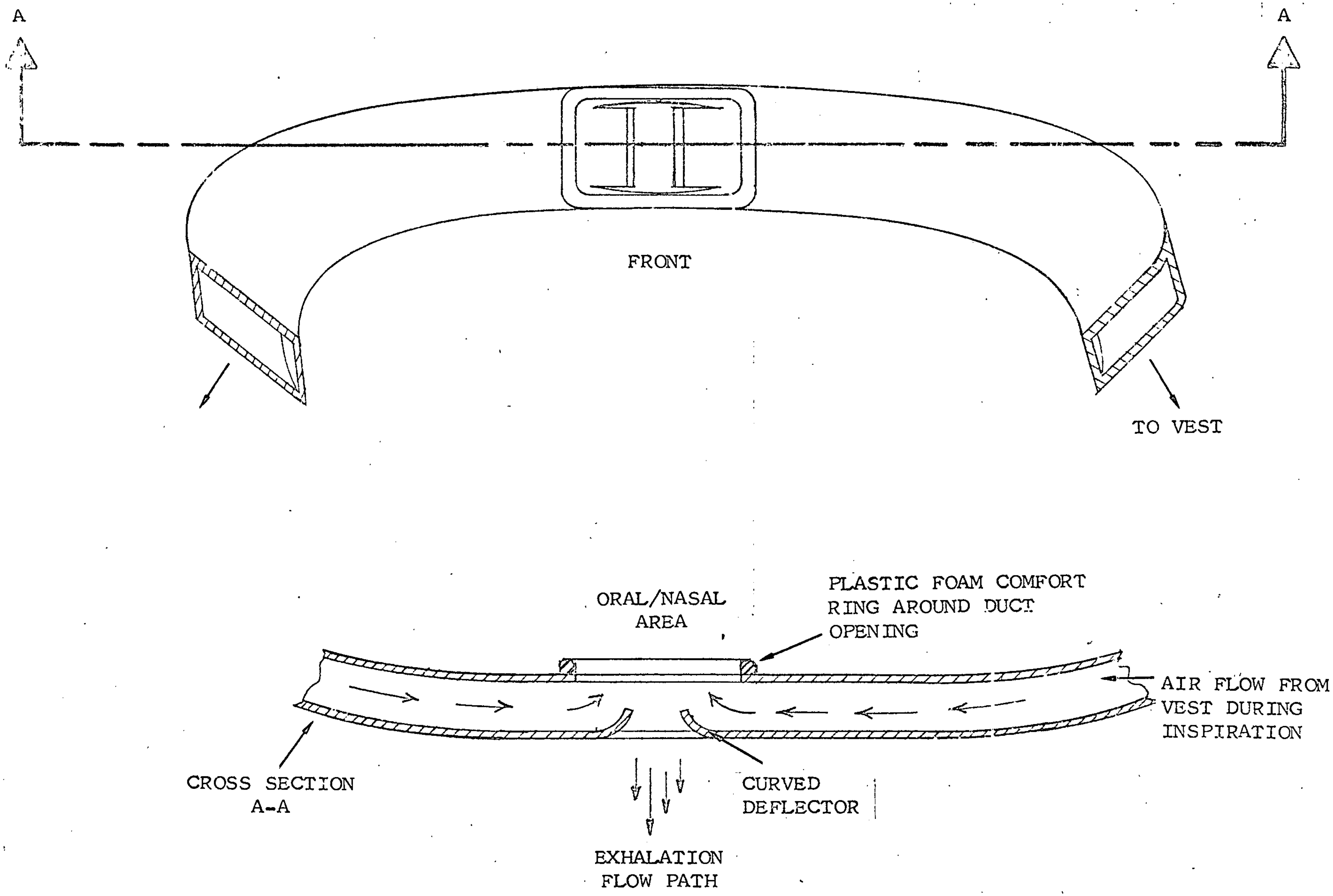

Figure 34. New Duct Geometry

inlet gas flow from the PLSS). The slight positive pressure is ample to prevent any back flow as long as there is another way for the exhaust gas to escape.

The unique feature of this duct opening/vest combination is that the shape of the duct opening at the oral/nasal region produces the effect of two mechanical valves (or a single mechanical shuttle valve) without the necessity of moving parts or the larger pressure differences required for a mechanical valve operation.

This new shape of duct opening was experimentally used for the first time involving a suit subject on July 22, 1969. The test not only verified the duct performance at high metabolic rates (2000 BTU/hr and 1-1/4 cfm air with an inspired CO_2 level of 4.5 mm to 6.8 mm) but also gave confirmation to an earlier method of measuring metabolic rate (percent CO_2 in suit exhaust gas).

The cooling to the LCG was provided by a closed-loop water circulation system which, in turn, was cooled by a controllable Freon refrigeration system. The subject was, in addition, able to select the amount of cooling that provided thermal comfort.

The total test lasted eight minutes with an equilibrium state for both percent CO_2 in suit exhaust (4.1 percent in 1-1/4 cfm flow) and ΔT across the LCG (8.5°F at 240 lb/hr flow). The calculated metabolic rate from both sets of measurements gives the same number, or 2050 BTU/hr.

It was initially thought that metabolic rate measurement based upon $\dot{W}\Delta T$ should have added to it the respiratory loss of approximately 135 BTU/hr (at an MR of 2000 BTU/hr). This would give a total MR of 2185 BTU/hr. It is highly probable, however, that most of respiratory heat (sensible and latent) is absorbed on the LCG before the gas exits the suit, thereby establishing $\dot{W}\Delta T$ as a measurement of the total metabolic heat produced by the body (when an LCG is used).

Redesigned Breathing Duct

A fiberglass breathing duct was fabricated to allow integration with the crewman communication carrier as presently used for Apollo missions. While yet to be tested in a spacesuit the duct performance as tested by the helmet duct evaluator (reference Figure 4 of Stage I) looks very good. The X factor reading obtained from the evaluator at 1-1/4 cfm was 0.85 at 1/4 inch spacing between the duct and the oral/nasal region with a value of 0.80 at 1/2 inch spacing.

These results are to be compared with an X factor of 0.75 required for an inspired CO_2 level of 7.6 mm at 2000 BTU/hr (see Progress Report No. 4, Item 2).

The important advantage of the new duct (see Figure 35) compared with those previously tested lies in the fact that it is locked to the communication carrier headset in a manner that automatically locates the duct opening directly in front of the oral/nasal region. By this technique the relative position of the duct to the head is fixed and the crewman is free to move his head to any position within the helmet while maintaining a constant inspired CO_2 level.

There was some concern before construction that the configuration would either require some form of sizing adjustment or would require a number of sizes to permit fitting all subjects. This, however, was not a problem. The unit was tested with a half dozen subjects at Litton of various head proportions and the fit appeared universally good. In each case the communication carrier had sufficient latitude in its fit to the head to permit the unit (command carrier plus duct) to be positioned so that the duct was properly oriented.

