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ZERO-GRAVITY LIQUID/GAS SEPARATOR

FINAL REPORT

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MARTIN MARIETTA CORPORATION

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ZERO-GRAVITY LIQUID/GAS SEPARATOR
FINAL REPORT

September 1969

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FOREWORD

This document is submitted in accordance with the requirements of National Aeronautics and Space Administration Contract NAS9-9526.

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SUMMARY

A laboratory prototype liquid/gas separator was designed, fabricated, and tested at Martin Marietta's Denver Division to prove the principle of the hydrophilic screen separation process. The basic hydrophilic screen technology was developed while designing a hydrophilic screen for a propellant expulsion tank.

Testing of the hydrophilic liquid/gas separator consisted of performance tests, filtration techniques, and urine compatibility. Two basic test systems were evaluated. One system evaluated the above parameters against only the discharge line flow resistance. The second system evaluated only flow performance against a 0.6-psig head as required by the contract.

Performance tests indicated that maximum liquid/gas separation flow rates of 1 gpm liquid at 10 scfm gas can be achieved for the no delivery head system. When operating against a 0.6-psig head, maximum liquid/gas separation flow rates of 0.7 gpm liquid at approximately 1 scfm gas may be obtained.

Filtration techniques evaluated were a cone filter placed inside the separator screen, a fine filter, and a gross filter installed in the two-phase inlet. The cone filter decreased the maximum flow rates by approximately 20% as compared with no filtration. The fine filter effectively shut down the operation. However, the gross filter provided operational flows. A cone filter is recommended for all applications and a gross filter is recommended in applications involving wash water.

Urine was run through the separator simulating a urination-rinse cycle. Separation was effective and short-time compatibility was observed.

The liquid/gas separator was successfully operated in a gravity environment and its zero-g operation is reasonably assured because in all testing the separator operated in opposition to gravity. The performance data defined herein can be improved by designing the optimum separator size and configuration for the various life support applications.

I. INTRODUCTION

In a spacecraft, water is available in various forms -- as potable water, humidity condensate, wash water, and urine. Such fluids must be collected, stored, reclaimed, and purified in a reliable, safe fashion in a zero-g environment. A gas drag is used for collecting and transporting waste water. This gas must then be separated from the liquid for obvious reasons.

The engineer can use various techniques to separate liquid from gas. These methods may be based on the difference in density of fluids, or may utilize centrifugal forces, frictional forces imposed on a liquid droplet by a flowing gas stream, hydrophilic and hydrophobic surfaces, capillary action, electrostatic forces, liquid surface tension, etc.

The liquid/gas separator system described herein utilizes a flowing gas stream to collect the liquid, centrifugal force to separate it from the gas and deposit it on a hydrophilic screen, and the surface tension of the liquid over the screen pore to prevent gas inclusion. The liquid on the screen is then transferred and collected. The only moving part in the entire liquid system is a blower.

II. HARDWARE DESIGN

A. SCREEN

The phase separator design is based on a porous screen used as a hydrophilic surface. As the primary element in the separation process, a screen of Dutch twill weave 304L stainless steel with an absolute micron rating of 15 to 18μ (250 x 1370 mesh) was selected. When wetted, the screen becomes hydrophilic, thus creating a stable gas/liquid interface. A hydrophilic screen will pass liquid and reject gas if the screen is entirely wetted and the pressure differential across it does not exceed a figure characteristic of the individual screen (the "bubble point"). If the pressure differential exceeds the bubble point, the screen will pass gas along with the liquid.

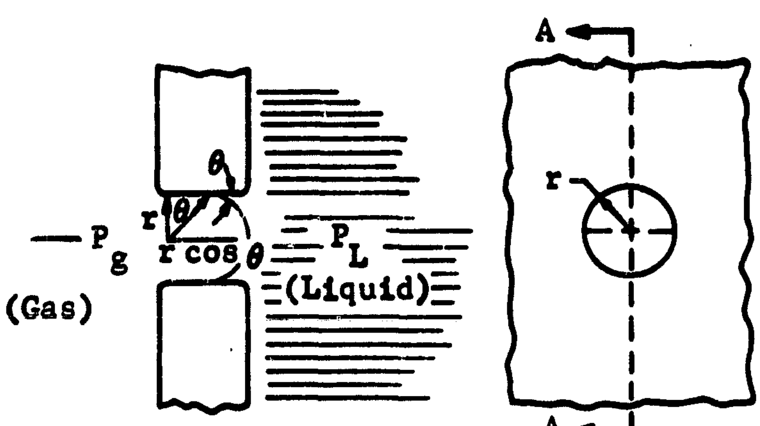


Fig. II-1 Stability of a Liquid/Gas Interface in a Cylindrical Hole

The stability of the liquid/gas interface in a hole (Fig. II-1) may be calculated from Eq [1]

$$P_g - P_L = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \quad [1]$$

where

P_g = pressure on gas side,

P_L = pressure on liquid side,

σ = surface tension,

r_1 and

r_2 = principal radii of curvature of the liquid/gas interface.

For a cylindrical hole,

$$r_1 = r_2 = r/\cos\theta \quad [2]$$

where

r = radius of cylindrical hole,

θ = contact angle.

Substituting into Eq [1]

$$P_g - P_L = \frac{2\sigma(\cos\theta)}{r}. \qquad [3]$$

This concept is used to change a two-phase (liquid/gas) flow stream into two separate single-phase flow streams. As the two-phase flow approaches the hydrophilic screen, it is caused to change direction. The liquid droplets impinge on the screen due to centrifugal force and are forced through it by a pressure differential.

The rate at which the liquid is separated from the gas stream by the hydrophilic screen is directly proportional to the pressure differential across the screen and the total pore area of the screen. The pressure differential can be increased to the bubble point of the screen. Depending on the micron rating of the screen, the bubble point may be as high as 1 psid in alcohol. The only limit to screen area results from trading off flow capacity, weight, and volume.

Figure II-2 presents empirical data on the bubble point versus screen pore size. From the graph, the bubble point for the 250 x 1370 screen in Isopropyl alcohol is 0.44 psid. Since water is used in the test, the bubble point is raised by the ratio of the surface tensions (σ) of the two liquids:

$$\sigma_{H_2O} = 20 \text{ dynes/cm};$$

$$\sigma_{alcohol} = 23 \text{ dynes/cm}.$$

Therefore psid = $\frac{70}{23}$ 0.44 = 1.3 psi. = 36 in. H_2O.
In our final system configuration, when operating against a 0.6 psig head (16.5 in. H_2O), the blower operating at a vacuum of approx. 40 in. H_2O, the bubble point of the screen cannot be exceeded. This is due to the fact that the maximum differential pressure that exists across the screen is 40 minus 16.5 or 23.5 in. H_2O which is well below the bubble point of the screen (36 in. H_2O).[2]

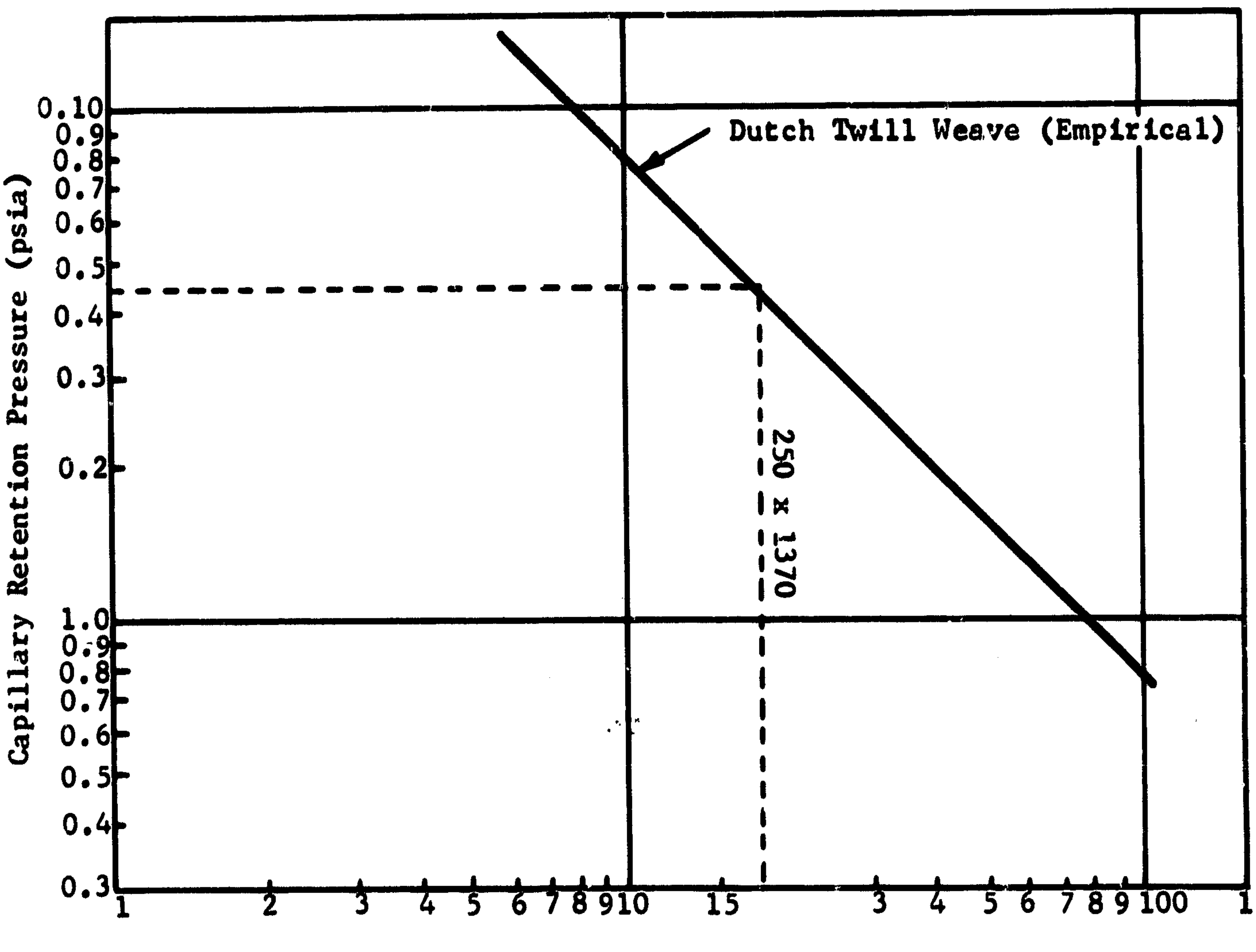


Fig. II-2 Bubble Point vs Screen Pore Size in Isopropyl Alcohol

B. SEPARATOR ASSEMBLY

The screen is used in the separator assembly in a conical shape and is soldered to a stainless steel fastening ring (Fig. II-3).

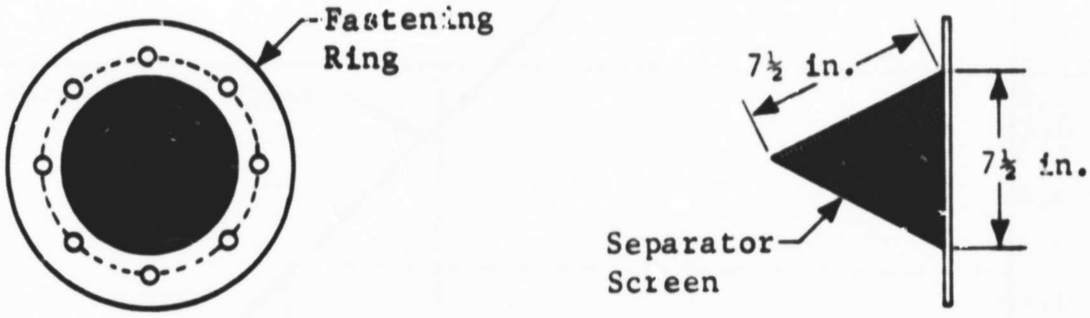


Fig. II-3 Separator Assembly

Also included in the assembly are the base cone and outer funnel cone. The base cone is a fiberglas base and cone combined with stainless steel flow tubes (Fig. II-4).

