SUBCRITICAL LIQUID OXYGEN STORAGE AND SUPPLY SYSTEM FOR USE IN WEIGHTLESS ENVIRONMENTS

H. ROBERT LUNDEEN

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FOREWORD

This report has been prepared by The Bendix Corporation, Pioneer-Central Division, under Contract Number AF 33(615)-2308. The work described in this report was conducted under the sponsorship of the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio 45433, under Project Number 6373, "Equipment for Life Support in Aerospace," Task Number 637302, "Respiratory Support Equipment." The contract monitor was Mr. Clyde G. Roach, Biotechnology Branch, Life Support Division, Biomedical Laboratory, Aerospace Medical Research Laboratories. At Pioneer-Central, Robert Lundeen was the project leader; Dr. George H. Bancroft, Staff Scientist, and Dr. Blase J. Sollami, Senior Engineer, provided technical consultation; Paul J. Gardner, Chief Engineer, Cryogenics, provided administrative supervision. The report summarizes work begun 1 January 1965 and concluded 3 May 1966.

This technical report has been reviewed and is approved.

WAYNE H. McCANDLESS
Technical Director
Biomedical Laboratory
Aerospace Medical Research Laboratories

ABSTRACT

A subcritical liquid oxygen storage and supply system for use in weightless environments was designed, combining (1) the properties of the capillary-wick to displace gas phase from a two-phase mixture, thus assuring liquid phase delivery, with (2) the dominant surface tension forces which cause liquid phase to accumulate at the periphery and gas phase to locate at the center of a spherical container in a weightless environment. A 10-liter prototype unit was fabricated based on these concepts. The complete system includes, in addition to the storage container, associated temperature, pressure, acceleration, and strain sensors to monitor system performance in weightless conditions. Liquid phase delivery from the pressure vessel has been demonstrated by the oxygen-nitrogen mixed gas test technique. The testing program conducted on the prototype unit gave every indication that the design concept is satisfactory for weightless operation.

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SECTION I

INTRODUCTION

In modern-day manned aircraft, breathing oxygen supply is usually stored in the liquid form because of weight and space advantages. This subcritical pressure, two-phase system utilizes the pressurized blanket of gaseous oxygen maintained over the liquid oxygen interface to accomplish liquid-phase delivery. The liquid, having the gravity contributed characteristic of weight, is constantly exposed to the supply port of the container. The pressure differential created by the pressurized gaseous oxygen thus forces liquid from the vacuum-insulated storage vessel to an evaporating heat exchanger coil.

In space system storage of liquid oxygen, the absence of gravity or acceleration orientation forces prevents the use of standard two-phase systems, since random orientation of the liquid phase during weightless conditions prevents continual communication between the liquid phase and the supply port.

Space system storage of liquid oxygen is currently accomplished by pressurization of the cryogen to the supercritical pressure or single-phase state. The absence of gravity or acceleration orientation forces does not affect the delivery of fluid since the supply port is in direct communication with a homogeneous fluid at all times. Although this is a satisfactory system, its weight per pound of oxygen stored is greater than that encountered with the low-pressure two phase system (see Figure 1). For this reason, subcritical liquid oxygen storage systems are desirable for long duration space flights, in which system weight is severely limited.

This investigation concerns the design and development of a subcritical, two-phase liquid oxygen supply system for operation in a weightless environment. The design concept utilizes the properties of the capillary-wick to perform phase separation. The capillary-wick interface is suited to the function of vapor displacement from a two-phase mixture, thus assuring liquid phase for supply. The dominant surface tension forces in a weightless environment will cause liquid adherence to the tank walls and other internal surfaces. This phenomenon is utilized for assuring gas phase delivery for relief venting through the relief port which is located in the center of the container.

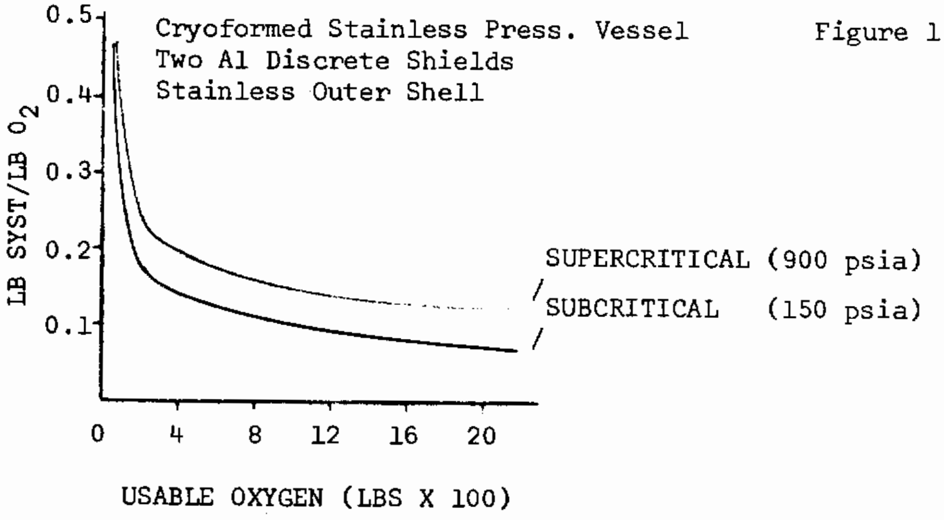


Figure 1. Comparison of Subcritical and Supercritical Tankage Weights

SECTION II

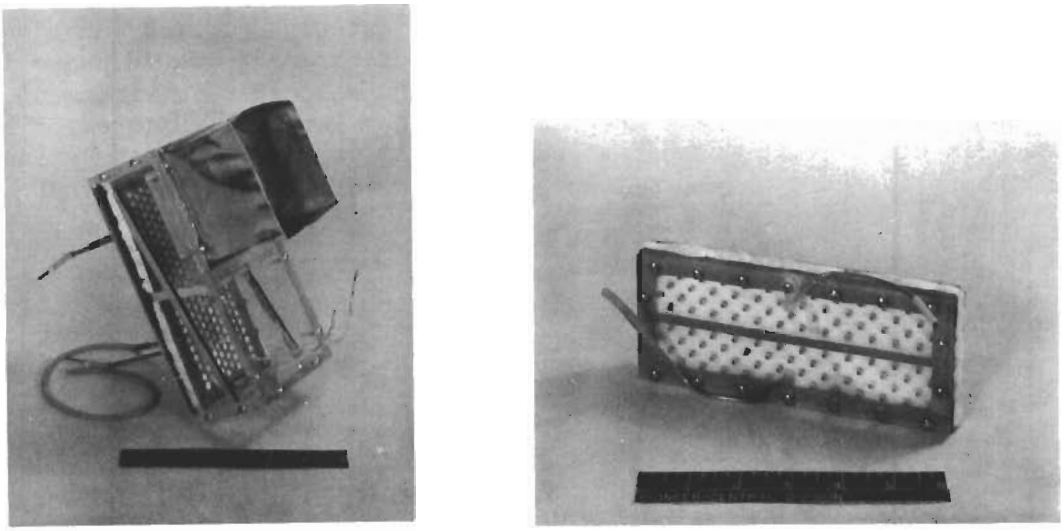
DESIGN PHASE TEST PROGRAM

A. Capillary-Wick Concept

1. General Design Concept

Several experiments (ref. 2) have been conducted in high drop towers with transparent containers to observe the effect upon fluid at near weightless conditions as simulated by the drop. These experiments have shown that in a weightless environment "the configuration of the liquid-vapor interface in spherical tanks for liquid nitrogen and liquid hydrogen is a totally wetted tank wall". In addition, "the contact angle of liquid nitrogen and liquid hydrogen on glass is 0°". Because liquid oxygen also has a 0° contact angle (ref. 1) and because all presently studied materials are wetted by liquid oxygen (similar to liquid nitrogen and liquid hydrogen), in a weightless environment liquid oxygen will wet the wall of a spherical container, and the gas phase will form in a bubble near the center.

Laboratory tests on models shown in Figure 2 have shown that liquid-gas separation control can be affected by compression of a fibrous network over a capillary orifice on which the maximum fiber density would occur at the orifice-fiber mat interface. The fibrous mat serves to collect and concentrate the liquid phase of the cryogenic fluid by exclusion of the gas phase.



(a) (b)

Figure 2. Fluid Phase Separation Control

The interface design between the capillary orifice and the type of fibrous mat determines the liquid-gas seal and the liquid flow characteristics (Figure 3). Application of the observed capillary-wick fluid phase separation control to a subcritical, two-phase liquid oxygen system involves the location of several capillary tube-fiber wick units within the liquid storage tank. These units have high wetting and surface tension characteristics for liquid and cause displacement of gas. The wick units are interconnected with small diameter tubes to maintain liquid continuity between the wick units and to provide the capillary flow of liquid between the wick units should one or more be exposed to the gas phase. This prevents vaporization "drying out" of the wicks which would allow gas phase leakage to the supply line. The object is to deliver only liquid phase to the supply line.

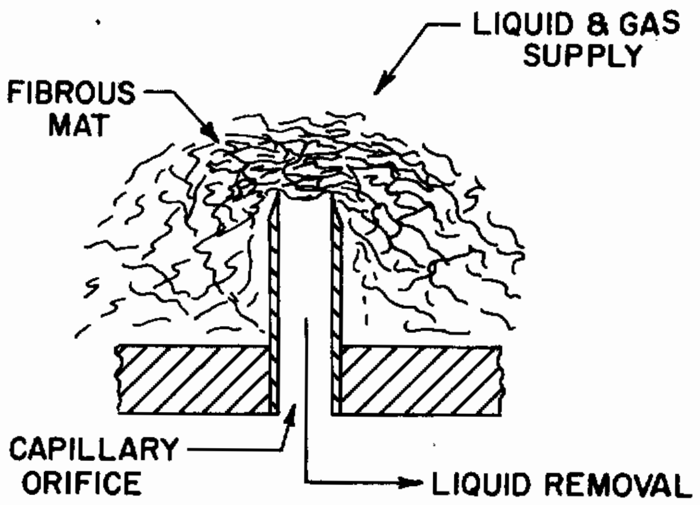


Figure 3. Capillary-Wick Interface

2. Wick Design (Refer to Figures 4 and 5)

Capillary tube bundle, "A," is soldered to funnel shaped wick retainer, "B," that contains surgical type cotton, "C," as wick material. The wick material is compressed and held in place by cover plate, "D," which has a series of holes to expose the top surface of the wick material to the surroundings. End cap, "E," provides the leak tight transition from capillary bundle, "A," to feed tube, "F," that connects to other capillary-wick units.

The inner surface of retainer, "B," is polished so that the wetted and precompressed wick material compresses uniformly during assembly and gives uniform fiber density and loading at the interface with capillary bundle, "A."

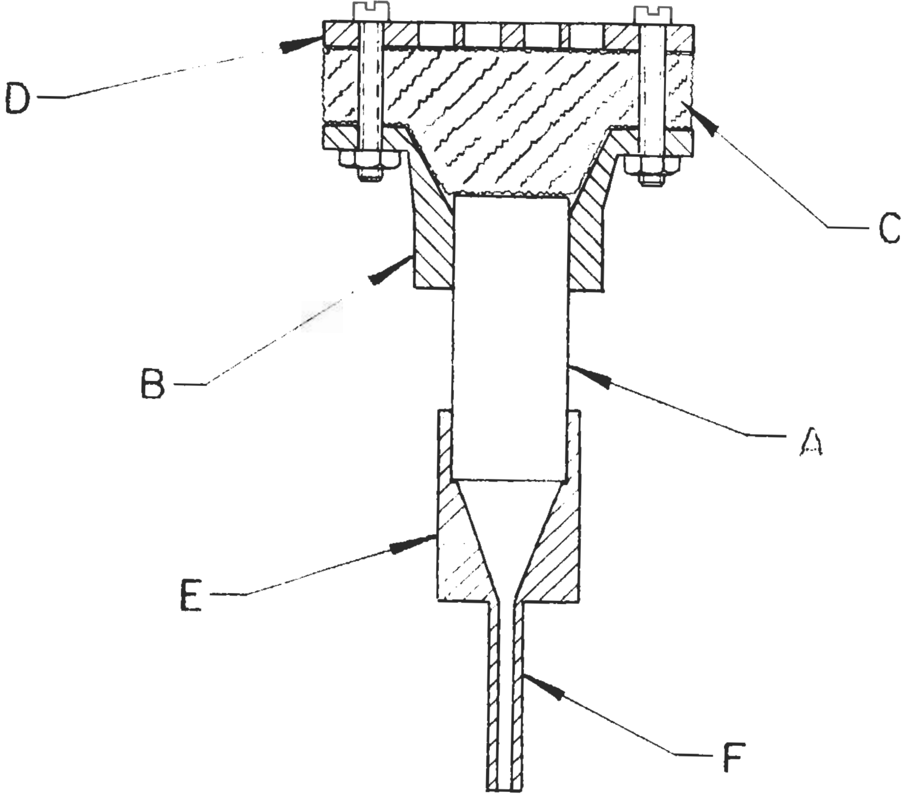


Figure 4. Capillary-Wick Assembly

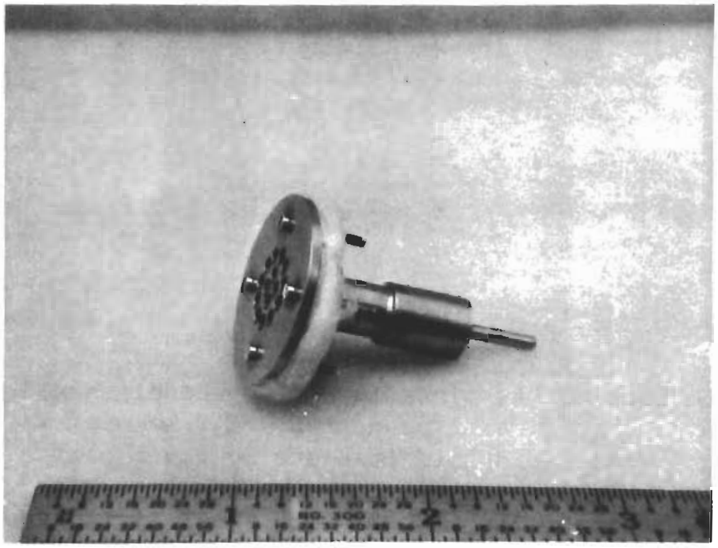


Figure 5. Capillary-Wick Unit

The capillary tube bundle consists of a stainless steel sheath, 5/16-inch diameter by 3/4-inch long, enclosing 900 capillary tubes, 0.009-inch diameter by 0.0015-inch wall thickness. (See Figure 6.)

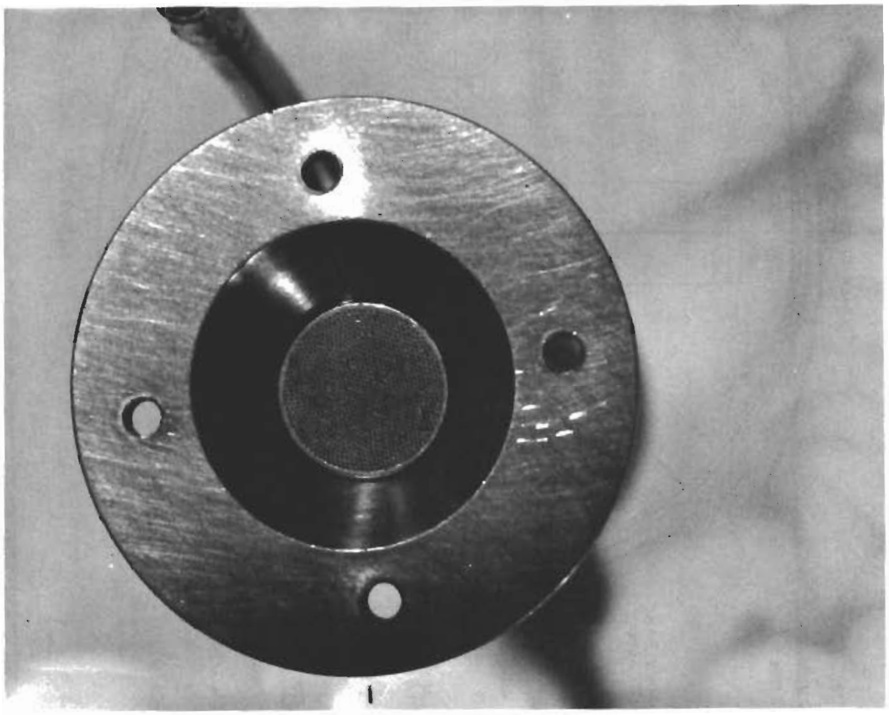


Figure 6. Capillary Tube Bundle

3. Capillary-Wick System Performance (Refer to Figure 7.)

The basic tank is a spherical 10-liter unit of the radial bumper suspension design. Six wick units are located approximately 90° from each other on a support ring at the periphery of the spherical liquid container. One wick unit is mounted approximately at the center of the container. The wick units are each connected to a manifold located near the bottom of the container, from which supply fluid transfers through tubing in the vacuum space to the supply port. All capillary-wick units are fairly well matched in terms of liquid-gas seal and liquid retention characteristics.

The function of each wick is to absorb liquid and displace the gas phase because of the higher capillary attraction between the fibrous wick and the liquid than between the wick and gas phase. The fibrous wick network serves as the liquid feed system to the capillary tube bundle - wick interface; fiber density is highest and most uniform at this region, therefore liquid-gas seal and liquid retention properties are determined by the interface region.

Liquid flow from wick unit to wick unit is by a capillary pumping action. If the tank is filled with liquid, all wick units are wetted by direct

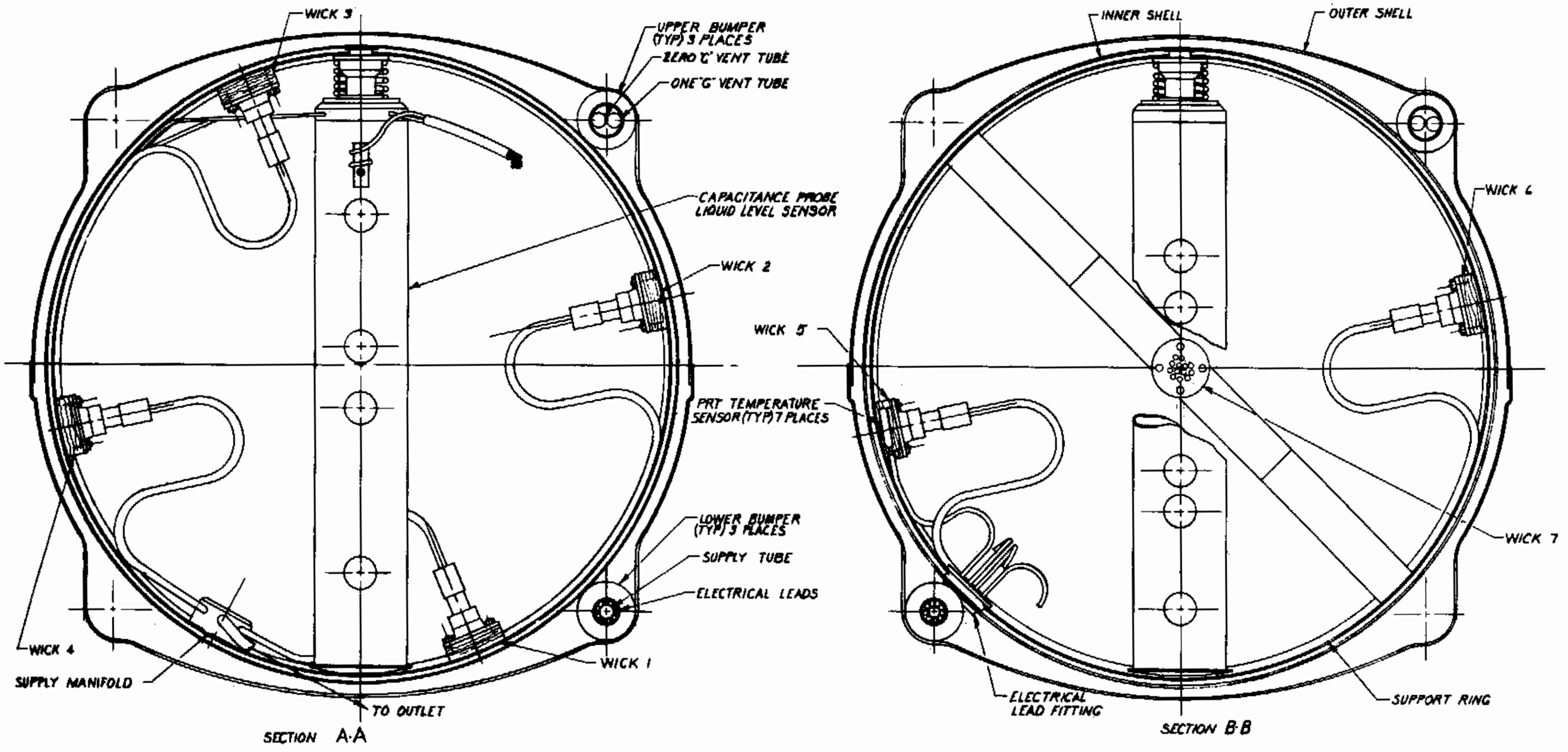


Figure 7. Container - Subcritical Liquid Oxygen Storage and Supply System

contact with the liquid; supply liquid flow will be maintained from all wick units. If, in a weightless condition and with a partially filled container, one or more wicks are exposed to gas phase, the bulk density in the wick goes down; the exposed wicks will receive liquid from those wicks exposed to liquid phase by means of capillary pumping action. Thus wetted, these wicks will provide a liquid-gas seal, and although exposed to gas phase, no gas will enter the feed system. Liquid supply to the manifold will be maintained by the pressure differential created by the gas bubble (presumably located near the center of the tank) forcing liquid through those wicks located in liquid phase. The worst situation appears to be in a gravity environment in which liquid covers only the lowest unit, wick 1. Liquid must be supplied to all other wicks by capillary pumping to maintain wetness and liquid-gas seal. The actual liquid flow to the wick units to maintain wetting is very low. As long as one wick unit is maintained sufficiently wet to provide a liquid-gas seal in each of the exposed wicks then only liquid phase will be supplied to the supply manifold.

Since liquid phase will form around the periphery of the tank in a weightless environment, wick 7 located near the center will be exposed to gas phase. A liquid-gas seal will be maintained at this wick by capillary pumping from the peripheral wicks (wicks 1 through 6).

If accelerative disturbances or other forces cause liquid to form at the center of the container, away from peripheral wicks, then wick 7 will be located in liquid phase. Capillary pumping to the peripheral wicks will maintain the liquid-gas seal, and the pressure differential due to gas-phase pressure within the tank will force liquid supply from the fully-wetted center wick to the supply manifold unit, and thus out to the supply port.

B. Preliminary Capillary-Wick Test Studies Utilizing Water

Initial testing of capillary-wick performance included examination of the following:

a) Wick thickness and compression load versus saturated liquid flow and gas seal characteristics at various Δ P's (across the capillary tube bundle-wick interface) for individual capillary-wick assemblies, utilizing various wick materials.

b) Feed, flow and gas seal characteristics between a master dual feed assembly and two extremity feeders, one above and one below the master.