TESTING OF PLSS

A series of tests (unmanned and manned) was initiated at NASA-MSC on the Litton PLSS as delivered in April, 1969, at the end of Stage I. The first

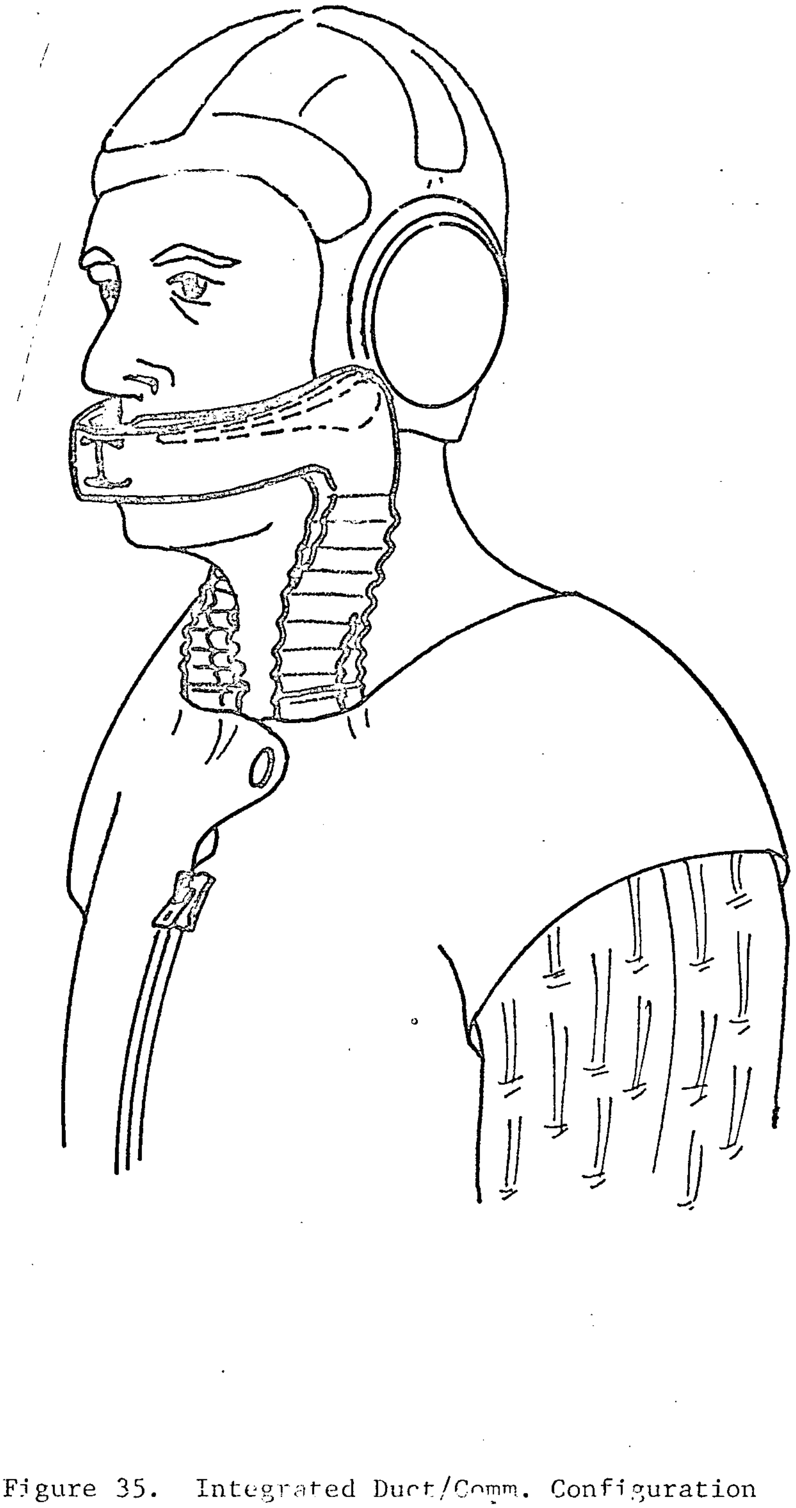

Figure 35. Integrated Duct/Comm. Configuration

test of the series was conducted July 30 through August 1, 1969, with a Litton engineer (D. Curtis) as an observer. A successful umnanned test (constant system performance) was completed July 31, lasting 3 hours and 20 minutes at a heat load of 1920 BTU/hr. Seven pounds of water, as initially stored in the system accumulator, were used during the test.

The manned run experienced a procedural difficulty that forced its postponement until rescheduling could be arranged.

DESIGN REVIEW

A design review was held midway through Stage II of the contract to establish system configuration and the interfaces between breathing vest and LCG, and breathing duct with astronaut communication carrier.

The system configuration approved was the so-called Litton "E" approach illustrated in Figure 33 where the system expendables oxygen and water are packaged together and chest-mounted below the suit electrical and water connectors. The functional parts of the ELSP, the sublimator and pulse pump are located in a part of the case above the two connectors that will also accommodate controls and status instrumentation.

The schematic layout is identical with the one presented at the design review except for the addition of a quick disconnect oxygen input connector downstream of the system oxygen regulator. This connector, in conjunction with the water fill valve, allows the system to operate from an auxiliary expendable source (such as oxygen and water bottles stored in a back pack). In this manner the basic 45-minute system can be extended to any desired duration.

Prior to the design review, breathing vest and duct interfacing alternatives were considered. The review established that the breathing vest would be integrated with an LCG as shown in Figure 36. In addition, the configuration of Figure 35 was chosen as the best candidate for duct/comm. carrier interfacing.