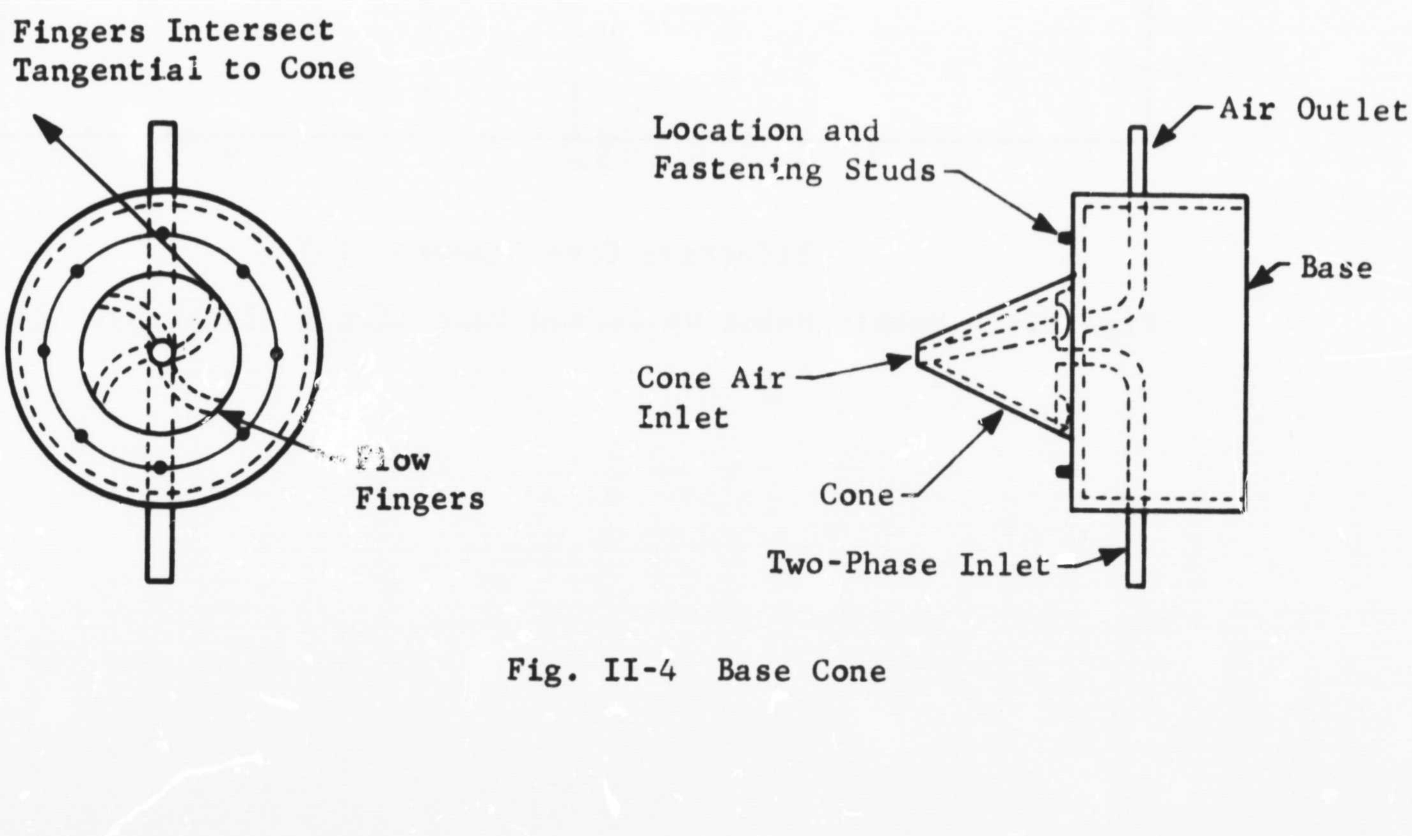


Fig. II-4 Base Cone

The two-phase inlet tube enters the side of the base and bends to the base of the cone where it is joined to four flow fingers. These fingers curve from the center of the cone and exit tangential to the outside of the cone. An air outlet tube bends from the top of the cone to the air outlet position.

With the aid of location and fastening studs fixed in the base, the screen cone is positioned over the base cone. Clearance between the two conical surfaces is approximately ½ in. The outer funnel cone, which collects the liquid passed through the screen and provides the liquid outlet at the apex, covers the screen. The cone is a glass funnel set about ½ in. above the screen and fastened to the base by a metal ring (Fig. II-5).

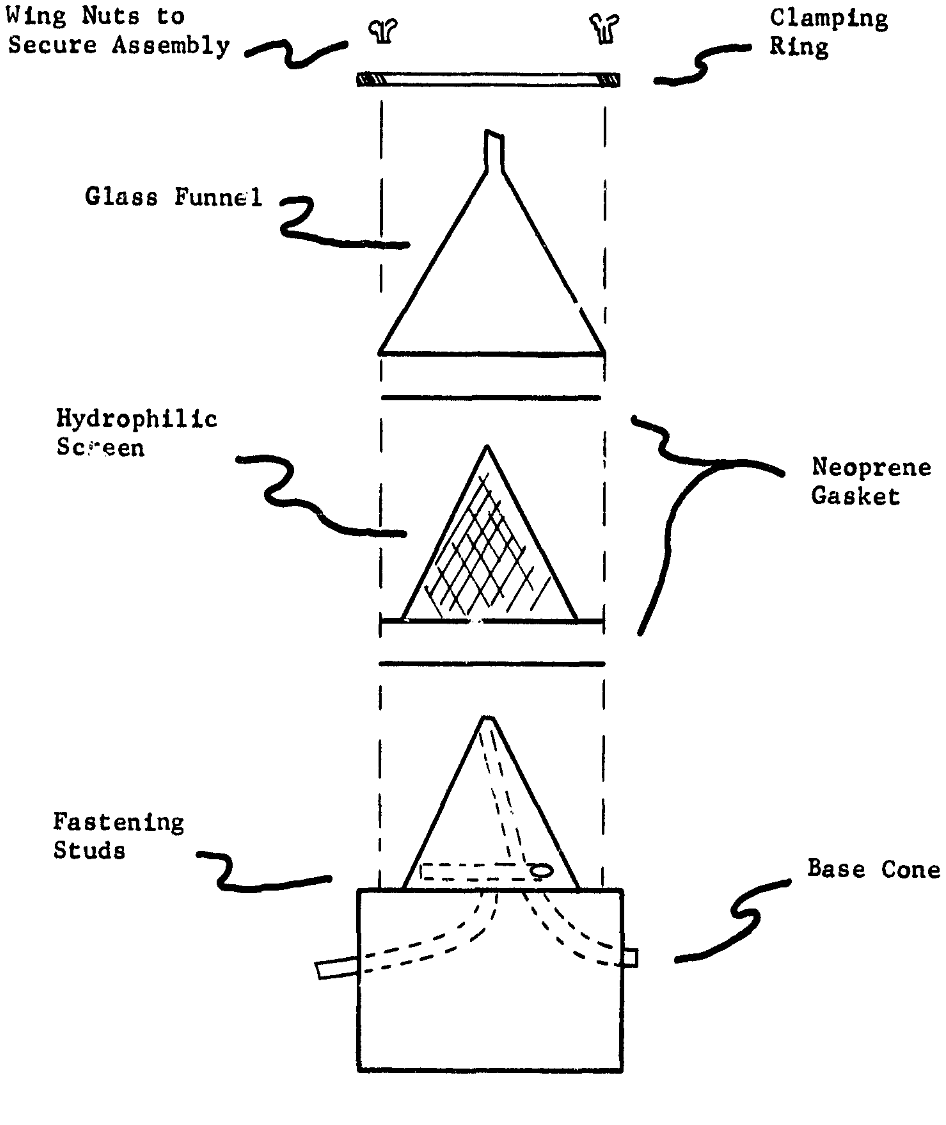


Fig. II-5 Outer Funnel Cone

A photograph of the individual components and the assembly is shown in Figure II-6.

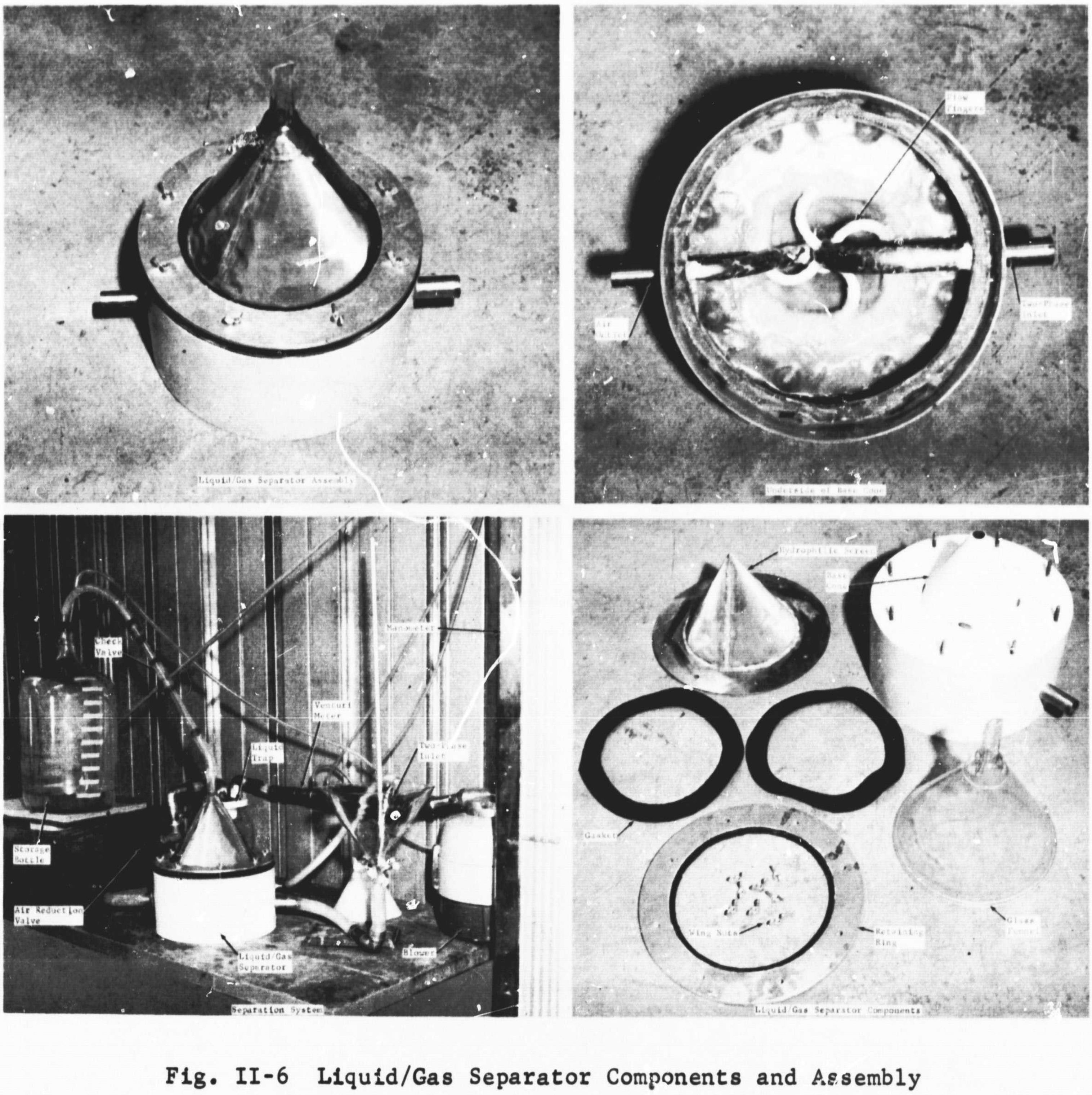


Fig. II-6 Liquid/Gas Separator Components and Assembly

C. PRESSURE CHARACTERISTICS

Operating pressures are determined by the blower and venturi characteristics and are necessary to provide the ΔP across the screen. A typical characteristic curve for the blower is shown (Fig. II-7). As the air flow is decreased, suction pressure increases.

