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Research Report

(Phase A)

DESIGN AND FABRICATION OF A PROTOTYPE FOR AN AUTOMATIC TRANSPORT SYSTEM FOR TRANSFERRING HUMAN AND OTHER WASTES TO AN INCINERATOR UNIT ONBOARD SPACECRAFT

Contract No. NAS2-6386

GARD Project No. 1523

Chemical & Environmental Systems Group
Systems Engineering Department

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FOREWORD

This report summarizes the results of an experimental study on the automatic transport of wastes for aerospace applications. The work was conducted for the Ames Research Center of the National Aeronautics and Space Administration, under Contract No. NAS2-6386, by the General American Research Division of the General American Transportation Corporation during the period from April 2, 1971 to December 2, 1971.

The NASA Project Monitor was Dr. Jacob Shapira of the Environmental Control Research Branch. Personnel in the Chemical and Environmental Systems Group at GARD performed the activities under the direction of Mr. George A. Remus; Mr. Lawrence J. Labak served as Project Engineer and Mr. Roger Mansnerus served as Engineering Assistant.

ABSTRACT

Three transport system concepts were experimentally evaluated for transferring human and non-human wastes from a collection site to an incineration unit onboard spacecraft. The operating parameters, merits, and shortcomings of a porous-pneumatic, nozzle-pneumatic, and a mechanical screw-feed system were determined. An analysis of the test data was made and a preliminary design of two prototype systems was prepared.

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SECTION 1

INTRODUCTION AND SUMMARY

Under a prior contract - NAS2-5442 - GARD designed, fabricated, and tested the GARD Model 1493 Waste Incineration System. This system, shown in Figures 1-3, was designed to automatically incinerate the wastes produced by four men onboard a spacecraft; the wastes consisted of 600 grams of fecal matter, 600 grams of urine distillate residue containing 50% solids, toilet tissue, and other miscellaneous wastes, such as plastic storage bags, hair, and fingernail clippings. The incinerator was initially designed to operate on a daily batch cycle, with all wastes collected in the incinerator canister, visible in Figure 3, at a separate location. After collection, the canister was to be manually inserted into the Waste Incineration System as shown in Figure 2; the system was then closed and the automatic, 24-hour incineration cycle started.

At the end of the incineration cycle, the system was allowed to cool, the canister opened, and the ash vacuumed from the canister. Two canisters were to be used, alternating as collector and incinerator.

Although the GARD Model 1493 Waste Incineration System does not require manual handling of wastes, transfer of the canister did entail handling the canister as part of the operating cycle. In addition, using the canister in the collection mode required manual attachment of a cover to retain the wastes in zero gravity.

Automatic transfer of waste material from the collection site to the incinerator is preferred to manual transfer to eliminate possible contamination of the incinerator itself and of the spacecraft. Concurrently, the need arose for greater system capacity to accommodate six men instead of four without significantly modifying the present incineration configuration.

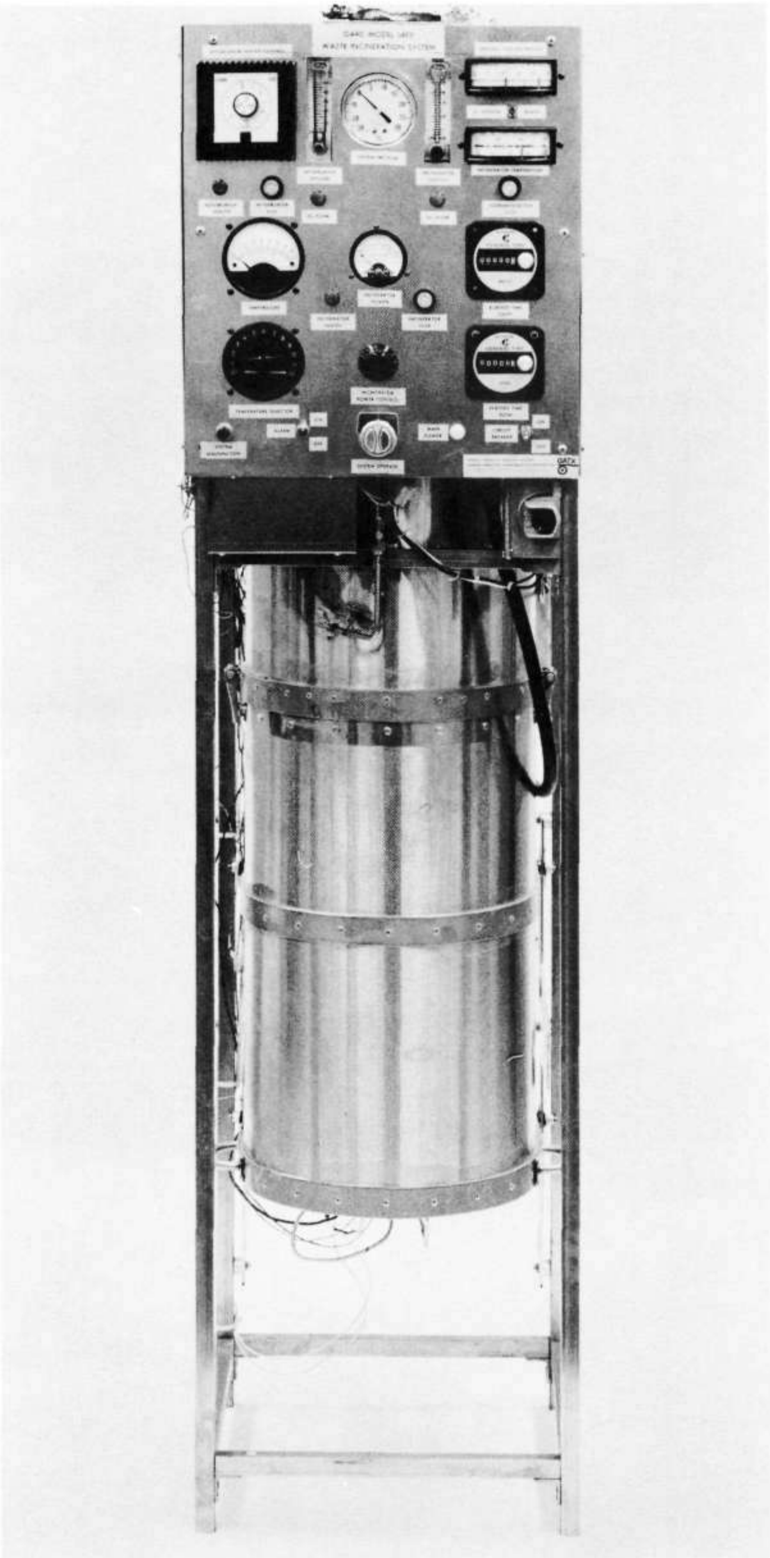

Figure 1. GARD MODEL 1493 WASTE INCINERATION SYSTEM -- FRONT VIEW (CLOSED)

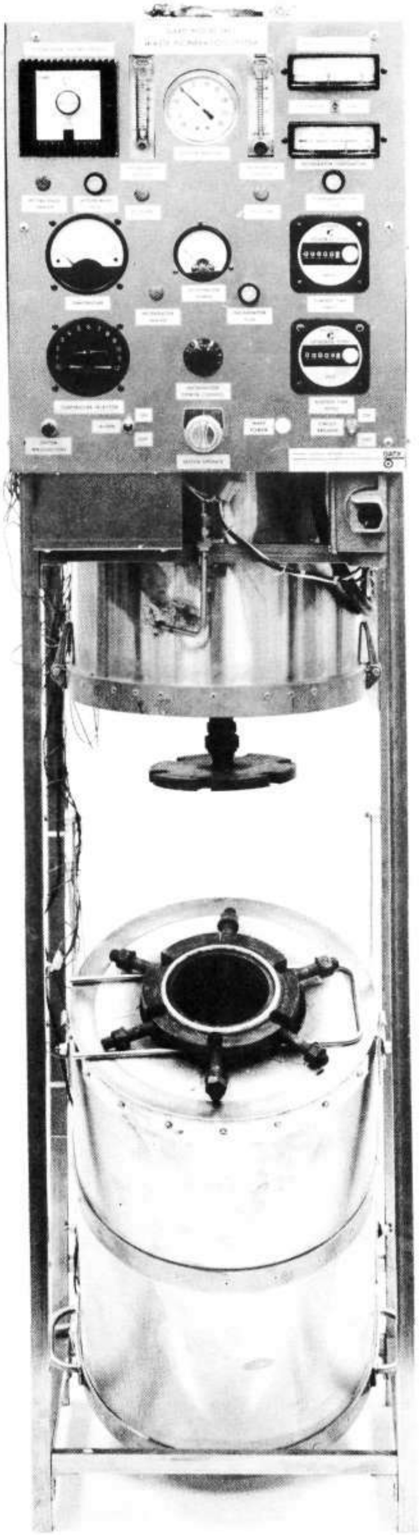

Figure 2. GARD MODEL 1493 WASTE INCINERATION SYSTEM -- FRONT VIEW (OPEN)