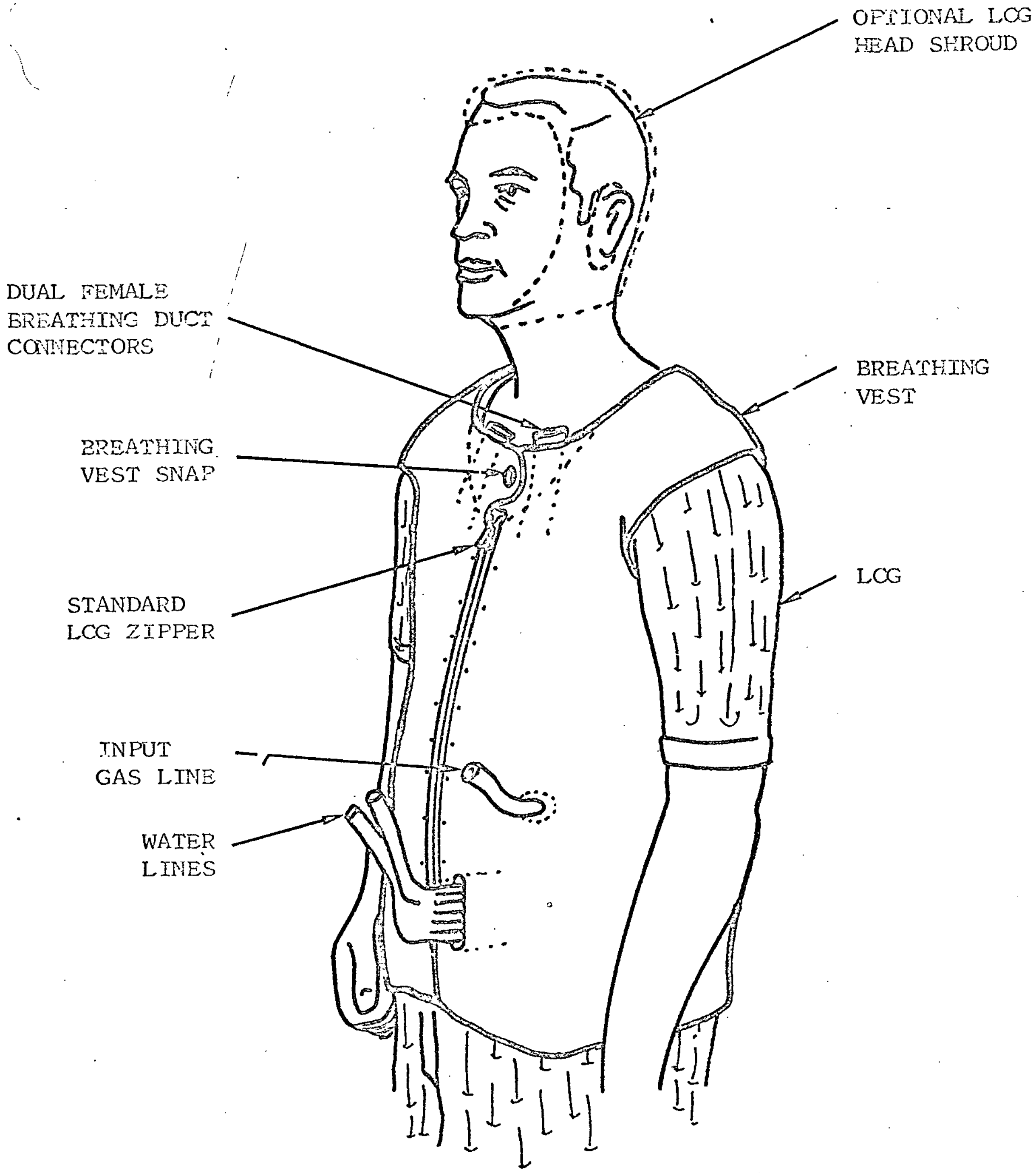

Figure 36. Integrated Breathing Vest/LCG

Vest interfacing to the LCG involved modifying the slip-over garment by a cut down the garment front and then resealing the resultant two open edges. The altered garment was attached (sewn) to the LCG on each side of the zipper so that closing the zipper and vest top snap complete vest/LCG donning (except for the necessary water and gas connections to the appropriate suit pass-through fittings).

The most satisfactory breathing duct/comm. carrier interface solution is shown in Figure 35. This configuration has the immediate advantage over several other approaches that were considered in that the position of the duct opening is fixed with respect to the oral/nasal region. The crewman is, therefore, free to turn his head to any position he wishes without affecting the percentage of duct oxygen reaching the oral/nasal region. As stated earlier, permissible inspired CO_2 levels limit the distance between the duct opening and the oral/nasal region to approximately 1/2 inch. The configuration illustrated ensures that this relation is maintained while at the same time guaranteeing that the duct will not physically touch the face.

The duct is molded with a groove along its inside surface to accept the mike boom.

The duct is fastened to the comm. carrier by a metal clip-on device. The clip-on is fastened to the duct on one end and formed to slip over (and behind) the tapered, silicone rubber boom/comm. carrier transition piece.

ENCLOSURE

With the finalization of system design and packaging details it was possible to complete the design of the case in which the total system is housed. It is made of aluminum, in two halves, and shaped to enclose the system within the smallest possible compass. The main part of the case, in which all components are mounted, constitutes the front half, and the cover, against the wearer's body. is readily removable using Dzus fasteners.

SYSTEM WEIGHT

An estimate of the filled weight of the ELSP was made before the program began, in Litton Publication No. 11-69-266, "Proposal for an Emergency Life Support System". It is of interest to compare this early estimate with the estimate made toward the end of the contract. The breakdowns are as follows:

Item	Orig. Est. Wt. (lb)	Pres. Est. Wt. (lb)
Breathing Vest	1.0	1.0
Oxygen Bottles (4)	5.0	4.66
Water Storage	2.2	2.8
Pulse Pump	1.0	1.0
Sublimator	1.2	1.10
Regulator	1.0	0.74
Control Box	0.5	----
Case	1.0	2.0
Misc. (Valves and Plumbing)	2.7	2.7
	15.6	16.0

The major uncertainty factor in both columns was the estimate given for the miscellaneous category (2.7 pounds), because this involved many small items. The major difference between the two estimates appears in the case weight (2 pounds, versus 1 pound). The present 2-pound estimate was based upon using 40-mil aluminum for the case, a rather heavier gauge than was first planned.

At the close of the program, fully assembled and including the breathing vest and the suit output pressure controller, the empty weight is 13.5 lb, and the filled weight is 16.4 lb.

PREDELIVERY TESTS

Tests performed following final assembly included measurement of air flow through the two pressure dropping lines in the system. Also, the hole sizes of the two orifices that allow a portion of the gas flow to bypass the pump were experimentally established.

Pressure Dropping Line Tests

A test was made for the purpose of determining the lengths (ℓ_1 and ℓ_2) of the two pressure dropping lines used to establish the 1.25 cfm and 2.5 cfm delivered by the ELSP to the suit. The test schematic (see Figure 37) consists of a pressure source, the 27 mil I D pressure dropping line, an output pressure measuring gauge, a flow meter, a throttle valve and a vacuum pump.

The Carleton Control regulator used in the ELSP has a regulating output pressure of 67 psig. When used in a vacuum the regulating pressure will therefore be 67 psia or 52.3 psi above atmospheric (as set by the regulator and first pressure gauge).

The length of the 1 cfm line was determined by establishing a pressure of 3.7 psia at the output of the line and altering the length until an output flow of 1 cfm (at 3.7 psia) was measured by the rotameter. By this method the length of the 1 cfm line (ℓ_1) was established at 18.5 inches.

The length of the 1.25 cfm line that supplies the normal flow to the breathing vest is a little more difficult to determine because the line terminates at the pump and orifice bypass line rather than at the suit. The pump input pressure must therefore be known and the output flow of the line measured at this pressure and then adjusted for the expanded volume flow at 3.7 psia.