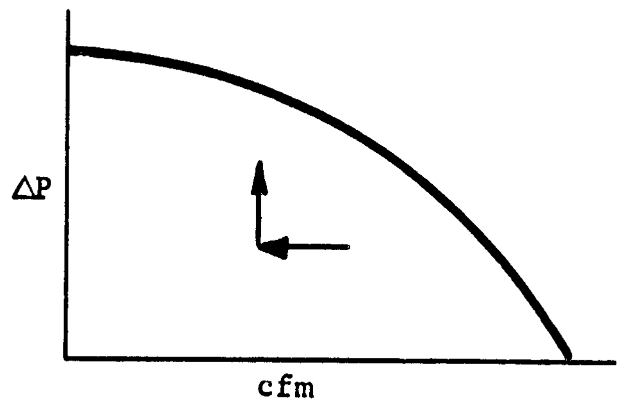


Fig. II-7 Blower Characteristic Curve

The venturi is also used as a suction device. A pressure tap taken at its throat connects it with the supply bottle. The negative pressure created at the throat depends on airflow through the venturi (Fig. II-8),

$P \propto Q^2$, where Q = volume flow rate.

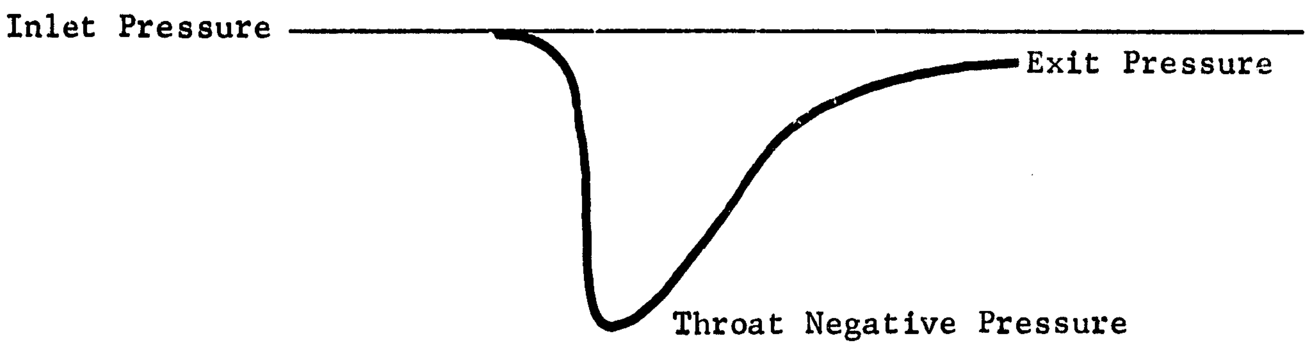
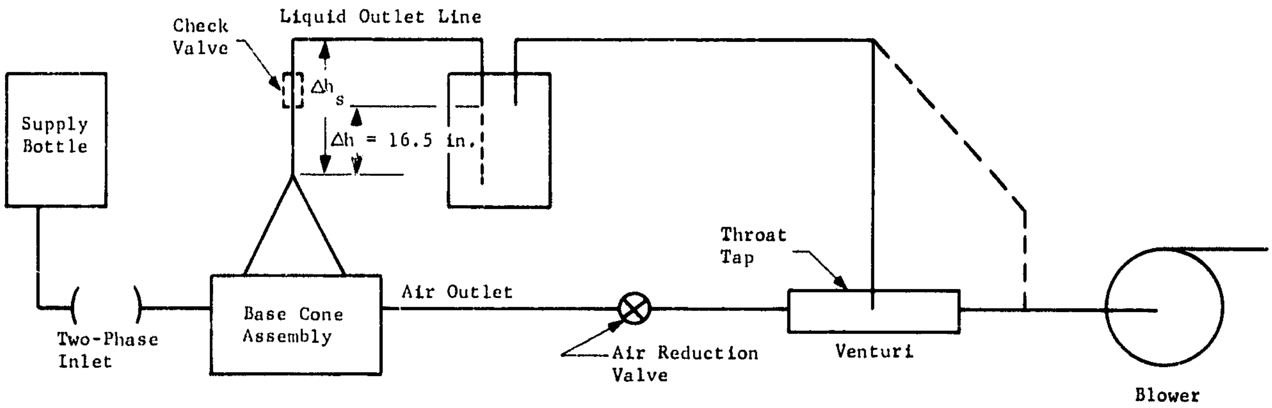


Fig. II-8 Venturi Pressure

When the venturi and blower are in series, their operating pressures add to provide the vacuum pressure on the liquid side of the screen. As airflow is decreased, blower suction increases while the throat pressure becomes less negative.

D. SYSTEM CONFIGURATIONS

Two system configurations were used in testing. The first was the original design while the second evolved to meet contract requirements (see Fig. II-9).



Note: System 1: Liquid outlet line exit level with cone top, no check valve, negative pressure provided by venturi and blower, startup head (Δh_s) was 25 in.

System 2: Liquid outlet line exit 16.5 in. above top of cone, check valve to maintain wetted screen, pressure tap moved to blower entrance (pressure becomes a function of blower pressure only), startup head (Δh_s) was 20 in.

Fig. II-9 Zero-g Liquid/Gas Separator Configurations

1. No Delivery Head System

This system consisted of the cone assembly, air reduction valve, venturi, blower, and supply and storage bottles connected with plastic tubing. The liquid outlet line was connected to the supply bottle with its exit at the height of the top of the separator cone. A pressure tap located at the throat of the venturi provided a vacuum pressure to the storage bottle. During operation, the two-phase mixture was moved from the inlet through the flow tubes into the screen. After separation, the liquid-free air passed out of the separator assembly through an air reduction valve, venturi, and blower. As the air passed through the venturi, a negative pressure was created at the throat, providing suction at the liquid storage bottle. This negative pressure was also felt on the liquid side of the screen and, with essentially atmospheric pressure on the two-phase side of the screen, provides the ΔP necessary for liquidflow.

2. Delivery Head System

The present system works in a similar manner; however, it is designed to give continuous liquid delivery against a 0.6-psig head. Therefore, the liquid outlet line exit is 16.5 in. above the top of the cone. The large negative pressure needed because of the delivery height is obtained by closing down the air reduction valve raising blower negative pressure. Because of the reduced airflow, the venturi was ineffective and was thus eliminated. The pressure tap was located at the blower entrance and a check valve was added to the liquid delivery line to retain liquid in the outer funnel and maintain the screen in a wetted condition.

E. FLOW OPERATION

With the blower in operation, airflow from the two-phase inlet through the separator assembly, valve, venturi, and blower is established. When water is introduced at the two-phase inlet, it becomes entrained in the moving air and is transported through the flow fingers, where the two-phase mixture emerges with a velocity tangential to the base-cone side (Fig. II-10). Thus the flow is directed at the hydrophilic screen where water droplets impinge on and are conducted through the screen. As the screen reflects the flow, a circular flow pattern around the cone is formed. Since the air exit is at the top of the cone, a conical spiral flow up the cone is also established. As the flow proceeds up the cone, impinging water is removed by the screen so the exit air is free of water. If the flow pattern is considered to consist of flow tubes of constant area, the mixture velocity remains constant. However, as the flow proceeds up the cone, its angular acceleration is greatly increased (Fig. II-11). In this manner, small droplets are accelerated into the screen, further increasing the efficiency of the separator. Once the liquid has passed through the screen, it collects in the outer funnel and is moved to the storage bottle.

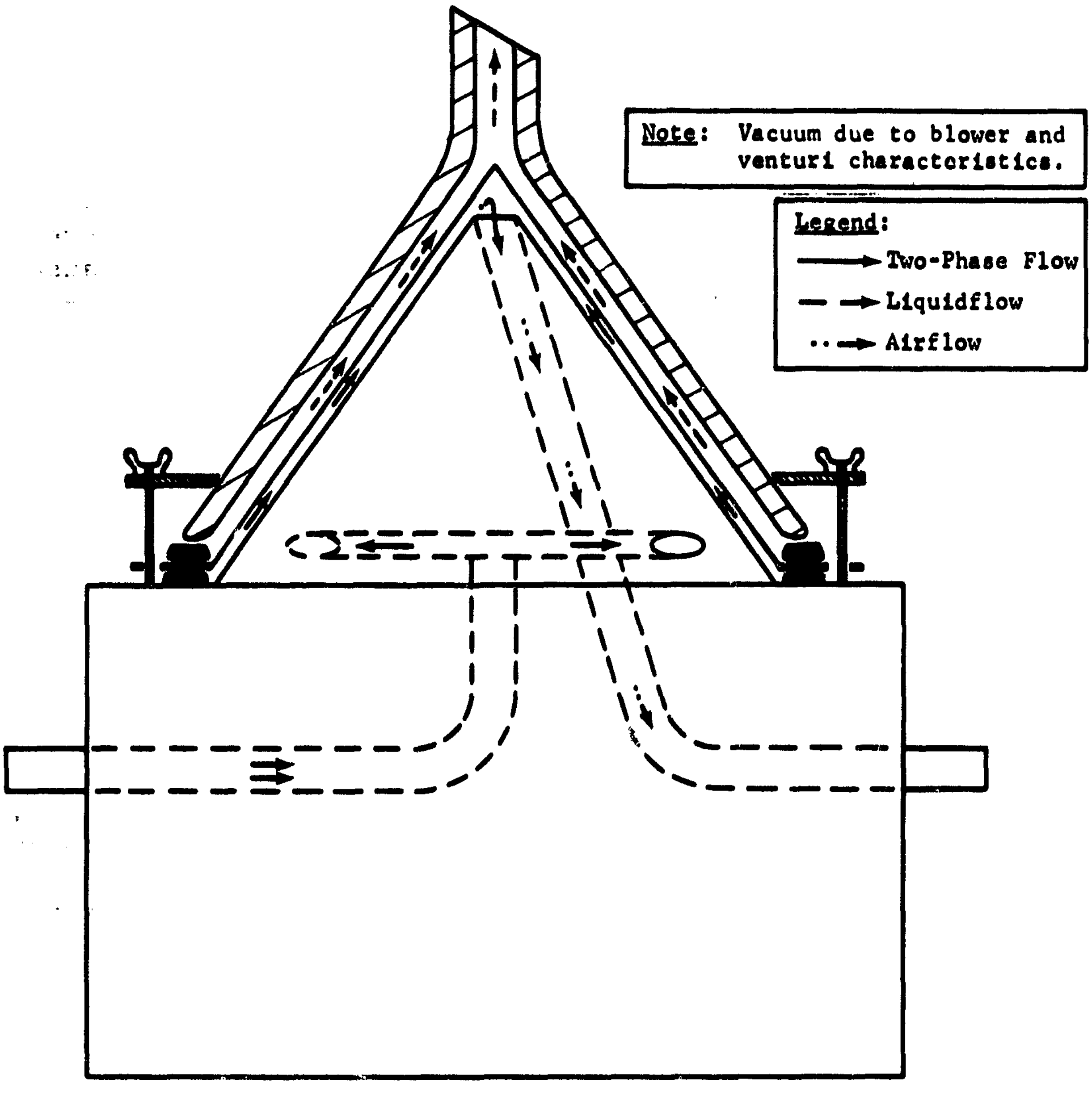


Fig. II-10 Flow Operation

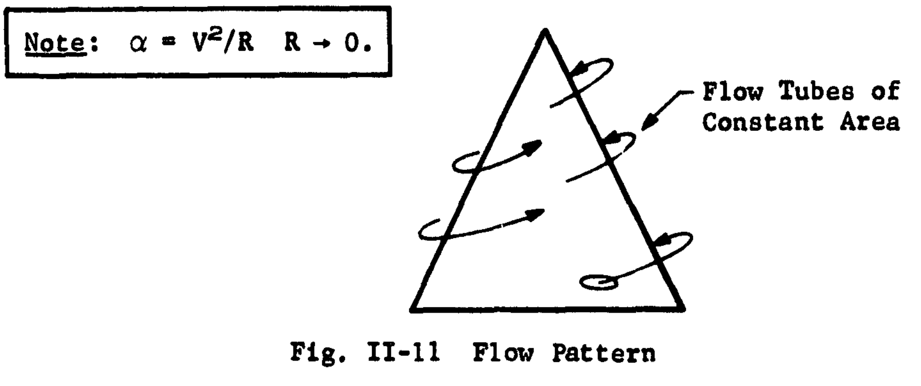


Fig. II-11 Flow Pattern

III. SYSTEM TEST SETUP

A. MEASUREMENTS

The tests were conducted to determine airflow and liquidflow rates for the separator under various filter and operating conditions. Airflow rates were measured with a venturi meter and manometer. The venturi was sized and built to ASME specifications (see the appendix). The equation is