1. Wick Thickness and Compression; Wick Material

Individual capillary-wick assemblies (Figure 8) were tested to determine the maximum head of water (Δ P) which could be maintained by the unit. Different wick materials were used; the amount of wicking material and its compression on the capillary-tube were varied. Water flow rates through saturated-wicking material units at the maximum head obtainable were also examined. Wick materials used include: a) Refrasil, b) Surgical cotton, c) Filter cotton, d) Dacron, e) Combinations of above.

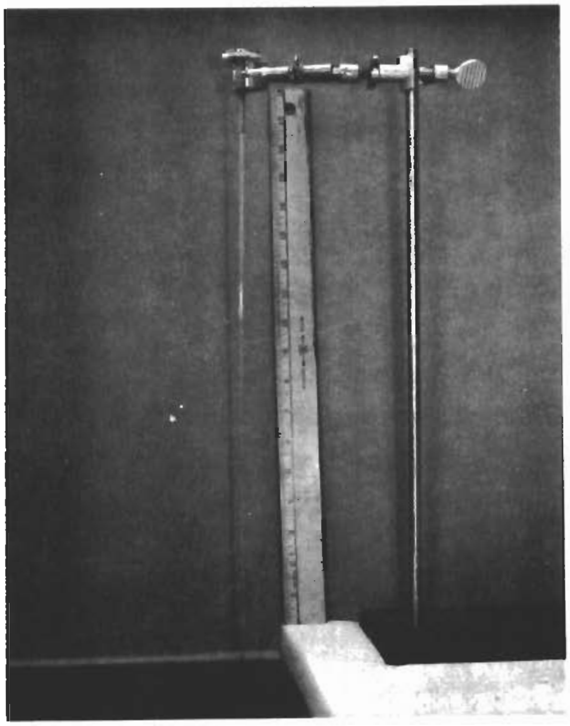


Figure 8. Individual Capillary-Wick Testing.

Tests performed with the above wick materials indicated that a wick material comprised solely of surgical cotton performed in a manner superior to all others, in terms of maximum Δ P and flow characteristics. Single unit assemblies were varied in terms of wick compression to yield liquid-gas seal properties between 38 mm H_2O Δ P and 267 mm H_2O Δ P at minimum saturation. The water flow rate at saturation varied from over 454 gm/hr for the 38 mm H_2O Δ P assemblies to less than 45 gm/hr for the 267 mm H_2O Δ P's. A dry cotton weight of 1.2 gm between the 2.5 cm diameter cover plate and the wick retainer was determined experimentally to yield good performance characteristics, when wet-compressed in the wick retainer.

2. Multiwick Testing

Feed, flow and gas seal characteristics were studied on a multiwick system comprised of a master dual-feed wick assembly and two extremity feeder wicks (Figure 9).

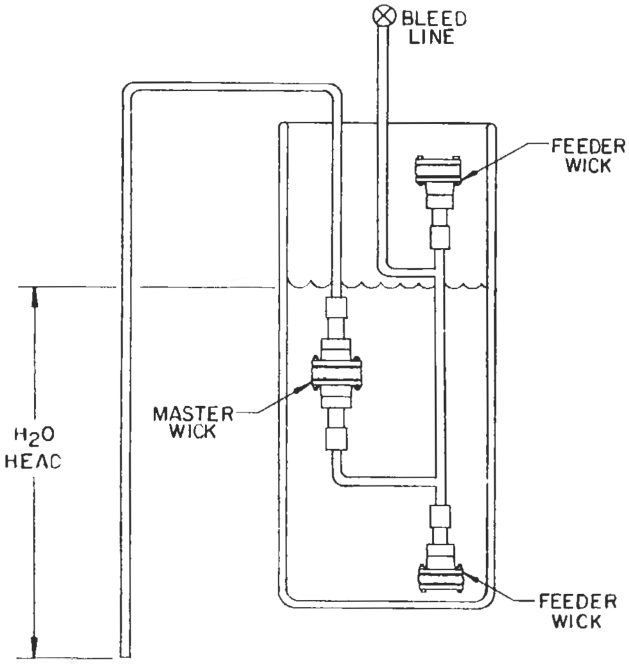


Figure 9. Capillary Feed System Model

The purpose of the master wick assembly was as follows: If gas breakthrough occurred in the upper feeder wick assembly and a two-phase mixture was supplied, then the master wick assembly would cause gas phase to be displaced from the system at this point so that only liquid would be delivered from the system. 1.2 gm of surgical cotton was utilized as wicking material, with the compression varied to determine ultimate performance of the system. Tests indicated that a bleed line was necessary to evacuate air from the system before liquid continuity between the wicks could initially be attained. The basic feed system concept was subsequently demonstrated with this system: liquid phase feed was maintained when the upper feeder wick and the master wick were exposed to gas phase and only the lower feed wick was wetted with liquid phase. Wick compression was not found to be extremely critical in the extremity feeder wicks; wick compression determined from individual assembly tests was maintained, as it yielded good flow and gas sealing characteristics. Wick compression in the master wick, however, proved to be a critical factor in the performance of the system. In some tests, liquid-phase flow through the feed system ceased as the water level dropped below the master wick, exposing it to gas phase. The liquid-gas seal in these instances was broken at the master wick, and gas phase entered the system, causing liquid-phase flow to stop. This gas breakthrough was in many cases stopped by increasing master-wick compression; liquid-phase flow then continued until the lower feeder wick was exposed to gas phase.

Testing of the multiwick system demonstrated the basic feed system concept. The main problem area concerned the critical wick compression in the master dual-feed wick assembly.

C. Ground Test Procedure for Evaluation of Capillary-Wick Phase Separation Control and Feed System

It was considered both practical and essential that ground laboratory test techniques be established that would give reasonable assurance of feed system function both in gravity and weightless environments. It further appeared necessary to establish an instrumentation monitoring procedure that not only indicated proper system performance but also indicated whether the system was functioning according to the specific and prescribed concept.

The capillary-wick feed control system separates the liquid and gas phases and supplies only the former. In a liquid oxygen storage and supply system designed for relatively low flow rates, wherein the response to abnormal function by some sensible change is slow, it is not readily ascertained whether liquid phase, gas phase or a mixture is actually being supplied. It is important to know this to confirm actual phase separation control and proper wick function.

The fluid phase status in the supply fluid was verified throughout this program by utilizing an oxygen-nitrogen mixture for the cryogenic storage fluid. Since the vapor pressure of nitrogen is higher than the vapor pressure of oxygen the nitrogen composition will be higher in gas phase than in liquid phase. Figure 10 gives percent nitrogen in vapor versus percent nitrogen in liquid. An example is a liquid air mixture where the liquid composition is approximately 80% N_2 - 20% O_2; the gas phase composition is approximately 94% N_2 - 6% O_2. Thus by feeding a continuous sample of the supply fluid through a nitrogen analyzer the phase quality of the fluid supplied by the capillary wick units was readily determined.

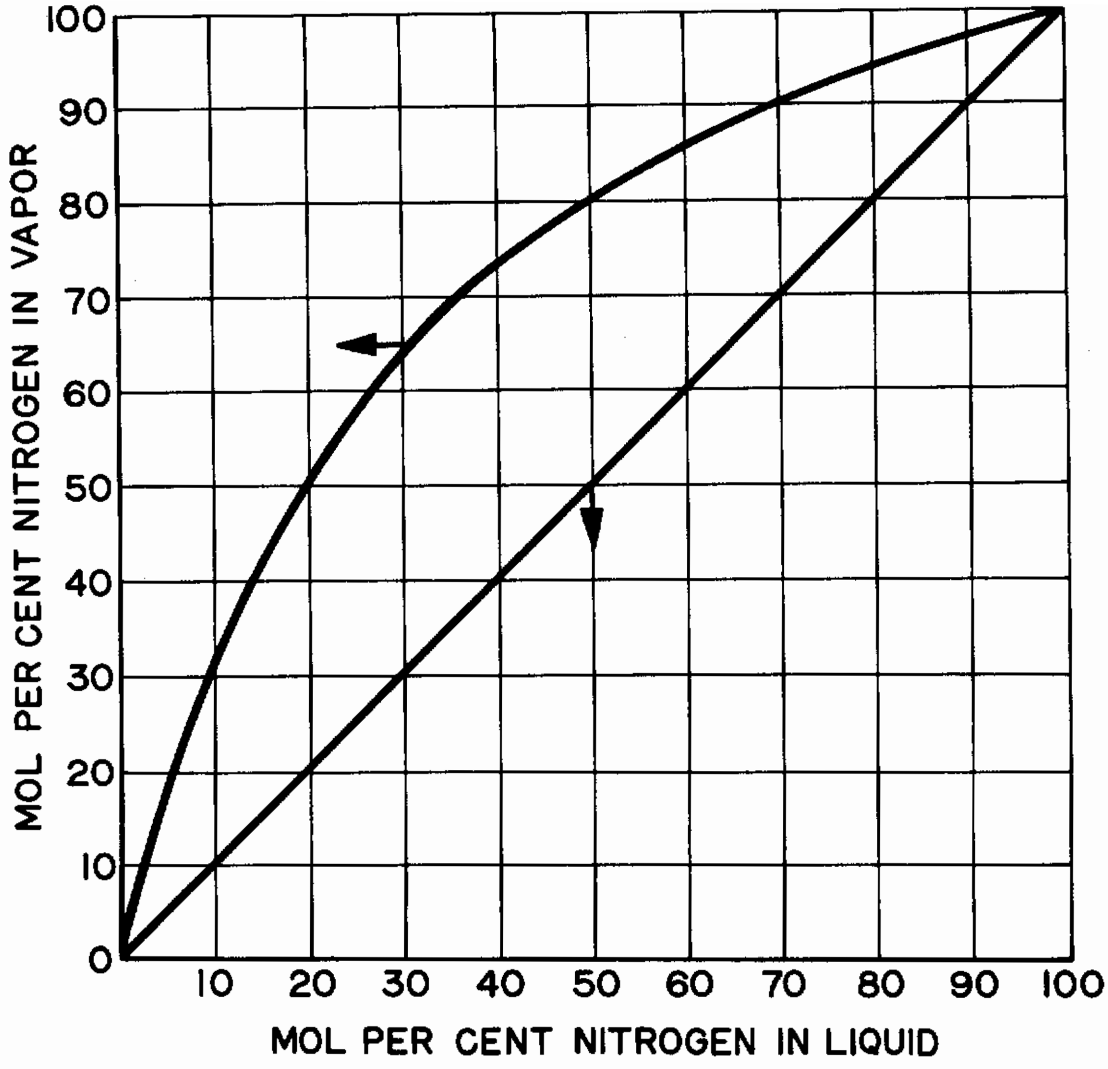


Figure 10. Liquid-Vapor Equilibrium Data for Nitrogen-Oxygen Mixtures at 760 mm Hg.

The mixed gas technique was used during the cryogenic test period to evaluate and verify the phase separation control and liquid-gas seal characteristics of the feed system. The apparatus was essentially as described in Figure 11. The test goal was to start out with an empty warm dewar containing a dry capillary-wick feed system; the dewar was then filled with a liquid O_2 - liquid N_2 mixture. A flow was then initiated from the supply line and sampled through the nitrogen analyzer. Flow was continued until the dewar was essentially empty. If liquid continuity and interwick feed flow to the vapor exposed wicks was maintained then gas break-through did not occur and the nitrogen composition in the supply remained essentially the same as that observed directly in the liquid phase. If gas break-through occurred in the upper wick then the nitrogen composition in the supply was greater than that observed in the liquid, or was equal to that composition observed directly in the gas phase.

The mixed gas technique provided an accurate and rapid response technique for determining whether gas phase or liquid phase fluid was being delivered.

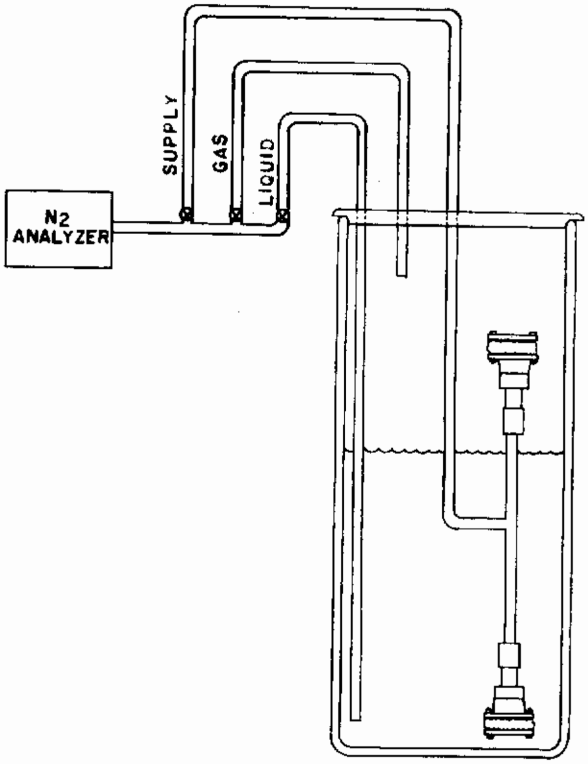


Figure 11. Basic Test Assembly

D. Final Capillary-Wick Test Studies Utilizing Liquid O_2-N_2 Mixtures

1. Vacuum Test Unit

The test apparatus initially used for mixed gas studies is shown schematically in Figure 12. However, this system did not include the surge tank as shown. The same multiwick feeder system used in water tests was employed. Refrasil was used in conjunction with surgical cotton for wicking material for some tests, but wicks fabricated solely of surgical cotton performed best.

Tests on the vacuum-operated feed system indicated that (1) the nitrogen analyzer gave a positive indication of both liquid phase feed delivery and also gas-seal breakdown and (2) a surging effect occurring in the system may have been responsible for gas-seal breakdown experienced when only one feeder wick of the multiwick system was in liquid phase.

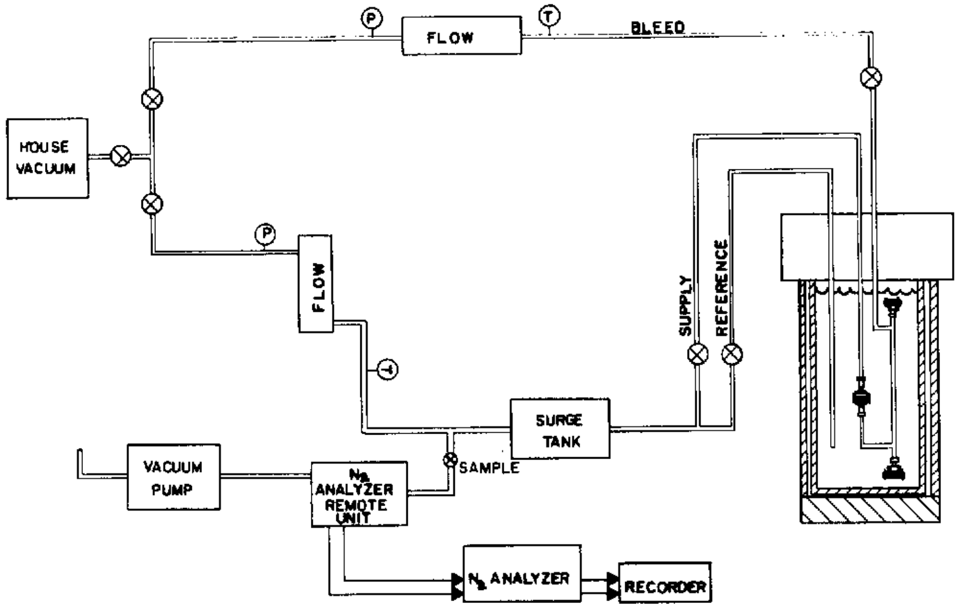


Figure 12. Schematic - Vacuum Test Unit

In initial testing, the use of the nitrogen analyzer gave a positive indication of the state of the fluid being supplied. Results showed that gas phase was easily distinguishable from liquid phase, and that the differences in percent N_2 of each followed fairly closely the curve presented in Figure 10. Thus, the presence of gas phase in the supply fluid was shown to give a higher percent N_2 than when only liquid phase was being supplied.

Initial testing also resulted in the observation of fluctuations in all instrument readings when both supply fluid and liquid reference fluid were withdrawn from the system. These fluctuations caused an inability to obtain proper nitrogen analysis. By observing flow from the dewar in small-diameter glass tubing, continuous surging in the plumbing was found to have caused these variations. Cryogen drawn through the supply (or liquid reference) plumbing gathered heat before it was transported from the test dewar, resulting in rapid vaporization of the liquid and the generation of large volumes of gas which propagated to both the instruments and the capillary-wick systems. The nitrogen analyzer, being extremely pressure-sensitive, fluctuated with this surging action.

One attempt to reduce surging consisted of insulating the transfer line, both on the inside and the outside of the test dewar. This action decreased fluctuations in instrument readings, but was not completely satisfactory.

The most effective solution, in terms of reducing variations in instrument readings, was the addition of a surge tank in the system, upstream of the instruments as shown in Figure 12. Although the surge tank eliminated the transmission of the surge fluctuations to the downstream instruments, it did not eliminate the surging effect in the capillary wick feed system. Gas-seal breakdown noted when the master wick and the upper feeder wick were exposed to gas phase was attributed to this surging effect.

Tests were conducted, using various types and sizes of tubes to transport liquid O_2 - N_2 from the test dewar, to show the effects on surging of (1) cross-sectional area and (2) thermal conductivity of the transport tube. The test setup is shown schematically in Figure 13. Results of the tests are presented in Table I. Some representative traces of the recorded percent N_2 for various tubes are given in Figure 14.

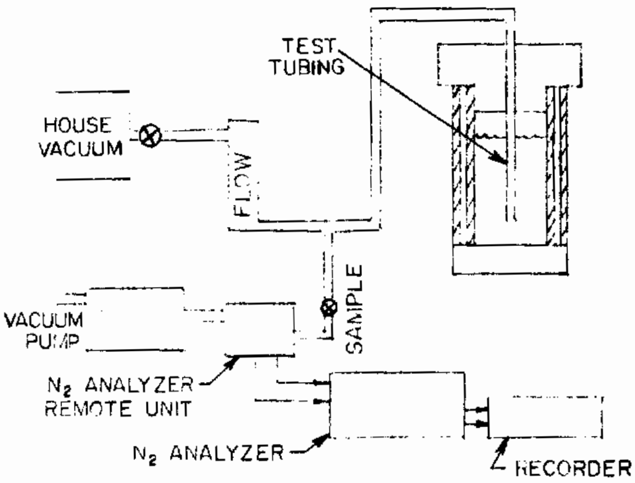


Figure 13. Schematic-Transport Tube Test.

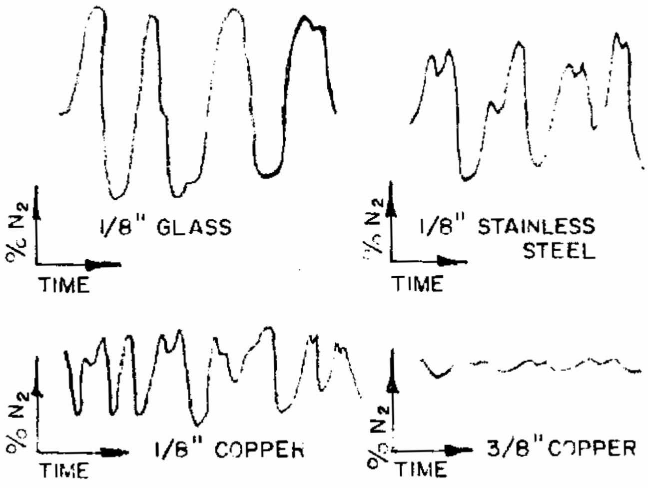


Figure 14. Effect of Transport Tubing on Surging.

TABLE I

EFFECTS OF TRANSPORT TUBING ON SURGING

TUBING	K g-cal/(sec)(sq cm) (°C/cm) at 0°C	VARIATIONS IN INSTRUMENT READINGS ΔPress mm Hg	*ΔFlow lpm	Δ%N_2
Glass	.002			
1/8"		108	5.0	59
1/4"		31	0.6	14
11/32"		21	0.3	22
Stainless Steel	.033			
1/8"		26	2.0	26
3/16"		31	0.5	20
5/16"		21	0.2	15
Copper	.925			
1/8"		26	2.0	14
3/16"		36	2.5	18
3/8"		5	0.6	2

* Minimum flow rate held constant at 1.0 lpm.

The following conclusions were drawn from the results of this testing:

1. The effects of surging are minimized by increasing the cross-sectional area of the transport line.

2. The effects of surging are minimized by increasing the thermal conductivity of the transport line.

These conclusions substantiate what had previously been assumed to be the cause of surging in the lines. By observing flow from the test dewar in small-diameter glass tubing, a column of liquid was drawn up the tube to a certain height (about 30 cm above the liquid level); the column then dropped and liquid and gas were forced back into the dewar. Accompanying this were a pressure rise, a flow increase, and fluctuations in the percent N_2 as noted on downstream instruments. This surging effect was then ascertained to be the result of intermittent vaporization of large amounts of liquid in the transport line.

This intermittent vaporization was thought to be caused by the fact that the heat input to the top layer of liquid in the tube was large enough to cause vaporization only when the liquid had reached a certain height in the tube. When the top layer of this liquid vaporized, the resulting gas expansion forced liquid and gas back into the dewar, and a large volume of gas was forced downstream to the instruments, where fluctuations were noted. Because the minimum flow rate in the tubing tests of Table I was held constant at 1.0 lpm (i.e., in those intermittent periods when surging did not occur, the flow rate was 1.0 lpm), an increase in the cross-sectional area of the transport tube was accompanied by a lower fluid velocity. In a given time period, the fluid traveling at a lower velocity (in large tubing) received more heat from the tubing than did fluid with a higher velocity (in small tubing). Thus when the upper liquid layer finally vaporized in the large tubing, there was a smaller volume of liquid available to vaporize and to be forced from the tube. In addition, there was a larger volume above the liquid column in which the vaporized liquid could expand. Therefore, the surging effect was reduced by increasing the transport line cross-sectional area.

When the thermal conductivity of the transport line was increased, surging effects were reduced due to the greater heat input to the column of liquid in the tube. Thus, a smaller volume of liquid was present in the transport tube when vaporization occurred, resulting in a smaller volume of generated gas.

Test results indicated that 3/8-inch copper tubing provided the best reduction of surging in the transport line from the dewar. A new test setup was fabricated, using 3/8-inch copper tubing for transferring liquid from the wicks to the external plumbing (see Figure 15). This configuration did not include the bleed line previously employed, since test results previously indicated that system performance (with a cryogenic working fluid) was not impaired when the system was not bled before operation.