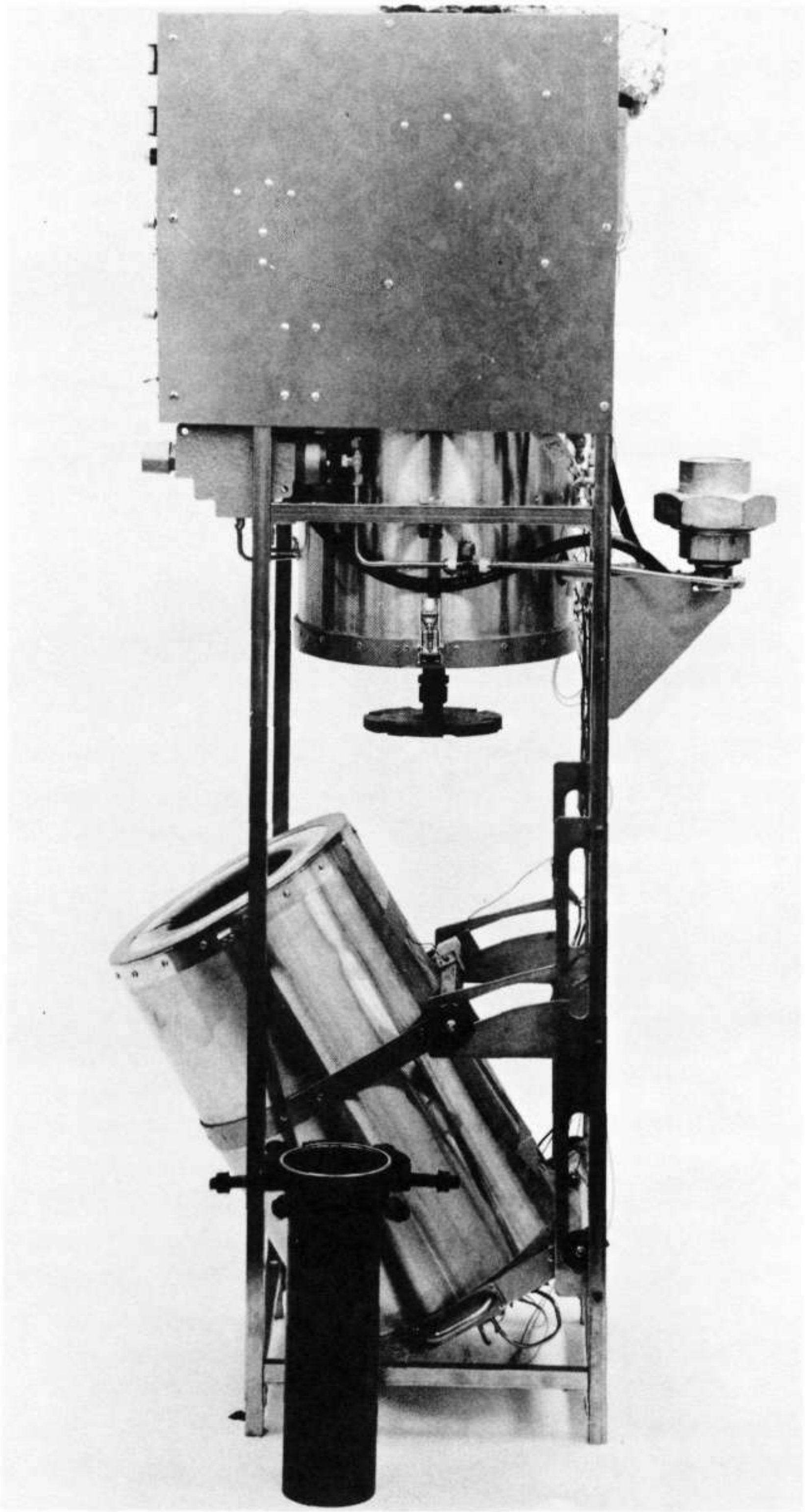

Figure 3. GARD MODEL 1493 WASTE INCINERATION SYSTEM -- SIDE VIEW WITH INCINERATOR/CANISTER REMOVED

Based on these operating criteria and design features, it was decided to continuously run the incinerator hot and to feed waste materials into it on an as-required basis. Together, these features impose the following design considerations on any prospective transport system:

(1) No waste material can remain in the collector or transfer device.

(2) The ash, vapors, and gases generated by the incineration process must not exhaust back through the transfer device.

(3) Since the incinerator continuously runs hot, heat conduction will cause the terminal end of the transfer device to also run hot. The resulting high temperature can cause sticking and caking of the wastes, which can eventually plug the transfer device. The transport system must be designed to prevent this plugging.

(4) If it becomes necessary to flush the transport system with water, the amount of water used must be minimized to prevent overloading the incinerator, in terms of both volume and thermal energy.

(5) The size of the transfer device with respect to the amount waste materials handled must be selected to prevent physical plugging of the transport system.

(6) The transport device must transfer both liquid and solid wastes. It must be safe, reliable, easily maintainable, capable of minor repairs with minimum crew participation, and impose minimum weight and power requirements on the spacecraft.

The objectives of the current program are to develop a prototype-model of a suitable, zero "g" waste transport system and to integrate it with the GARD Model 1493 Waste Incineration System. Under Phase A of the program, GARD theoretically and experimentally studied several transport system concepts and was to select one for further development; a preliminary design of the selected concept was also to be prepared. Phase B of the program will include a design review meeting, final design preparation, and fabrication and testing of the prototype transport system.

Under Phase C of the program, GARD will make any modifications to the waste incinerator that are necessary to facilitate its integration with the prototype transport system. The two systems will then be integrated and subjected to evaluation testing.

Three waste transport system concepts were tested in the laboratory and evaluated; the three concepts were: porous-pneumatic, nozzle-pneumatic, and screw-feed. Results of the former two concepts showed that solid and liquid feed materials could be suspended on an air cushion and readily transported through a tube. The air cushion is created by using a porous tube, positioned within a larger tube, with pressurized air admitted to the annular space between the tubes. Material transport through the tube is obtained by employing a tube containing many small directional nozzles through its wall in place of a portion of the above porous tube. The pressurized air in the annulus flows through the nozzles where its initial pressure energy is converted to kinetic energy. Air leaves the nozzles in the form of a jet, reducing the pressure within the core of the tube. The nozzled tube acts as an air ejector pump inducing several times more outside air into the tube. The combination of the nozzled and porous tubes thus provides a means of sucking in waste feed materials, imparting a pneumatic drag effect to transport them through the tube, and creating an air cushion to prevent the wastes from contacting the tube walls. Since the wastes do not touch the tube walls, no residual wastes remain in the tube and no caking or sticking of the wastes at the hot incinerator end of the tube is experienced.

The laboratory tests revealed that a porous tube with a 2.0 micron pore size performed better than tubes of different pore sizes, either smaller or larger. The results showed that the air cushion effect is a function of both air flow through the pores and annular air pressure. A minimum air pressure drop of 260 mm Hg through the 2 micron porous tube, equivalent to an air flow of 0.22 liter/sec/cm^2 of porous surface, was required to obtain the air cushion effect.

Testing also revealed that a more efficient and practical system results if the number of nozzles is minimized. With fewer nozzles, more air is induced into the tube per nozzle and less work is expended than when a large number of nozzles is used.

Test results of the screw-feed waste transport system indicated that a continuously rotated incinerator canister could be readily moved into and out of a hot heating zone. The rotating canister receives waste materials at the cool end of an outer sealed container; the centrifugal force of rotation confines the wastes to the walls of the incinerator canister for zero-gravity capability. The rotating incinerator is then moved into the hot zone, where incineration of the wastes takes place. Upon completion of incineration, the canister is returned to the cool zone where the residual ash is automatically scraped from the incinerator walls and removed by a vacuum source.

In addition to the actual waste transport device, two methods of waste size reduction were studied. Laboratory tests showed that a macerator-pump was not effective for both macerating and pumping semi-solid wastes, whereas a chopper-blade assembly, identical to a commercial household blender, combined with nozzled tube-pressurized annulus feed and discharge tubes readily shredded the wastes and transported them through the system.

Based on the laboratory testing two preliminary prototype system designs were prepared. Both systems described above -- that is, the nozzled-porous pneumatic tube combination and the screw-feed mechanical system -- appeared to have sufficient merits worthy of further development; attempts to select one as the most effective system were not successful. It was therefore decided that both concepts should be subjected to additional testing.

SECTION 2

CONCEPTUAL DESIGNS

2.1 Background

This program is based upon three waste transport system concepts conceived by GARD and proposed to NASA/ARC. Since their inception, these three concepts have been studied, evaluated, and modified to provide NASA with a safe and reliable waste transport device. The three initial concepts were described in GARD's Proposal No. 91309-A.

Initial activities on the program resulted in modifications and improvements to all three initial concepts. The original design of the pneumatic system was expanded to include three versions, all based on only pneumatic conveyance. The initial macerator design was modified to include pneumatic forces as well as pumping forces to transport the wastes. Finally, the initial helical-conveyor design was changed to a design using a rotating container transported into the incinerator by a motorized Acme-thread screw. This latter system operates on a batch basis; the other four systems are capable of either batch or continuous operation. These five modified conceptual designs are described below.

2.2 Modified Waste Transport System Concepts

2.2.1 Pneumatic Systems

Of the three versions of the pneumatic waste transport system, two are positive-pressure systems and one is a negative-pressure, or vacuum system.

Positive-Pressure Systems

Both modified positive-pressure systems utilize two concentric tubes separated by a thin annular space. Pressurized air is fed into the annulus; the waste materials are fed into the inner tube. In the first positive-pressure system, the walls of the inner tube contain a large number of closely spaced pores; in the second system, numerous small-orifice nozzles penetrate the inner tube wall, directed toward the tube axis and angled forward in the desired direction of flow. The pores and nozzles allow the pressurized air flowing within the annulus to flow through the wall into the inner tube. By proper selection of air pressure, air flow rate, pore and nozzle spacing, a thin layer of air will form around the inside circumference of the inner tube. This cushion of air will prevent the waste materials from contacting the walls of the inner tube as they flow through the tube. A sketch of both systems is shown in Figure 4.