$$Q_{cfm} = CA_o \sqrt{\frac{\Delta Pg/\gamma}{1 - (A_1/A_o)^2}}$$

where

A_1 = throat area,

A_o = upstream area (see Fig. III-1 for curve of Q vs monometer ΔP).

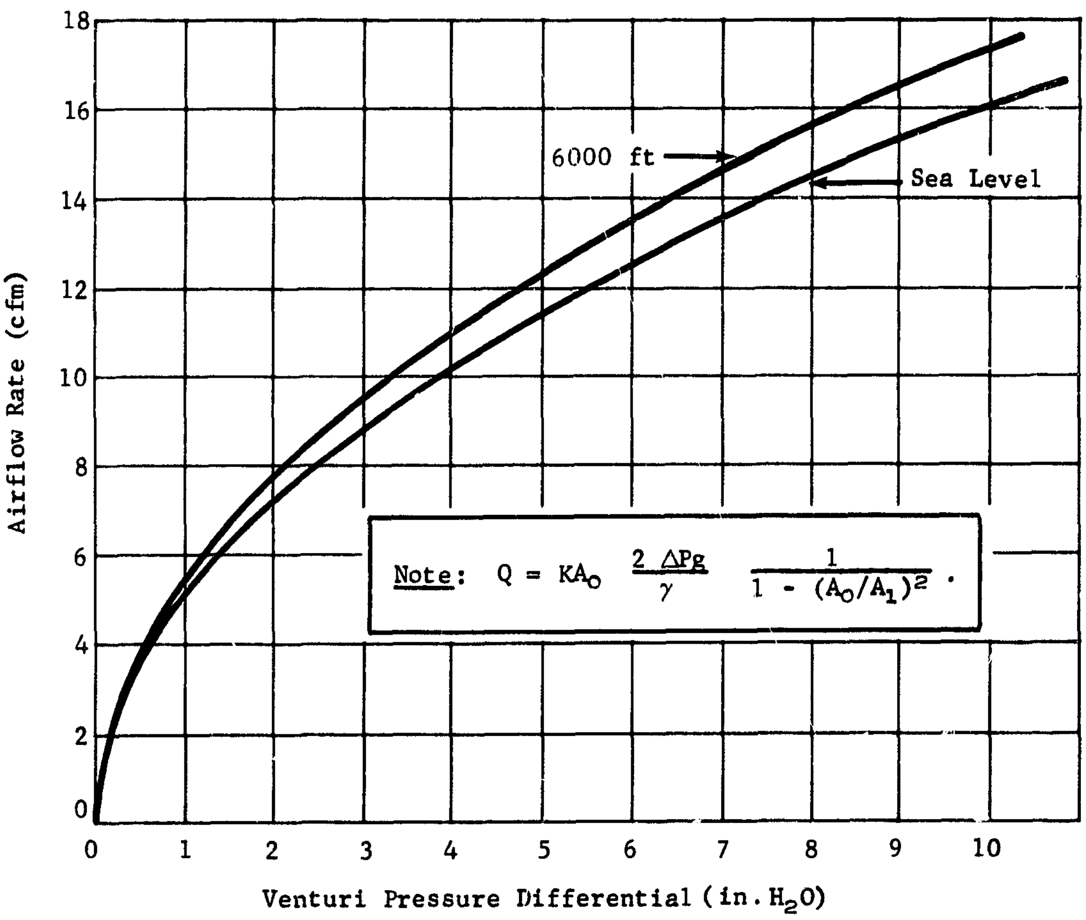


Fig. III-1 Airflow Rate

Liquidflow rates were measured with a stop watch and calibrated storage bottle. The bottle was calibrated in 2-liter increments. The equation is

$$Q_{gpm} = \frac{\Delta V}{\Delta t}.$$

Vacuum pressures were metered with a manometer.

B. SYSTEM CONFIGURATIONS

Two test configurations were used during testing (Fig. III-2). System 1 had no delivery head and was used to investigate:

1) Filtering techniques;
2) Urine separation and compatibility.

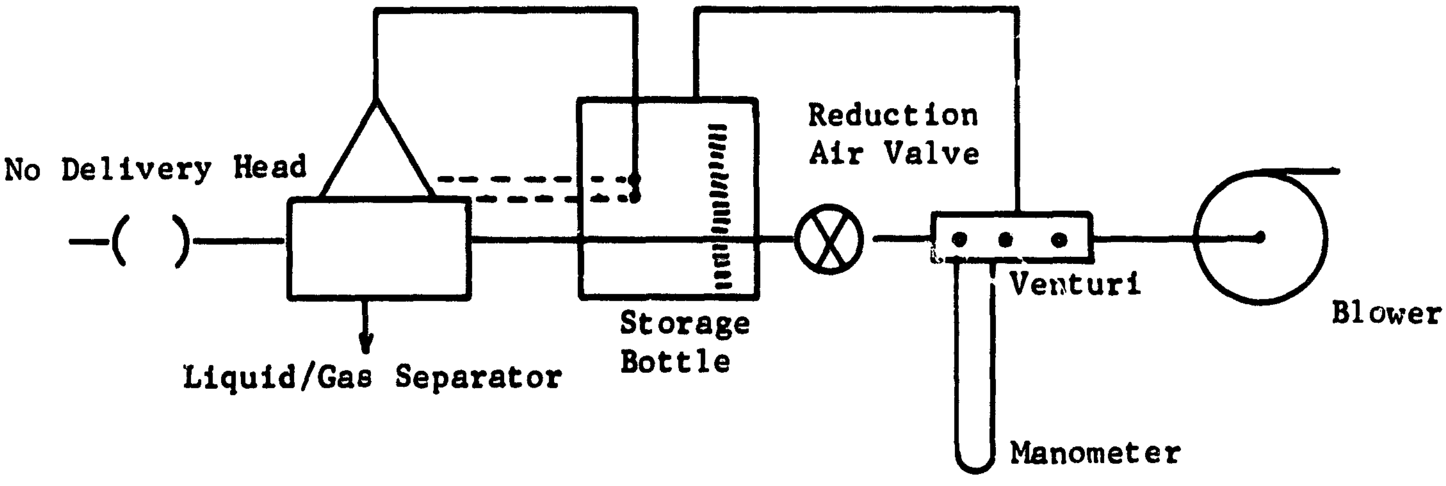
System 2 was set up to deliver to a 0.6-psig head.

Startup and continuous operation, along with flow rates, were investigated for both systems.

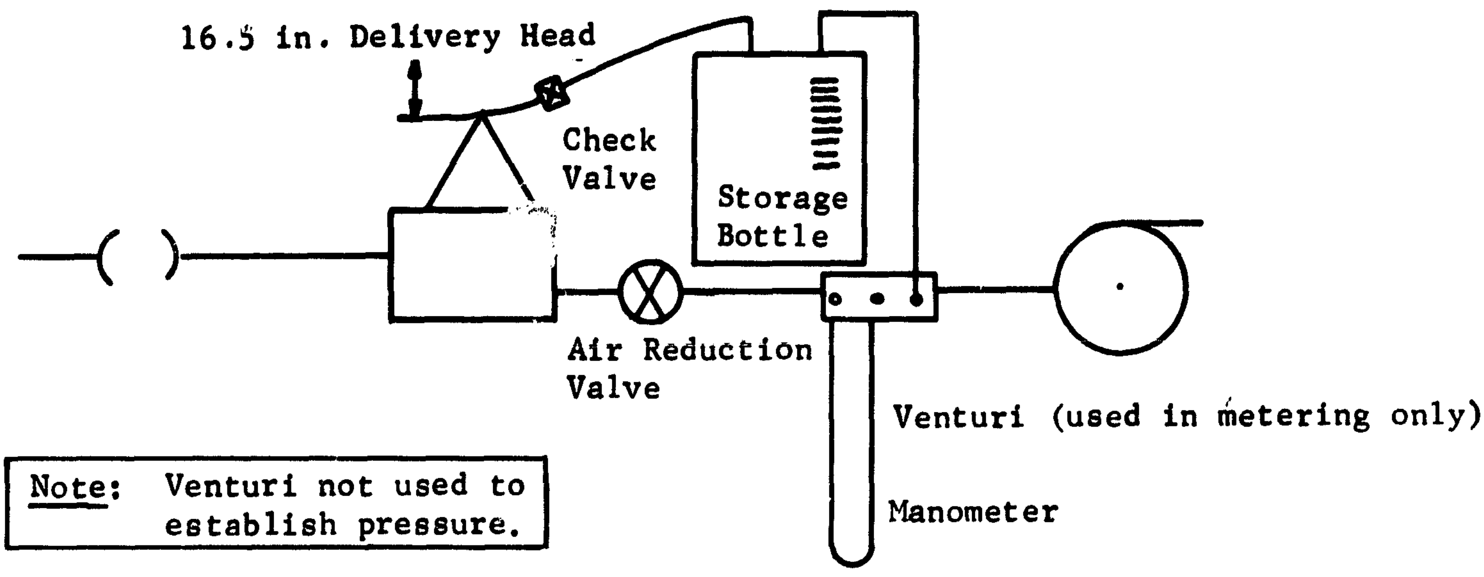
C. PROCEDURES

The procedure used to determine maximum flow was:

1) The blower was turned on;
2) The air reduction valve was,
   a) Opened completely for System 1,
   b) Closed almost fully to raise blower vacuum pressure for System 2;
3) A small liquidflow was established at the two-phase inlet;
4) The liquidflow was increased until water was noticed in the air outlet line (this point was called breakthrough and indicated maximum liquidflow);
5) Liquidflow into the storage bottle was metered by a stopwatch and 2-liter graduation marks on the bottle.



(a) No Delivery Head Test Setup



(b) Delivery Head Test Setup

Fig. III-2 Test Configurations

The filtering test consisted of passing 50 gallons of water through the screen without a filter, with a polyurethane foam filter, cone shaped and placed on the inside of the screen; and with a filter on the two-phase inlet. The procedure was:

1) Liquid was introduced until maximum flow was established;
2) While flow rates were recorded, 5 gallons of water were passed by the screen;
3) The system was then shut down and the storage bottle emptied;
4) Steps 2 and 3 were repeated for the 50 gallons.