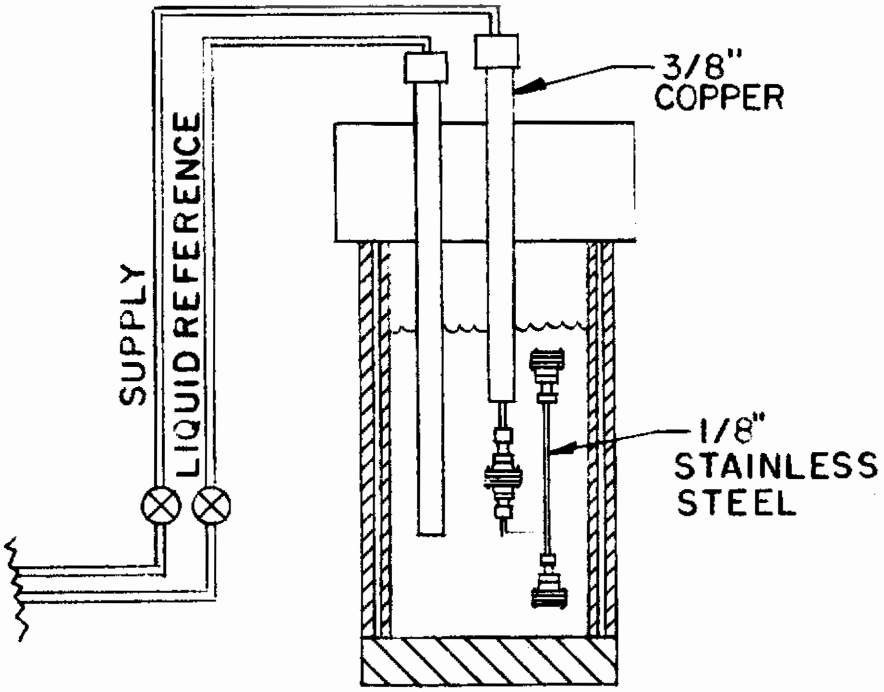


Figure 15. Vacuum Test Unit - 3/8" Copper Transport Line

Testing of this system at flow rates of 5 lpm showed that instrument fluctuations were greatly reduced; however, surging was not eliminated completely in the wick system, possibly accounting for gas-seal breakdown when only one feeder wick was wetted with liquid phase and the upper feeder wick and master wick were exposed to gas phase.

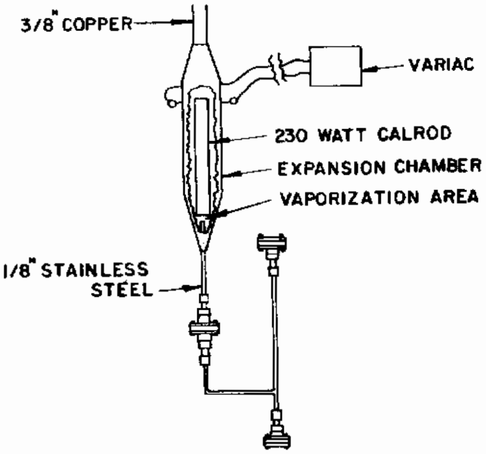


Figure 16. In-Line Heater

Since the surging effect was found to be a result of uncontrolled vaporization near the capillary-wick feed system, an in-line heater was fabricated and placed immediately downstream of the wick system (see Figure 16). By controlling the power to the heater, liquid drawn from the wick-system into the expansion chamber would be immediately vaporized. There would be no build-up of liquid in the tube to intermittently vaporize and produce surging effects. Tests conducted with this system indicated that again surging was greatly reduced, but was not completely eliminated. Some pressure fluctuations were noted downstream, along with slight flow variations. Power input to the heater varied from 0 to 50 watts,with flow rates from the system nominally at 5 lpm. Gas-seal breakdown occurred when the master and upper feeder wicks were exposed to gas phase, at both low and high power inputs to the heater. Gas was also observed issuing from the submerged feeder wick, further indicating that (1) the surging effect was not eliminated and (2) gas-seal breakdown was essentially caused by surging.

2. Pressurized Test Unit

A second test unit was assembled which utilized a pressurized system to force fluid from the test dewar through the wick system (see Figures 17 and 18).

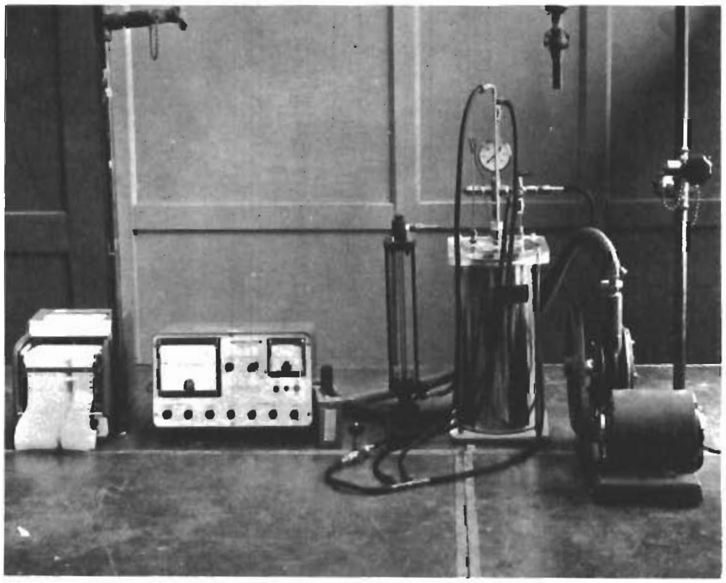


Figure 17. Pressurized Test Unit

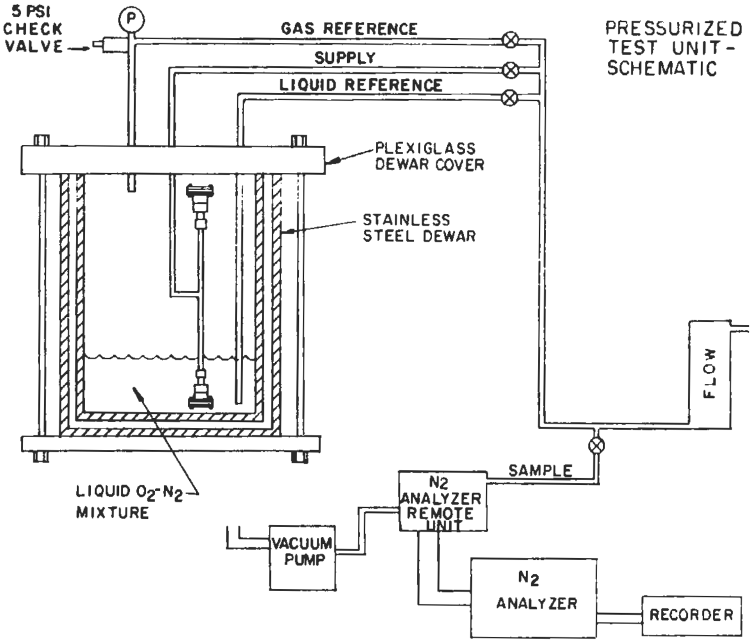


Figure 18. Schematic - Pressurized Test Unit

Pressure buildup in the dewar was accomplished by normal heat input from the environment; thus no external pressurizing source was required. The 5-psi check valve maintained the system at an adequate operating pressure. Orientation of the wick system was determined by observation through the Plexiglass dewar cover. The initial feed system utilized two capillary-wick units, with a 10-cm head differential (see Figures 19 and 20).

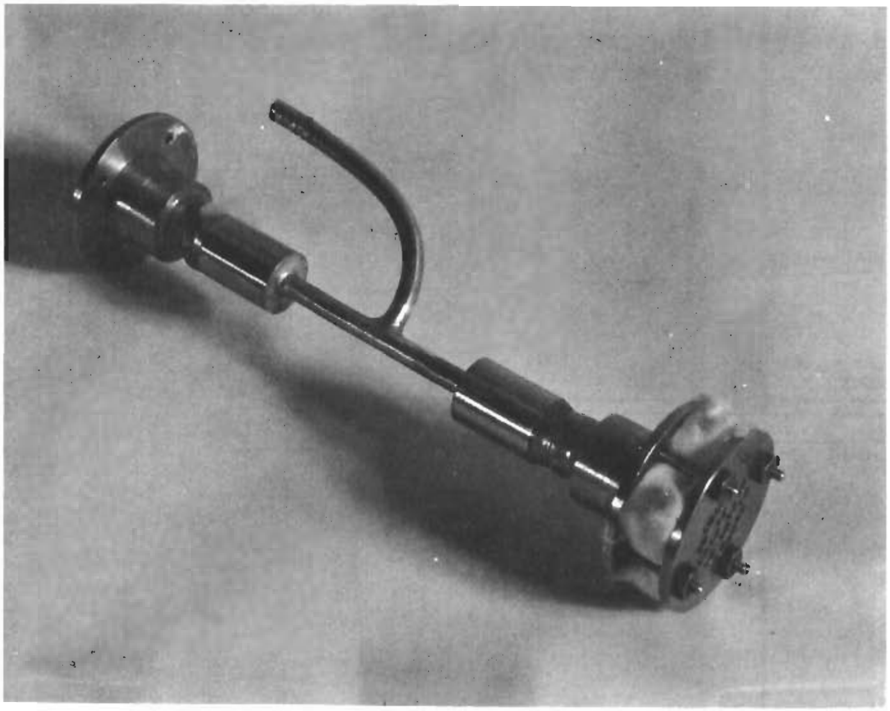


Figure 19. Two Capillary-Wick Feed System

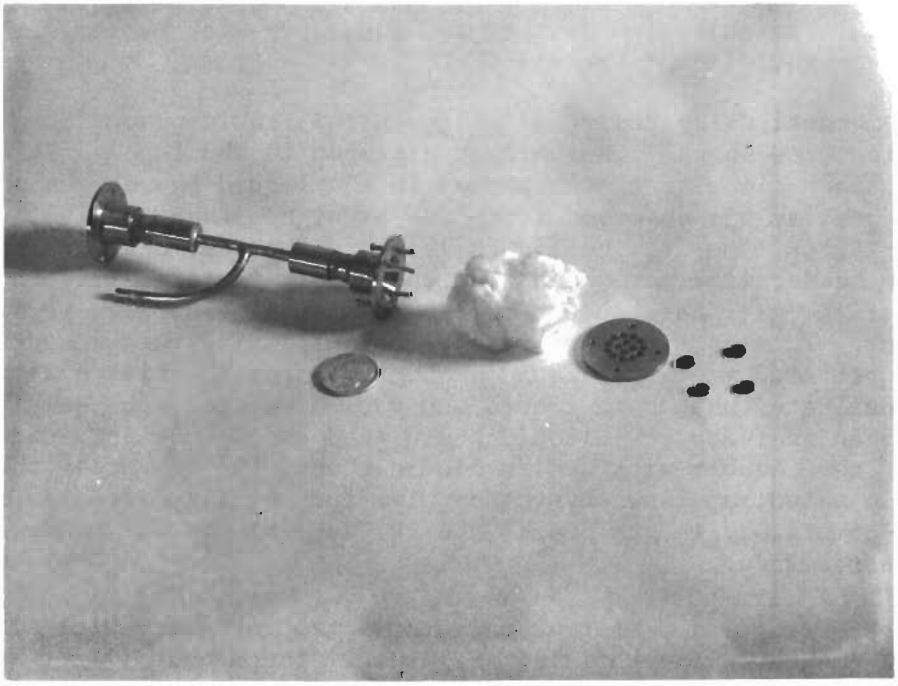


Figure 20. Two Capillary-Wick Feed System - Disassembled

The master-wick system used in the vacuum test unit was not employed in this testing program, since it was not proven that the master-wick concept contributed to proper wick system performance. Surging in the feed system was observed in the Pressurized Test Unit; however, the effects of this action did not appear to create problems in system performance. The results of initial tests performed on the Pressurized Test Unit are presented in Figure 21. The cross-bar, or feeder-wick junction to the outlet supply line, was located midway between the two feeder-wicks. Flow rates of 4.5 lpm to 10 lpm were employed.

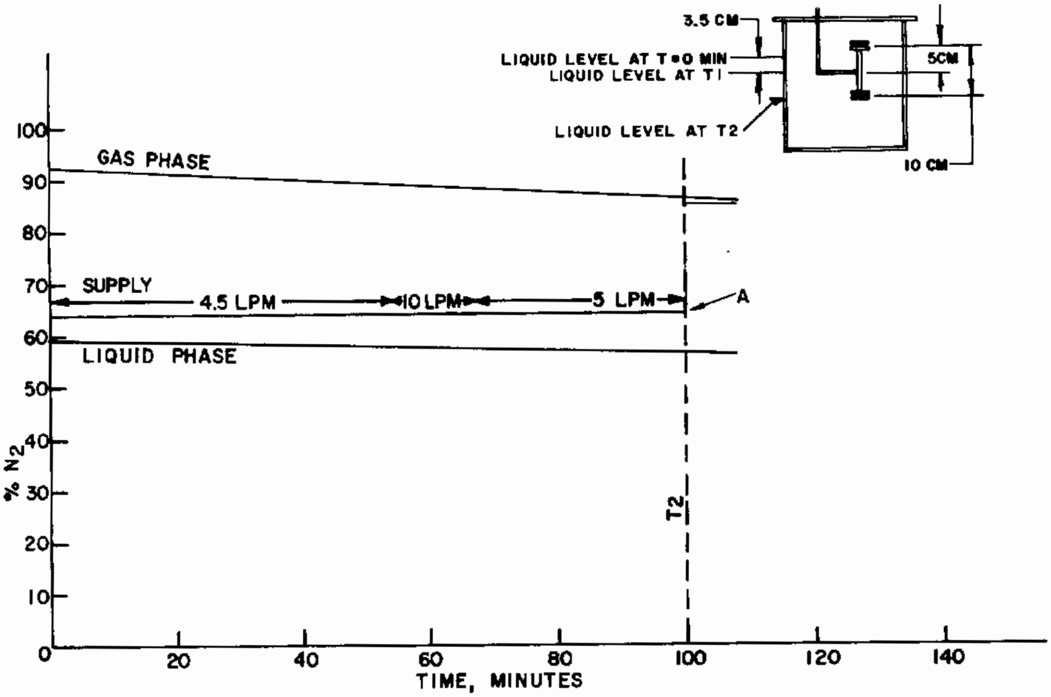


Figure 21. Variable-Flow Test of Two Capillary-Wick System with Equidistant Crossbar.

The system continually delivered preferential liquid-phase fluid throughout the test, as shown. The percent nitrogen in the supply fluid at all times remained close to that observed in the liquid phase; gas phase nitrogen quality was observed to be 20-25% higher than supply fluid quality. After time T2, the liquid level in the test dewar dropped below the lower feeder wick, at which time the supply fluid quality increased to that of the gas phase due to the absence of liquid phase wetting the lower wick. This initial performance test utilizing the Pressurized Test Unit demonstrated that (1) liquid phase feed from the wick system was readily evaluated when both liquid and gas references were sampled through the nitrogen analyzer, (2) liquid phase feed could be maintained when only the lower feeder-wick was in liquid phase, (3) gas break-through could be quickly noted, as shown by the supply fluid quality when the lower wick was completely in gas phase, and (4) surging did not hinder wick-system performance.

Extensive testing was performed on various two capillary-wick systems having 23-cm head differentials. Figures 22 through 24 illustrate test results obtained with an equidistant cross-bar system.

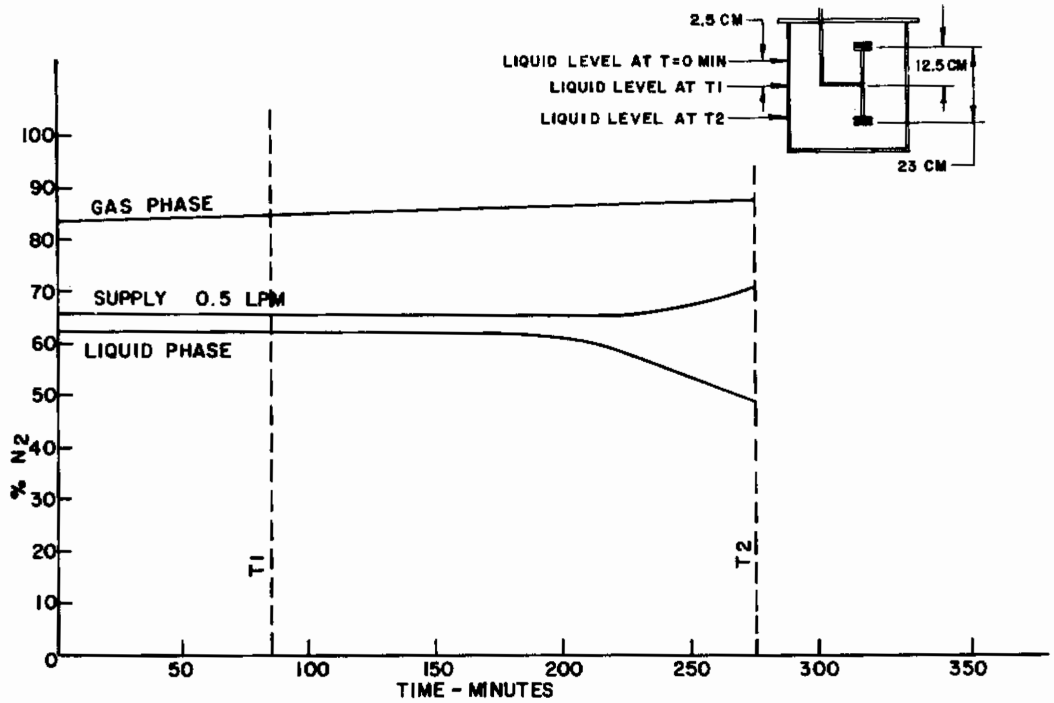


Figure 22. 0.5 LPM Flow Test of Two Capillary-Wick System with Equidistant Crossbar.

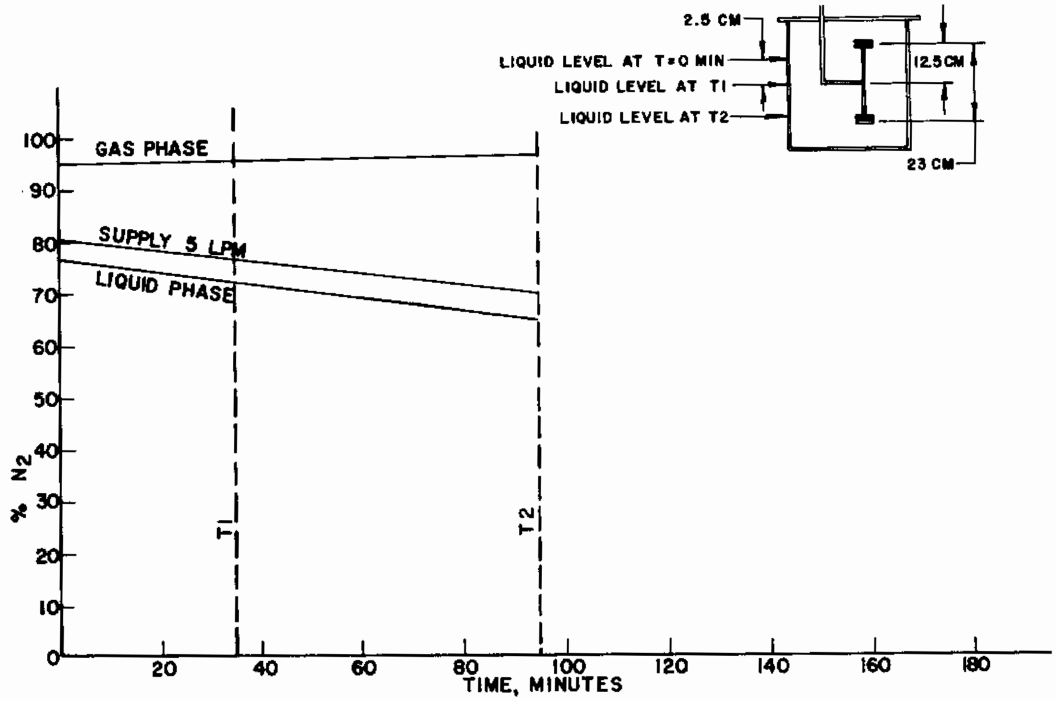


Figure 23. 5 LPM Flow Test of Two Capillary-Wick System with Equidistant Crossbar.

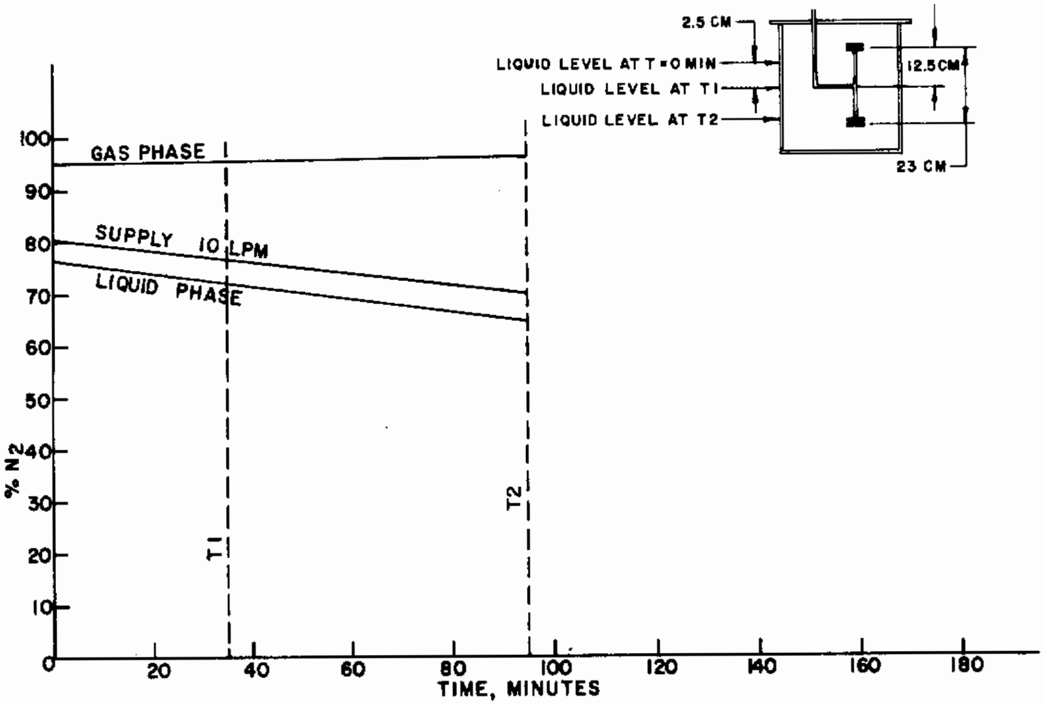


Figure 24. 10 LPM Flow Test of Two Capillary-Wick System with Equidistant Crossbar.

At the minimum flow of 0.5 lpm (Figure 22) the system delivered preferentially liquid phase throughout the test period. No change in nitrogen quality was noted when the cross-bar was exposed to gas phase. The increase in percent nitrogen in the supply near the end of the test period indicates that some gas phase was present in the supply. However, at time T2, when the lower wick was only partially submerged in the liquid phase, the quality of the supply fluid indicates preferential liquid phase delivery. Tests performed with 5 lpm and 10 lpm flow rates (Figures 23 and 24) resulted in predictable data. The percent nitrogen in the liquid phase decreased with time, from an initial 76% N_2 - 24% O_2 to 64% N_2 - 36% O_2 at time T2. Since the vapor pressure of nitrogen is higher than that of oxygen, the concentration of nitrogen in the mixture decreases with time due to its more rapid vaporization. Percent nitrogen of the supply fluid remained close to that of the liquid throughout the test period, again indicating preferential liquid phase delivery from the wicking system.