The waste materials can be made to flow through the inner tube either by pumping them or by allowing the existing pneumatic forces to act upon them. Pneumatic pumping takes place in the following manner.

In the porous transport system a higher pressure will exist at the upstream or collection end of the tubes, if the pressure drop of the air across the inner tube wall is assumed constant for the entire length of the tube. The pressure in the center tube will decrease over the length of the tube and approach a minimum value at the terminal or incinerator end of the tube as indicated below.

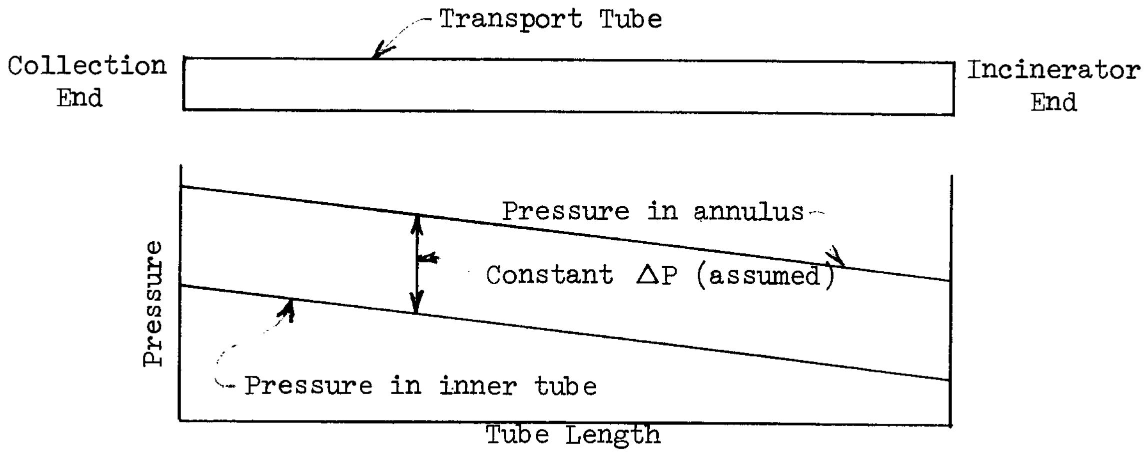

Figure 5. PRESSURE GRADIENT FOR POROUS-PNEUMATIC TRANSPORT SYSTEM

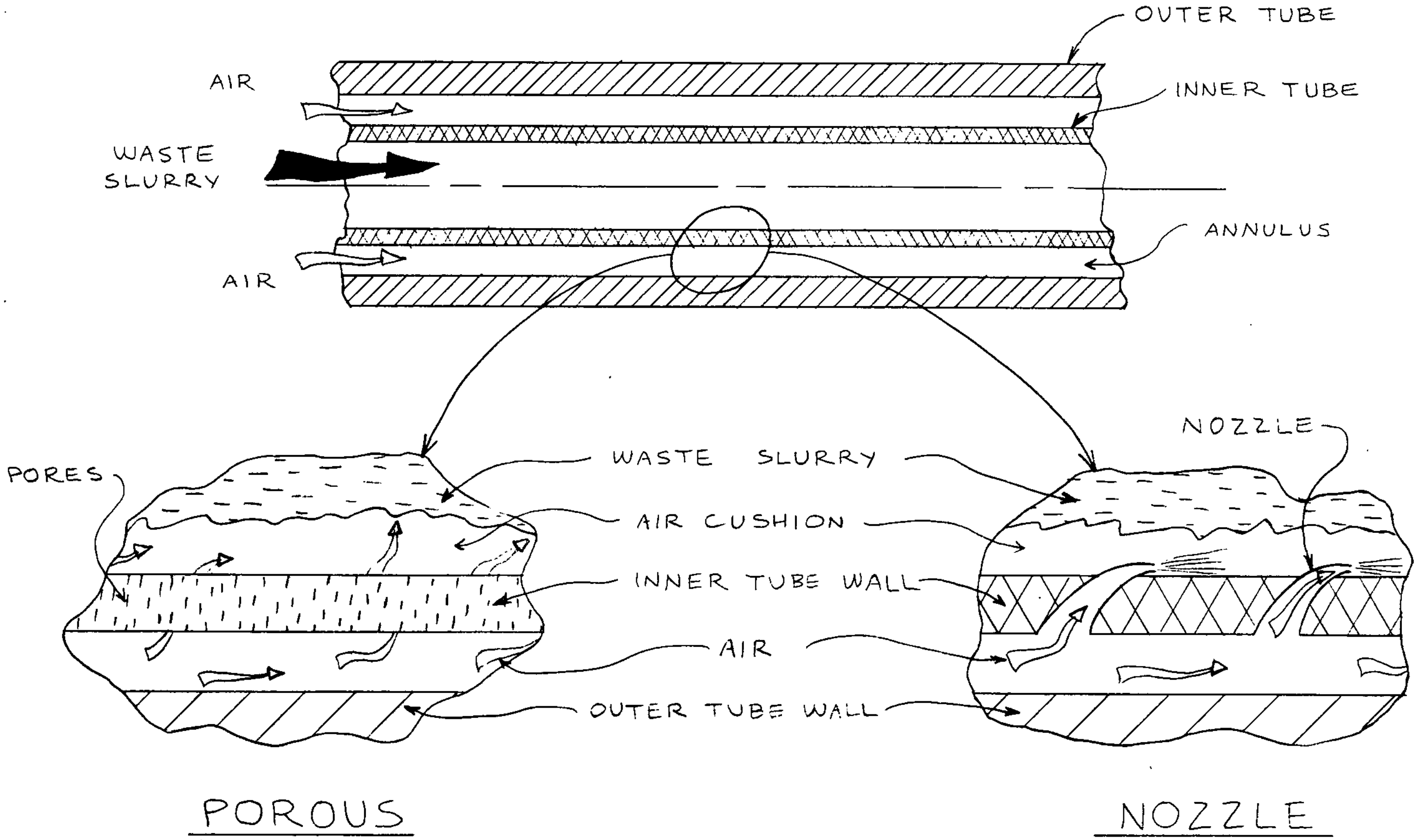

Figure 4. PNEUMATIC WASTE TRANSPORT SYSTEM CONCEPT: POSITIVE-PRESSURE

The developed pressure gradient will force the waste materials from the collection end to the terminal end.

In the nozzle transport system, the pressurized air flow in the annulus will attain a high velocity as it flows through the nozzles. If the nozzle openings are near the inside wall of the inner tube and if the nozzles are angled toward the incinerator, the resulting high-velocity jet will both create an air cushion and impart momentum to the wastes to move them toward the terminal end of the tube.

In both cases, the waste materials are prevented from contacting the tube walls; thus, no residual wastes will remain in the tube and the wastes will not cake at the hot or incinerator end of the tube.

Negative-Pressure System

Another modified pneumatic technique for transporting the wastes from a collector to an incinerator employs negative-pressure, or vacuum transport. With this technique wastes are drawn through the transport tube by the pressure differential created by a vacuum pump at the outlet of the incineration system. This approach is similar to the Liljendahl SANIVAC* system, which is currently replacing conventional gravity sewer systems throughout the world. A small pump maintains the closed SANIVAC system at 0.5 to 0.6 atm pressure. When the system is actuated, atmospheric pressure pushes the wastes out of the toilet bowl into a small-diameter exit pipe. When the system is opened, approximately 1 to 1.5 liters of water are used to flush the bowl and to provide a small residual in the bowl after the timer-valve closes. As the plug of wastes and water moves through the pipe, friction forces cause the plug to spread, eventually losing contact with the pipe walls and breaking the vacuum. The vacuum is restored by utilizing pockets or traps, which

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* Licensed by National Homes Corp., Lafayette, Indiana.

collect the broken plug pieces. When the pocket fills, differential vacuum pressure is restored and the plug continues to move toward the collection point.

Since the wastes contact the tube walls, it would be necessary to flush the zero "g" collector and transport system with water. It would also be necessary to properly size the transport tube to prevent the plug from breaking apart, since a pocket would be difficult to handle in zero "g". A sketch of the negative-pressure system is shown in Figure 6.

2.2.2 Macerator/Pneumatic System

In this modified system a macerator-pump is used to macerate all waste materials into a pumpable form. The wastes, along with sufficient flush water, are then pumped to the incinerator. Since the waste slurry touches the tube walls, there would be residue build-up and caking at the hot terminal end of the transport tube. This situation may be avoided by providing pneumatic drag along the terminal end of the tube. One technique for providing this pneumatic drag is described below.

Before entering the incinerator, the transport tube tapers down to form an orifice and terminates without connecting to the incinerator. An open tube or sleeve attached to the incinerator fits over the tapered end of the transport tube, as shown in Figure 7. The waste slurry exits the transport tube in the form of a jet with a diameter less than that of the sleeve. Air is blown through the sleeve to create an air cushioning effect, similar to that in the positive-pressure pneumatic transport systems. The wastes thus enter the incinerator without touching the hot sleeve walls and thereby do not plug the transport tube.