To establish urine separation and compatibility (with the separator in the operating mode), the procedure was:

1) Ten 50- to 100-ml urine samples were obtained;
2) One urine sample was introduced at the two-phase inlet approximating urination;
3) A 150-ml wash sample was then introduced and passed by the screen;
4) The blower was shut down for 2 minutes;
5) Steps 2 thru 5 were repeated for the 10 samples;
6) The screen was then cleaned with MEK;
7) Steps 2 thru 5 were again repeated with nine samples;
8) Again the cycle was repeated 10 times using 100 ml of water in place of the urine sample.

For startup conditions with System 1:

1) The blower was turned on;
2) With the air valve wide open, water was introduced at the two-phase inlet,
   a) Slowly,
   b) In large quantities;
3) With the air valve 1/2 turn from being closed, water was slowly introduced.

For startup for System 2:

1) The blower was turned on;
2) The air valve was turned down within two turns of being completely closed;
3) Liquid was slowly introduced at the two-phase inlet;
4) The air valve was adjusted for various vacuum pressures and startup tried;
5) The minimum startup storage bottle vacuum to raise the liquid to 0.6 psi was established.

For continuous operation with System 1:

1) The air valve was wide open;
2) Various waterflow rates were introduced at the inlet.

For System 2:

1) The air valve was adjusted from maximum opening for startup to a 1- to 2-cfm opening;
2) Maximum liquidflow rates at the various vacuum pressures were metered.

D. APPARATUS

The phase separator cone assembly consisted of:

1) Base cone - Fiberglas body with stainless steel tubing;
2) Screen cone - 250 x 1370 mesh 304L stainless steel screen with 15- to 18-micron rating attached to stainless steel fastening ring with soft solder;
3) Funnel cone - Pressed glass funnel with a 8½-in. diameter and a 60° incline.

The system assembly consisted of:

1) Cone assembly;
2) Venturi designed for the system to provide ½ psi negative throat pressure at flow of 19 cfm per ASME standards (used for suction and metering with System 1 and metering with System 2);
3) Airflow valve - 1-in. globe valve:
4) Blower - GE vacuum cleaner;
5) Supply and storage bottles - 5-gal water jugs. The storage bottle was calibrated in 2-liter increments;
6) Check valve - Ball check.

The metering system consisted of:

1) 30-in. water monometer;
2) 500-ml beaker;
3) Stopwatch.

Additional components consisted of:

1) Foam cone filter;
2) Pall filter element [Part No. MBY2001YC, 25μ absolute, 5μ nominal (98%), 1 ft^2 filter area];
3) Aircraft filter (10μ rating).

IV. DISCUSSION OF RESULTS

A. FILTERING TECHNIQUES

Since the main element of the phase separator is a screen with a 15- to 18-micron rating, we had to consider eliminating solids in the liquid of a size larger than 18μ. While the screen separates, it also blocks particles larger than the mesh size and acts as a filter. It was thus desirable to determine whether contamination of the screen in this manner would require frequent replacement and precipitate the need for filtering the fluid.

The test objective was to pass 50 gallons of water through the screen while recording maximum liquidflow rates: (1) without a filter, (2) with a replaceable cone filter situated next to the screen, and (3) with an upstream filter on the two-phase inlet line. Testing included startup and shutdown every 5 gallons. With the airflow at maximum, waterflow was increased until liquid was noticed in the air line. This condition was termed "break-through" and indicated screen saturation and no flow. Waterflow rates were determined with the 5-gallon storage jug calibrated in 2-liter increments

$$GPM = \frac{\Delta V}{\Delta t}.$$

Airflow rates were measured with a venturi meter and water manometer

$$Q_{cfm} = C_D A_O \sqrt{\frac{2\Delta PG/\gamma}{1-(A_O/A_1)^2}}^{\,*}.$$

The venturi was sized and built to ASME specifications.

*Fluid Meters, Their Theory and Application. American Society of Mechanical Engineers, New York, N.Y., 1959.

1. No Filter

The flow rate determination with no filter serves to establish flow rates for the no delivery head system and determine the role of screen contamination with tap water as the two-phase liquid.

As shown by Table IV-1, liquidflow rate times for 2-liter increments varied over a wide range (430 to 25 sec). Most times, however, occurred in the 30 to 50-sec range and, because of this, typical flow rates for each 5-gallon bottle were taken from the 8- to 14-liter times. A plot of the average liquidflow rates (Fig. IV-1) results in a rough curve. This variation in flow rates is caused by the difficulty in establishing a maximum flow rate. Liquidflow at the inlet must be increased until breakthrough occurs. When this happens, indicating maximum flow, the liquidflow must be cut back until steady-state has been reached. Because of the poor maximum flow rate repeatability, the maximum flow rates may vary.

Table IV-1 Time Intervals, Phase Separator with No Filter

Liters/Gal	Bottle No. 7/24/69			7/25/69								Average Time	Average Flow Rate (gpm)
	1	2	3	4	5	6	7	8	9	10	11		
0	--	--	--	--	--	--	--	--	--	--	--	--	--
0 to 2	--	--	--	227*	95	119	95	55	53	94	58	81.3	0.39
2 to 4	300*	65	58	90	51	26	29	73	52	56	105*	55.6	0.57
4 to 6	110*	48	29	54	40	26	28	54	49	55	45	42.8	0.74
6 to 8	430*	46	28	35	36	25	28	36	46	47	42	36.9	0.86
8 to 10	250*	41	32	32	33	28	29	34	42	37	39	34.7	0.91
10 to 12	43	38	31	33	32	31	33	35	35	36	35	34.7	0.91
12 to 14	37	35	35	34	36	34	34	38	37	39	35	35.8	0.88
14 to 16	34	36	39	35	32	37	36	42	39	42	38	37.3	0.85
16 to 18	--	--	--	47	44	43	43	50	51	59	45	47.8	0.66
5 gal	--	--	--	21	28	28	34	28	43	38	38	32.3	--
Venturi Pressure (in. H_2O)													
P_1	--	2.3	2.3	2.1	2.0	1.5	1.7	2.3	2.0	1.9	1.9	--	--
P_2	--	2.1	2.3	1.5	1.9	2.0	2.0	1.8	1.8	1.6	2.2	--	--
P_3	--	2.0	--	2.0	2.1	2.3	2.6	1.8	2.1	2.2	2.3	--	--

*Numbers not used in averages.

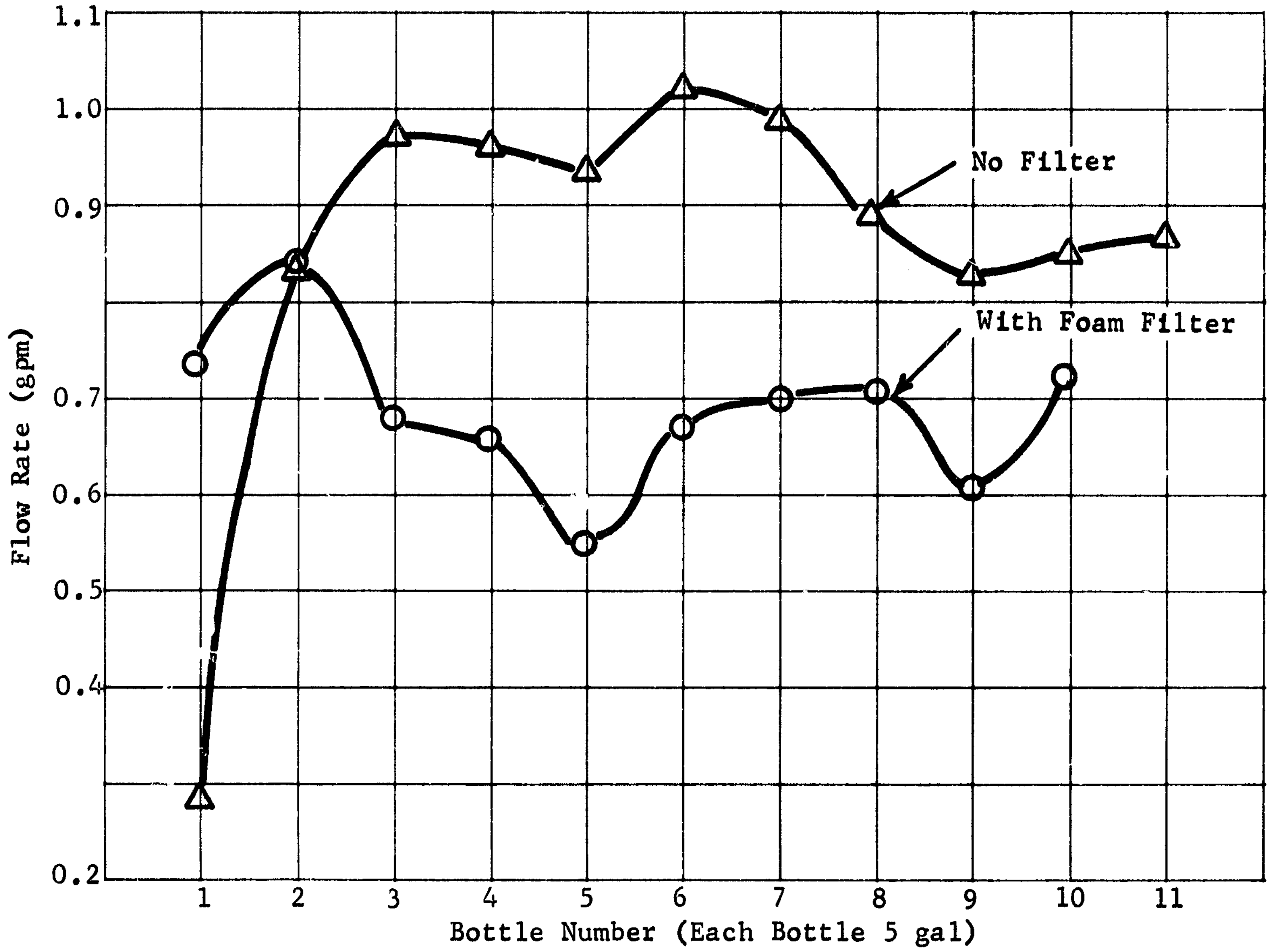


Fig. IV-1 Liquidflow Rates under Nonfilter and Filter Conditions

The graph indicates a slight decreasing flow rate trend although it is not significant. Contamination from tap water does not present a great problem and with condensate or potable water, the problem would be alleviated.

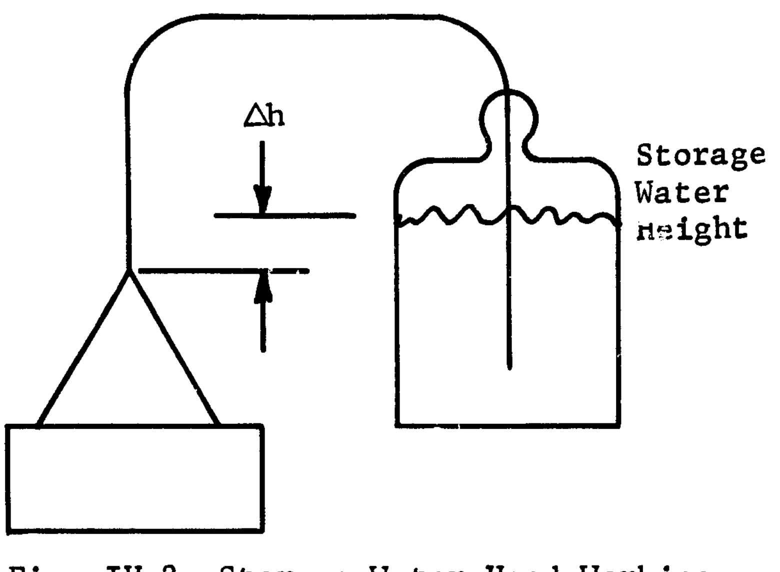


Fig. IV-2 Storage Water Head Working Against the Vacuum Pressure

Operation is shown in Fig. IV-2. During each 5-gallon run it was noted that the average flow rate by 2-liter increments starts slow, increases to a maximum in the 8- to 14-liter range, and then decreases. The low beginning flow rates were due to startup where a liquid flow siphoning action had to be established. Slowly water flow was increased until breakthrough occurred, corresponding to the maximum flow times. The decrease in flow was caused by the negative head developed in the storage bottle reducing the storage bottle vacuum.