Pump inlet pressure should be determined by an actual measurement while the pump is moving 4 lb/min through the actual external circuit consisting of the LCG, sublimator, connectors and lines. In lieu of this measurement an approximation was made by assuming an external circuit water pressure

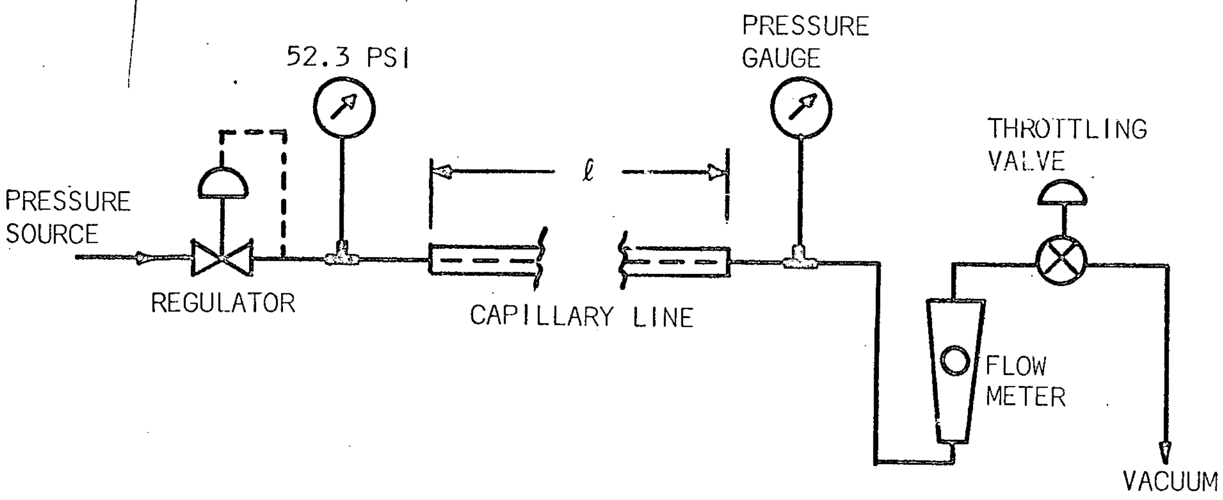

Figure 37. Pressure Dropping Line Test

drop of 4.3 psi at 4 lb/min flow. The absolute inlet gas pressure is then the sum of the pressure drop, the suit pressure and the reservoir pressure (gas plus elastic bands) or 4.3 + 3.7 + 2 = 10 psia. This number may have to be altered slightly after the system is placed in operation as it does depend on water pressure drop which may be different from the assumed 4.3 psi.

Setting the outlet line pressure to 10 psia, the length of line was then adjusted for an output flow of 1.25 x 3.7/10 or 0.44 cfm at 10 psia). The line length (ℓ_2) was then determined to be 12.5 inches.

Orifice Bypass Tests

A determination was also made as to the size of the two orifice holes in the pump bypass circuit. The primary function of this circuit is to permit most of the flow (1 cfm of the total 1.25 cfm) to bypass the pump. In addition a pressure divider is formed that allows the gas side of the water reservoir to be maintained one psi higher than suit pressure.

The test schematic that was used to establish the size of the two orifices is shown in Figure 38. All flow measurements were made with an orifice inlet pressure of 10 psia and an orifice outlet pressure of 3.7 psia as set by the two throttling valves. The total pressure drop across the two orifices was thereby established at 10 psia minus 3.7 psia, or 6.3 psi.

As indicated in the test schematic, orifice (1) will have a pressure drop of 5.3 psi and is therefore the orifice having the controlling influence on flow. In fact, if orifice (2) were removed the total flow would only be increased from 1 cfm to 1 x 6.3/5.3 or 1.2 cfm. The size of orifice (1) was determined then by initially eliminating orifice (2) and altering the diameter of the number one hole until a downstream flow of 1.2 cfm was established. Orifice (2) was then added and the diameter of its hole adjusted until a pressure drop of 1 psi was measured across the orifice. As expected the extra pressure drop reduced the total flow from 1.2 cfm to the desired 1 cfm confirming that a correct orifice selection had been made. Using a set of precision drill

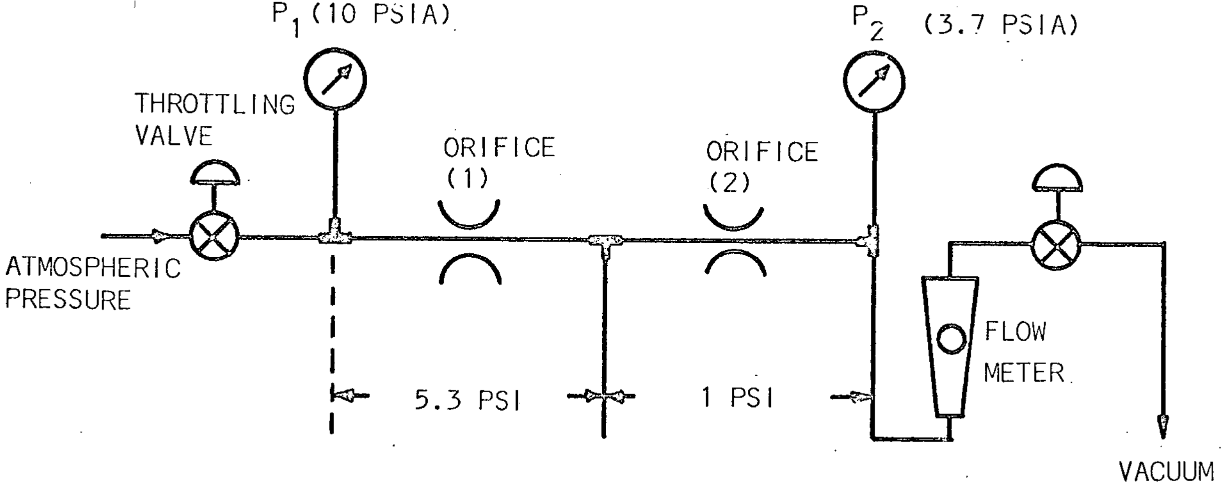

Figure 38. Orifice Bypass Test

rods, the diameter of the two orifices was then measured to be 0.043 inch and 0.0625 inch, respectively.

LEAK TESTS

Leak testing of the ELSP after completion of assembly was initially conducted with the application of a soap solution to suspect joints while under internal pressure. This approach appeared to be time consuming and also somewhat difficult as some of the connections are awkward to reach. It was finally decided to modify the approach and simply immerse the whole unit in water with the application of 5 psig internal gas pressure to both the gas and liquid loops. Using this method, leaks were readily located by the presence of escaping gas bubbles. This method proved highly satisfactory and greatly reduced the amount of time spent in searching for leaks.

VACUUM TESTS

The schematic diagram in Figure 39 shows the test set up with the ELSP and LCG installed in the Litton high altitude vacuum chamber, and the arrangement of test apparatus external to the chamber.

Water filling is accomplished by first vacuum exhausting the system through a water trap and then pressurizing the trap to 2 psig until flow ceases. The system water inlet valve is then closed, thus fixing the filled system water pressure at 2 psig.

Inlet gas pressure is then set to approximately 53 psig causing the pump to begin functioning at about 3 pounds/min. With pump operation determined to be normal, the system exhaust pressure is reduced from atmospheric to 3.7 psia causing the pump operation to accelerate as a result of the increased system volume flow.

With satisfactory pump operation established at the lower exhaust pressure, the chamber is then evacuated to about 100 microns and the water control valve is opened fully and heat loads from 1800 to 2000 BTU/hr are applied to the water loop until system water is exhausted (indicated by pump stoppage).