Further testing of the two capillary-wick feed system involved variation of the cross-bar junction. No pronounced effects had been noted in previous testing (Figures 22 through 24) when the cross-bar was exposed to gas phase, denoted by time T1 of each test. Results of testing a two capillary-wick system with the cross-bar junction located near the lower feeder wick are presented in Figures 25 through 27. At 0.5 lpm supply flow rate (Figure 25) preferential liquid-phase flow was continually delivered. A slight increase in percent nitrogen was noted at 5 lpm (Figure 26) when the cross-bar was exposed to gas phase. This discontinuity may have been attributable to improper wick compression in the upper feeder wick. The 10 lpm flow rate test (Figure 27) again resulted in preferential liquid-phase delivery, with no cross-bar effects noted.

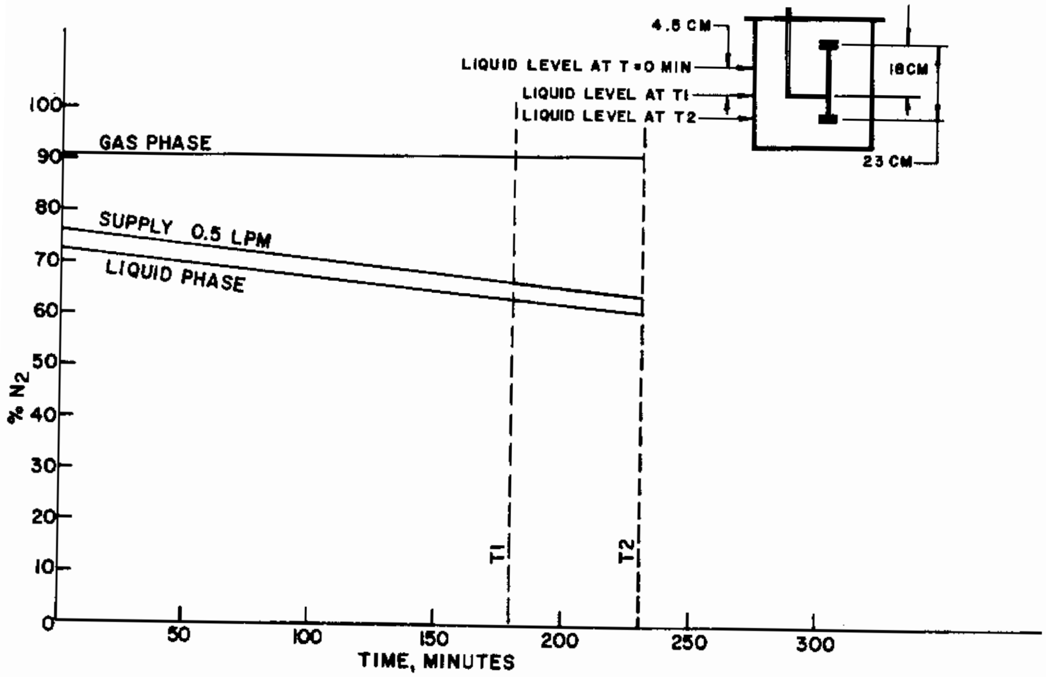


Figure 25. 0.5 LPM Flow Test of Two Capillary-Wick System with Low Crossbar.

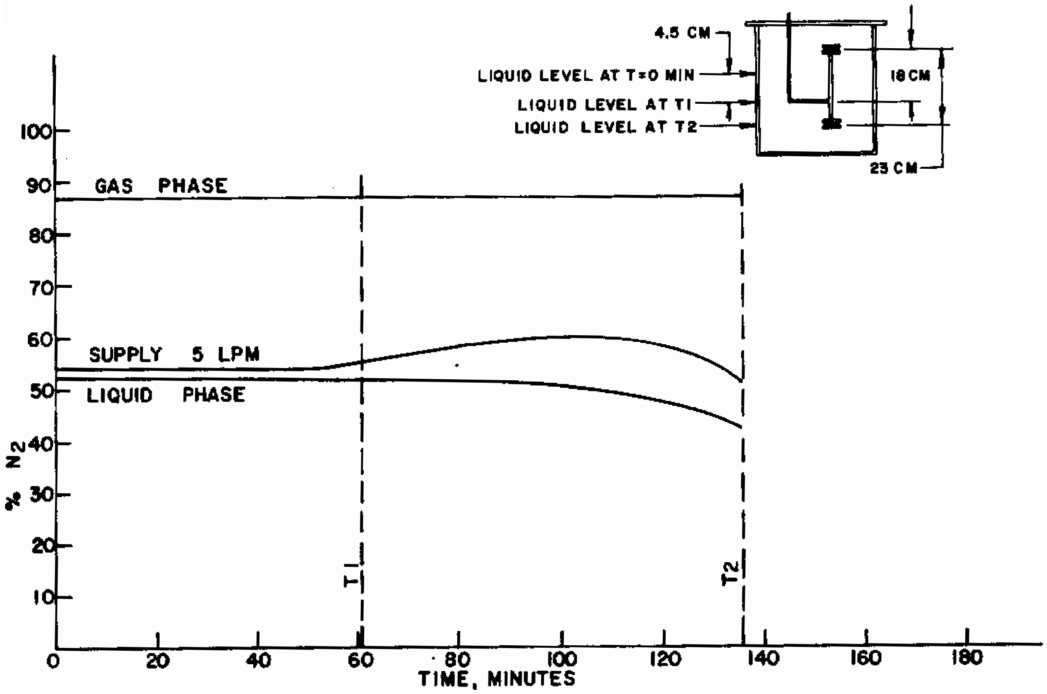


Figure 26. 5 LPM Flow Test of Two Capillary-Wick System with Low Crossbar.

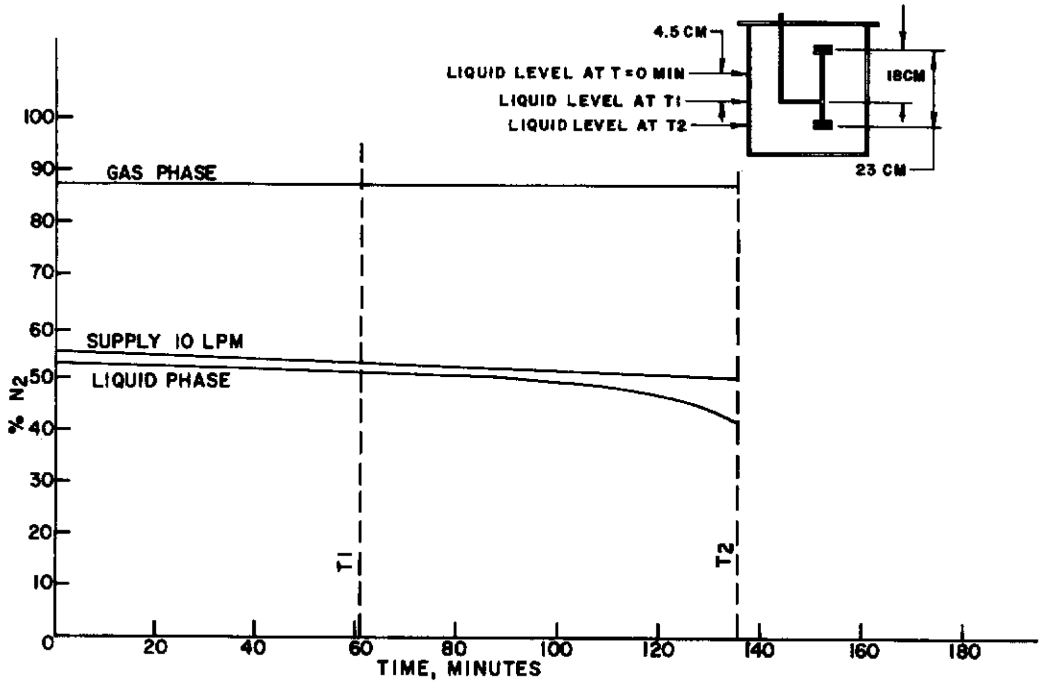


Figure 27. 10 LPM Flow Test of Two Capillary-Wick System with Low Crossbar.

Figures 28 through 30 show results of testing a two capillary-wick feed system with the cross-bar junction located near the upper feeder wick. Preferential liquid-phase fluid delivery was demonstrated with 0.5, 5, and 10 lpm supply flow rates, with no apparent effects on supply fluid quality due to cross-bar replacement.

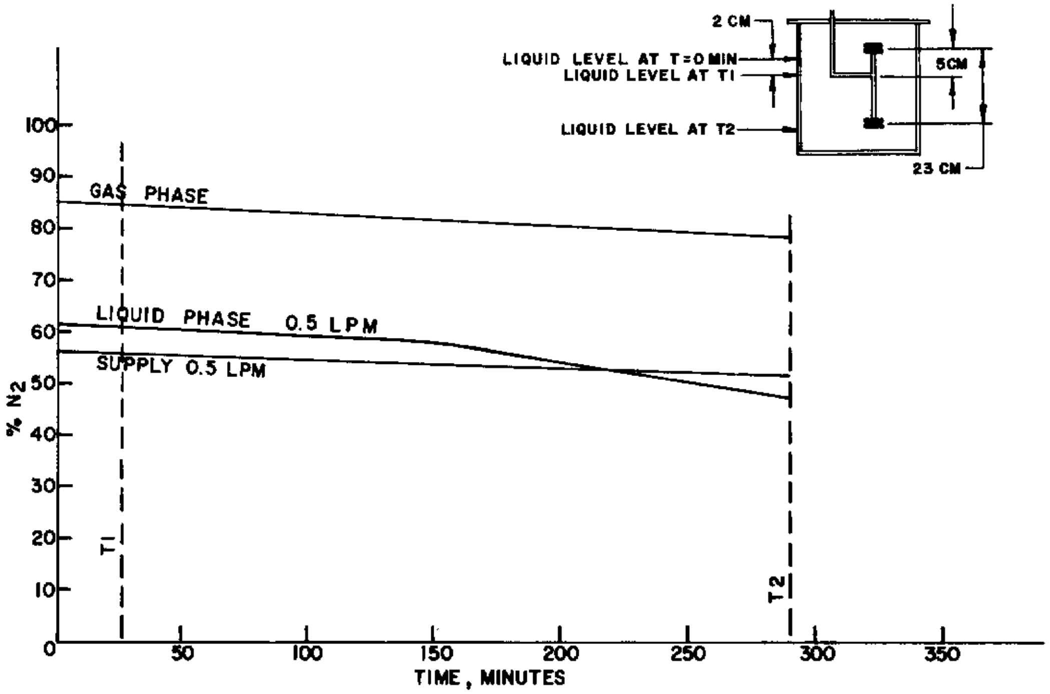
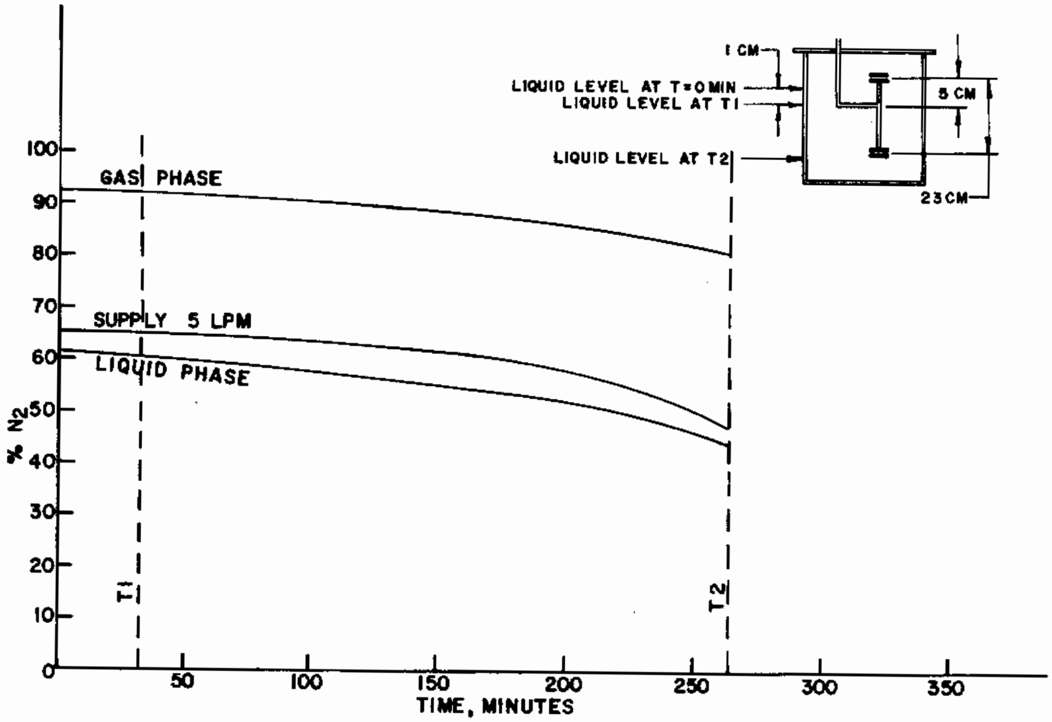


Figure 28. 0.5 LPM Flow Test of Two Capillary-Wick System with High Crossbar.



igure 29. 5 LPM Flow Test of Two Capillary-Wick System with High Crossbar.

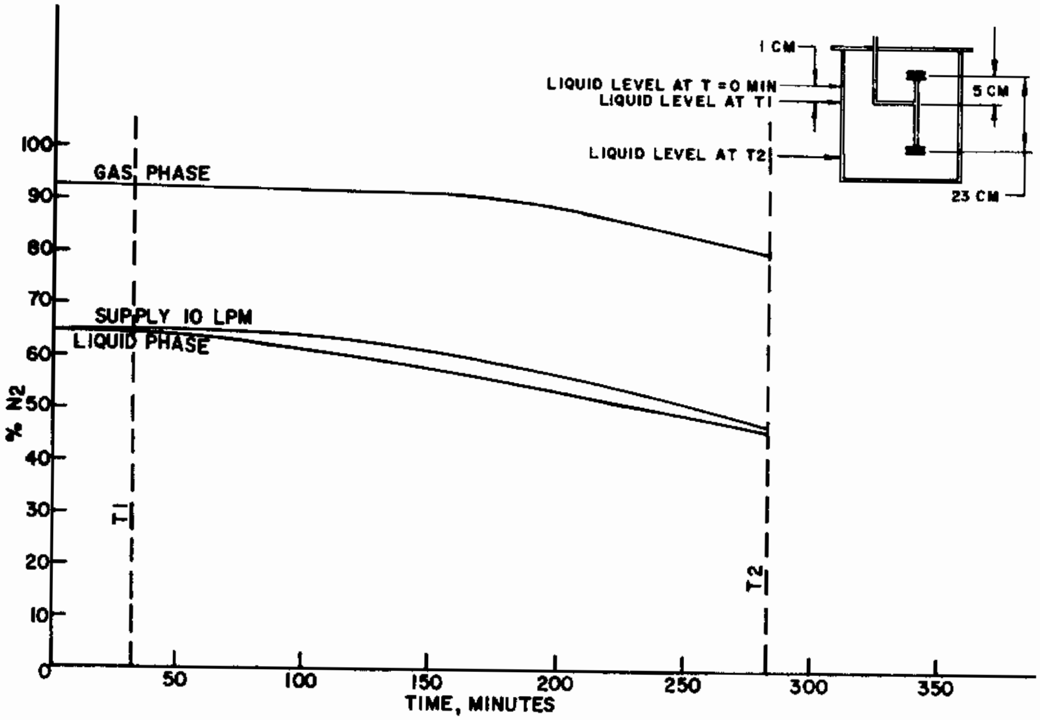


Figure 30. 10 LPM Flow Test of Two Capillary-Wick System with High Crossbar.

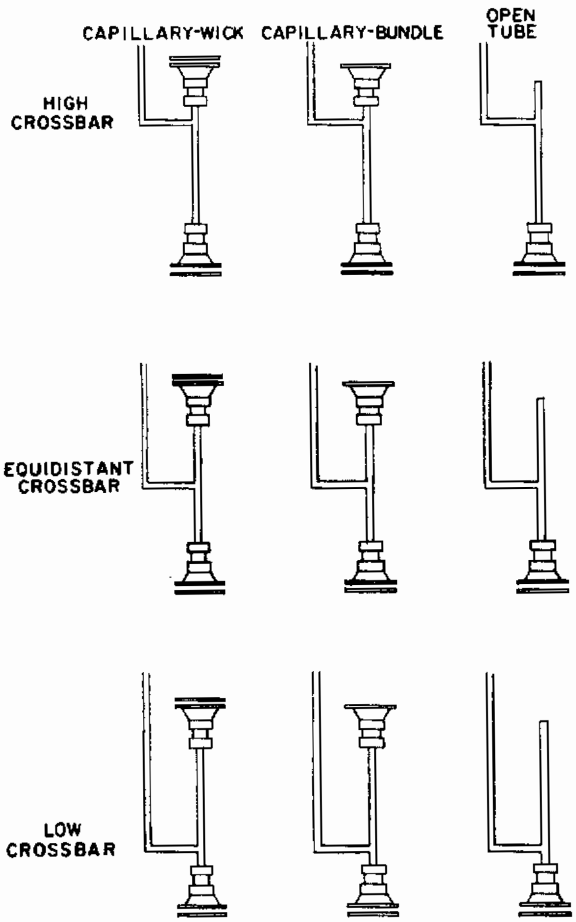


Figure 31. Comparison of Gas Sealing Characteristics.

Tests were conducted to compare the gas-sealing characteristics of the capillary-wick system with (1) a system in which the cotton wick was removed from the upper capillary-bundle, and (2) a system in which the upper wick assembly was completely removed, leaving only an open tube exposed to the gas phase. In addition, the cross-bar junction was varied as in previous tests. The various configurations are shown in Figure 31. Test data resulted in the following conclusions:

(1) Preferential liquid phase was supplied from all systems when the cross-bar was in liquid phase. Liquid apparently sealed the small diameter tubing above the cross-bar junction, as shown in Figure 32, thus preventing gas phase from entering the open-tube and capillary-bundle systems. In like manner, liquid may have sealed the upper feeder-wick tube in the capillary-wick system; however, capillary pumping action to the upper wick and subsequent displacement of gas phase from the wetted wick are assumed to be predominant in maintaining preferential liquid phase delivery from this system.

(2) The open-tube system supplied only gas phase when its cross-bar was exposed to the gas phase. As shown in Figure 33, the liquid column above the cross-bar, assumed previously to cause a gas seal, was no longer present in a condition where the cross-bar was above the liquid level in the test dewar. Gas flow through the upper portion of the system apparently blocked liquid from entering the outlet tubing, resulting in only gas phase supply.

(3) The capillary-wick system supplied preferential liquid-phase fluid when its cross-bar was exposed to gas phase.

(4) The capillary-bundle system (with no cotton wick) supplied preferential liquid phase fluid when its cross-bar was exposed to gas phase, although the percent nitrogen present in the supply fluid was at all times considerably higher than that of the fluid supplied by the normal capillary-wick system. During this testing ice tended to form across the exposed ends of the small-diameter capillary tubes; this icing apparently prevented complete gas flow into the system through the exposed capillary bundle. In addition, the small-diameter tubes offer high resistance to gas flow and therefore may have reduced the amount of gas entering the system.

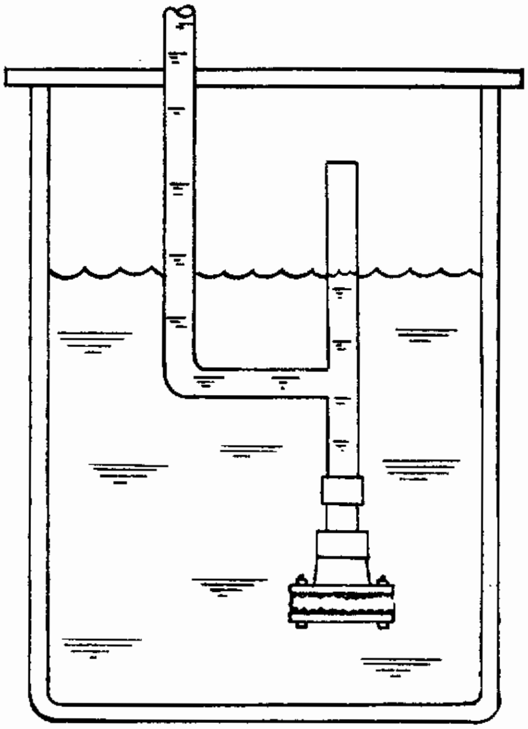


Figure 32. Crossbar in Liquid Phase.

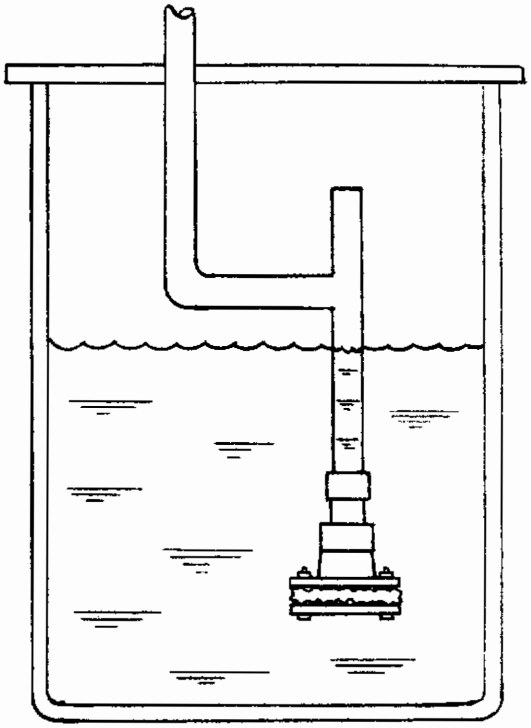


Figure 33. Crossbar in Gas Phase.

The final feed system studied in the Design Phase Test Program was a six capillary-wick configuration, shown in Figure 34. The system was fabricated in such a manner that during testing, five feeder-wicks could be exposed to gas phase while one wick was wetted in liquid phase. Results of 0.5, 5, and 10 lpm flow tests are presented in Figures 35 through 37. Preferential liquid phase was delivered from the system at all flows. Some gas phase was observed in the supply during the latter portion of the 0.5 lpm test (Figure 35); this situation could be attributed to improper compression of one of the gas-exposed feeder wicks. The feed system performed well at the higher flow rates, as indicated by Figures 36 and 37.

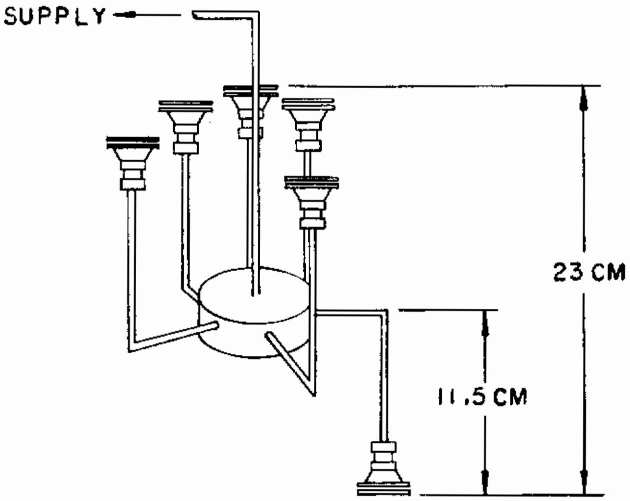


Figure 34. Six Capillary-Wick System.