2.2.3 Screw-Feed System

The modified screw-feed waste transport system initially consisted of

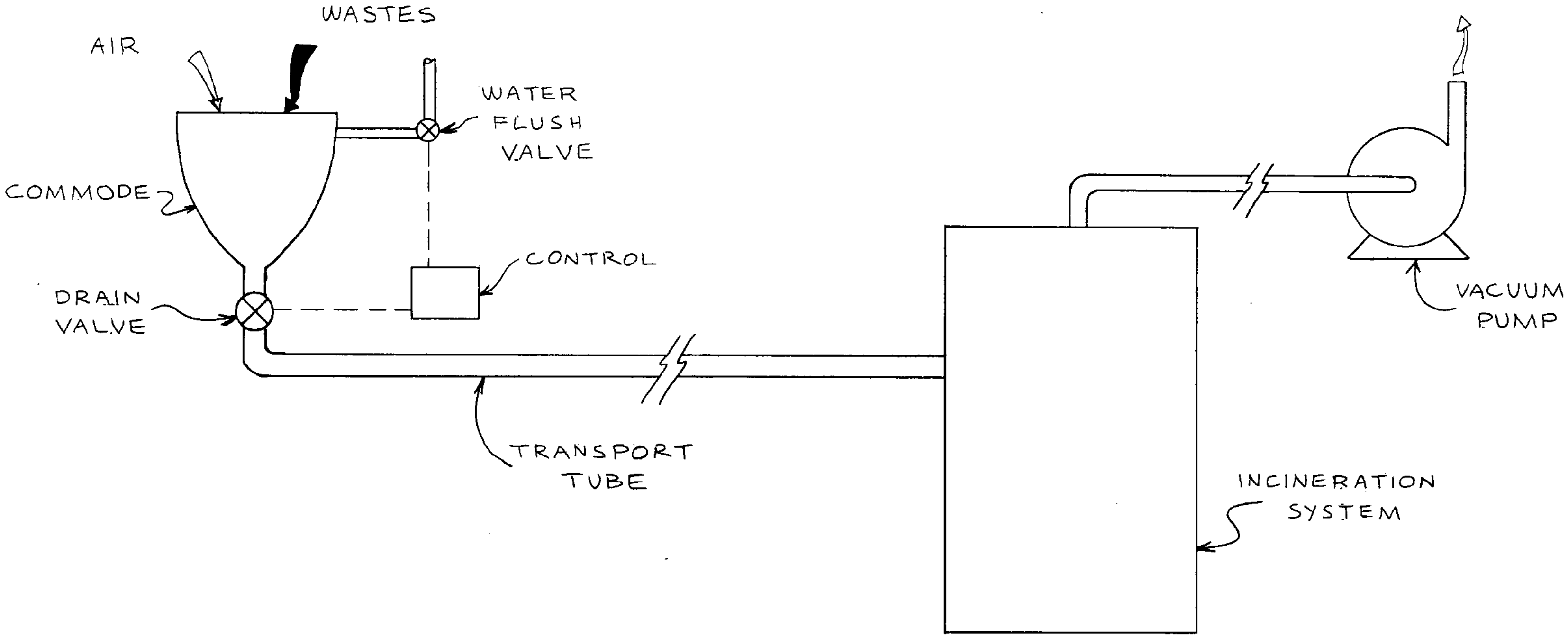


Figure 6. PNEUMATIC WASTE TRANSPORT SYSTEM CONCEPT: NEGATIVE-PRESSURE

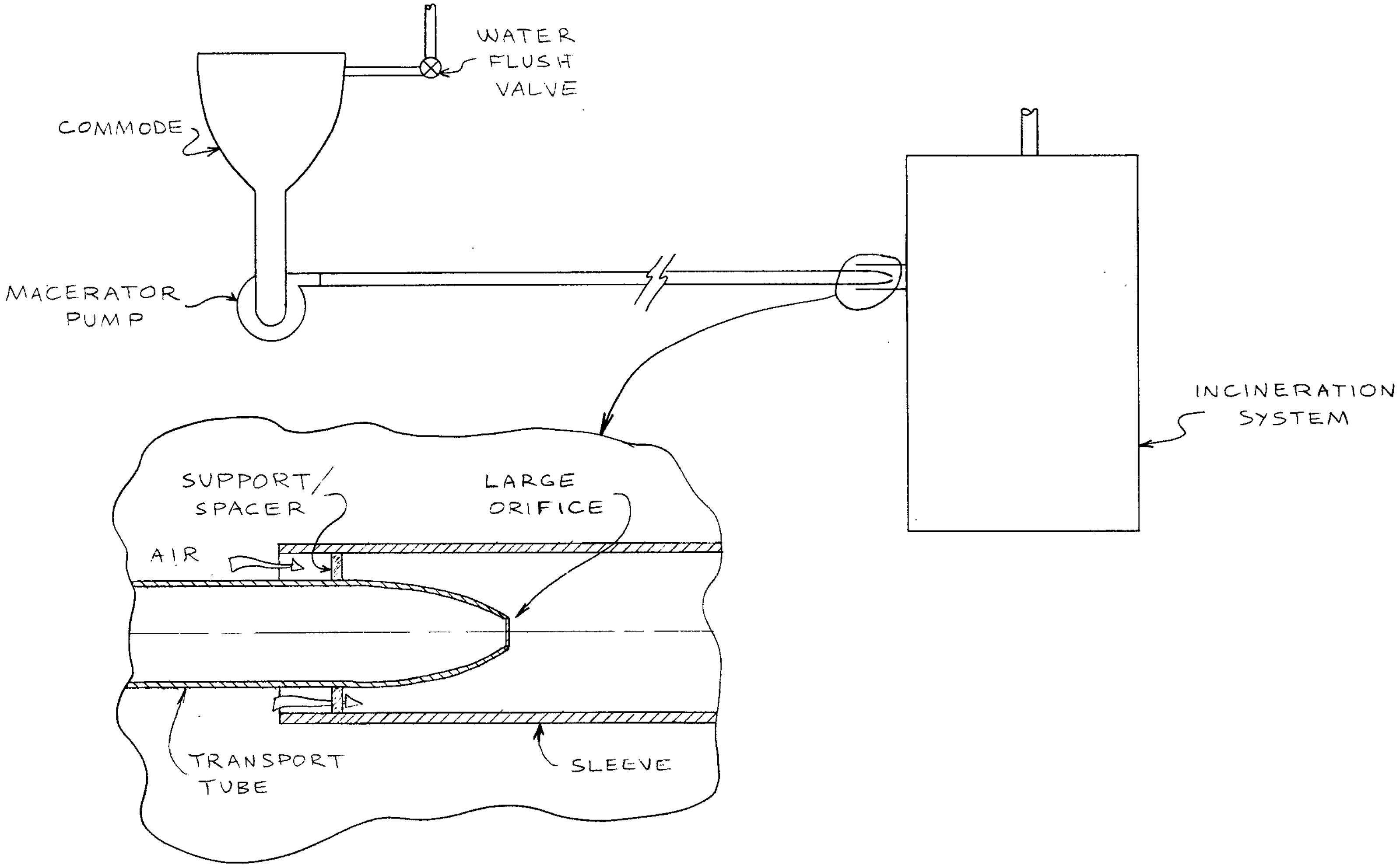


Figure 7. MACERATOR/PNEUMATIC WASTE TRANSPORT SYSTEM CONCEPT

a long, closed cylinder, insulated and heated at one end. A small, cylindrical waste-containing vessel within the cylinder is mechanically moved back and forth by a motor-driven Acme screw. The waste vessel is attached at one end to a long, rotating hollow shaft; the shaft and vessel move forward and backward as a unit as the vessel moves into or out of the heated end of the cylinder housing, while a motor continuously rotates the shaft and vessel.

Wastes were to be initially fed into the vessel through a quick-disconnect coupling attached to the hollow shaft; the wastes were constrained within the vessel by the centrifugal force of rotation. When the vessel is filled to capacity, it moves into the heated zone where incineration takes place. Solids and ashes from the incineration process are retained in the vessel, while vapors and gases exhaust out of the cylinder housing.

When incineration is complete, the vessel moves out of the heated zone back into the cool zone; the ashes were then to be removed by a vacuum attached to the quick-disconnect end of the rotating, hollow shaft. The initial, modified system is shown in Figure 8.

2.3 Concepts Selection

Of the five conceptual designs described above, three appeared to be technically feasible and worthy of further development. The other two concepts, however, appeared to have serious technical shortcomings.