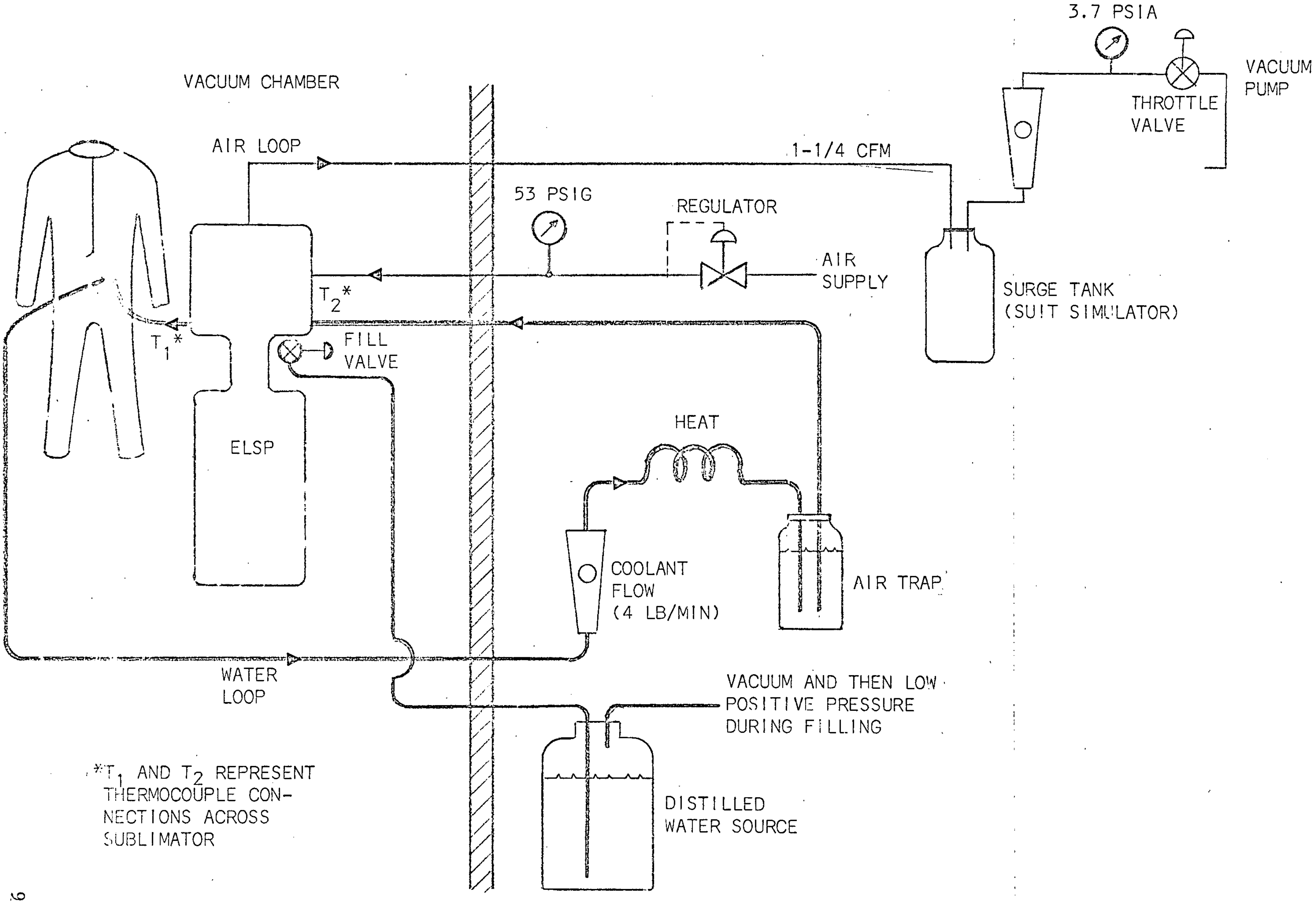

Figure 39. ELSP Test Schematic

Test results were good with subsequent minor adjustments and procedural changes in an attempt to optimize system performance and determine the most favorable operational procedures. The sublimator, for instance, required some adjustment as the outlet temperature was 46°F at 2000 BTU/hr instead of the desired 44°F maximum.

A full report of the testing of the ELSP in vacuum under simulated operational conditions is presented in Appendix D.

APPENDIX A

Figure A-1 shows the CO_2 sampling schematic as used to monitor inspired and exhaust CO_2 when using a suit-subject combination. The inspired CO_2 was monitored by a 1/16 in. ID plastic line sampling the oral region as defined by a SCUBA mouthpiece.

The 6-foot line was brought out through the helmet feed port and terminated at the Beckman LB-1 CO_2 analyzer. The small Beckman pump was used to provide a constant flow rate down the line of 500 ml/min. The diameter of the line was found to be important as a line inside diameter larger than about 3/32 in. was found to allow an excessive amount of diffusion to a step in CO_2 concentration. The net result was a reduction in analyzer response which at high ventilation rates would cause an indication of an inspired CO_2 level higher than actually present.

In operation the analyzer is calibrated immediately preceding and following a test using a gas containing a 2 percent concentration of CO_2. Respiratory CO_2 is monitored on a continuous basis except during the measurement of the suit exhaust CO_2 which is obtained on a once-per-minute basis. All results are recorded on a Sanborn recorder using a paper speed of 1 mm/sec.