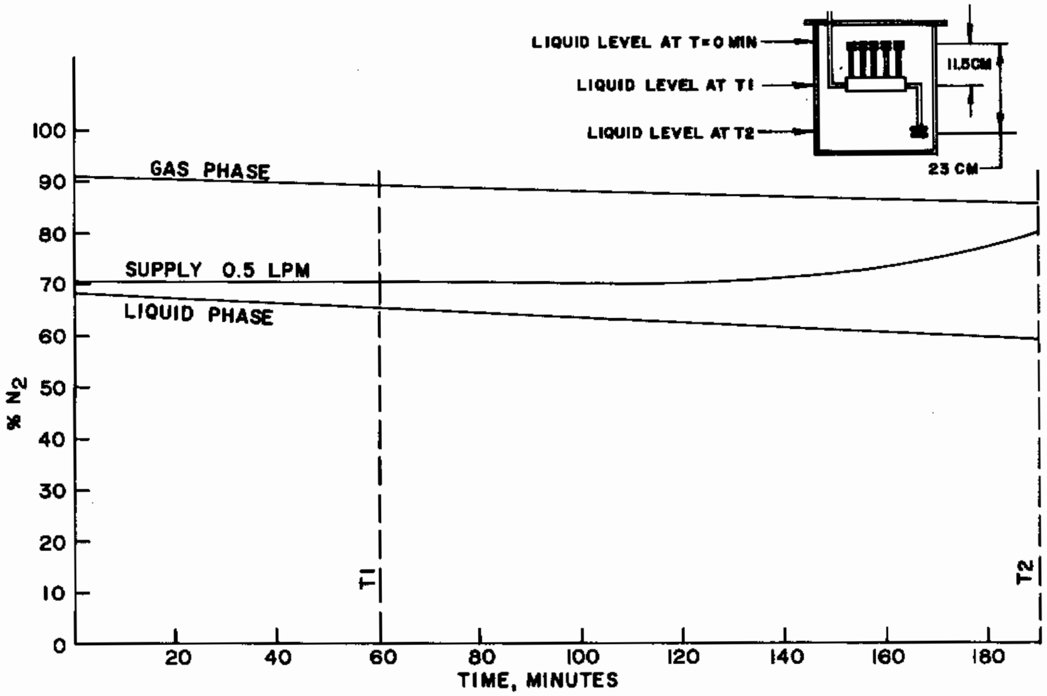


Figure 35. 0.5 LPM Flow Test of Six Capillary-Wick System

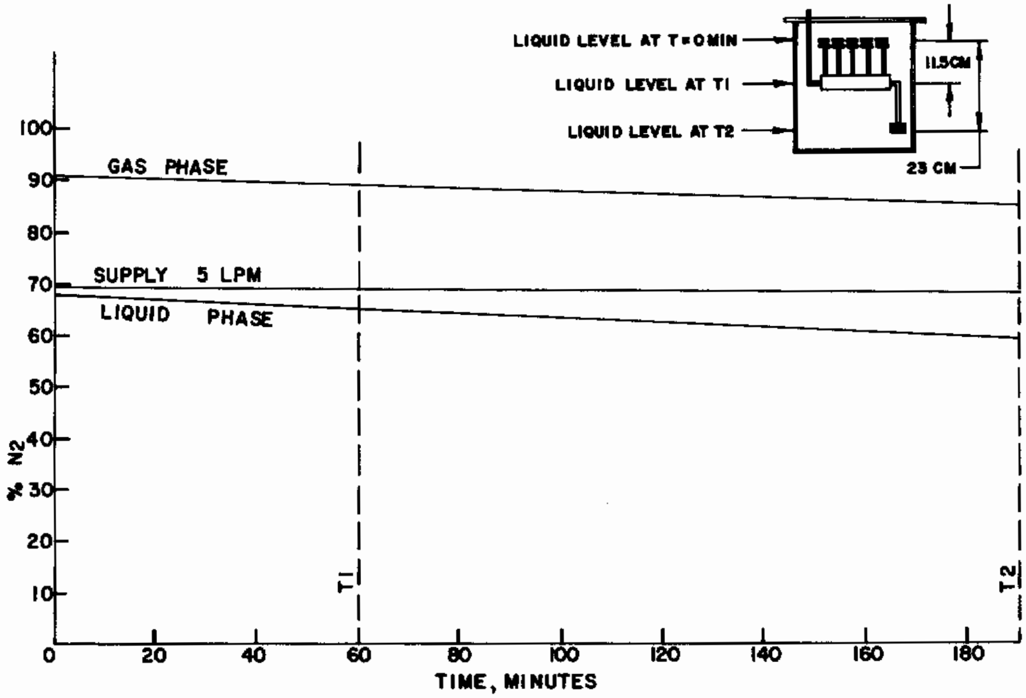


Figure 36. 5 LPM Flow Test of Six Capillary-Wick System

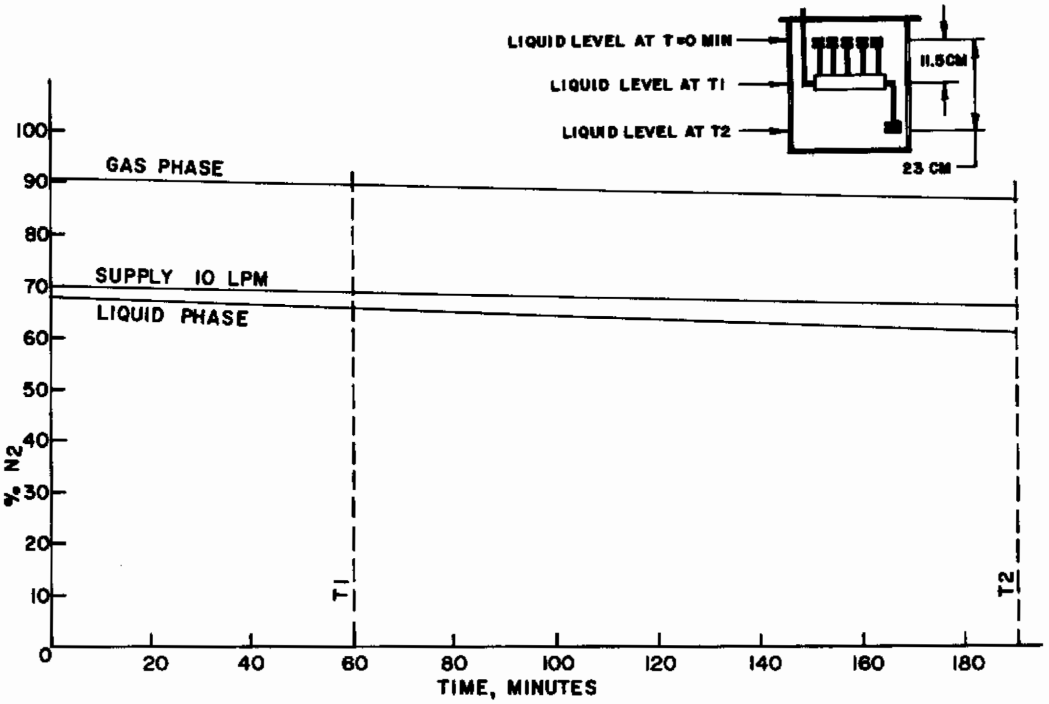


Figure 37. 10 LPM Flow Test of Six Capillary-Wick System

During the performance of tests utilizing the Pressurized Test Unit, it was not known if the feeder wicks exposed to gas phase were continually wetted by capillary pumping action from the wick located in liquid phase. All testing indicated that this action occurred, since the capillary-wick units did not "break through" and allow full gas phase delivery in the supply fluid. Because of the insulation problems associated with the plexiglass dewar cover on the test unit, a temperature profile in the dewar was obtained (Figure 38). Results indicated that the wicks exposed to gas phase were surrounded by gas that was 143°C higher than the liquid phase. A temperature increase of 17°C was observed across the liquid-gas interface. This temperature differential would be adequate to vaporize any low velocity liquid being pumped by capillary action to the upper feeder wicks. However, since it was repeatedly demonstrated that the upper, gas-exposed wick units sealed gas phase from the feed system, then either (1) the pumping capacity of the capillary bundles was sufficient to supply liquid-phase to the wick material, thus maintaining it in a wetted condition, or (2) the capillary-wick units functioned as high-resistance barriers to gas-phase input to the system. Because of the repeatable satisfactory performance of the various

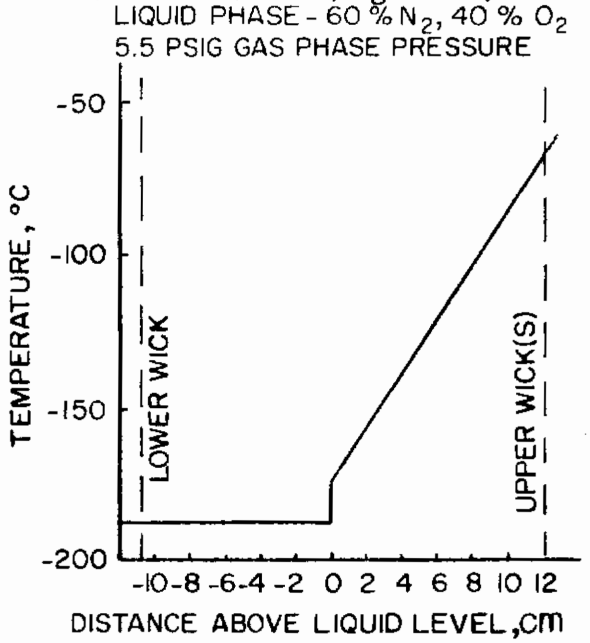


Figure 38. Temperature Profile - Test Dewar.

feed-system configurations tested in the Design Phase, with wick compression not appearing to be a critical factor, it is probable that the wick units did in fact remain wetted and they performed as liquid-gas seals when exposed to gas phase.

E. Venting

Although the principal objective of this program was the development of a prototype liquid oxygen storage system that would assure liquid phase supply in a weightless environment, it was also necessary for safety considerations to provide overboard pressure relief of the system. In addition, relief venting from excessive pressure build-up must result in losing the least possible quantity of fluid, i.e., the least mass flow of fluid through the relief valve per unit heat input. It is generally assumed that the least mass flow of fluid per unit heat input occurs when gas phase is delivered from the tank to the relief venting line. However, previous testing at Pioneer-Central indicates that this is not necessarily true. Lower equilibrium flow rates have been observed when liquid phase is delivered to the venting circuit. Although the results obtained previously were inconclusive, they did indicate that consideration should be given to the technique of liquid phase delivery to the relief venting circuit.

A study was conducted which investigated liquid and gas-phase relief venting from a 20-liter aircraft-type liquid oxygen converter. The results of this investigation are presented in Figure 39 and Table II. Because of the duration of the tests, average mass flow vented for each 24-hour period was plotted in Figure 39 to illustrate major rate changes. Table II lists the quantity of liquid oxygen remaining throughout each venting test.

Test results indicated that the mass flow through the relief valve was less with liquid phase venting than with gas phase venting, for the initial portion of the venting period when thermal stratification was occurring. During this period the heat flow into the container in Tests 3 and 4 went almost entirely into the lower, colder liquid layers in the thermally stratified container, such that the bulk temperature of the entire fluid contents approached the thermal equilibrium temperature corresponding to the system pressure (105 psia). This increase in temperature decreases the density of the liquid phase which increases the volume occupied by the liquid. Associated with this expansion, the small volume already occupied by the gas phase is further reduced with subsequent condensation of the gas until this volume is exceedingly small. Eventually, there is essentially no gas phase and as the liquid phase continues to increase in bulk temperature liquid is forced out of the submerged relief pressure venting port. This mode of releasing pressure requires more BTU's per pound of fluid removed than that required to vaporize one pound of liquid. Further heat input to the system caused an expansion and temperature increase throughout such that the container eventually was filled with a non-stratified liquid at the thermal equilibrium temperature corresponding to operating pressure. Additional heat input resulted only in vaporization, and thus large mass flow rates were experienced, as shown by the graphs of Tests 3 and 4 in Figure 39. Flow rate maximized in Test 3 at about the end of the fifth day, since at this time the relief pressure venting port, located on the side, became exposed to gas phase. The relief port in Test 4 was located at the bottom of the container and therefore the liquid was completely expelled, as shown in Figure 39 and Table II.

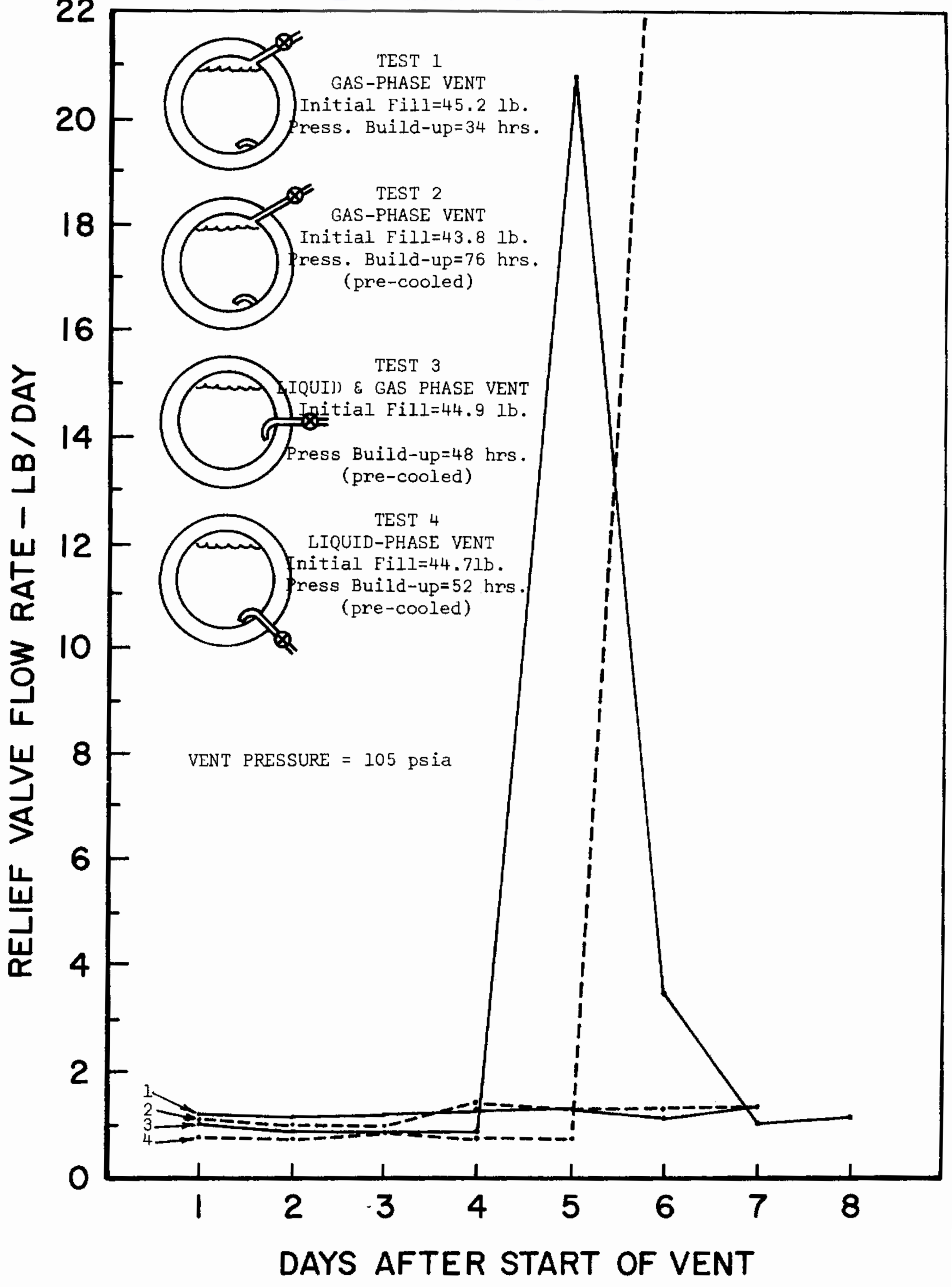


Figure 39. Liquid and Gas Phase Relief Venting.

TABLE II

WEIGHT OF LIQUID OXYGEN REMAINING DURING LIQUID GAS PHASE VENTING TESTS

Time After Start of Vent Period, Days	Weight of Liquid Oxygen Remaining, lb.			
	Test 1 Gas-Phase Vent	Test 2 Gas-Phase Vent	Test 3 Liquid-Gas Vent	Test 4 Liquid-Phase Vent
0	44.5	43.8	44.9	44.7
1	43.4	42.8	43.9	43.9
2	42.3	41.8	43.1	43.2
3	41.2[A]	40.9[B]	42.3	42.4
4	40.3	39.6	41.5	41.8
5	38.4	38.3	20.7[C]	41.1
6	37.5	37.0	17.1	13.9[D]
7	36.2	35.7	16.1	0
8	Stop Test	Stop Test	14.9	Stop Test

NOTES:

A - Corresponds to weight of liquid oxygen remaining when mass flow rate began slight increase at end of third day of Test 1. (See Figure 39.)

B - Corresponds to weight of liquid oxygen remaining when mass flow rate began slight increase at end of third day of Test 2. (See Figure 39.)

C - Weight of liquid oxygen remaining when mass flow rate began rapid increase during fifth day of Test 3 (See Figure 39) = 40.9 lb.

D - Weight of liquid oxygen remaining when mass flow rate began rapid increase during sixth day of Test 4 (See Figure 39) = 41.0 lb.

Since the initial relief venting mass flow rates were greater with gas phase venting, and since the gas phase is at the relief port which inherently has a slight leakage when at pressure, it is assumed that a greater portion of the total heat input was transferred to the upper, warmer liquid layers in the temperature-stratified container. Thus the gas phase could not be entrapped as was the case in Test 3 and 4 and was readily released from the system. Hence more liquid was vaporized than in Tests 3 and 4, and the resultant gases were expelled from the container. It is evident that a portion of the heat input went into the lower, colder regions,since loss rates shown in Figure 39 for Tests 1 and 2 were lower initially. As in Tests 3 and 4, this resulted in liquid expansion and an increase in temperature of the lower liquid. When the entire liquid mass was at thermal equilibrium with the operating pressure, all heat input resulted in liquid vaporization, and the mass flow rates in the latter portions of the gas-phase venting tests were therefore greater than those observed prior to the attainment of temperature equilibrium.

Table II lists, in addition to weights remaining at the end of each 24-hour venting period, the approximate weight of liquid oxygen remaining in each test when a notable increase in relief valve flow rate occurred. It has previously been stated that prior to the mass flow increases noted in each test the container was filled with a non-stratified liquid at thermal equilibrium with the operating pressure. The weight of liquid to completely fill the container at thermal equilibrium with the operating pressure was calculated as follows:

Saturated liquid oxygen density = 1.007 g/cc at 7 atm press. (103 psia)

Internal volume of test container = 18,550 cc

Liquid oxygen weight at thermal
equilibrium, 7 atm press. = 18,550 cc X 1.007 g/cc = 18,679.9 gm (41.10 lb.)

From Table II, the weights corresponding to flow increases for Tests 1 through 4 were, respectively, 41.2, 40.9, 40.9, and 41.0 lb. Comparison with the theoretical equilibrium weight of 41.1 lbs. indicates that the fluid contents were near thermal equilibrium just prior to the flow rate increases, and that the flow increases were caused by the fact that any additional heat to the liquid contents could only cause vaporization.

Because of insufficient testing time to pursue the feasibility of liquid-phase relief venting, gas-phase venting was established as the goal for this prototype. Initial investigation involved the testing of various porous materials to determine the ability of each to seal liquid oxygen flow yet pass gaseous oxygen with small pressure differentials; in addition, the materials tested should not be wetted by liquid oxygen. A vent pick-up fabricated of this hypothetical material would be assembled within the container in such a configuration that it would vent only gas phase during both ground and weightless conditions.

The following materials were investigated in this program, and all were found to be wetted by liquid oxygen:

duPont CTR Filter Type 1411C

duPont CTR Filter Type 1511A

duPont CTR Filter Type 1511CY

duPont Microporous Teflon MPTF-70

Panoramic Sintered Stainless Steel Filter Type C-3

Panoramic Sintered Stainless Steel Filter Type C-5

Silicon Monoxide

Magnesium Fluoride

Glass

From prior testing approximately thirty other materials were also found to be wetted by liquid oxygen. Because of the data obtained from this investigation, there are presently no known materials available to be used in the proposed vent pick-up configuration.

The venting approach selected for the prototype consists of two relief ports within the container. One port is comparable to that employed in a conventional liquid oxygen storage system designed for a gravity environment. The pick-up tube for this port is located near the top of the inner container, for gas-phase venting during normal operation in a gravity environment. A second relief port from the inner container is connected to a vent assembly having its pick-up opening near the center of the container as shown in Figure 40.

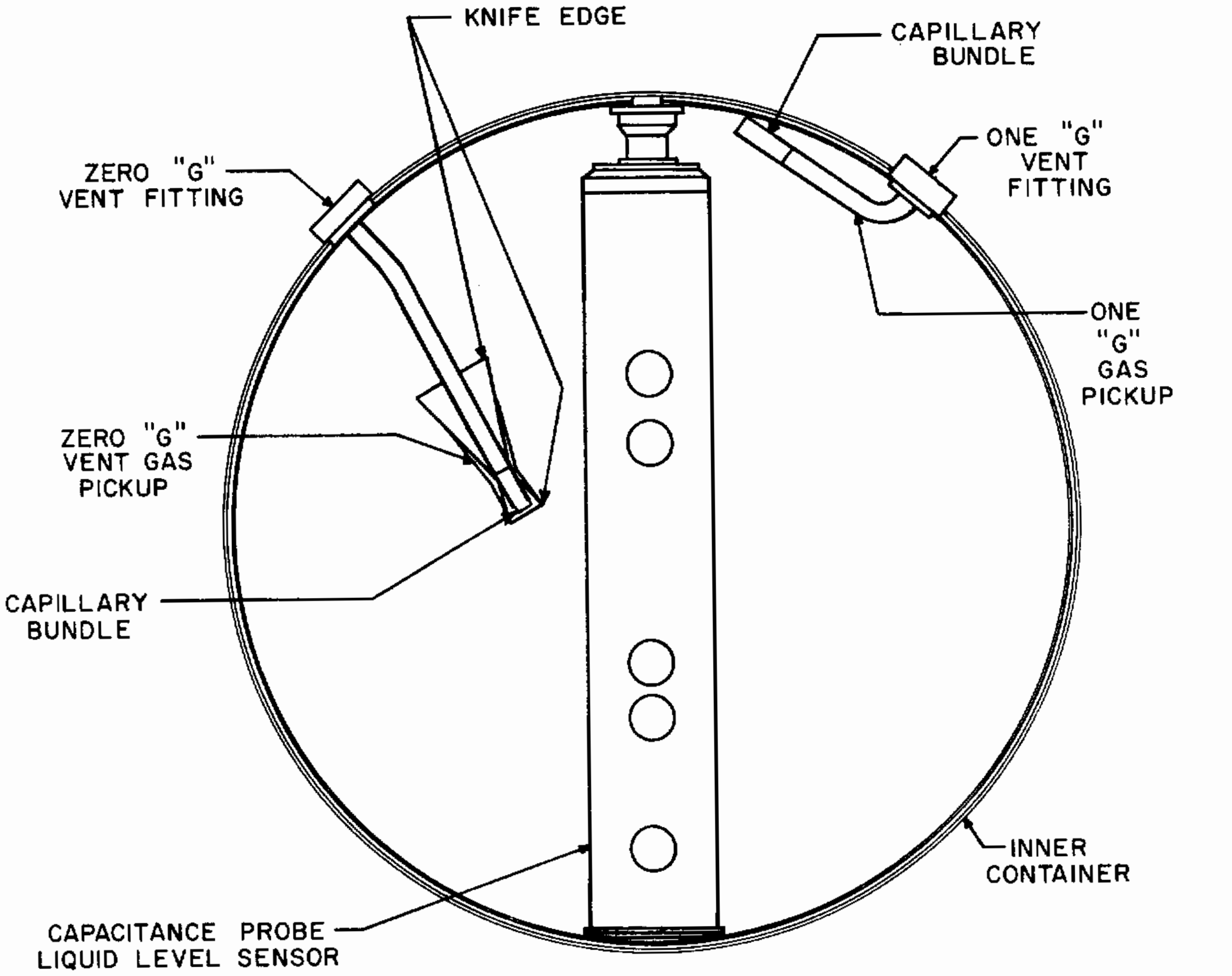


Figure 40. Schematic - Zero "G" and One "G" Vent Assemblies.