The negative-pressure pneumatic concept was not considered to be a satisfactory method of waste transport since the wastes would contact the tube walls, requiring a water flush. Also, this technique relied on the developed vacuum to move a plug of wastes through a pipe. Frictional drag forces tended to break this plug and thereby destroy the differential pressure driving force. For household sanitary systems, the "broken" plug is readily reformed and the vacuum restored by utilizing pockets to collect the plug

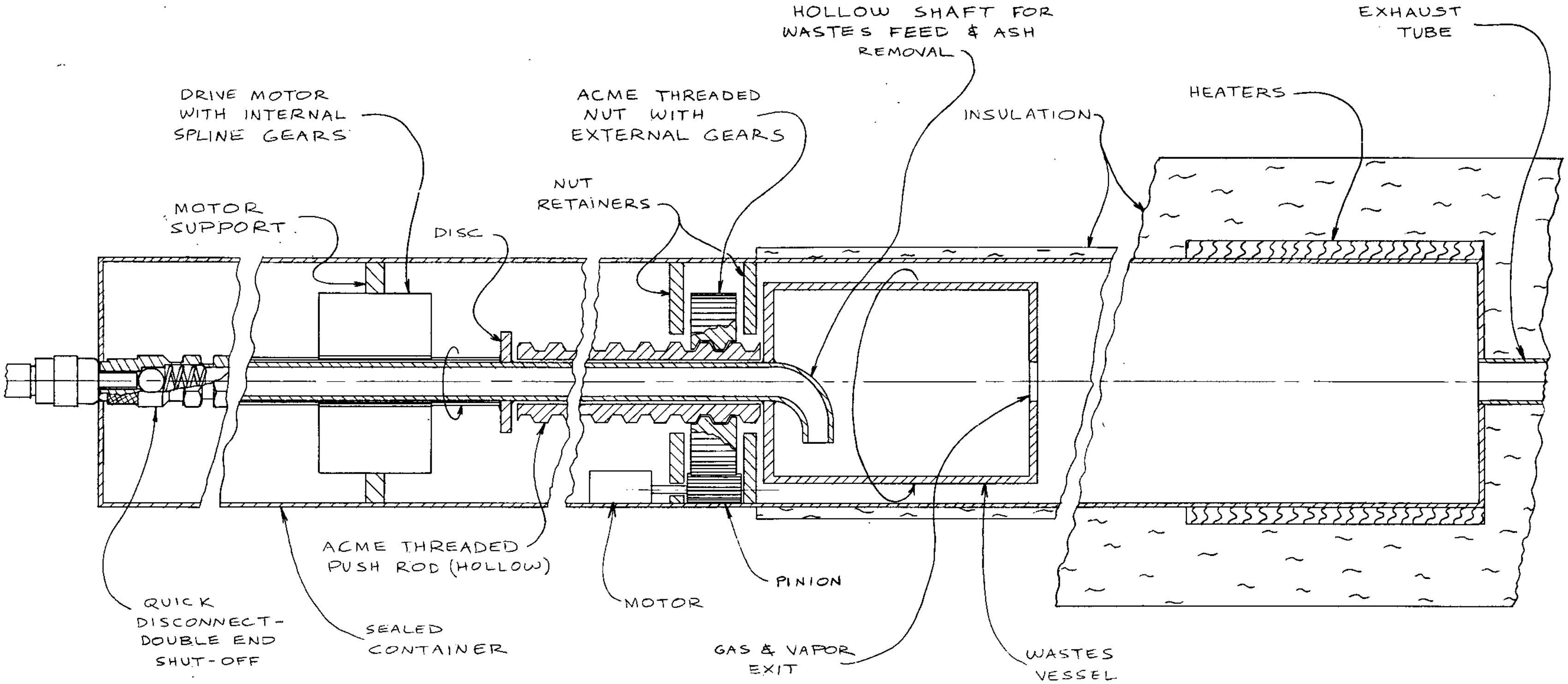


Figure 8. SCREW-FEED WASTE TRANSPORT SYSTEM CONCEPT -- INITIAL MODIFIED DESIGN

pieces. Under zero-gravity conditions, it would be difficult to collect waste plug pieces to re-establish the vacuum. Finally, in this system the transport tube would be connected directly to the hot incinerator. This would cause the waste plug to stick and cake on the tube walls and eventually plug the tube. The negative-pressure pneumatic waste transport system was therefore eliminated from further evaluation in favor of the other techniques.

The macerator/pneumatic concept was also considered not worthy of further evaluation since the wastes contacted the tube walls, again requiring a large water flush. In addition, the opening to the atmosphere created by the pneumatic sleeve was considered undesirable since air would have to be continuously blown or drawn into the sleeve to prevent the escape of wastes and incineration gases. If the air blowing or sucking equipment were to fail, wastes and incineration gases could easily leak into the spacecraft cabin. Finally, the proximity of the nozzled tube to the hot incinerator walls appeared to be a major shortcoming of this method since it was anticipated that heat transfer to the nozzle would be considerable and waste caking would take place.

In view of the above analysis, it was decided to eliminate these two concepts from further study and to evaluate the remaining three waste transport system concepts. Thus, the following techniques were subjected to laboratory design verification testing:

1) Porous-pneumatic system
2) Nozzled-pneumatic system
3) Screw-feed system

The results of the design verification testing are presented in Section 3, DESIGN VERIFICATION TESTING, and an analysis of these results is presented in Section 4, FINAL CONCEPT SELECTION.

2.4 Additional System Requirements

In addition to the basic waste transport system, the total incineration system will require size reduction of the wastes and removal of residual ash from the incinerator unit. The wastes must be reduced in size to prevent clogging of the transport system and the incinerator and to insure uniform distribution of the wastes within the incinerator for proper heat transfer. Also, flushing of the transport system with water to remove any residual waste particles is facilitated by first reducing the size of the wastes; the flush water requirement is thereby minimized. Two size reduction techniques were subjected to design verification testing: a macerator-pump and a chopper-blade assembly. Test results are presented in the next section.

Residual ash must be removed from the incinerator after completion of the incineration process and stored. This will allow the incinerator volume to be used at maximum capacity and will permit attainment of maximum heat transfer rates from the electrical heaters to the waste materials.

Prior incineration tests at GARD have shown that the final ash residue tends to adhere to the incinerator walls and is not readily removed by a vacuum cleaner alone. This ash is best dislodged by a mechanical device; little force, however, is required to loosen the ash.

Since the screw-feed waste transport system employs a separate incinerator canister, the design of the laboratory model included a mechanical scraper mechanism that was automatically engaged when the incinerator canister was returned to the cool zone. No other scraper mechanisms were evaluated since such a device is not included in the present contract.

SECTION 3

DESIGN VERIFICATION TESTING

Design verification testing was conducted with the three waste transport system concepts selected as most promising: porous-pneumatic, nozzle-pneumatic, and screw-feed. The tests were designed to evaluate:

1) Basic system operation,
2) Adequate operating parameters,
3) Required system characteristics, such as component sizes and configuration,
4) Possible problem areas,
5) Overall concept feasibility, and
6) Additional components required to achieve proper system operation.

Laboratory test set-ups, test data, test results, and a brief discussion are presented below for each of the concepts studied. Thorough analyses of the test data and of each concept are presented in Section 4, FINAL CONCEPT SELECTION.

3.1 Porous-Pneumatic Waste Transport System

Attempts to theoretically study the pneumatic waste transport concept with porous tubes did not produce significant results. This was due to the complex flow relations that exist within the annulus and the inner porous tube. Equations developed for this system included several simplifying assumptions, which apparently were valid for only very simple flow arrangements. In addition, these relationships were valid only in a one-gravity environment. Zero-gravity operations simplify the flow relations somewhat since the large gravitational force is eliminated and surface tension forces dominate liquid behavior.

3.1.1 Initial Laboratory Testing

Initial laboratory testing of the porous-pneumatic transport concept was performed with commercially available, porous plastic tubes. Three pore sizes were evaluated: 10 micron, 100 micron, and 0.08-cm diameter pores. The initial laboratory test set-up for this system is shown schematically in Figure 9 and a photograph of the actual equipment in Figure 10.

The outer tube was a LUCITE acrylic, clear plastic tube; the inner tube was a LABPOR high-density, hydrophobic, linear polyethylene, porous tube. The blower was a Clements CADILLAC QUIK-VAC, Model F-10, which was used as both a blower and a vacuum source; the maximum capacity of the blower was 44.8 liters/sec. In later tests, the blower was removed from the system and a connection to a high pressure air supply on the lab bench was substituted.

The blower-end of the porous tube was sealed with a rubber stopper. A porous spacer was fitted between the tubes at the blower-end and a solid spacer was used at the terminal-end of the tubes. This arrangement forced the air leaving the blower to flow into only the annular space, through the pores of the inner tube, and finally out the end of only the porous tube. The spacers also provided a uniform annular spacing.

The terminal-end of the transport tube was attached to the upper portion of a large plastic collection bottle; the attachment was such that the air entered the top of the bottle tangentially to produce a centrifugal swirling or cyclonic action within the bottle. An exhaust tube was force-fitted into the mouth of the bottle; the inlet of this exhaust tube was located well below the tangential inlet to prevent short-circuiting of transported materials. A feed tube near the blower-end of the system was positioned through the annulus and attached to the inner, porous tube; this permitted feed materials to enter only the inner tube. The blower speed was regulated by a conventional