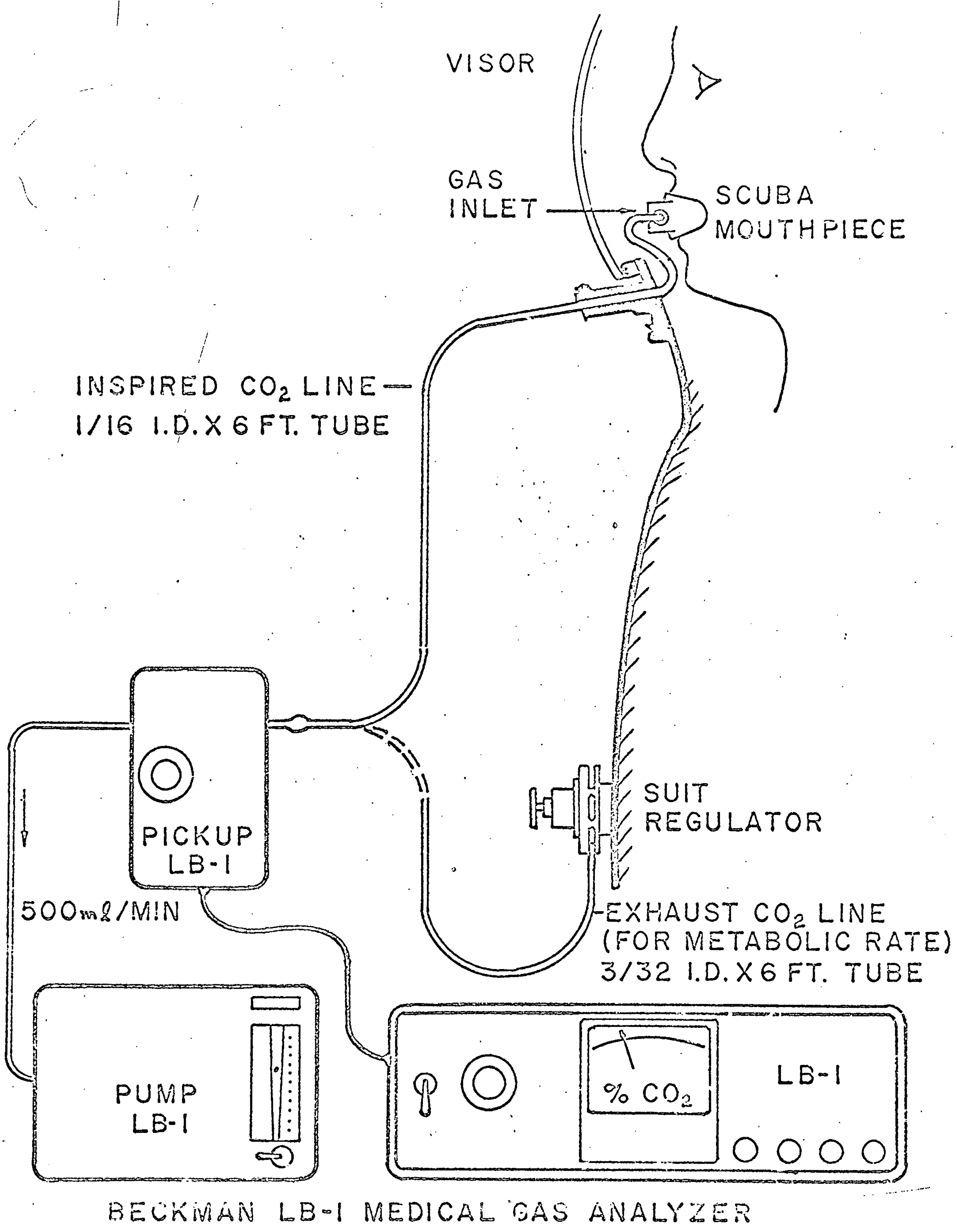

Figure A-1. CO_2 Sampling Schematic

APPENDIX B

TEST REPORT

TEST OBJECTIVE: To determine whether the AiResearch pressure relief valve No. 800278-6-1 ices under the following environmental conditions:

Air Flow	1-1/4 acfm
Air Temperature	80°F
Relative Humidity	90%
External Pressure	0.05 psia ≅ 2.6 mm Hg

PROCEDURE: The pressure relief valve was mounted inside the Litton Space Environment Simulator and the chamber evacuated (see Figure B-1). Lab air was bubbled through warm water to obtain the proper temperature and humidity before being exhausted through the valve. The valve was examined for signs of icing through a chamber window.

RESULTS: The following data were recorded:

TIME	CHAMBER PRESSURE (mm Hg)	AIR FLOW (acfm)*	AIR TEMP (°F)	R.H. (%)	VALVE TEMP (°F)
10:50	0.08	1.27	79	88	78
11:30	0.08	1.27	81	96	78
11:45	0.08	1.27	81	95	81
1:05	0.08	1.27	80	95	77
1:35	0.08	1.27	79	94	76

There were no signs of valve icing at any time during the test.

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*Pressure within the valve was approximately 3.8 psia.

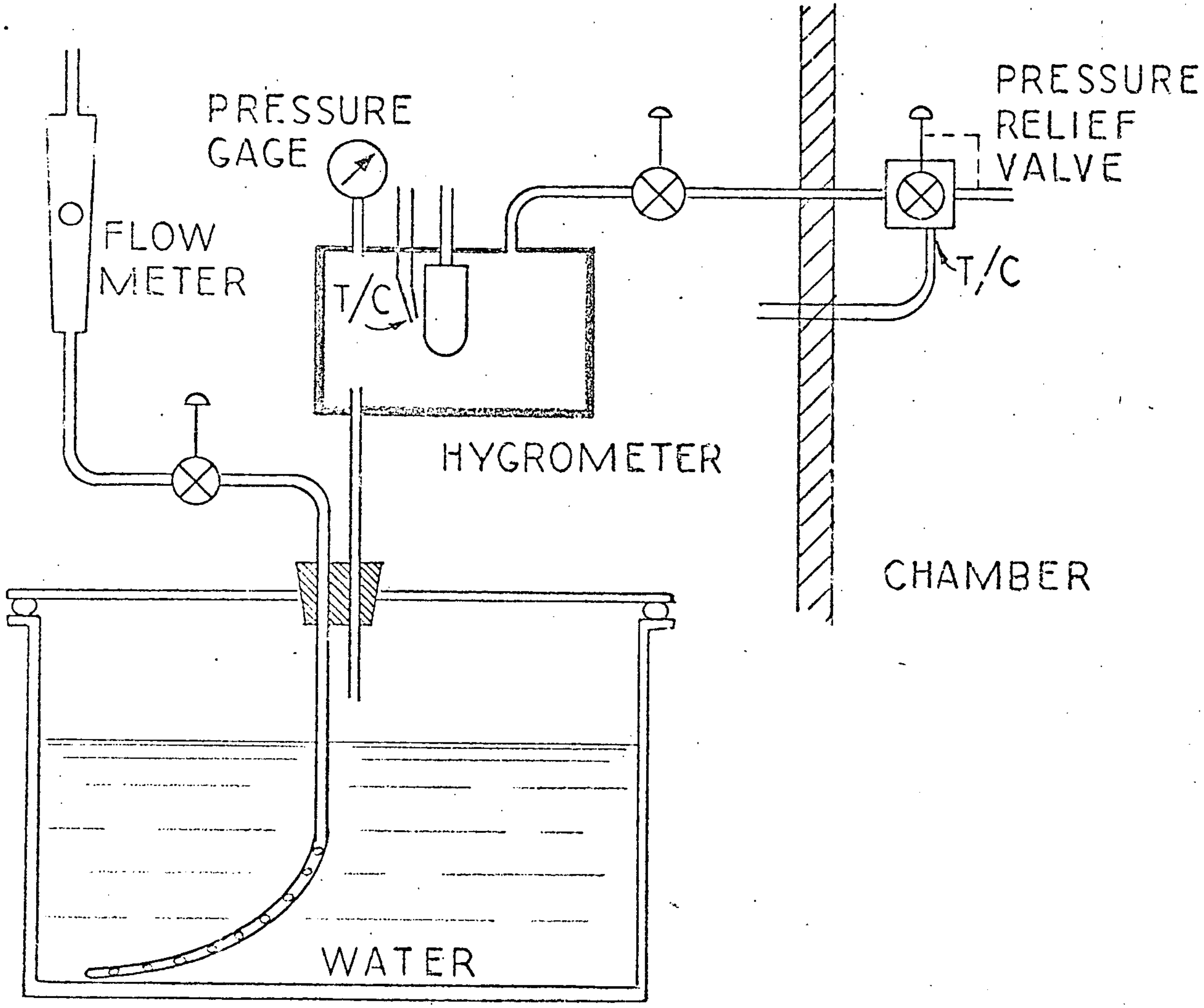


Figure B-1. Arrangement of Equipment for Valve Test

APPENDIX C

Table C-I presents a summary of the design goals of the present contract PLSS unit together with a proposed system that could be constructed by replacing the low pressure bottles with high pressure oxygen storage vessels. A comparison of the two columns will show that the systems are essentially identical except for the additional weight of oxygen stored.