Because of the wettability of liquid oxygen on all materials tested in both this study and prior investigations, liquid phase oxygen will cover all surfaces within the container in a weightless environment (assuming no external accelerative forces). Due to the large surface area offered by the wall of the container, most of the liquid phase will form at the periphery of the container around the capillary-wick units, as previously discussed. All other surfaces located away from the periphery of the container (capacitance probe, Zero-G vent assembly, support ring) will be wetted by a thin film of liquid phase. The gas phase will form as a bubble at the center of the container.

During periodsof non-venting in a weightless environment, liquid oxygen will also wet the capillary bundles located in the ends of the One-G and Zero-G vent pick-up tubes. A seal will be formed, preventing a wetting-type flow of liquid into the vent tubing exiting from the inner container into the vacuum annulus, since the liquid must displace the gas contained within the dead ended tubes. It is desirable to prevent liquid from entering the dead ended vent tubes, as it will absorb heat and vaporize when it reaches the portions of tubing nearest the outer container. This condition would result in premature relief valve operation due to gases expanding toward the external vent port. Gases expanding into the inner container would possibly disturb the two-phase mixture to such an extent that gas-seals at those capillary wicks exposed to gas phase might be broken, resulting in partial gas-phase supply delivery.

When the container pressure rises to the pre-selected relief pressure, due to an imbalance between supply fluid withdrawn and environmental heat input, the relief valve will open and fluid will be forced from the container. At ground conditions, two solenoid valves in the external circuitry will be constantly powered, and as described in Section IV, venting of gas phase will be performed through the One-G vent tube located at the top of the container. In a weightless environment, no power will be applied to the solenoids, and the external circuitry dictates that vent flow will be accomplished only through the Zero-G vent tube located near the center of the container (Figures 40 and 48). Initial flow through the Zero-G vent tube will consist of the gas located within the tube prior to relief-valve opening and also the thin film of liquid phase wetted on the capillary bundle face. Further flow will include some wetted liquid from the inner walls of the cup surrounding the end of the pick-up tube. As liquid adhering to the outer external surface of the flow restrictor "creeps" on the surface to the open capillary bundle and thence out the container, the knife-edge cup, offering a minimal radius of curvature, breaks the liquid adhesion to the surface. Further liquid movement along the wetted flow restrictor is thus halted. The larger knife-edged end of the flow restrictor, away from the pick-up tube opening, in like manner prevents the liquid film on the inside surface of the larger end from passing across the edge to the external surface of the flow restrictor. Since the Zero-G pick-up tube end is now completely exposed to the gas bubble, gas phase will be vented until container pressure declines below the relief pressure.

F. Fluid Temperature Stratification Considerations

With the increase in cryogenic space system development test work, the effect of fluid temperature stratification on pressure control has become particularly important. Laboratory test work and analyses are supported by observed pressure decay noted in several experimental cryogenic tanks exposed to a weightless environment in suborbital and orbital space flights. Pressure decay phenomena are observed in both subcritical and supercritical pressure storage of cryogenic fluids. This is due to non-uniform distribution of thermal energy in the contained fluid. Actual pressure decay is caused by fluid mixing and agitation, due either to vehicle roll or tumbling or possibly by fluid displacement mixing due to density gradient surface tension displacement action.

It was originally planned in the program to include a static thermal conductor within the inner container, in order to distribute thermal energy from the upper liquid layer to the lower liquid region. This non-uniform distribution of thermal energy (temperature stratification) is caused by filling the container (no thermal conductor) with atmospheric stabilized liquid and allowing the container to pressurize while the liquid remains in a quiescent state. Upon attaining operating pressure as a result of environmental heat input to the system, the liquid at the bottom would be at a cold temperature (corresponding to atmospheric pressure), while the top layer would be at a warmer temperature (corresponding to operating pressure). If this liquid is agitated, temperature stratification will be disturbed, and pressure within the container will degrade as colder liquid regions are oriented next to the gas phase. Use of a thermal conductor would result in a more uniform temperature distribution so that when the liquid is agitated, pressure will only degrade slightly and will depend upon the temperature distribution in the liquid.

The basic theory supporting the idea that in a weightless environment, liquid will form around the perimeter of the vessel with a gas bubble in the center, is that the adhesion forces between the liquid and the wetting surface of the inner container wall are greater than the cohesion forces between individual liquid droplets. In essence, then, surface-tension forces will hold liquid to any wetting surface within the container (in a weightless environment). The surface area of a spiral thermal conductor would be fairly large, even though circular portions would be removed for weight optimization. A thermal conductor with 2.5 spirals, that could be utilized in a 10-liter container, has a total surface area of 3615 cm^2; if 50% of the material is removed for weight optimization, the total surface area would be 1808 cm^2. The inner surface area of the spherical 10-liter container is 2362 cm^2. Neglecting the exposed surface area of the support rings, feeder wick connecting tubing, and the quantity sensor (which has an appreciable surface area exposed at the center of the container), 43% of the total wetting surface area will be contributed by the thermal conductor. Only 57% will be at the periphery of the container. It is highly probable that in weightless conditions, about as much liquid mass will gather on the thermal conductor as does on the periphery of the container. With the thermal conductor not in the container, almost all of the total wettable surface area will be at the periphery; the tendency for all liquid to accumulate around the peripheral feeder wicks will then be increased. It was therefore concluded that it would not be advantageous to use a static thermal conductor in the container.

An alternate technique for destratification utilizes motor-fans for mixing the fluid. This technique is specified for the Apollo Tankage, and appears to be the lightest approach for relatively large tankage.

One method to avoid temperature stratification (and hence pressure decay) without using a thermal conductor or motor-fan would be to fill the container with liquid stabilized at the operating pressure (95 psia), instead of atmospheric-stabilized liquid. The container would not be vented to atmosphere during fill, but would be vented through a relief valve, which would be set at slightly above 95 psia. Upon completion of fill, the system would contain a uniform liquid stabilized at 95 psia. A temperature gradient in the fluid would still exist, but this gradient would not be as extreme as that encountered in the normal atmospheric-vented fill process. A thermal conductor would then not be necessary, since thermal energy would be uniformly distributed. In order to increase standby time, the container might be filled with liquid stabilized at 40 or 50 psia.

SECTION III

FABRICATION OF PROTOTYPE

The complete Subcritical Liquid Oxygen Storage and Supply System is shown in Figure 41. The unit consists of the container shock mounted to a platform containing associated sensing devices; provisions are made for filling, overboard venting, and controlling supply flow. Electrical connectors provide for power input to a voltage regulator and for output from the various sensors.

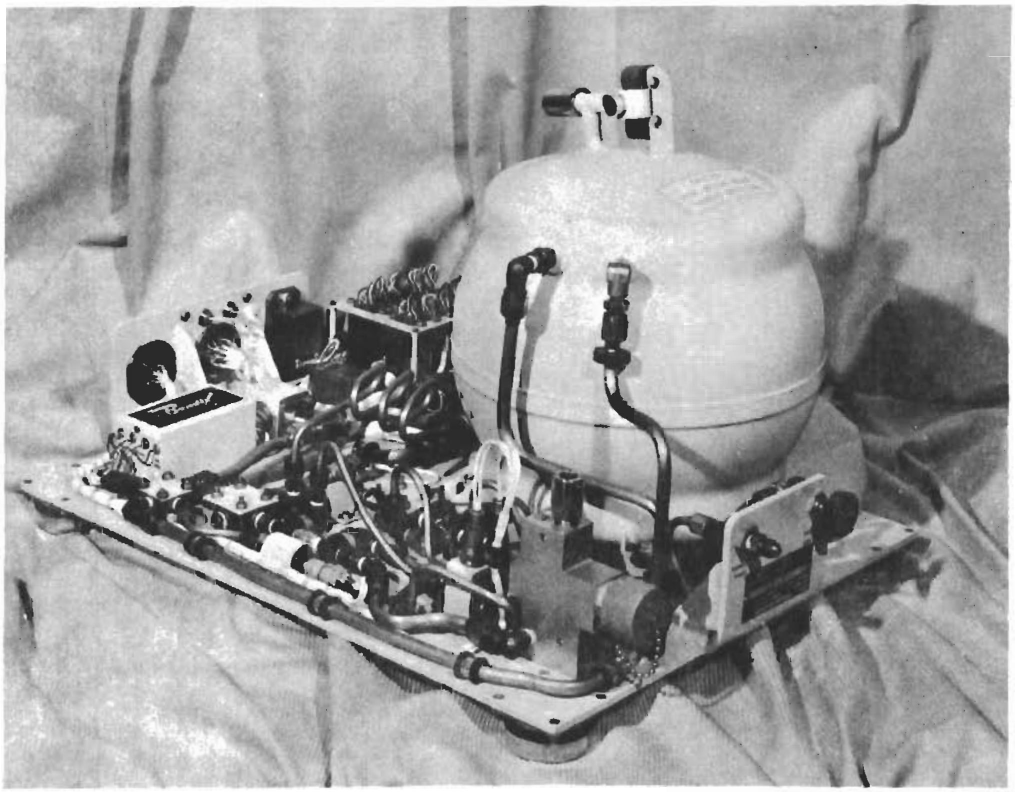


Figure 41. Subcritical Liquid Oxygen Storage and Supply System

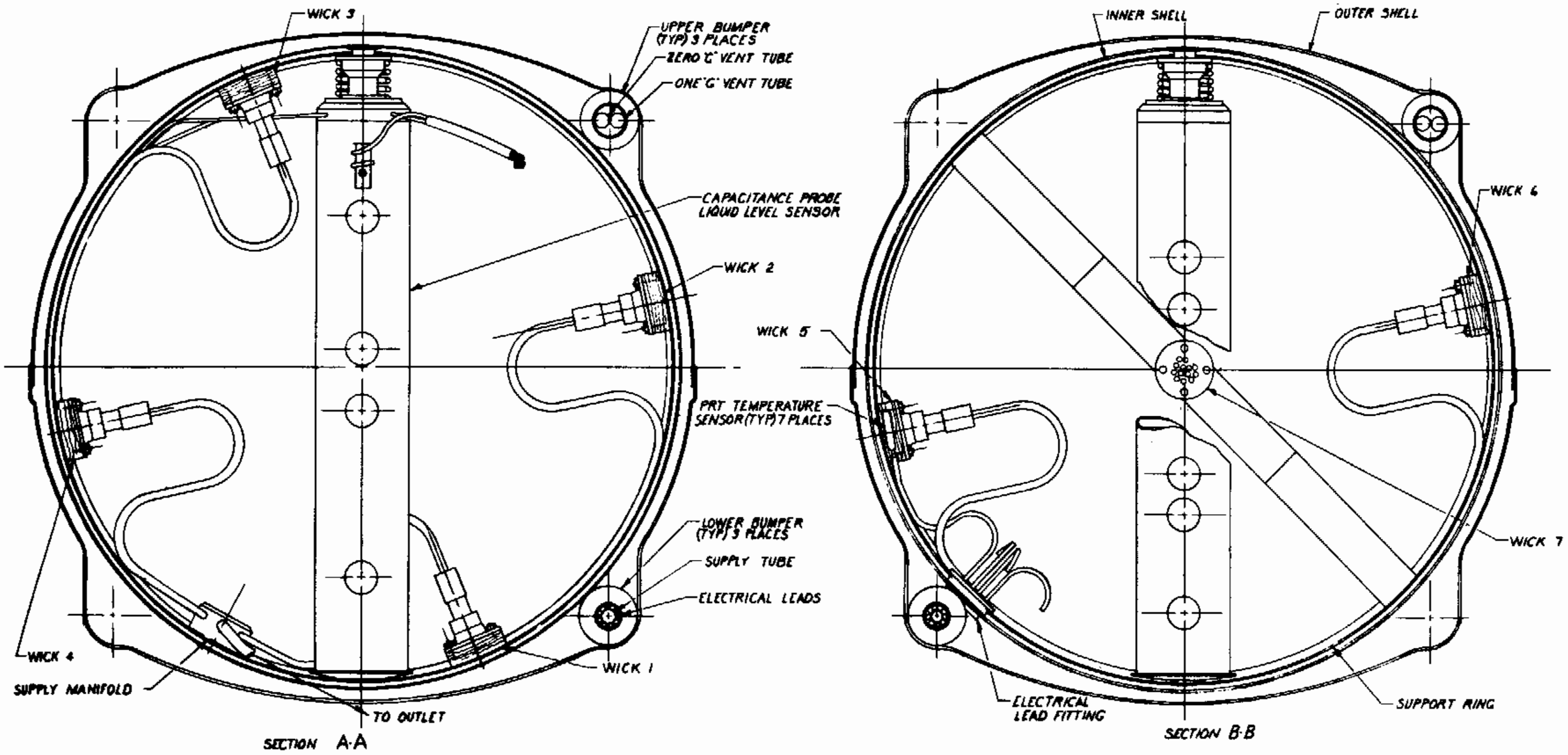


Figure 42. Container - Subcritical Liquid Oxygen Storage and Supply System

A. Description of Container (Refer to Figure 42)

The container consists of an inner and outer shell of heliarc welded stainless steel. The inner container is suspended within the outer container by six Kel-F bumpers mounted on the container fill and vent tubes. A very high vacuum is maintained in the annular space between the inner and outer shells; a chabasite getter brazed to the inner shell stabilizes the vacuum by absorbing outgassed particles. The vacuum-exposed surfaces of the inner and outer shells are silver- and copper-plated, respectively, to reduce radiation heat input to the stored cryogen.

Seven capillary-wick units are mounted within the pressure vessel: six of these are located approximately 90° apart at the periphery, with one unit mounted at the center near the capacitance probe assembly. The support assembly for the feeder wicks, their common manifold, and the capacitance probe is shown in Figure 43. The six peripherial wick units are located on the support ring by threaded fasteners, shown in Figure 44; wicking material is compressed against the support ring surface, with a series of holes at each location permitting liquid transfer to the wick from the 2 mm gap between the support ring and the pressure vessel. Small temperature sensors, located within each wick, provide information concerning gas-phase location and stratification within the pressure vessel. Stainless steel sheathed electrical leads for these sensors and for the capacitance probe exit from the inner container through leak-tight braze joints in an electrical lead fitting, located on the support ring and heliarc welded to the inner container.

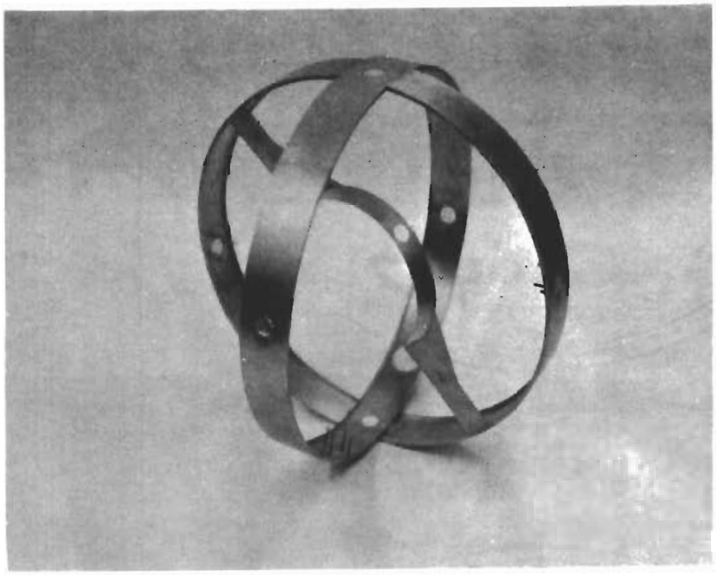


Figure 43. Support Ring

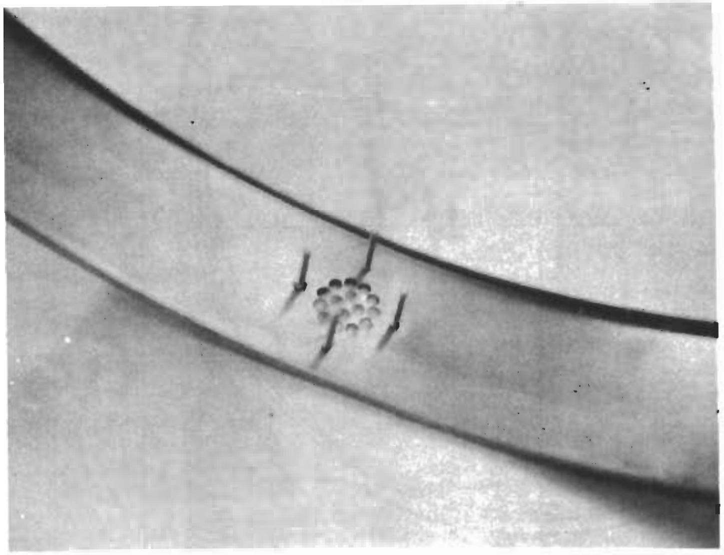


Figure 44. Capillary-Wick Location

The completed inner assembly, consisting of seven capillary-wick units and inter-connecting tubing, supply manifold, capacitance probe, and electrical lead fitting, is shown in Figure 45. Installation of the inner assembly within the lower inner container is shown in Figure 46. Placement of the inner assembly in the upper inner container (Figure 47) shows orientation of the Zero-G vent tube (Figure 48) and the One-G vent tube. Two vent tubes therefore exit from the pressure vessel and pass through three Kel-F radial bumpers in the void (Figure 49); bumpers on the lower portion of the pressure vessel are mounted on the supply tube, with electrical leads positioned concentrically around the tube (Figure 50).

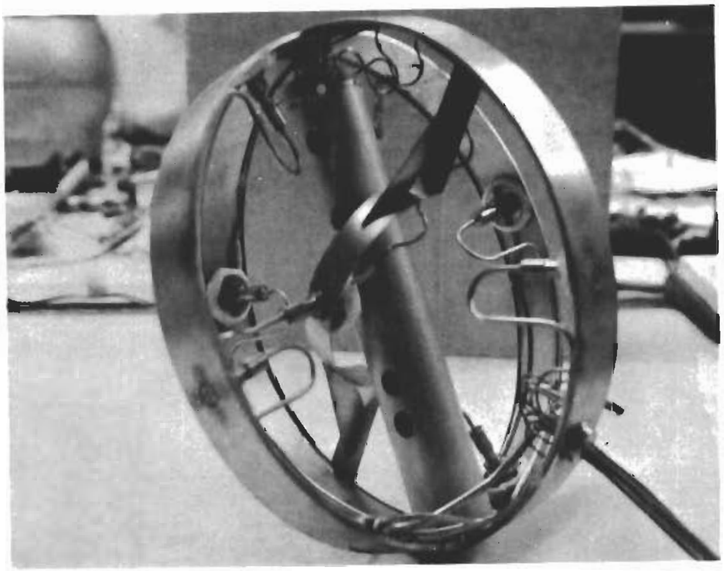


Figure 45. Feed System

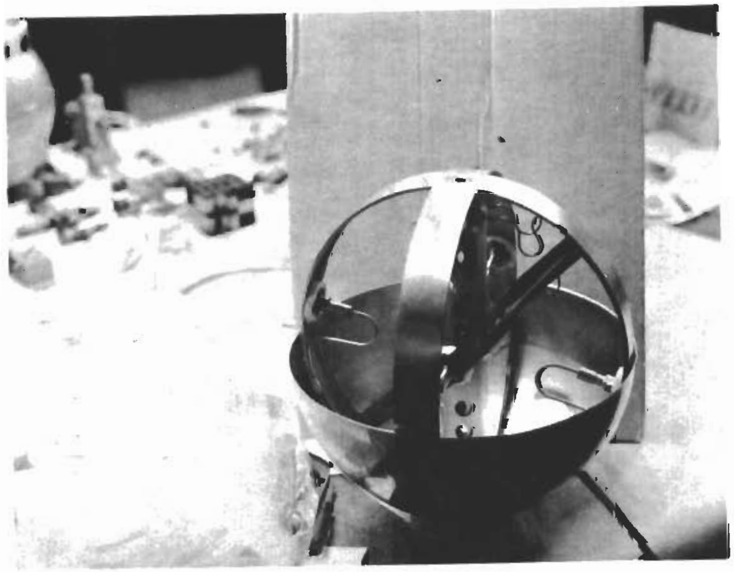


Figure 46. Feed System in Lower Inner Shell

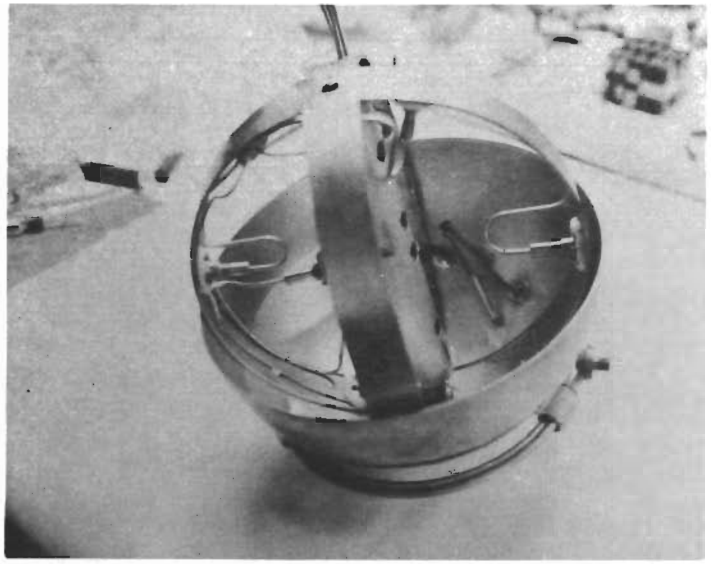


Figure 47. Feed System in Upper Inner Shell

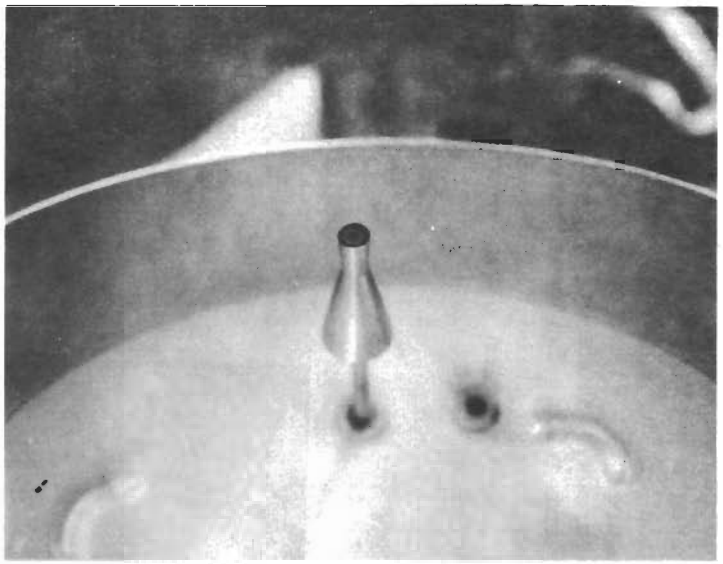


Figure 48. Zero "G" Vent Assembly

Figure 49. Vent Tubes, Upper Inner Shell

Figure 50. Supply Tube, Lower Inner Shell

Wherever possible in the fabrication of the container, basic components of the Pioneer-Central type number 29073-C, 10-liter liquid oxygen converter were utilized. Major components used included both inner and outer containers and the capacitance probe assembly.