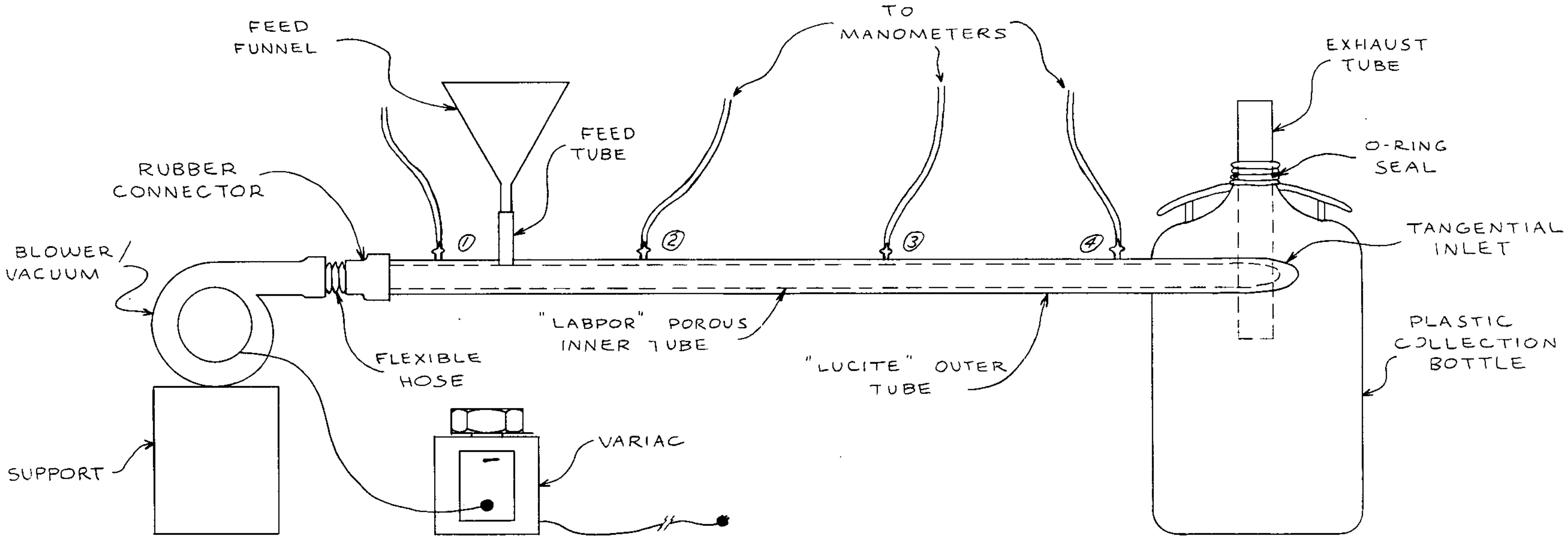


Figure 9. INITIAL LABORATORY TEST APPARATUS SCHEMATIC — POROUS-PNEUMATIC WASTE TRANSPORT SYSTEM

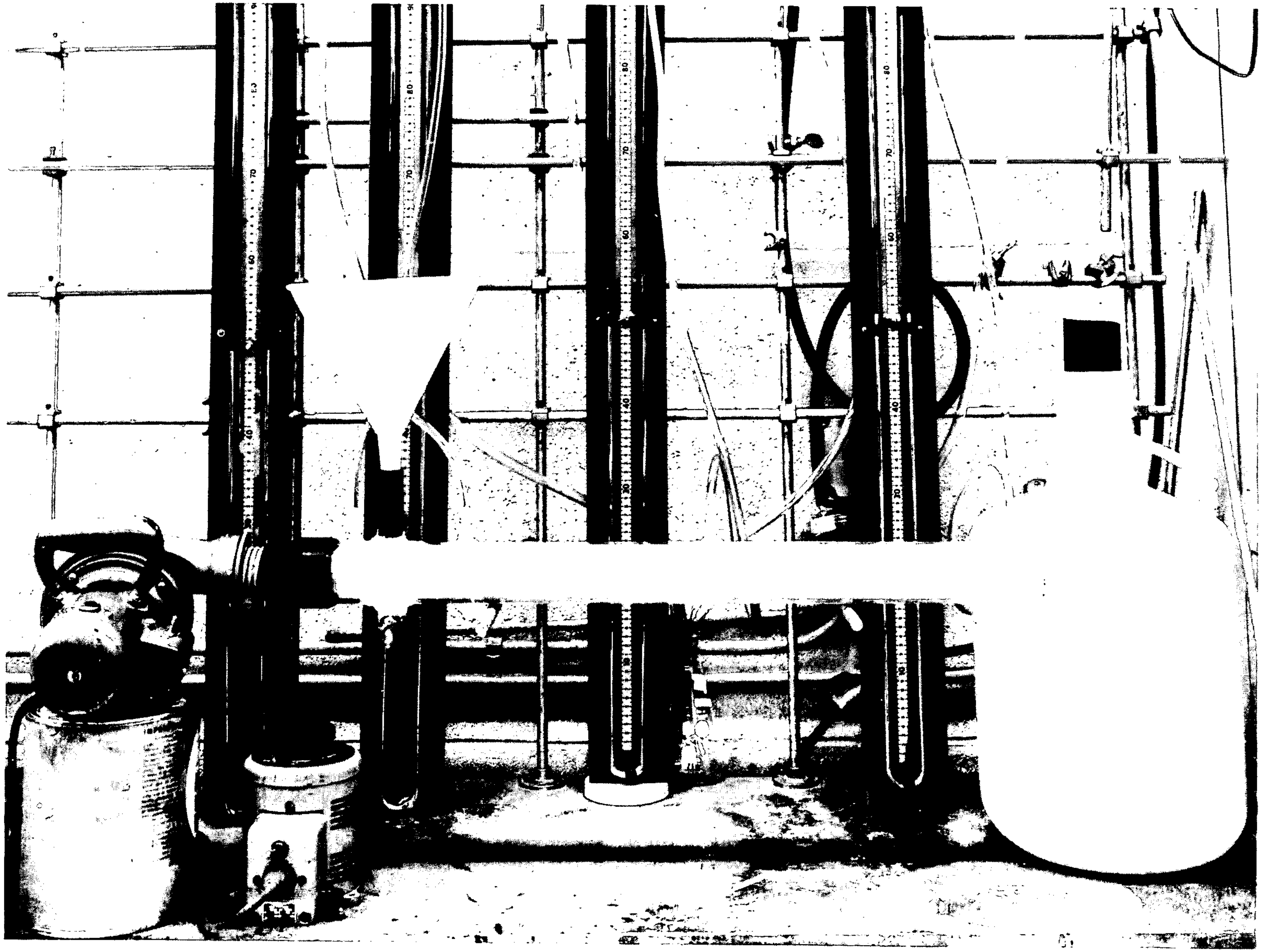


Figure 10. INITIAL LABORATORY TEST APPARATUS -- POROUS-PNEUMATIC WASTE TRANSPORT SYSTEM

Variac. All items were force-fitted together and sealed with SILASTIC.

Three dry feed materials were used in the initial tests: MICROTHENE (finely divided polyethylene powder -- approximately 30-50 micron particle size), WEDRON (ashtray or banksand -- approximately 100-200 micron particle size), and alumina chips (approximately 1-2 mm particle size).

In most of the initial tests, only the polyethylene powder was transported from the feed tube to the collection bottle; partial transport of the other feed materials was also obtained in some tests. Table 1 is a summary of the results obtained with a 4.2 cm I.D., 10-micron pore size tube and an annular space of 0.08 cm.

3.1.2 Determination of System Characteristics

The initial tests described above were not satisfactory since neither particle suspension nor adequate particle transport were experienced. Therefore, it was decided to study the characteristics of the porous-pneumatic concept in greater detail by employing small, simple test set-ups to determine what approaches would be best to develop a workable system. Specific testing objectives included determination of pore size, pore spacing, volumetric air flow, and pressure required to create an air cushion and thereby suspend various materials, particularly liquids.

A 70-micron pore size, 0.48-cm thick, porous plastic disc was sealed on a flanged cylinder. Compressed air was admitted to the cylinder through the bottom as shown below:

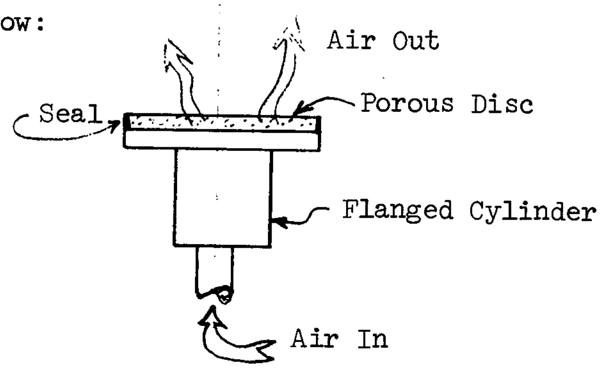


Table 1. INITIAL LABORATORY TEST RESULTS OF POROUS-PNEUMATIC WASTE TRANSPORT SYSTEM (10 μ PORE -- 0.08 cm ANNULUS)

TEST NO.	BLOWER STATUS			LAB AIR			FEED TUBE STATUS	MANOMETER READINGS + (mm Hg)				FEED MATERIAL**	RESULTS
	BLOWING	SUCKING	SPEED	ON	OFF	PRESSURE (atm)		1	2	3	4		
1	X		Maximum		X	--	Open	--	--	--	--	A, B, C	A, B blown out of feed tube
2		X	Maximum		X	--	Open	2*	8*	9*	10*	A, B, C	A, B, C rapidly transported
3		X	Maximum		X	--	Plugged	12*	23*	23*	24*	A, B, C	A mostly transported B, C partially transported
4	X#	X#	Maximum		X	--	Plugged	20	9	8	6	A, B, C	Same as test No. 3
5	--	--	--	X		5.5	Plugged	41	17	17	15	A, B, C	A, B, C partially transported
6		X	Maximum	X		5.5	Plugged	17	11*	12*	14*	A, B, C	A, B, C partially transported
7		X	75% of Max.	X		5.5	Plugged	38	8	8	7	A, B, C	A partially transported
8		X	75% of Max.	X		6.8	Plugged	58	13	15	11	A, B, C	A, B, C partially transported
9	--	--	--	X		6.8	Plugged	72	27	29	25	B (wet)	B mostly transported
10		X	75% of Max.	X		6.8	Open	66	17	20	18	B (wet), C (wet)	B mostly transported C partially transported

\+ See Figure 9 for manometer locations

** A - Finely divided polyethylene powder (30-50 μ)
B - Bank sand (100-200 μ)
C - Alumina chips (1-2 mm)

* Vacuum

Closed-loop condition

Blower: Clements CADILIAC QUIK-VAC Model F-10 (44.8 liters/sec maximum capacity)