TABLE C-I. LITTON PORTABLE LIFE SUPPORT SYSTEM
(Open Loop with Breathing Vest)

ITEM	PRESENT CONTRACT	PROPOSED SYSTEM
MISSION		
Mission duration, hr	0.38	3.5
Contingency Provision, hr	0.12	0.5
Average Metabolic Rate, BTU/hr	1600	1600
Pk. Metabolic Rate, BTU/hr	3000	3000
Heat Leak Max., BTU/hr	+250	+250
SYSTEM		
Total Weight (less LCG), lb	30.6	39
Envelope; in. x in. x in.	19.5 x 17.3 x 6.9	19.5 x 17.3 x 6.9
O_2 Storage, lb	0.84	7.1
H_2O Storage, lb	7.3	7.3
O_2 Initial Pressure, psi	400	3500
SUIT (2000 BTU/hr MR)		
Pressure, psia	3.7	3.7
Primary Flow Rate, lb/hr	1.68	1.68
Primary Flow Temp., °F	50	50
Inspired CO_2, Max, mm Hg	7.5	7.5
Inspired Relative Humidity, %	25	25
O_2 consumed, lb/hr	0.325	0.325
CO_2 produced, lb/hr	0.390	0.390
Overboard Flow Rate, lb/hr	2.0	2.0
THERMAL LOOP (2000 BTU/hr)		
Flow Rate, lb/min	4	4
Suit Inlet Temp., °F	48	48
Suit Outlet Temp., °F	56	56
Pump Pressure rise, psi	6	6
Sublimator Flow, lb/hr	2	2
REMOTE CONTROL UNIT		
O_2 Control, lb/hr	0, 1.68, 3.36	0, 1.68, 3.36
Thermal control, BTU/hr (Approximate values)	0, 600, 1200, 1800, 2400	0, 600, 1200, 1800, 2400

APPENDIX D

TEST REPORT ON ELSP IN VACUUM

The test installation is shown schematically in Figure 39.

For the vacuum test an initial condition was that the ELSP system oxygen bottles be filled through the charging valve to 3650 psig. The water reservoir and transport loop were then evacuated through the water fill valve and distilled water bottle and then refilled with water to a pressure of one psig at which time the system water fill valve was closed.

The auxiliary air supply was then set to 53 psig with the ELSP exhaust connected through a surge tank to a vacuum pump. The throttle valve was adjusted to a surge tank pressure of 3.7 psia with the observation that the flow as indicated by the rotameter was 1-1/4 cfm (at 3.7 psia). It was also observed that the coolant flow was in excess of 4 lb/min for these conditions.

With the system in operation from the auxiliary air supply, the chamber was pumped down to approximately 100 microns. A test run was started by first opening the ELSP master air valve closing the auxiliary air supply and then opening the feedwater control valve. The manual control of the above two valves was done from a point external to the chamber by means of a metal wand penetrating the chamber through a rubber grommet. The chamber end of the wand was forked to allow a turning of the wand to engage and rotate the system control knobs.

A typical system run of almost one hour's duration is shown in Figure D-1. Water start temperature was 70°F. The initial system cooldown was done in the absence of external heat with about 5 minutes required for a transport water

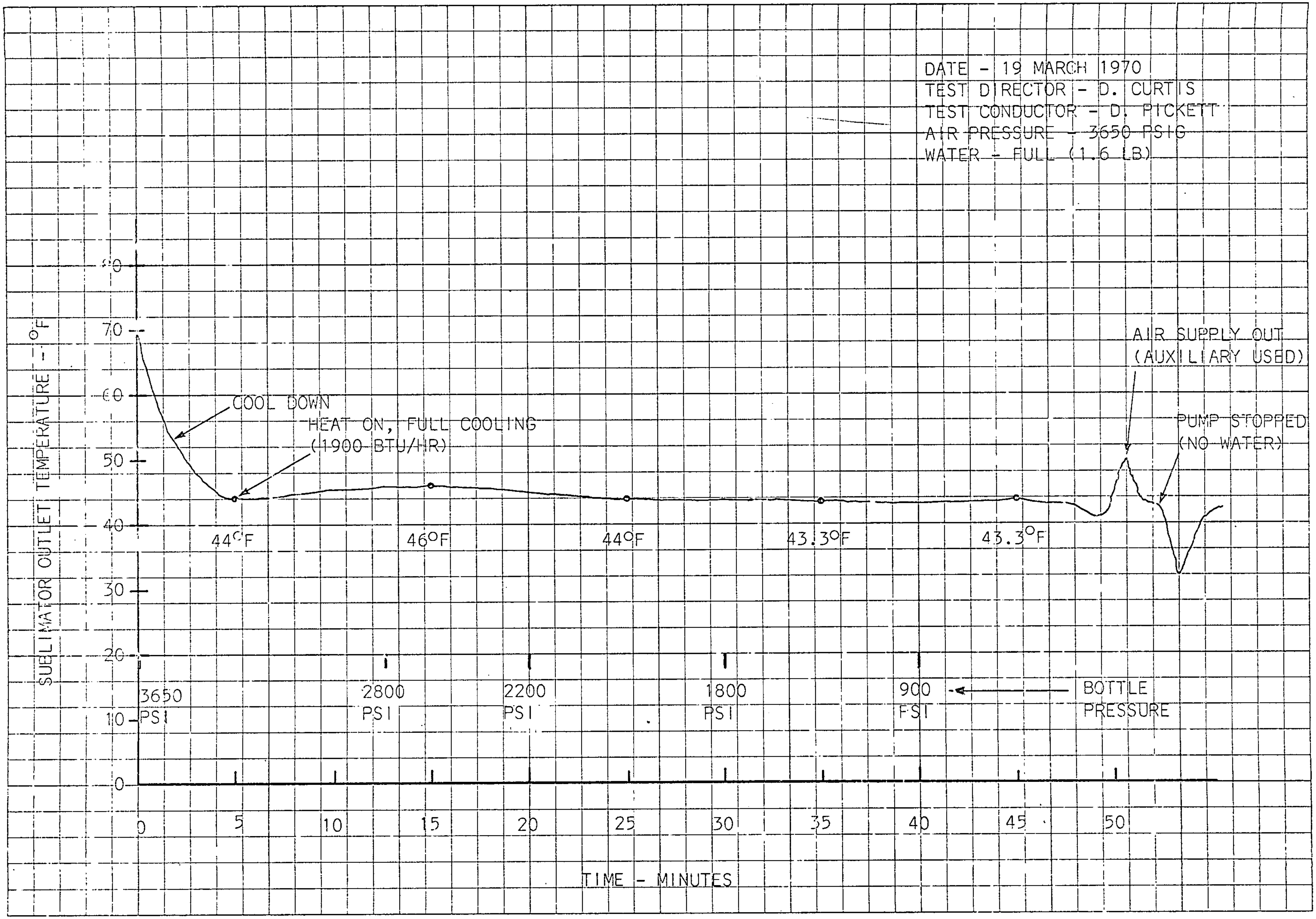


Figure D-1. ELSP Full Functional Checkout temperature reduction of 25°F. The initial cooling rate is estimated to be in excess of 4000 BTU/hr based upon a comparison of the 1900 BTU/hr heating slope of Figure D-2 with the cooling slope of Figure D-1.