B. Description of System

Major items of importance are presented in Table III.

TABLE III

SUBCRITICAL LIQUID OXYGEN STORAGE AND SUPPLY SYSTEM
PHYSICAL CHARACTERISTICS

WEIGHT, DRY	18.513 kg (40.813 lb)
WEIGHT, FULL, 10 LITERS LOX	29.853 kg (65.813 lb)
OVERALL DIMENSIONS	65.10 cm x 45.72 cm x 40.01 cm (25.63 in x 18.00 in x 15.75 in)
INPUT POWER:	
VOLTAGE REGULATOR	+28 V DC ± 10% @ 300 MA
SOLENOIDS (GROUND ONLY)	+28 V DC ± 10% @ 1 AMP each
OPERATING TEMPERATURE RANGE	-54° C to +74° C
Sensors	
Temperature (10)	Indicate temperatures at 7 locations within converter, supply and vent oxygen temperature and environmental temperature.
Pressure (3)	
Differential (2)	Monitor supply flow and vent flow
Absolute (1)	Monitors supply pressure
Acceleration (3)	
X Axis (1)	Indicates yaw
Y Axis (1)	Indicates pitch
Z Axis (1)	Indicates roll
Strain Gages (2)	
X Axis (1)	Measures strain along X axis
Y Axis (1)	Measures strain along Y axis

The system schematic presented in Figure 51 outlines all flow paths and electrical requirements for system operation in both gravity and weightless environments. Component identification and envelope dimensions are given in Figure 52.

Three accelerometers mounted to the system base provide for measurement of acceleration in three axes. Two bridge type strain gage systems, located on the base under the container, measure system strain in the plane of the base. Two differential pressure transducers and two temperature sensors monitor flow through orifices located in the supply and vent tubing. A temperature sensor on the system base provides environmental temperature. As discussed previously, one miniature temperature sensor is located in each capillary-wick unit within the container. Each of the ten temperature sensors utilized in the system is a temperature dependent resistance sensor employed as one leg of a precision resistance bridge. The main bridge modules, or Triple Bridge Units, are mounted on the system base near the electrical connectors.

The system voltage regulator performs three functions: (1) it transforms the 28 v dc input to the system to 24 v dc for operation of the accelerometers, and to 10 v dc for operation of the pressure transducers, Triple Bridge Units, and the strain gages, (2) it maintains these voltages at a constant level despite allowable fluctuations in the input voltage (28 v dc ± 10%), and (3) it provides a standard 30 mv output which can be used to achieve greater measurement accuracy.

Two solenoid valves, one normally open and one normally closed, are used to perform fill and vent operatons in a gravity environment. When in a weightless environment, no power is applied to the solenoid valves for proper venting performance.

The modified Bendix type number FR-23-B1A valve used on this system is a combination component which permits filling and relieving excess pressure. Atmosphere venting during the fill operation is accomplished by removal of the atmosphere vent cap located in the One-G vent line. For pressurization of the container, the vent cap is replaced; relief of excess pressure is performed by the relief valve located within the FR-23-B1A valve. An additional relief valve, Bendix type number FR-121-AZ, is located in the Zero-G vent tube and is included for safety precautions.

The system also includes a five-psi differential check valve, Bendix type number FR-29-A1A, installed in the supply line between the liquid outlet port from the container and the supply control valve. The valve prevents the return of warm oxygen into the container assembly once it is converted into gas in the supply line. The supply control valve provides accurate manual adjustment of supply fluid to meet flow requirements for the system.

An ion pump was included in the system to perform two functions: (1) it removes outgassed materials from the vacuum between the inner and outer shells of the container, and (2) it provides an accurate means of determining the vacuum, since the power required to operate the unit is proportional to the pressure. The ion pump and its power unit (not a component on the system) are not necessary for operation of the system in flight.

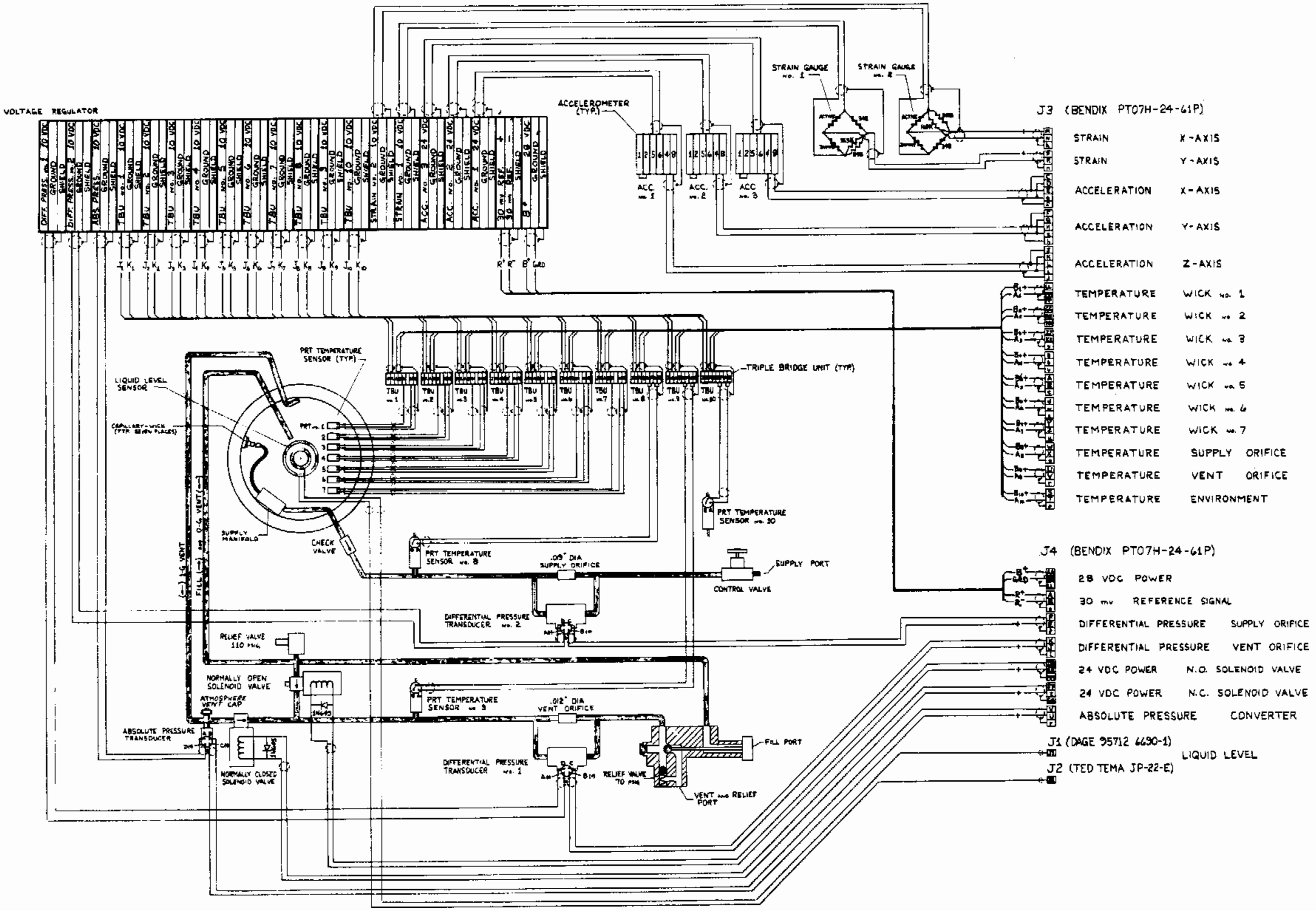


Figure 51. System Schematic

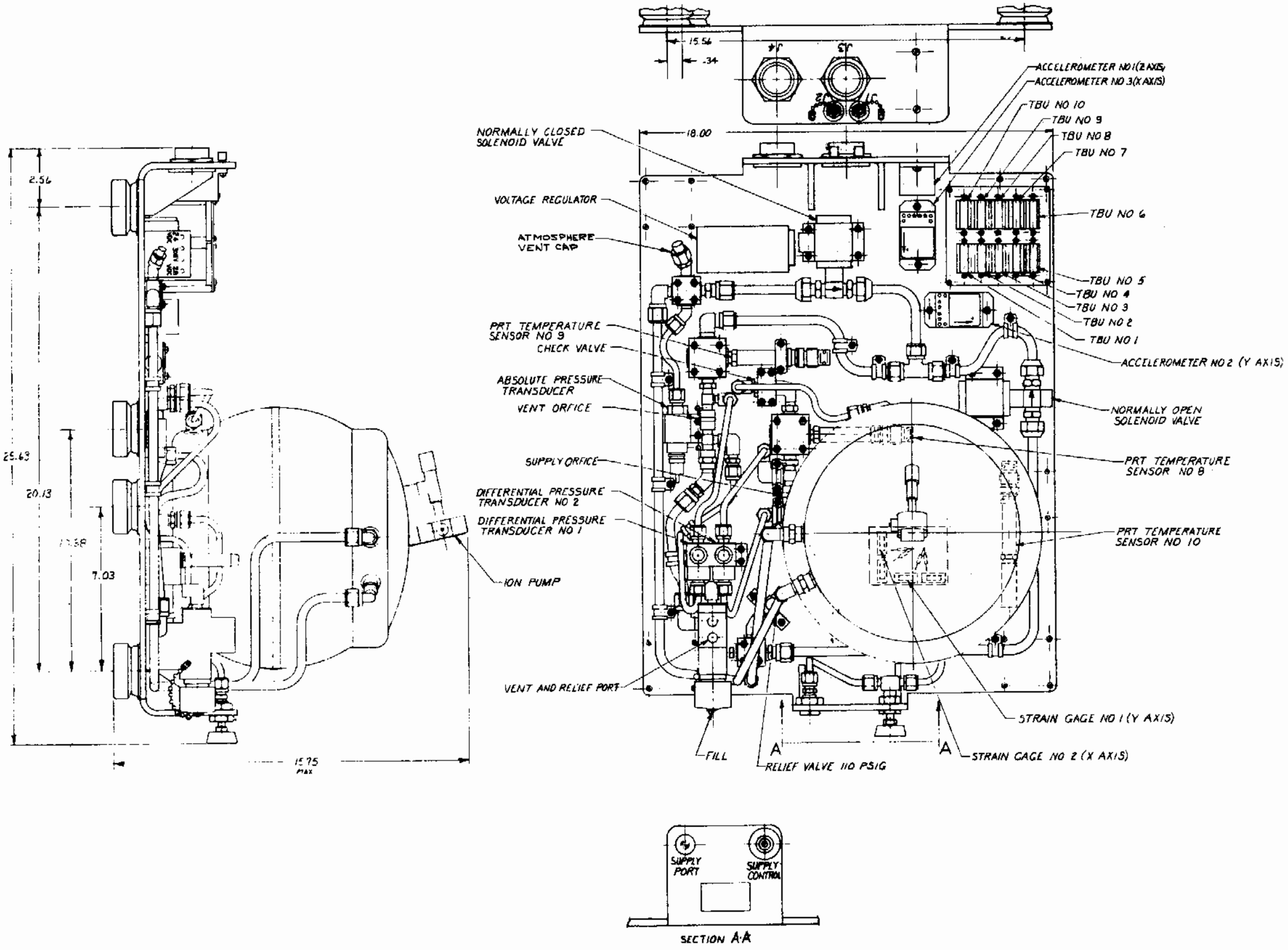


Figure 52. Component Identification

Electrical connectors provide for input power to the voltage regulator and solenoid valves, output from sensors to on-board telemetry, and output to a liquid quantity gage for liquid level determination in a gravity environment.

Vibration isolation of the container from the system base is accomplished by four shock mounts attached to the outer container, while the system itself utilizes six vibration isolators located on the underside of the base.

SECTION IV

SYSTEM OPERATION

In discussing the operation of the system, it is advisable to refer to the System Schematic, Figure 51. It will be assumed in the discussion that appropriate electrical connections to the system have been performed, and that ground filling is employed.

Prior to filling the container, it is imperative that the unit be purged with warm oxygen gas to remove water vapor from the system. The atmosphere vent cap is removed to provide free flow of purge gas through the container. Power applied to the solenoid valves in the vent plumbing permits flow of purge gas into the unit through the Zero-G vent line. The container is purged by connecting a purging unit (Bendix P/N 31TB1849-2, "Heater Assembly Purging Liquid Oxygen System," or equivalent) to the system fill port and supplying oxygen at 100 psig to the purging unit to result in a regulated flow at 35 psig into the container. Upon completion of the purge, the fill operation should be initiated. As in purging, power is applied to the solenoid valves, and the atmosphere vent cap is removed. The container is filled by connecting a filler nozzle (Air Force 55D3795) to the system fill port and pressurizing the liquid oxygen storage supply cart to 30 psig to insure continuous flow of liquid oxygen into the container. Liquid oxygen flows into the inner container through the Zero-G vent tube, absorbs heat and vaporizes until the container is cooled to liquid oxygen temperature. Vent gases are expelled through the One-G vent tube out the atmosphere vent port, from which the cap has been removed. Liquid oxygen issues from the atmosphere vent port when the inner container is full. The system is placed in a pressure build-up position when the filler nozzle is removed and the atmosphere vent cap is replaced. Environmental heat input results in an operating pressure (80 psig) build-up time of approximately 40 hours for a filled container. During build-up, it is assumed that the system is in a gravity environment. Power must therefore be supplied to the solenoid valves during this period, since liquid will be expelled from the center of the container through the Zero-G vent tube and 80 psig relief valve if the solenoid valves are in their normal, un-powered state and container pressure is 80 psig.

When a weightless environment is encountered, power is removed from the solenoid valves. Liquid oxygen under weightless conditions will collect on the periphery of the inner container, while the gas phase will form near the center. The Zero-G vent tube, extending to the center of the container, will therefore be in direct communication with gas phase. When overboard pressure relief of the container is required due to an imbalance of environmental heat input over supply flow rate, gas will be removed through the Zero-G vent tube according to the venting action discussed in Section II(E). Gas-phase relief flow in the external lines will occur through the normally open solenoid valve, the vent orifice, and thence the relief valve in the combination fill-relief valve assembly. When operation of the system is desired in a gravity environment, the gas phase will be located at the top of the container. Therefore, as discussed previously, the solenoid valves must be powered for proper pressure-relief performance. Vent flow is monitored by Temperature Sensor No. 9 and by Differential Pressure Transducer No. 1. Liquid phase supply is obtainable in the pressurized position by manually setting the supply control valve to meet required flow rates. Liquid forced through the feeder wicks into the supply manifold by the pressurized gas-phase bubble is expelled from the container, flows through the check valve and supply orifice downstream to the system supply port. The coiled tube which serves as a heat exchanger and is located between the container supply port and the check valve increases the temperature of the fluid before it exits through the supply control valve. Supply flow is monitored by Temperature Sensor No. 8 and Differential Pressure Transducer No. 2. As discussed in Section II, preferential liquid phase delivery is assured even in the event that only one feeder-wick unit is exposed to liquid phase, since a liquid-gas seal in those wick units exposed to gas phase prevents break-through into the feed system. Preferential liquid phase delivery will continue until the pressure vessel is essentially empty, since the six peripherial capillary wick units are located within 2 mm of the vessel wall. In the event that an appreciable mass of liquid temporarily is positioned near the center of the container, the seventh capillary-wick unit will adequately supply liquid phase to meet flow requirements.

Sensor outputs supplied to telemetry during flight testing will include the vent and supply functions discussed above, temperatures at each capillary-wick location, environmental temperature, container pressure, acceleration, and strain. In addition, a well-regulated 30 mv reference signal will be supplied from the voltage regulator.

SECTION V

TESTING AND PERFORMANCE

The following tests were performed on the prototype:

A. Vented Evaporation Loss

B. Pressure Build-up

C. Pressurized Evaporation Loss

D. Flow and Phase Control Characteristics

E. Vibration

F. Vented Evaporation Loss Following Vibration

A. Vented Evaporation Loss

A vented evaporation loss test was conducted to determine the insulating quality of the container with no external plumbing attached. The container was filled with 10.67 kg (23.44 lb.) of liquid oxygen and vented to atmosphere: weight loss due to liquid vaporization by environmental heat input was determined from a recording scale.

In the 36 hour test period, 0.823 kg (1.81 lb.) of liquid oxygen was vaporized. The heat input rate was calculated as follows:

$$Q = \dot{m} \, (h_g - h_f)$$

where:

Q = heat input, J/hr

$\dot{m}$ = loss rate, gm/hr

h_g = enthalpy of saturated vapor at 1 atm., J/gm

h_f = enthalpy of saturated liquid at 1 atm., J/gm

$h_g - h_f$ = latent heat of vaporization at 1 atm., J/gm

$$Q = 823/36 \, (354.59 - 140.80)$$

$$= 4880 \text{ J/hr } (4.61 \text{ Btu/hr})$$

B. Pressure Buildup

Because the majority of the testing phase involved testing the unit with liquid oxygen - liquid nitrogen mixtures to determine capillary-wick feed system performance, pressure buildup data is available only for a 40.6 mol percent oxygen and 59.4 mol percent nitrogen mixture. After filling to the maximum into the precooled container, the unit was sealed and pressure buildup resulted from environmental heat input. The results of this test are presented in Figure 53. Pressure buildup to 84 psig (relief-valve pressure) required 44.5 hours with this mixture. A time period of similar magnitude would be required to attain the same pressure if the container were filled only with liquid oxygen. An equal or perhaps shorter time would be required if the container is initially warm prior to filling with liquid oxygen, due to the residual heat capacity of the metal container.

C. Pressurized Evaporization Loss

Utilizing the same 40.6% O_2 - 59.4% N_2 mixture from the Pressure Buildup Test, a weight loss at the operating pressure of 84 psig was obtained. In a 22 hour test period, 0.539 kg (1.19 lb) of the cryogenic mixture was evaporated due to environmental heat input. Data for oxygen-nitrogen mixtures at 75 psia (Reference 3) were used to estimate heat input at pressure as follows:

$$Q = \dot{m} \; (h_g - h_f)$$

$$= 539/22 \; (88.4 - \{ -93.0\})$$

$$= 4440 \text{ J/hr } (4.21 \text{ Btu/hr})$$

D. Flow and Phase Control Characteristics

An operational flow test was performed on the supply system, utilizing a liquid oxygen-liquid nitrogen mixture for determination of phase control performance. The container was filled with a mixture of 0.560 kg (12.38 lb) liquid oxygen and 0.357 kg (7.88 lb) liquid nitrogen, corresponding to 57.9 mol percent oxygen and 42.1 mol percent nitrogen. Time to pressurize to 80 psig require 43 hours; upon attaining operating pressure, approximately 16 percent of the mixture was withdrawn from the system through the supply port for instrumentation check-out. The results of this test presented in Figure 54 therefore start with 84% of the original fluid quantity weight remaining in the container. The variable gaseous supply flow rate (flow rate of liquid from the supply port after vaporizing and expanding to room temperature) was maintained throughout the test by the system supply control valve. Quantity of fluid remaining was determined by continuous system weight recording; system pressure data were obtained from a gauge located in the atmosphere vent port. Percent nitrogen in both the supply fluid and the vented gas phase was monitored by a nitrogen analyzer unit, as in the Design Phase Test Program (Section IIC). Figure 54 presents, in addition to the above data, the total number of capillary-wick feed units exposed to gas phase as the liquid level in the container decreased due to supply liquid removal.