Porous tube I.D.: 4.2 cm

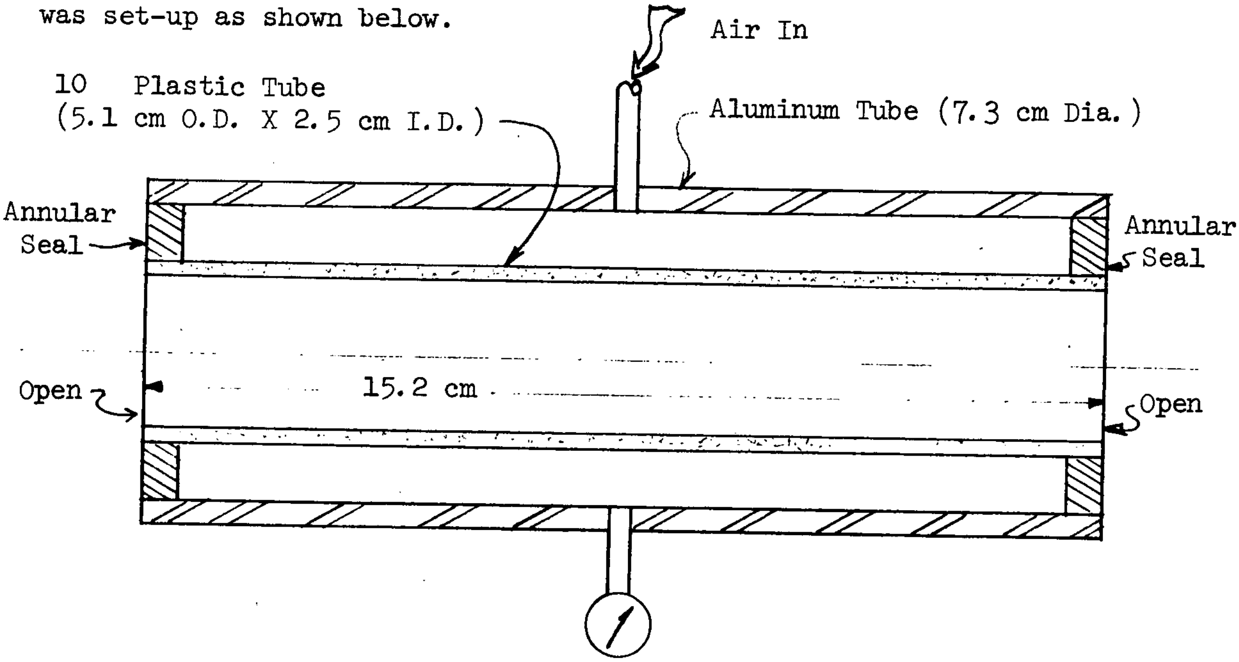
With the air flowing at 3.3 liter/sec, a pressure of 7.4 mm Hg was developed within the cylinder. This air flow, which was approximately 0.07 liter/sec/cm^2 of porous surface, was able to float smooth solid objects with densities up to 6 g/cc. Water placed on this disc readily foamed and eventually evaporated.

A 2.5-cm diameter disc, cut from the above porous plastic material was fitted into a 2.5-cm TYGON tube. Air was then blown through the tube at 2.4 liter/sec, or 0.49 liter/sec/cm^2 of porous surface; this developed an upstream air pressure of 51 mm Hg. Again, water placed on the porous disc foamed and wetted the disc; no air cushion was detected.

A 2.5-cm diameter, 0.64-cm thick disc of 10 micron porous plastic material was then substituted in the above tube. Air blown into the tube at 0.94 liter/sec (0.19 liter/sec/cm^2 of porous surface) developed a pressure of 362 mm Hg. Water drops placed on the porous disc did not foam but appeared to roll around the disc in a semi-stable condition, similar to water beads on a hot plate. Mechanical disturbance of the drops caused them to fragment into small droplets, which retained the semi-stable rolling condition. Although no air cushion could be detected visibly, the semi-stable drop behavior indicated that one was present.

The surface of this 10 micron disc was then impregnated with silicone grease and wiped clean in an attempt to plug a portion of the pores and to provide a more hydrophobic surface. An air pressure of 100 mm Hg was sufficient to prevent water drops from wetting the porous disc. The water drops were shaped in the form of flattened spheres and contained several tiny air bubbles; the presence of an air cushion was clearly indicated in this test. These drops tended to break up slowly, and the resulting droplets were rapidly blown away. Addition of a mild detergent to the water resulted in less-coherent drops, which fragmented more readily; some foaming was also experienced. Drops of raw urine behaved similarly to the detergent-containing water drops. A 100 micron disc impregnated with silicone grease did not perform as well as the 10 micron disc because the developed air pressure was too low.

Since the above 10 micron porous material and air pressure created an air cushion capable of supporting water drops, a 10 micron tubular arrangement was set-up as shown below.



Air was blown into the annulus as shown at 10.4 liter/sec and developed an annular pressure of 413 mm Hg. Water injected into one end of the porous tube was readily broken into small droplets, which were blown out the other end. Although no foaming occurred, some wetting of the porous tube was noted.

When the inner surface of this porous tube was impregnated with silicone grease and wiped clean to plug some of the pores and to provide a more hydrophobic surface, the water drops rolled neatly out. A mixture of dog food and water, containing approximately 20% solids by weight, also rolled out in well-confined drops.

A 60 micron ALUNDUM (aluminum oxide) porous tube, 2.5-cm I.D. x 0.64-cm wall thickness, was also evaluated in this test apparatus. This tube had a low resistance to air flow and a high tendency to absorb water by capillary action. It was not evaluated further.

The above tests indicated that a pore size of 10 microns or less was required to create an air cushion capable of floating liquid droplets. To determine an optimum pore size, three porous stainless steel discs of 0.5 micron, 2 micron, and 5 micron pore sizes were obtained and separately bolted to the flanged cylinder; each disc was 0.16-cm thick.

Performance characteristics of the 2 micron and 5 micron porous discs were similar when drops of water were placed on the discs. A pressure of approximately 260 mm Hg within the flanged cylinder was required to suspend water drops above the disc for both pore sizes. This pressure resulted in air flows of 0.22 liters/sec/cm^2 for the 2 micron disc and 0.37 liters/sec/cm^2 for the 5 micron size.

The 0.5 micron porous disc operated at a much lower air flow (approximately 0.02 liter/sec/cm^2 at 260 mm Hg pressure). At pressures above 780 mm Hg (0.06 liter/sec/cm^2), water drops placed on the 0.5 micron disc fragmented readily and were blown away as a fine mist; at pressures below 780 mm Hg, the water drops merely foamed. Figures 11 and 12 are photographs of water drops on the 2 micron disc with the air pressure at 260 mm Hg. The air cushion suspending the drops is readily detected in these photographs.

Wet dog food chunks placed on these same porous discs flattened on their underside and developed a smooth bottom surface; the dog food was easily suspended above the discs. Figures 13 and 14 are photographs of dog food suspended over the 2 micron disc at 260 mm Hg air pressure; again, the air cushion can be readily seen.