For the 5-gallon runs, airflow rates were measured with the venturi meter and U-tube manometer. During the runs, manometer readings were about 2 in. of water differential, varying from 1.5 to 2.6 in. (6.25 to 8.22 cfm). The variation was due to the change in liquid flow rates. As water was introduced, the airflow area was reduced resulting in a decrease in airflow.

2. Cone Filter

A cone filter was fabricated out of a coarse pore polyurethane foam and placed inside the screen to filter the water passing through the screen. Because only the liquid is filtered, the air passes through the phase separator unimpeded once phase separation takes place.

Fig. IV-1 shows that flow rates dropped about 20% from the nonfilter configuration. However, the maximum flow rates over the 50 gallons were fairly constant. Table IV-2 indicates that running characteristics similar to those for the nonfilter run were obtained.

Table IV-2 Time Intervals, Phase Separator with Foam Filter

Liters/Gal	Bottle No. 7/29/69 1	2	3	4	5	6	7	8	9	10	Average Time	Average Flow Rate (gpm)
0	--	--	--	--	--	--	--	--	--	--	--	--
0 to 2	399*	81	100	62	88	78	75	99	77	71	81.2	0.39
2 to 4	49	47	66	70	62	43	53	73	46	51	56.0	0.57
4 to 6	36	40	54	63	69	46	45	82*	52	51	50.7	0.62
6 to 8	38	38	45	51	57	42	57	48	131*	45	46.8	0.68
8 to 10	43	36	45	50	79*	45	45	45	35	42	42.9	0.74
10 to 12	42	37	46	46	34*	46	44	43	42	47	43.7	0.72
12 to 14	43	40	48	48	60*	51	46	46	75	43	48.9	0.65
14 to 16	44	44	47	47	59*	48	45	67	103*	51	49.1	0.65
16 to 18	66	48	55	51	8*	60	61	63	118*	79	60.4	0.52
5 gal	44	28	42	30	89*	61	60	66	63	57	50.1	--
Venturi Pressure (in. H_2O)												
P_1	2.2	2.4	2.8	3.2	3.2	2.4	1.7	1.4	0.6	2.2		
P_2	1.9	2.4	2.4	2.8	3.1	2.6	1.6	0.7	2.9	2.2		
P_3	2.6	2.8	2.8	3.0	3.5	2.8	1.8	1.6	3.7	2.6		

*Numbers not used in averages.

An additional feature of the cone filter was that it retained water and kept the screen wetted.

Filtering to 18 microns is not achieved with the 1/8-in.-thick foam cone filter. However, the foam pores route the liquid in paths that tend to trap contaminants in corners. Because of the thickness and flow paths, the effective filter area is much larger than the screen area.

3. Two-Phase Filter

To test the two-phase filtering technique, a Pall Corporation filter rated at 25μ absolute with 1 ft^2 of filter area, and a Purolator hydraulic filter with a 10μ element were each fitted over the two-phase inlet. In each case, the flow restrictions effectively shut down separator operations. The fine filter had to filter both liquid and air. When the filter became wetted, air had to break through the bubble point of the filter to pass into the phase separator. The pressure drop associated with this breakthrough caused the airflow to be reduced to a small level, ceasing to carry the liquid into the phase separator. Flow rates were not recorded for this condition.

A piece of polyurethane foam was then placed over the two-phase inlet. The large pore size achieved an airflow and vacuum that allowed water to be rapidly removed from a beaker while retaining hair and other debri on the foam's surface.

B. URINE RUN

Ten urine samples ranging from 50 to 100 ml were used to run through the separator in a simulated urination-rinse cycle. With the separator system in operation, the cycle consisted of pouring one bottle of urine into the two-phase inlet, pausing, and then rinsing with 150 ml of tap water. After each cycle, the blower was shut down for 2 minutes, restarted, and a new cycle begun.

As the urine was separated, it formed a yellow ring at the base of the cone that gradually rose and emptied into the storage bottle.

The screen was then pulled and cleaned with MEK; no large particles were noticed on the screen. The cycle was then run again with nine urine samples.

For both sets of runs, urine was separated well. However a small amount of liquid was noticed in the air outlet line after the rinse. The liquid was clear yet frothy, indicating a small amount of urine. More testing in this area is required before any conclusions can be reached.

In a related test, eight urine samples were titrated to form solutions with a pH from 6.0 to 8.0. As the pH increased, precipitates in the liquid also increased. This indicates that pH control may be useful in limiting contaminating solids. Screen material was then immersed in the solutions. After three days the screen was examined and found to be lightly covered with fatty-looking solids that did not adhere to the screen. On drying, the screen appeared clean except for a few small particles. This material was probably bacteria and would present a great contamination problem although a small amount of chlorine in the rinse water would probably control its growth. It is also important to process the urine before solids fall out of solution.

C. DELIVERY HEAD FLOW RATES

To obtain flow of the 0.6-psig delivery head, the blower vacuum had to be higher than the no delivery head system vacuum. This was accomplished by closing down the air valve until a vacuum pressure of 37 in. of water at the storage bottle was obtained. Liquid flow was established at this point. As the air valve was further closed, the vacuum pressure increased, thus increasing the maximum liquidflow rate (Fig. IV-3). With the blower running at maximum vacuum, a liquidflow rate of 0.7 gpm was obtained. At this rate however, the airflow was approximately 1 cfm and good liquid transportation was marginal.

An operating vacuum pressure of 40 to 41 in. of water resulted in good startup and continuous operation of 0.3 gpm water and 3 cfm air.

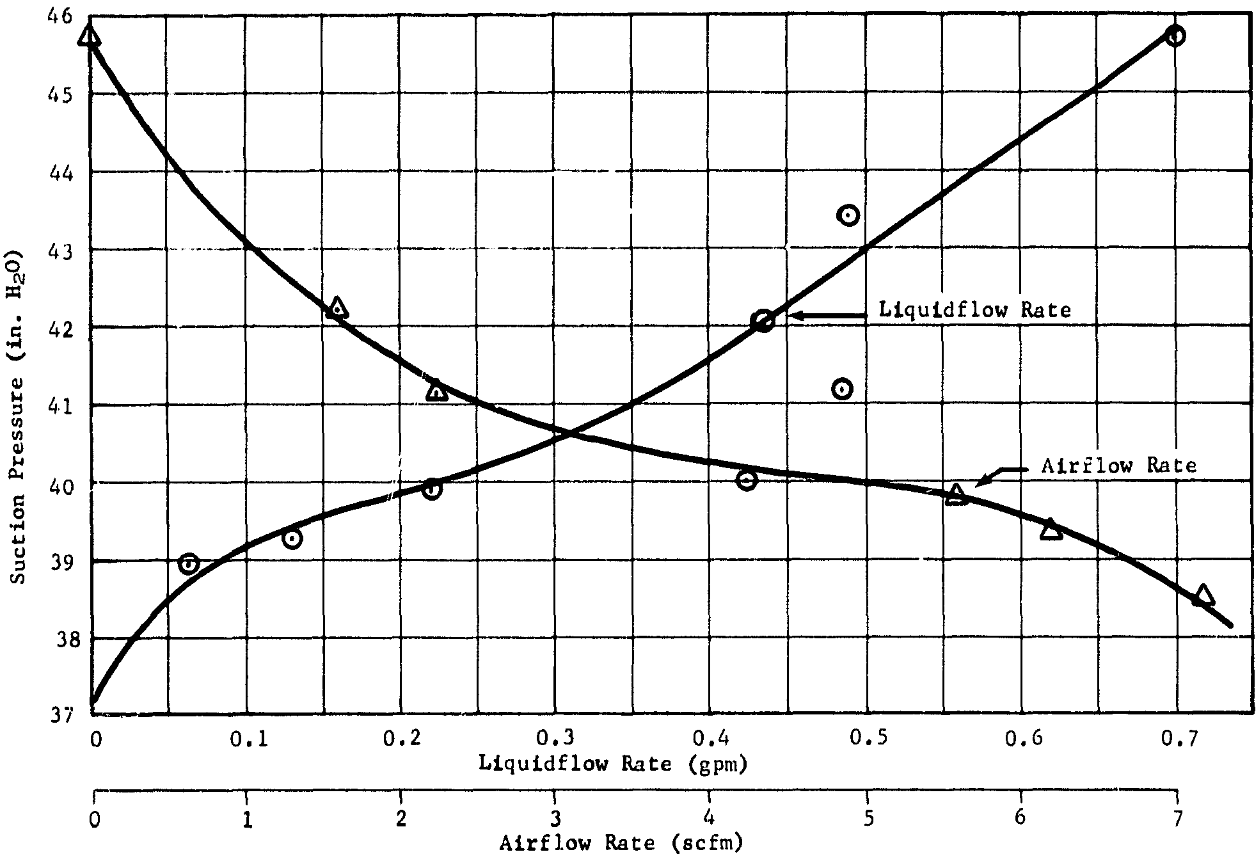


Fig. IV-3 Liquidflow and Airflow Rates for Delivery Head Configuration (0.6 psi)

1. Continuous Operation

For the no delivery head system, steady-state flow operation was established with the airflow valve fully opened. This results in an airflow rate of about 13 cfm. Water introduced at the two-phase inlet can be varied up to a maximum of approximately 1 gpm. Because the airflow area is reduced when water is flowing, the airflow rate drops to 11 cfm. Pressure at the venturi with waterflow reaches 33 in. vacuum (Fig. IV-4).

With the delivery head system, the vacuum is increased to about 40 to 41 in. of H_2O by closing down the air valve. While the airflows and liquidflows are reduced to 3.5 cfm and 0.3 gpm, respectively, continuous delivery against a 0.6-psig head is established.