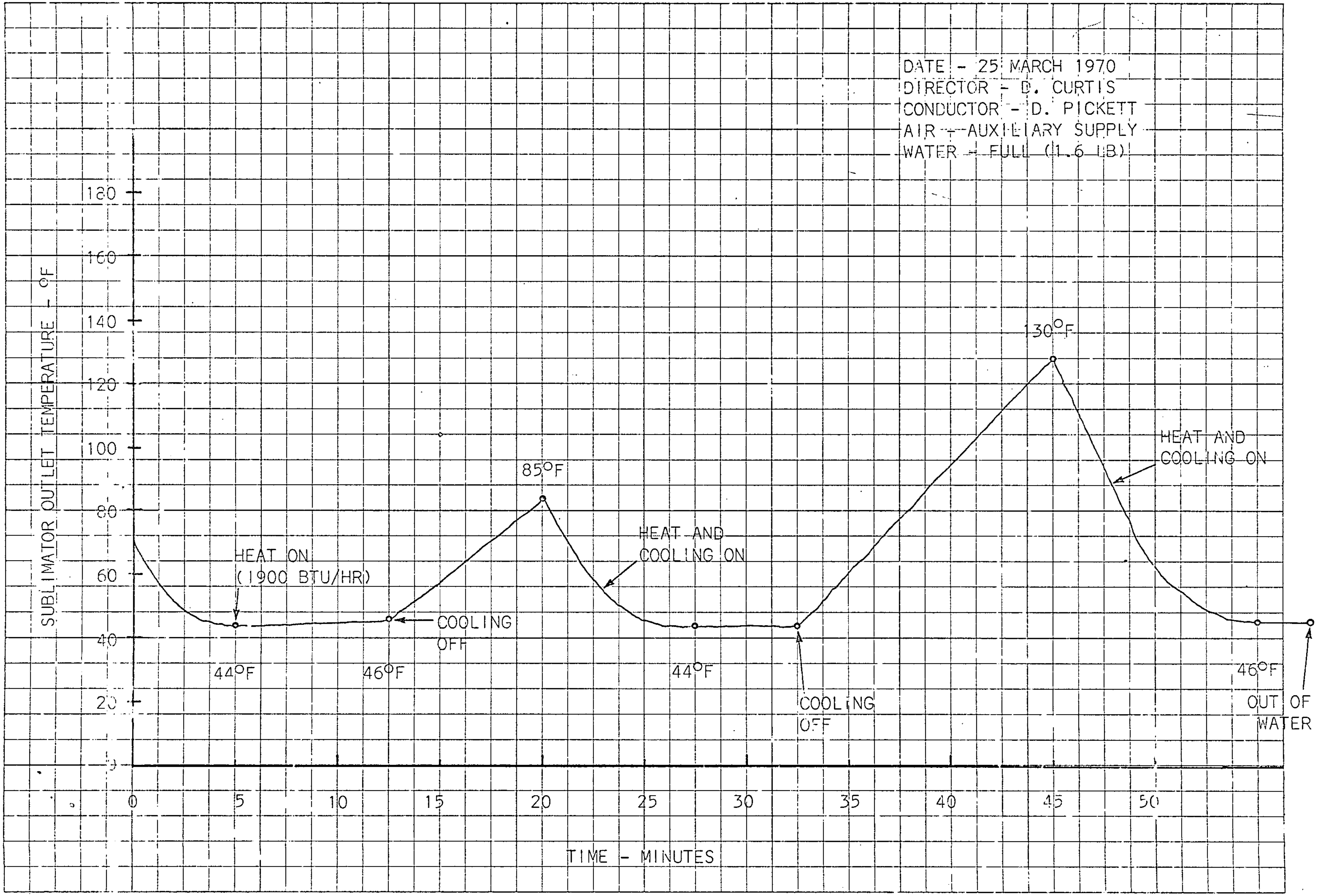
At a transport water temperature of 45°F, full system heat of 1900 BTU/hr was applied. The heat input was measured by taking the product of the transport water flow (240 lb/hr) and the temperature drop across the sublimator as measured to be approximately 8°F (using thermocouples and a Leeds and Northrup millivoltmeter).

The curve shown in Figure D-1 shows the sublimator outlet temperature as a function of time. The important features of the test results were that the temperature remained essentially constant at 44 to 45°F for the duration of the test and that the test duration was in excess of 45 minutes before system air and water were depleted.

The test curve shown in Figure D-2 results from first cooling the system to 44°F, turning on heat (1900 BTU/hr) for 7 minutes, and then turning cooling off until a system temperature of 85°F is achieved. With heat still applied, cooling was turned on full until a 44°F water temperature was again established. Cooling was again turned off allowing the water temperature to rise to 130°F. With heat maintained at 1900 BTU/hr, full cooling was applied resulting in a final system temperature of 46°F. Somewhat more ice than normal was observed on the sublimator surface for the latter test.

A final system test (not shown) was conducted with the unit enclosed in its case (all previous performance tests were conducted with the case off). As on previous runs an outlet sublimator temperature of 45°F was reached after a 5-minute cool down. 1900 BTU/hr was then applied and as on previous runs the temperature was maintained at essentially 45°F for the test duration (50 minutes).

A final test was performed to determine system flow rates if ambient conditions were used rather than exhausting into a 3.7 psia sink. At an



DATE - 25 MARCH 1970
DIRECTOR - D. CURTIS
CONDUCTOR - D. PICKETT
AIR - AUXILIARY SUPPLY
WATER - FULL (1.6 LB)

Figure D-2. Sublimator Hot Starts

exhaust pressure of one atmosphere (14.7 psia) the gas volume flow at the system exhaust was measured at 0.33 cfm. For this condition the resultant pumping speed of the system pump was reduced to approximately 3 lb/min. The system inlet pressure was set at 68 psig for this test in order to simulate the output pressure of the system regulator operating at a one atmosphere environmental pressure.

CONCLUSIONS AND RECOMMENDATIONS

The testing phase of the program was considered a qualified success. All performance requirements were met with the exception of the sublimator outlet temperature at an input heat load of 2000 BTU/hr. At 2000 BTU/hr the sublimator was to be capable of an outlet temperature of 41 to 44°F. The outlet sublimator temperature as measured from a number of runs varied between 45 and 46°F at a slightly lower metabolic rate of 1900 BTU/hr.

In order to correct the above deviation from performance requirements, it is planned that the next sublimator to be built will have approximately a 50 percent increase in heat exchanger surface area (within the same envelope dimensions and weight restraints). The increased surface area should significantly increase the sublimator heat transfer coefficient and thus lower the sublimator outlet temperature at full heat input. It is also noted that the follow-on life support system has an 1800 BTU/hr average heat input requirement instead of the 2000 BTU/hr. This reduction should also aid in lowering the sublimator outlet temperature.