Referring to Figure 54, an initial gaseous supply flow rate of 3 lpm was set and maintained from the container for 3 hours. As previously stated, the test was begun with 84% by weight of the original liquid fill; the upper feeder wick (wick 3 in Figure 42) was therefore exposed to gas phase at the beginning of the test, since this unit is exposed when the container is 99% full or less (in a gravity environment). Nitrogen composition in

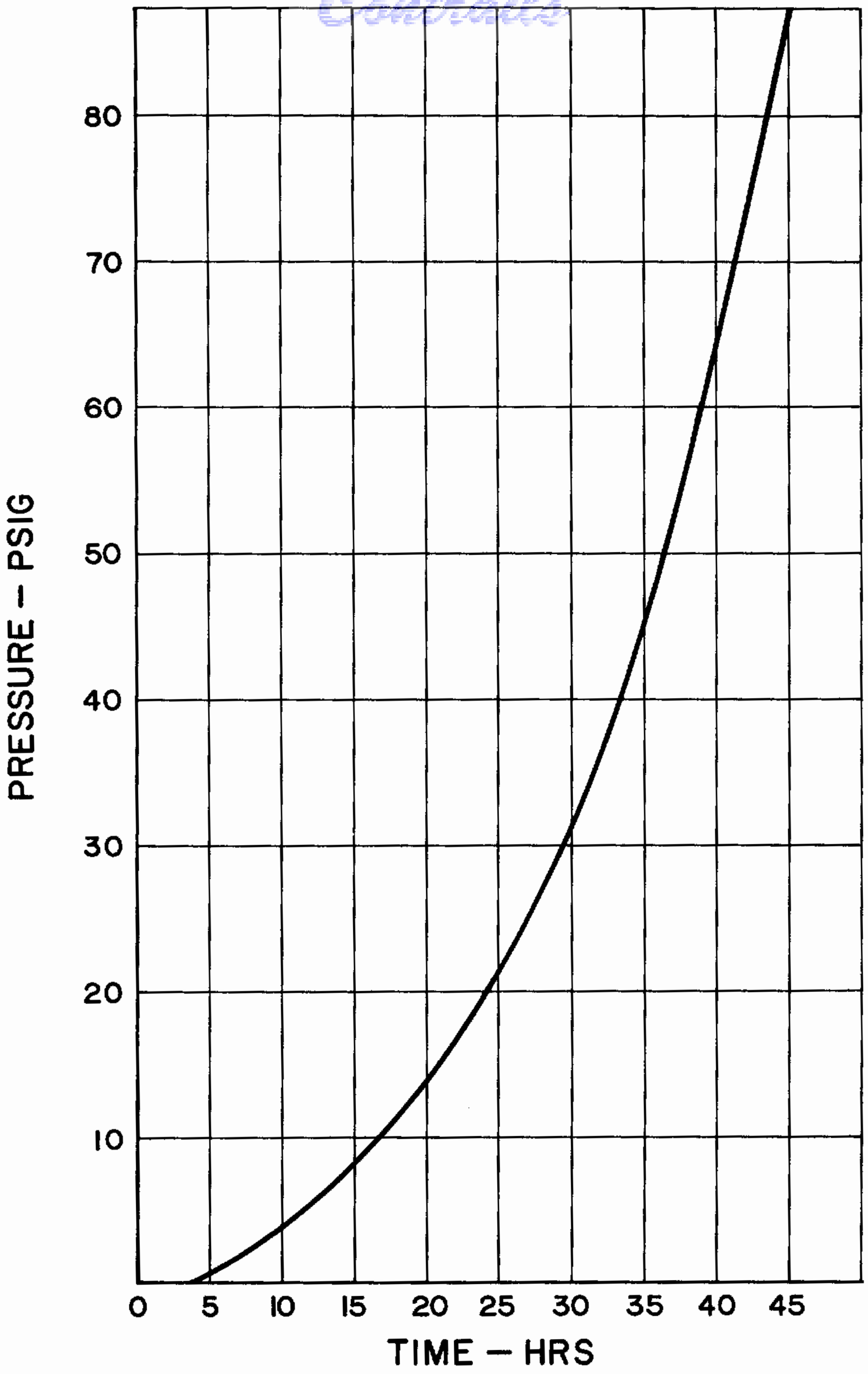


Figure 53. Pressure Buildup Test

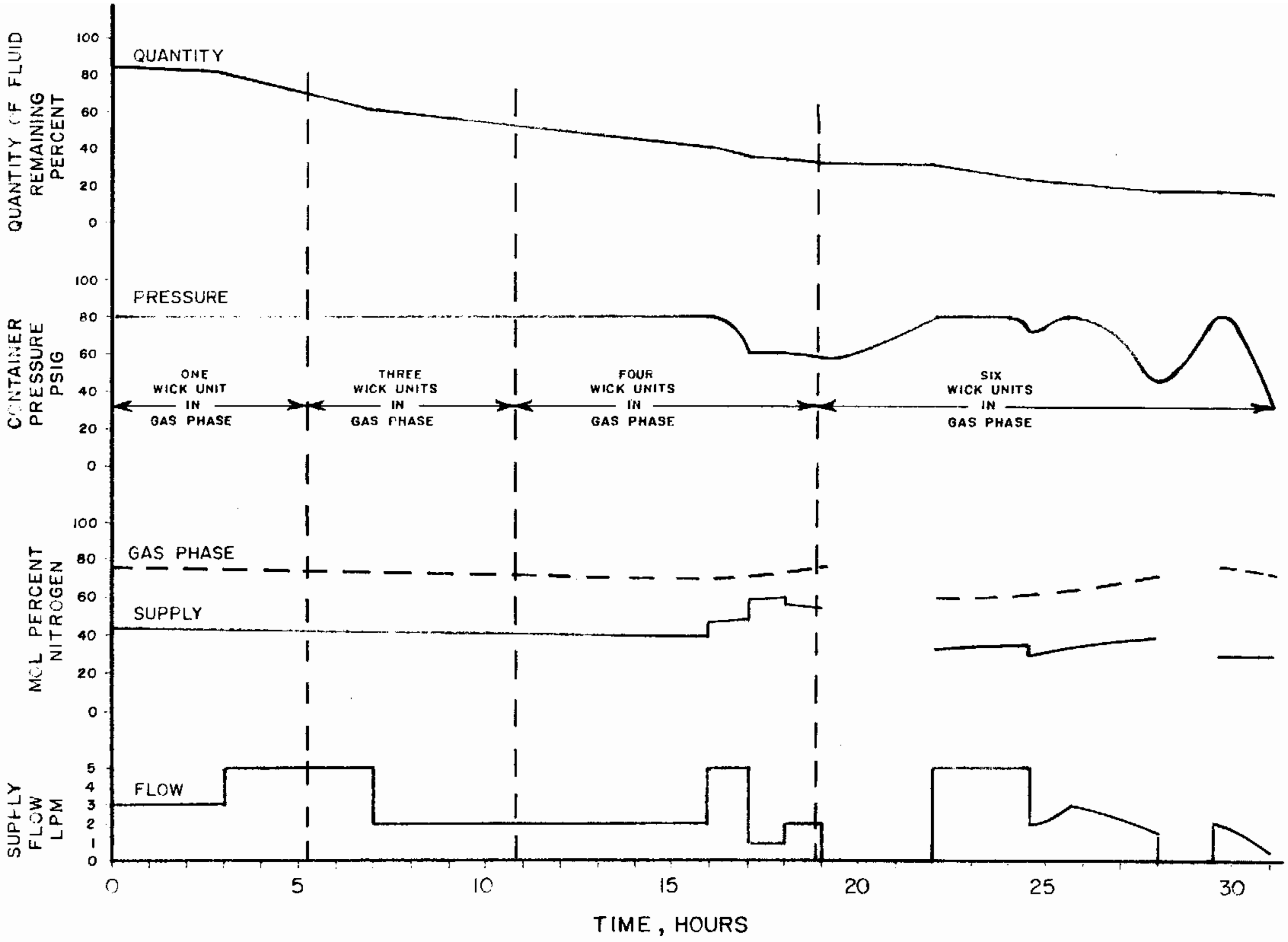


Figure 54. Operational Test.

the supply fluid was initially 43%, with the gas phase composed of 76% nitrogen. This compares favorably with the equilibrium data presented in Figure 10. With subsequent 5 lpm and 2 lpm flow rates maintained from the supply port of the container, liquid phase delivery from the capillary-wick feed system was assured, even when a total of four capillary wick-units (wicks 2, 3, 6 and 7 in Figure 42) were exposed to gas phase. This is evident since the nitrogen composition of the supply fluid remained substantially below that of the gas phase.

After a total test time of 16 hours, with 40% of the mixture remaining, the supply flow rate was increased from 2 lpm to 5 lpm, as shown in Figure 54. A gradual pressure degradation of 20 psi was accompanied by an immediate increase of 10% in the supply nitrogen composition. The instantaneous flow increase from 2 lpm to 5 lpm apparently disturbed the liquid continuity between wick units in the inter-connecting feed system and caused one of the gas-exposed wicks to become "dry". In a non-wetted condition, the gas-sealing characteristics of the capillary-wick interface are less effective. A certain amount of gas phase apparently entered the feed system, resulting in a pressure degradation and an increase in nitrogen composition of the supply fluid. The feed system continued to supply preferentially liquid phase, since the supply nitrogen composition remained below that of the gas phase.

Decreasing the flow from 5 lpm to 1 lpm was accompanied by another increase in the supply nitrogen percent; pressure, however, did not degrade but remained constant. Preferential liquid phase delivery was again prevalent, since percent nitrogen of the gas phase composition remained higher. Increasing flow to 2 lpm resulted in a decrease in supply percent nitrogen, rather than an increase. A very slight decrease in pressure was noted in this period.

Shortly after two additional capillary-wick units (wicks 4 and 5 in Figure 42) became exposed to gas phase due to the decreasing liquid level (resulting in a total of six capillary-wicks in the gas phase), the supply flow was shut off for a period of three hours. A pressure increase from 57 psig to the operating pressure of 80 psig occurred during this period as a result of environmental heat input to the fluid contents.

With only one capillary-wick unit exposed to the liquid phase, and with 35% of the oxygen-nitrogen mixture remaining, supply flow was resumed at 5 lpm. Nitrogen analysis of the vent and supply fluid indicated liquid phase delivery: the gas phase composition within the container was 62% N_2, while the supply fluid contained only 32% N_2. Liquid delivery was maintained at this flow rate for about 3 hours.

Continued testing of the unit with a single capillary-wick unit submerged in liquid phase and six capillary-wick units exposed to gas phase resulted in preferential liquid phase delivery, indicated by comparing nitrogen compositions in the supply and gas phase. With approximately 20% of the mixture remaining, some gas phase entered the feed system, as noted by a pressure decay. Reducing to a 2 lpm flow rate apparently permitted liquid continuity to be retained between the wick units, since an increase up to the operating pressure resulted. From this point, after approximately 25.5 hours total test time, until the conclusion of the test, pressure degraded as fluid was withdrawn from the system. Nitrogen analysis, however, indicated that the supply fluid was liquid phase. The apparent delivery of liquid phase accompanied by a pressure decay may have been the result of expansion cooling of the gas phase by expanded liquid in the delivery tube from the submerged wick (wick 1). As liquid is forced through the wicking material, across the wick material-capillary bundle interface, and then through the capillary bundle itself, a pressure drop is experienced. Some liquid in the interconnecting tubing will vaporize as a result of this pressure drop; the amount vaporized will depend upon the magnitude of this drop. As shown in Figure 42, the tubing interconnecting wick 1 to the supply manifold projects above the wick before bending downward to the manifold. Since a portion of this tubing projected into the gas phase near the end of the test (at 15% - 18% quantity remaining), then the gas phase may have been cooled by the vaporization of liquid within the tubing. This refrigerative action may have been sufficient to result in system pressure decay.

The capillary-wick feed system within the prototype container operated satisfactorily during this test in terms of preferential liquid-phase delivery. No pressure discontinuity or supply percent nitrogen increases were observed during the first 16 hours of the test, in which container quantity ranged from 84% to 40% full and a total of four of the seven feeder wicks were exposed to the gas phase. Excellent performance was also observed during 3 hours in the latter half of the test, when six wick units were surrounded by gas phase and the supply flow rate was at its required maximum of 5 lpm. During other portions of the latter half of this period, preferential liquid phase delivery was obtained, although pressure decay was experienced. This occurred when only 20% of the mixture remained.

The results of this test further indicate that the prototype system should perform most satisfactorily in an extended period of weightless environment. All testing performed on the prototype thus far has been necessarily conducted in a gravity environment. Because of this, it has been impossible to simulate the two-phase separation wherein the liquid phase forms at the periphery of the container, around the six peripherial wicks. As discussed above, and as noted in Figure 54, a total of four wick units in gas phase resulted in completely satisfactory performance; even with six wick units exposed to gas phase, good results were obtained. Therefore, when the system is tested in a weightless environment wherein six of the wick units will be in liquid phase, liquid phase delivery should be obtained without pressure degradation.

E. Vibration

The complete system underwent three vertical-plane vibration loading tests (see Table IV) with the container filled with liquid nitrogen. Accelerometers were mounted at the center and end of the system base and on the top of the container.

TABLE IV

VIBRATION TESTS

Test No. 1: 500-50 cps at 4 G, 50-25 cps at 0.020" double amplitude

Total Run Time = 4.85 min.

LOCATION	FREQUENCY cps	OBSERVATIONS G
Base, Center	250	15
Base, End	250	11
Container Top	250	10
Base, End	80	10
Base, Center	70	6
Container Top	70	7
Base, Center	22 (2.5 G)	3.5, 0.500" double amplitude

Test No. 2: 500-50 cps at 3.5 G, 50-100 cps at 0.020" double amplitude

Total Run Time = 6.61 min. (Revised system base shock mounting.)

LOCATION	FREQUENCY cps	OBSERVATIONS G
Base, Center	250	0.5
Base, End	250	0.5
Container Top	250	0.25
Base, Center	190	2
Container Top	80	1.5
Base, Center	10 (2 G)	1

TABLE IV

VIBRATION TESTS

Test No. 3: 500-50 cps at 6G, 50-20 cps at 0.036" double amplitude

Total Run Time = 5.32 minutes (Same shock mounting as Test No. 2)

LOCATION	FREQUENCY cps	OBSERVATIONS G
Base, Center	400	2
Base, End	400	1
Container Top	400	2.5
Base, Center	125	2.5
Base, End	125	1.5
Container Top	125	3
Base, Center	40 (4.5 G)	2.5
Base, End	40 (4.5 G)	1.5
Container Top	40 (4.5 G)	2

Initial testing (Test No. 1) utilized four high-frequency shock mounts located at each corner of the system base; the container itself was isolated from the system base by four low-frequency vibration isolators. Results of this test indicated that the mounts isolating the system base were too stiff, and that the base required support at its center. A 15 G output was observed at the center of the base at 250 cps. At 22 cps (with 2.5 G driver input, 0.020" double amplitude), the center of the base fluttered with about 0.500" double amplitude.

The four system base shock mounts were replaced for Test Nos. 2 and 3 with six lower-frequency mounts, four of which were located in the base corners and two located along the sides. Results from these tests indicated that the system was well isolated for the vibration loading ranges investigated, as shown in Table IV. The six shock mounts chosen for these tests are on the final unit.

An instrumentation check following Test No. 1 showed that all components functioned properly with the exception of the two differential pressure transducers. It was later learned that these transducers were not damaged by the vibration testing, but were malfunctioning due to extreme flow conditions immediately following the initial vibration test. The components were repaired and replaced in the system following the Vibration Test Program.

No malfunctioning of the instrumentation components was observed following Test No. 2 and 3 (the malfunctioning differential pressure transducers were removed for these tests).

F. Vented Evaporation Loss Following Vibration

A vented evaporation loss test utilizing liquid nitrogen was conducted following Vibration Test No. 3. In the 24 hour test period, 0.726 kg (1.60 lb) of liquid nitrogen was evaporated due to environmental heat input; the rate of heat input was calculated according to the following:

$$Q = \dot{m} \ (h_g - h_f)$$

$$= 726/24 \ (229.2 - 29.4)$$

$$= 6040 \text{ J/hr } (5.70 \text{ Btu/hr}).$$

This calculated heat input was somewhat greater than that determined from the vented evaporation loss test conducted previously which was 4880 J/hr (4.61 Btu/hr). Environmental temperature was higher during this test, however, and this was determined to be the contributing factor. A second vented evaporation loss test was performed with liquid oxygen instead of liquid nitrogen; 0.462 kg (1.02 lb) of liquid oxygen was evaporated in the 18-hour test period. Calculations for determining heat input rate are presented below:

$$Q = \dot{m} \ (h_g - h_f)$$

$$= 0.462/18 \ (354.59 - 140.80)$$

$$= 5480 \text{ J/hr } (5.20 \text{ Btu/hr}).$$

The calculated heat input for this second liquid oxygen vented evaporation loss test was lower than that of the liquid nitrogen vented test, due to lower environmental temperatures during the second test. However, the vented heat input rate from the test conducted with liquid oxygen prior to vibration was slightly lower than this second liquid oxygen test, i.e. 4880 J/hr (4.61 Btu/hr) versus 5480 J/hr (5.20 Btu/hr). This difference can be attributed to a slight leakage in the supply circuit plumbing, since the original vented evaporation loss test (prior to vibration) was performed on the container only, with no external plumbing, whereas later tests were performed on the complete instrumented storage system.

SECTION VI

RECOMMENDATIONS

Recent design consideration at Pioneer-Central have resulted in a modified approach to subcritical storage and supply of cryogen in weightless environments - an approach which utilizes the capillary-wick concept employed in the contract system described in this report, but which also includes a zero-gravity quantity measurement system and an improved pressure-flow control and pressure-relief concept. The recommended storage and supply system is shown schematically in Figure 55.

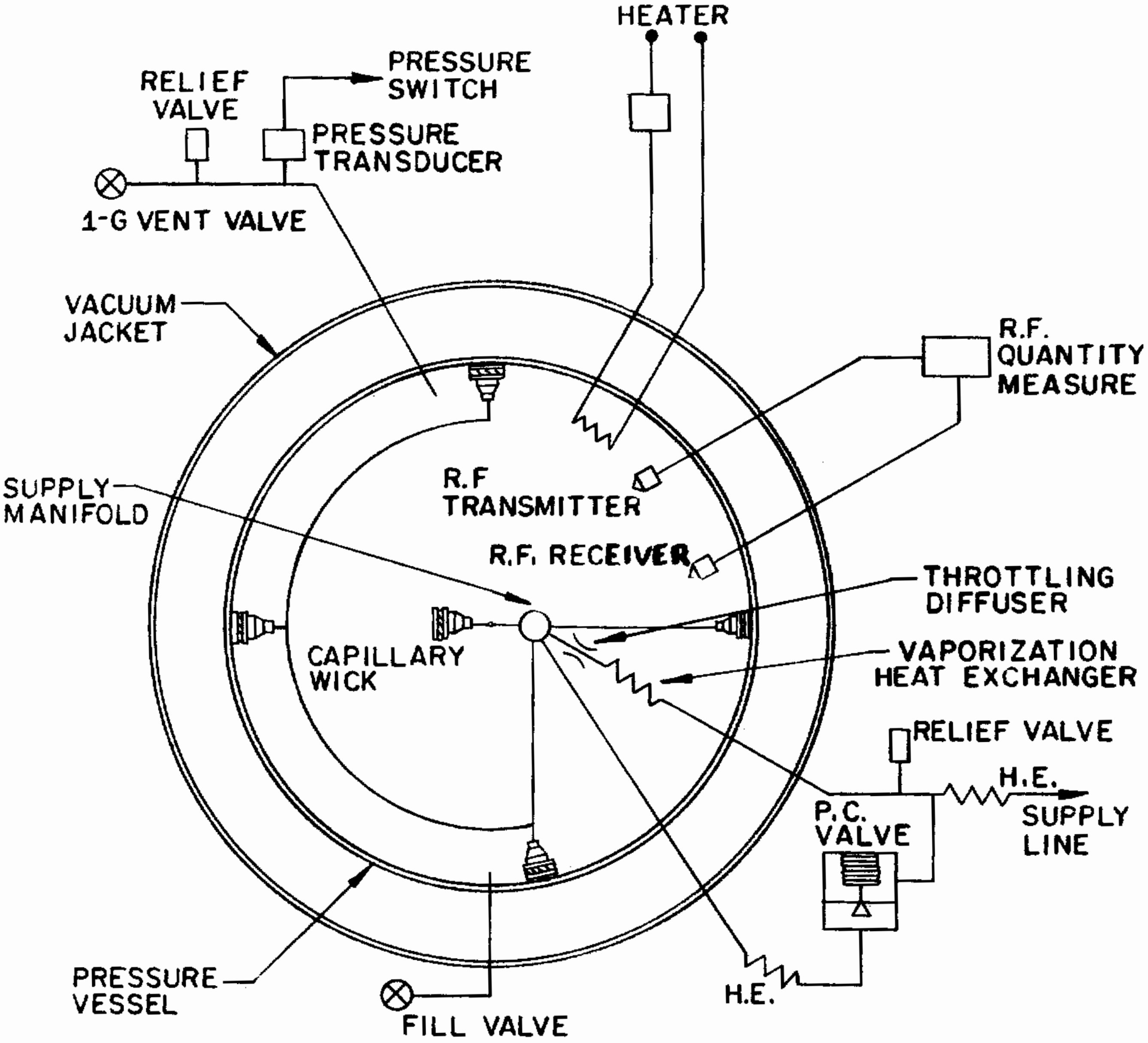


Figure 55. Recommended Subcritical Liquid Oxygen Storage and Supply System for Use in Weightless Environments

As shown in Figure 55, the ground fill and vent functions are similar to that employed in the contract system; likewise, a capillary-wick feed system consisting of seven interconnected wick units is used, with six wick units located at the periphery of the container and one wick unit located at the center. Two supply lines exit from the supply manifold: a throttling diffuser and heat exchanger are located within the pressure vessel in one of these lines, while the other transfer line exits directly to the outside. The major difference between this recommended system and the contract system lies in the method of pressure control. Because of the liquid-gas phase separation at the capillary-wick interface, liquid phase is supplied by the capillary-wick units to the supply manifold. If the supply demand is equal to or greater than the equilibrium flow rate to maintain pressure, flow will by-pass the diffuser and the internal vaporization heat exchanger and flow through the external pressure-closing flow valve. At extremely high emergency flow demand, pressure may degrade due to an imbalance between flow and environmental heat input. Supplemental heat supplied by the electrical heater and controlled by the pressure switch maintains system pressure. At minimum to average flow demands, environmental heat input results in a system pressure increase; the external pressure-closing valve closes, and flow transfers from the supply manifold through the diffuser and the vaporization heat exchanger, thence to the external supply line. As liquid flows from the manifold and through the diffuser, a pressure drop and subsequent expansion is experienced. This throttling process, or Joule-Thomson expansion, is one of constant enthalpy. Because the expanded fluid has an enthalpy equal to that at the high pressure side of the diffuser, the fluid now has a potential for absorbing heat, since the equilibrium enthalpy at the expanded low pressure state is higher than that at the upstream high pressure (container pressure) state. A portion of the liquid vaporizes in the internal heat exchanger; this refrigerative process is sufficient to reduce the temperature of the adjacent fluid and thus the pressure within the container. At non-flow conditions this same process maintains system pressure with minimum mass flow rate through the relief valve in the external supply line, even though the relief valve is supplied with liquid phase from the capillary-wick feed system.

The recommended quantity measurement concept is the R. F. mass measurement system. The system will operate in the two-phase region with cryogenic fluids within 1% accuracy. This concept operates on the princple of illuminating the tank with a small amount of R. F. energy, and measuring the number of resonant modes excited within a fixed frequency band. The measured number of resonant modes is a function of the dielectric mass contained therein. The concept feasibility has been established both analytically and experimentally through development work at Pioneer-Central and by subcontract R & D to the Electrical Engineering Department of Iowa State University, Ames, Iowa. An excellent experimental analogy has been developed which utilizes paraffin blobs in both cylindrical and spherical tanks to measure the effect of variations in mass, mass orientation and tankage configuration.

The R. F. measurement technique is particularly suited to cryogenic tankage design because of the simplicity, small size and reliability of the sensor antennae and electrical leads installed within the pressure vessel. The internally installed components are compatible to the cryogenic and vacuum processing required.

The recommended subcritical cryogenic storage and supply system presents improvements to the basic capillary-wick contract system, both in terms of pressure control and in the additional function of quantity measurement in weightless environment.

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13. ABSTRACT

A subcritical liquid oxygen storage and supply system for use in weightless environments was designed, combining (1) the properties of the capillary-wick to displace gas phase from a two-phase mixture, thus assuring liquid phase delivery, with (2) the dominant surface tension forces which cause liquid phase to accumulate at the periphery and gas phase to locate at the center of a spherical container in a weightless environment. A 10-liter prototype unit was fabricated based on these concepts. The complete system includes, in addition to the storage container, associated temperature, pressure, acceleration, and strain sensors to monitor system performance in weightless conditions. Liquid phase delivery from the pressure vessel has been demonstrated by the oxygen-nitrogen mixed gas test technique. The testing program conducted on the prototype unit gave every indication that the design concept is satisfactory for weightless operation.

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