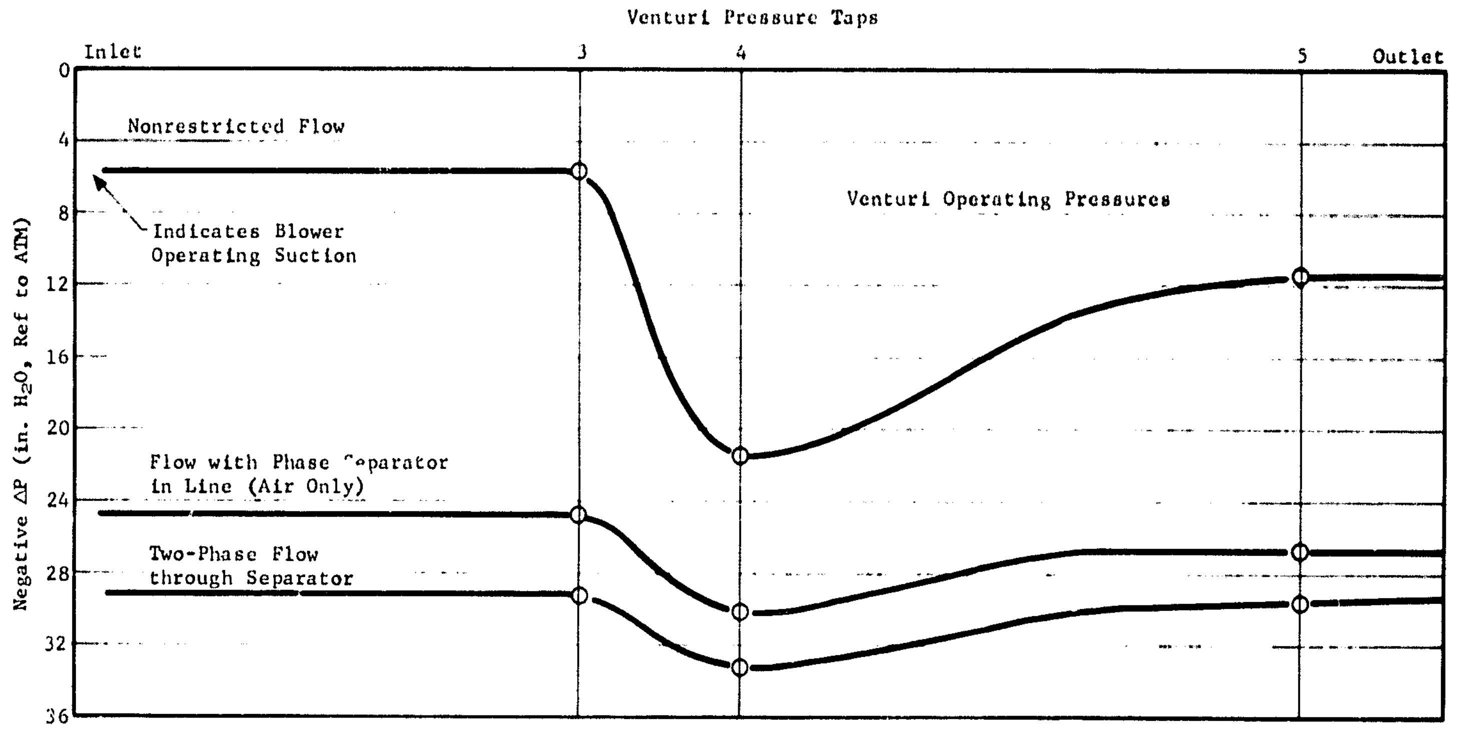


Fig. IV-4 Distance along Venturi (in.)

2. Startup

Startup at continuous operating conditions was not achieved with the first system. To lift the separated water 25 in. and establish flow, the air reduction valve was closed, thus increasing blower vacuum and raising the liquid the required height. Since the delivery head system operates at a high vacuum, this startup was not a problem.

In both cases, air was passed through the screen when it was dry. This presents a problem for storage unless the screen is prewetted or the breakthrough air is bled off.

3. Gravity Operation

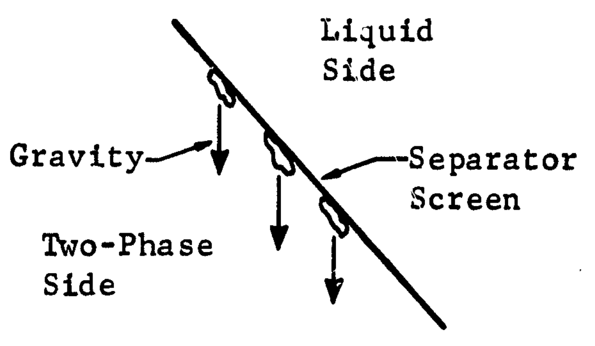


Fig. IV-5 Phase Separation with Cone Apex Up

In the upright position (cone apex up), the phase separation works against gravity (Fig. IV-5). Because of the conical shape of the screen, impinging water droplets are free to fall off the screen under the influence of gravity. This tendency to drop away from the screen impedes the liquid transfer.

In a zero-gravity field, water transfer through the screen should be improved.

V. CONCLUSIONS

The hydrophilic liquid/gas separator system was successfully operated in a gravity environment and its zero-g operation is reasonably assured since the separator operated in opposition to gravity. From the testing conducted during this contract, we reached the following conclusions:

1) Filtering adversely affects liquid and airflow rates;
2) Because of large pressure drops and flow restrictions, fine two-phase inlet filtering is impractical;
3) For use in a shower cleanup operation, a disposable large pore filter at the two-phase inlet would allow air and water to pass through it while filtering such large particles as hair;
4) Tap water did not greatly contaminate the screen and filtering may not be needed for potable water;
5) Urine is readily separated by the screen although long-term effects are not known;
6) The screen and system are compatible with urine;
7) Startup is easily accomplished with the delivery head configuration;
8) Maximum separation rates for the no delivery head configuration was 1 gpm of tap water and 10 scfm of air;
9) Maximum separation rates for the 0.6-psig head configuration was 0.7 gpm of tap water and approximately 1 scfm of air;
10) Separation of liquid/gas can be 100%;
11) Separator must be wetted before startup and its usage in a system or a procedure must be established during initial bleed in;
12) System is simple and easily maintainable;
13) Capacity of screen may be tailored to each flow condition by altering its shape, micron rating, and surface area;
14) Separator is capable of accepting varied flow rates of liquids and gases and percentages of each;

15) To achieve higher liquidflow rates and gaseousflow rates against a 0.6-psig head, either a higher negative pressure blower (i.e., one that operates at 60 in. of water at an output of 10 scfm) or a water pump (in the liquid discharge line) should be installed in the system;

16) On startup with a dry screen, a bleed system in the liquid feedline would prevent air from entering the storage tank.

VI. RECOMMENDATIONS

We recommend that the hydrophilic liquid/gas separator be further evaluated in a specific life support application such as a zero-g shower water collection system. In addition, we recommend that the design effort be continued to optimize the separator size and configuration for various life support applications.

APPENDIX - TEST RESULTS

A. SYSTEM 1

1. Test Run 1

Purpose: To determine flow rates and system characteristics of System 1 with no filtering devices involved.

	Run										
	1	2	3	4	5	6	7	8	9	10	11
Liters/Gal	Elapsed Time (sec)										
0	--	--	--	0	0	0	0	0	0	0	0
2	0	0	0	347	135	159	135	55	53	134	58
4	300	65	58	517	226	225	204	208	145	230	243
6	410	113	87	611	306	251	232	302	234	325	328
8	840	159	115	646	342	316	300	338	320	402	410
10	1090	200	147	718	415	344	329	412	402	439	449
12	1133	238	178	751	447	415	402	447	437	515	524
14	1170	273	213	825	523	449	436	525	514	554	559
16	1204	309	252	900	555	526	512	607	553	636	637
18	--	--	--	947	639	609	555	657	644	735	722
5 gal	--	--	--	1018	707	637	629	725	727	813	750
Venturi Pressure (in. H_2O)											
P_1	--	2.3	2.3	2.1	2.0	1.5	1.7	2.3	2.0	1.9	1.9
P_2	--	2.1	2.3	1.5	1.9	2.0	2.0	1.8	1.8	1.6	2.2
P_3	--	2.0		2.0	2.1	2.3	2.6	1.8	2.1	2.2	2.3
Fastest Run for 2 Liters (sec)	34	35	28	32	32	25	28	34	35	36	35
Breakthrough (at liters)	--	14	10	13	14	4	12	14	13	12	15
	7/24/69			7/25/69							

Note: ΔP Liquid/Gas Separator (two-phase liquid)

Full Flow: Off scale, +30 in. H_2O

Intermediate Flow: 23 ± 1 in. H_2O

2. Test Run 2

Purpose: To determine flow rates and characteristics of System 1 with a foam filter inside hydrophilic screen.

	Run									
	1	2	3	4	5	6	7	8	9	10
Liters/Gal	Elapsed Time (sec)									
0	0	0	0	0	0	0	0	0	0	0
2	399	81	100	62	88	78	75	99	77	71
4	448	128	166	142	150	121	128	172	123	122
6	484	168	220	205	219	167	173	254	171	173
8	522	206	255	256	276	209	220	302	302	218
10	565	242	310	306	355	254	265	347	337	260
12	607	279	356	352	489	300	309	390	379	307
14	650	319	404	400	549	351	357	436	454	350
16	694	363	451	447	308	399	402	503	557	401
18	760	411	506	498	516	459	463	566	775	480
5 gal	804	439	548	528	605	520	523	632	838	537
Venturi Pressure (in. H_2O)										
P_1	2.2	2.4	2.8	3.2	3.2	2.4	1.7	1.4	0.6	2.2
P_2	1.9	2.4	2.4	2.8	3.1	2.6	1.6	0.7	2.9	2.2
P_3	2.6	2.8	2.8	3.0	3.5	2.8	1.8	1.6	3.7	2.6
Fastest Run (sec)	36	36	45	46	57	42	44	43	35	43

Note: ΔP Liquid/Gas Separator (two-phase liquid)

Full Flow: 29 ± 5 in. H_2O

No Flow: screen top bare - 20.1 in. H_2O

screen covered - 27.1 in. H_2O

Comments: Air breakthrough (through screen) observed to be easier with foam filter in place than without. Water breakthrough easier to control than without filter.

Run 1: Startup, 225 sec; Breakthrough at 4 liters.

Run 2: Breakthrough at 14 liters.

Run 3: Probable error in recording times between 6 and 10 liters.

Run 4: Breakthrough at 15 liters.

Run 5: Obvious recording error from 14 liters on.

Run 9: Halted run at 6 liters to remove H_2O from manometer tubes; H_2O in tubes probable cause of low pressures recorded during tests with Bottles 7, 8, 9.

System 1 Characteristics, Airflow and Suction Pressure

	ΔP Venturi-Atmosphere (in. H_2O)			ΔP Venturi (in. H_2O)	Blower Suction (in. H_2O)
	3	4	5	3 & 4	
No Restriction	-5.9	-21.6	-11.5	15.7	+30†
Phase Separator with Air	-24.7	--	-26.9	5.4	+30†
Phase Separator with Air and H_2O	-29.1	--	-29.8*	4.1	+30†

*ΔP (3 to 5) = 0.7.

†Off scale.

B. URINE TEST RESULTS

Note: Urine samples are from 50 to 100 ml; rinse consists of 150 ml of water.

Procedure: Urine added by hand (poured into glass funnel), pause with blower on, rinse added in same manner as urine, blower shut down for 2 minutes between runs.

1. First Test

Run 1: Urine diffuses through bottom of screen; small trickle of H_2O in air hose, but no urine noticed. 2-min wait.

Run 2: Liquid passed (appeared in air hose) in steady trickle when urine added. 2-min wait.

Run 3: Urine in, 25 sec; rinse, 15 sec; liquid, as before appeared in air hose. 2-min wait.

Run 4: Air hose compressed during addition of urine (time in 30 sec), breakthrough after release; held during rinse, same result; waited, but it did not appear that liquid would stop flowing in air hose while blower on; color noticed in storage bottle. 2-min wait.

Run 5: Urine in, 23 sec; liquid breakthrough slight at startup, stopped, then increased beyond first amounts noticed at end of urination; additional water added (500 ml) to try and right system, not successful. 2-min wait.

Run 6: Urine in, 13 sec; liquid still in air hose. 2-min wait.

Run 7: Urine in, 14 sec; less liquid passed during addition of urine, picks up during rinse. 2-min wait.

Note: Water added at this point to get all air out of liquid hose (1000 ml) - appeared successful.

Run 8: Urine in 13 sec, liquid appeared in air hose at completion of urination in usual amounts. 2-min wait.

Run 9: When blower turned on, liquid appeared in air hose before urination. 2-min wait.

Note: Liquid observed in intake hose between runs.

Run 10: Urine in, 6 sec; same results. System completely flushed with water.

2. Second Test

Note: At start cone covered, water in recovery bottle covered the bottom of inlet pipe (between marks 2 and 4 liters); spillage bottle empty.

Procedure: Same as first.

Run 1: Perfect run, no breakthrough. 2-min wait.

Run 2: Slight liquid spillage during rinse. 2-min wait.

Run 3: Liquid continued to be passed slightly (2.3 in. H_2O, venturi). 2-min wait.

Run 4: Poured in rinse at slower rate and no overflow observed. 2-min wait.

Run 5: No overflow. 2-min wait.

Run 6: Relatively high overflow, putty was added before run to outlet hose to cut air leakage; venturi over 3.5 in. H_2O; cut back to 1.3 in. H_2O. 2-min wait.

Run 7: No liquid observed in air hose (1.3 in. H_2O). 2-min wait.

Run 8: Small puddle formed; steady stream for moment after rinse; unable to decide if stream continued or if optical illusion. 2-min wait.

Run 9: Breakthrough occurred at end of rinse. System flushed with water; water in cone seemed to become clearer at top first; more liquid seemed to be passed in flushing than before.

3. Third Test - Simulation

Procedure: Water added by hand (100 ml), pause with blower on, rinse added in same manner (100 ml H_2O), pause 1 minute with blower on, repeat cycle, stop for 2 minutes (blower off).

Run 1: No breakthrough. Pause.

Run 2: No breakthrough. 2-min wait.

Run 3: No breakthrough. Pause.

Run 4: No breakthrough. 2-min wait.

Run 5: No breakthrough. Pause.

Run 6: No breakthrough. 2-min wait.

Run 7: No breakthrough. Pause.

Run 8: No breakthrough. 2-min wait.

Run 9: No breakthrough. Pause.

Run 10: No breakthrough.

C. STARTUP PROCEDURES

Run 1: Venturi ΔP = 2.0 in. H_2O (without two-phase mixture).

Procedure: Water added slowly, no water appeared in air hose, more air bubbles in water storage bottle, water passed when water had hard time getting past top of cone, water tried to "fight" way to top of bottle, screen vibrated considerably; venturi ΔP then 2.4 in. H_2O, fluctuated during breakthrough.

Run 2: Maximum blower, venturi ΔP = 3.2 in. H_2O.

Procedure: Water added slowly, flow stopped at bend above cone, breakthrough followed, water flow increased (spillage also increased); when water filled tube to bottle, breakthrough ceased, water was separated with no breakthrough after that, liquid flow stopped but blower was still operated to see if air breakthrough would occur; during 5-min run three separate air bubble "pulsators" observed (air through screen).

Run 3: Maximum blower, venturi ΔP = 3.2 in. H_2O.

Procedure: Water started at slow rate, air bubbles steady in storage bottle, water level past cone into water tube (about halfway up) before stopping and breakthrough occurred slightly after; waterflow increased in attempt to get liquid into bottle (more water passed through air hose), breakthrough never stopped, run aborted to empty air line bottle.

Run 4: Maximum blower, venturi ΔP = 3.2 in. H_2O.

Procedure: Water started at high rate, large amounts of water breakthrough until liquid started flowing into retention bottle at which time water breakthrough ceased; same two bubbles as before during 5-min air run.

Run 5: Venturi ΔP = 2.0 in. H_2O.

Procedure: Water started at high rate, water breakthrough before screen covered; however, equilibrium maintained after surge completed and no water breakthrough observed.

Run 6: Venturi ΔP = 2.0 in. H_2O.

Procedure: Air hose constricted and water in at moderate rate, small breakthrough, good results.

Run 7:

Procedure: Flow valve shut to start, opened to 0.1 in. H_2O and run until liquid line was filled with water, valve then opened to 2.7 in. H_2O; initial breakthrough observed after valve opened to 2.7, but this was cleared up by system after a moment (light water flow).

Run 8:

Procedure: Flow valve shut to start, opened to 0.1 in. H_2O and left for awhile, water built up in inlet hose and pulsated into separator, valve opened slowly in stepwise process to avoid breakthrough in air hose, taken up to 2.7 without breakthrough and then opened in one step to maximum (4.0 in. H_2O); breakthrough occurred shortly after, water inlet closed and breakthrough continued for short period, then ceased. Water again flowing at light to moderate rate and breakthrough occurred.

D. SYSTEM 2

Flow Rate vs Startup Pressure

Pressure (in. H_2O)	Time for 2-Liter Intervals									8/21/69 8/22/69 Suction Pressures during Run (in. H_2O)
	0 to 2	2 to 4	4 to 6	6 to 8	8 to 10	10 to 12	12 to 14	14 to 16	16 to 18	
40.0	85	65	61	67	100	72	77	71	71	41.3 40.2
41.1	62	74	79	75	75	76	67	77	77	41.2
42.2	67	73	73	74	73	72	73	75	73	41.9
37.4				See Comments Below						37.9
38.5	--	460	500	520	--	--	--	--	--	39.3 38.9
39.3	180	250	260	260	260	--	--	--	--	--
44.4	165	155	137	123	105	90	75	58	53	43.5 43.3
43.4	55	61	79	65	--	--	--	--	--	--
45.7	34	46	46	50	44	47	48	45	48	49.0 45.7
39.8	115	145	155	153	182	205	170	145	145	40.0 39.8

Comments: Maximum suction (at pressure tap 5) - 46.6 in. H_2O.

Run 1: Breakthrough at 6 to 8 liters, cutback.

Run 2: Venturi ΔP = 0.2 in., screen breathing at these rates.

Run 3: Venturi ΔP = 0.1 in., screen breathing.

Run 4: Water passed at 37.9-in. suction (minimum suction), venturi ΔP = 2.0 in.

Run 5: Minimum suction 39.3 in. (with H_2O flow), venturi ΔP = 2 in., breakthrough at < 2, flow reduced slightly.

Run 6: Breakthrough at <2, flow reduced slightly, venturi ΔP = 1.5 in.

Run 7: Air bubble constantly in top part of liquid hose except at end of run.

Run 8: Vacuum smoked.

Run 9: ΔP negligible.

Run 10: ΔP = 1.2 in.

E. VENTURI SIZING (14.7 psia)

$$\dot{\omega} = \frac{\pi d^2\ CY_a}{576}\left(\frac{1}{\sqrt{1 - \beta^4}}\right)\sqrt{2 \times 144 g\ \gamma\ (p_1 - p_2)}.$$

Upon rearrangement and solving for d^2,

$$d^2 = 1.90\ \dot{\omega} \Big/ \frac{1}{\sqrt{1 - \beta^4}} \sqrt{\gamma_1\ (p_1 - p_2)}\ \ CY_a$$

$$Re = 2.27 \times \frac{10^4\ \dot{\omega}}{d\mu} = \frac{2.27\ (.0249)\ 10^4}{1.25\ (.0180)} = 2.51 \times 10^4.$$

C = 0.943 from Figure 88, p 125,*

Assure β = 0.2, Y_a = 0.9782, Table 6, p 63*

*<u>Fluid Meters, Their Theory and Application</u>. American Society of Mechanical Engineers, New York, N. Y., 1959.

$d^2 = 1.90\ (0.0249)/1.0008\ (0.943)(0.9782)\quad 0.748\ (0.5)$

$d^2 = 0.0473\ 0.923/0.923\ (0.193) = 0.266$ in.^{2}

$d_T = 0.515$ in., $d_p = 2.58$ in.

Assume $\beta = 0.4$, $Y_a = 0.9776$

$d^2 = 0.0473/1.013\ (0.943)\ 0.9776\ (0.193) = 0.262$ in.^{2}

$d_T = 0.512$ in., $d_p = 1.28$ in.

Assume $\beta = 0.5$, $Y_a = 0.9765$

$d^2 = 0.0473/1.0328\ (0.943)\ 0.9765\ (0.193) = 0.258$ in.^{2}

$d_T = 0.508$ in., $d_p = 1.015$ in.

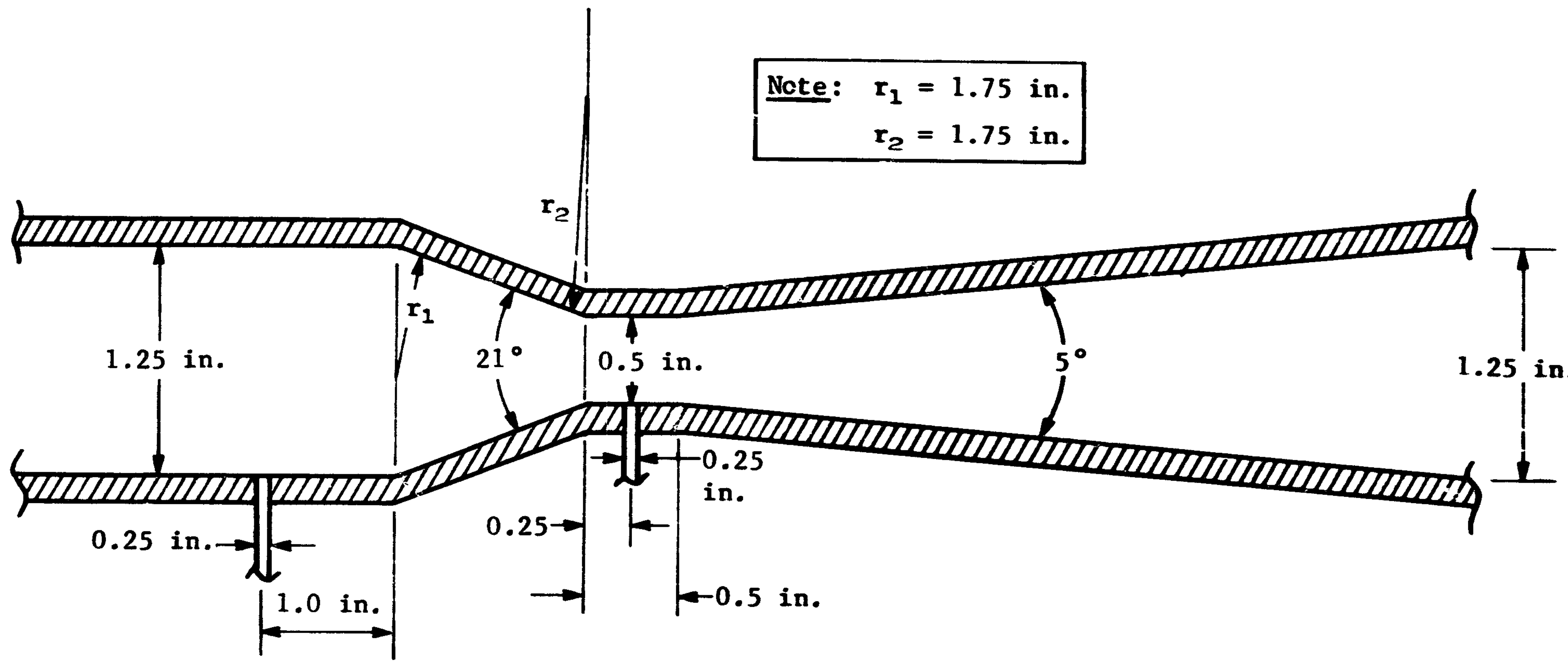
Recalculate with $d_T = 0.5$ and $d_p = 1.25$, $\beta = 0.4$

$$\dot{\omega} = \frac{\pi d^2\ CY_a}{576}\left(\frac{1}{\sqrt{1 - \beta^4}}\right)\sqrt{144\ (2g)\ \gamma_1\ (p_1 - p_2)}$$

$$\dot{\omega} = \frac{\pi\ (0.5)^2\ 0.943\ (0.9776)}{576}\ 1.013\ [288\ (32.2)\ 0.0748\ (0.5)]^{\frac{1}{2}}$$

$$\dot{\omega} = \frac{0.785\ (0.935)}{576}\ [347]^{\frac{1}{2}} = \frac{13.67}{576} = 0.0238 \text{ lb/sec}$$

$$\dot{\omega} = \frac{0.0238\ (60)}{0.0748} = 19 \text{ cfm.}$$



Venturi Characteristic	Size
Inlet and Outlet Pipe Internal Diameter	1.25 in.
Throat Diameter	0.5 in.
$\beta = D_T \, D_p$	0.4
ΔP (Inlet to Throat)	0.5 psi
ΔP (Total through Venturi)	0.1 psi
Flow Rate	0.0249 lb/sec = 19 cfm
Approximate Total Length	13 in.