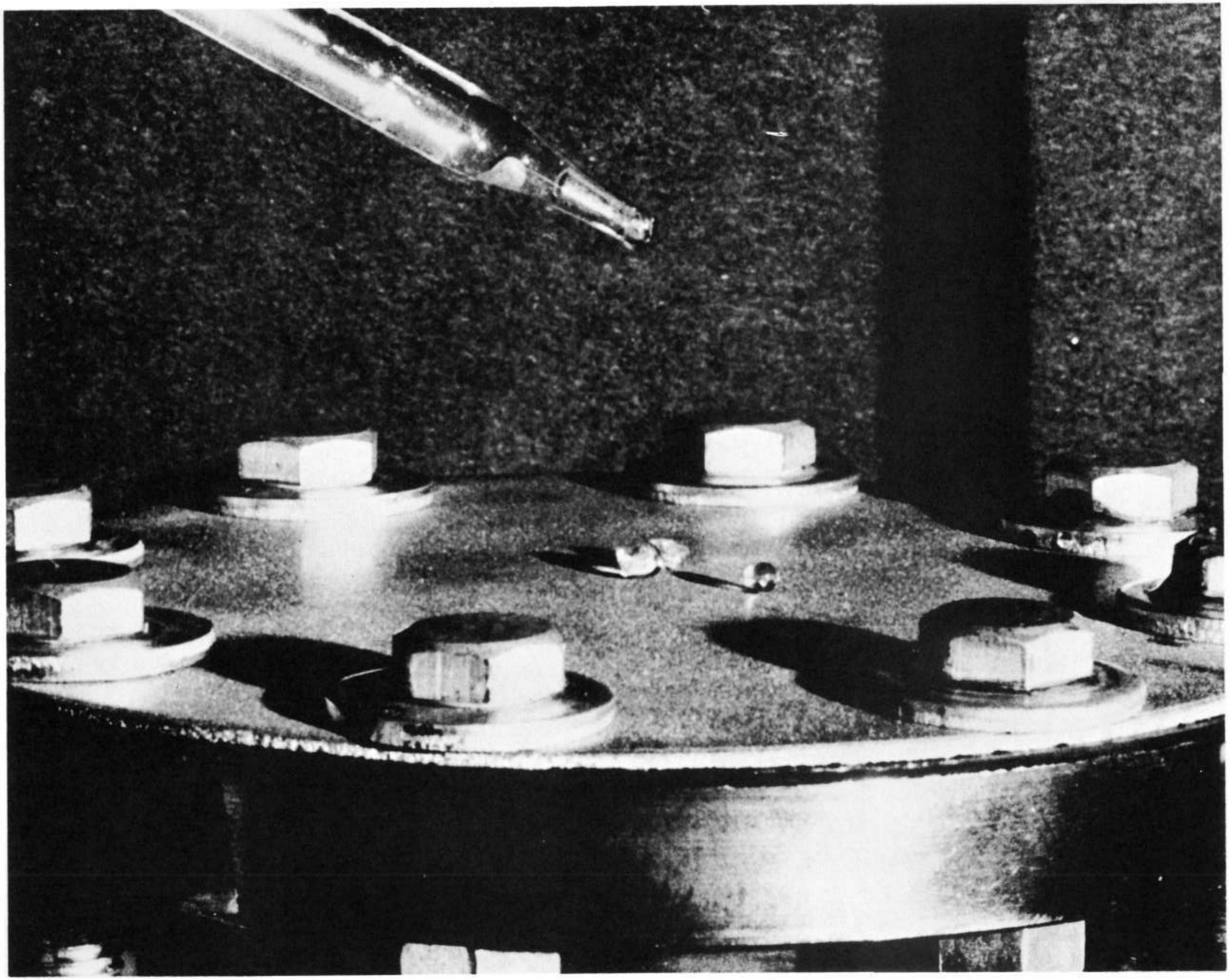


Figure 11. WATER DROPS SUSPENDED ABOVE 2 MICRON POROUS DISC

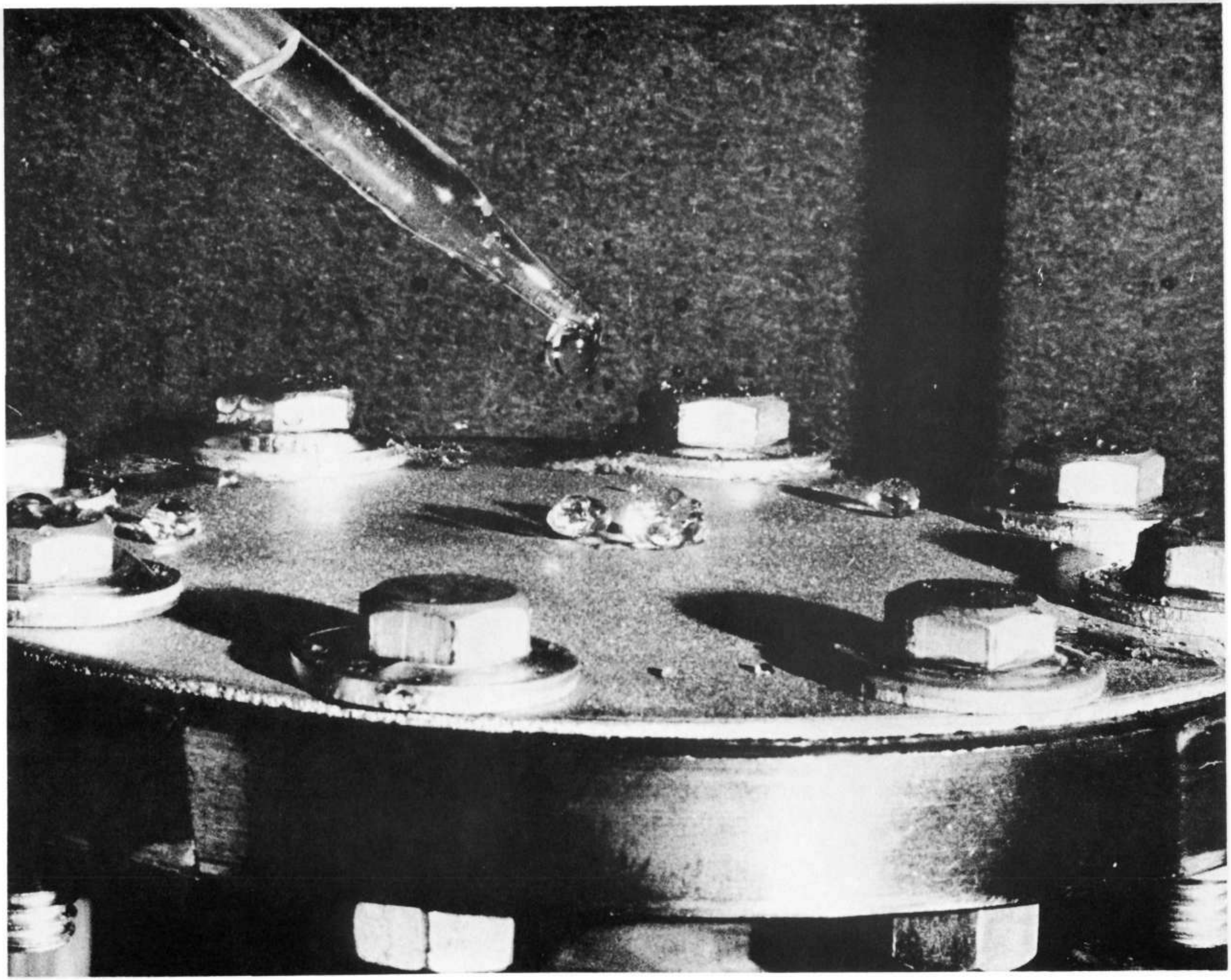


Figure 12. WATER DROPS SUSPENDED ABOVE 2 MICRON POROUS DISC

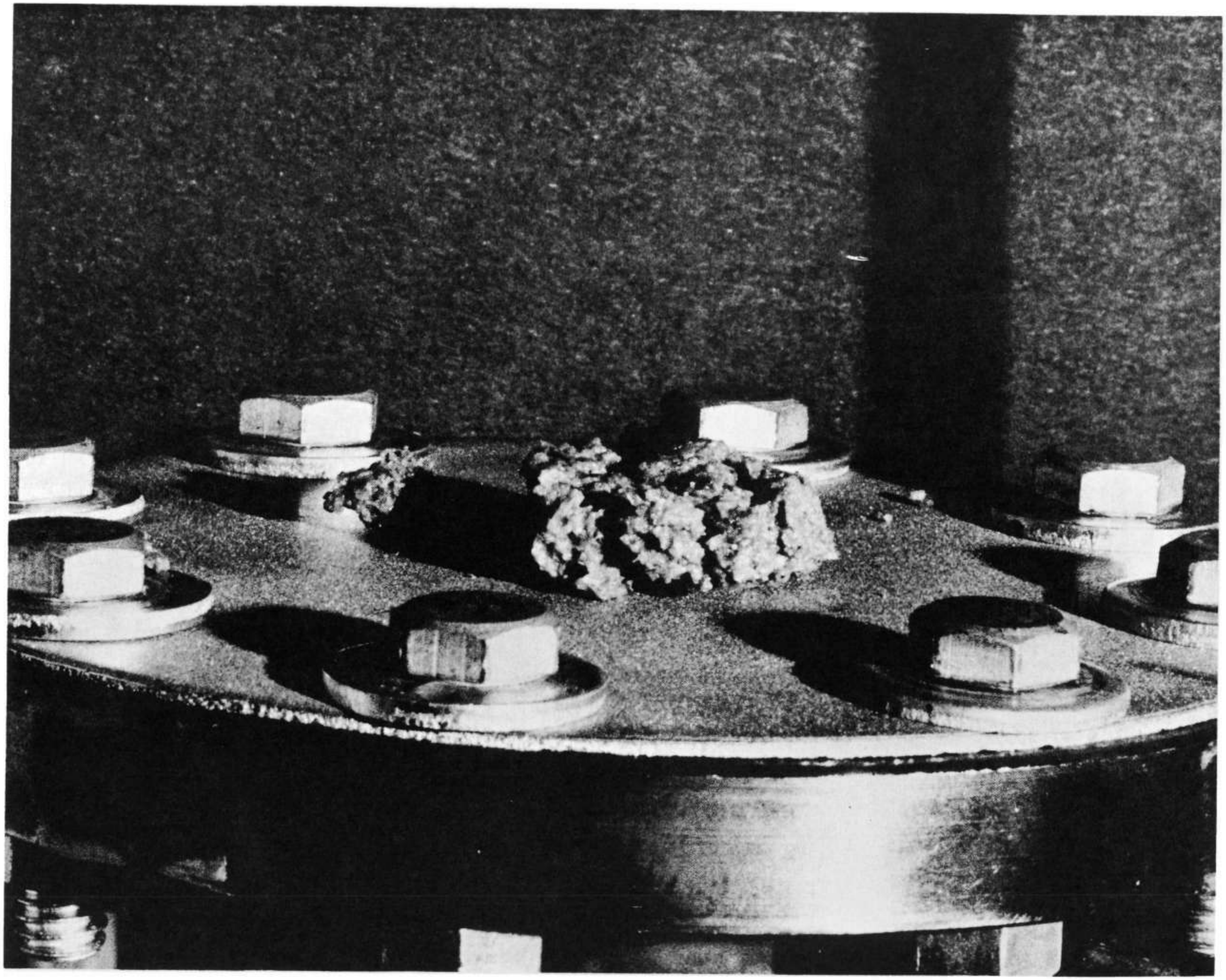


Figure 13. WET DOG FOOD SUSPENDED ABOVE 2 MICRON POROUS DISC

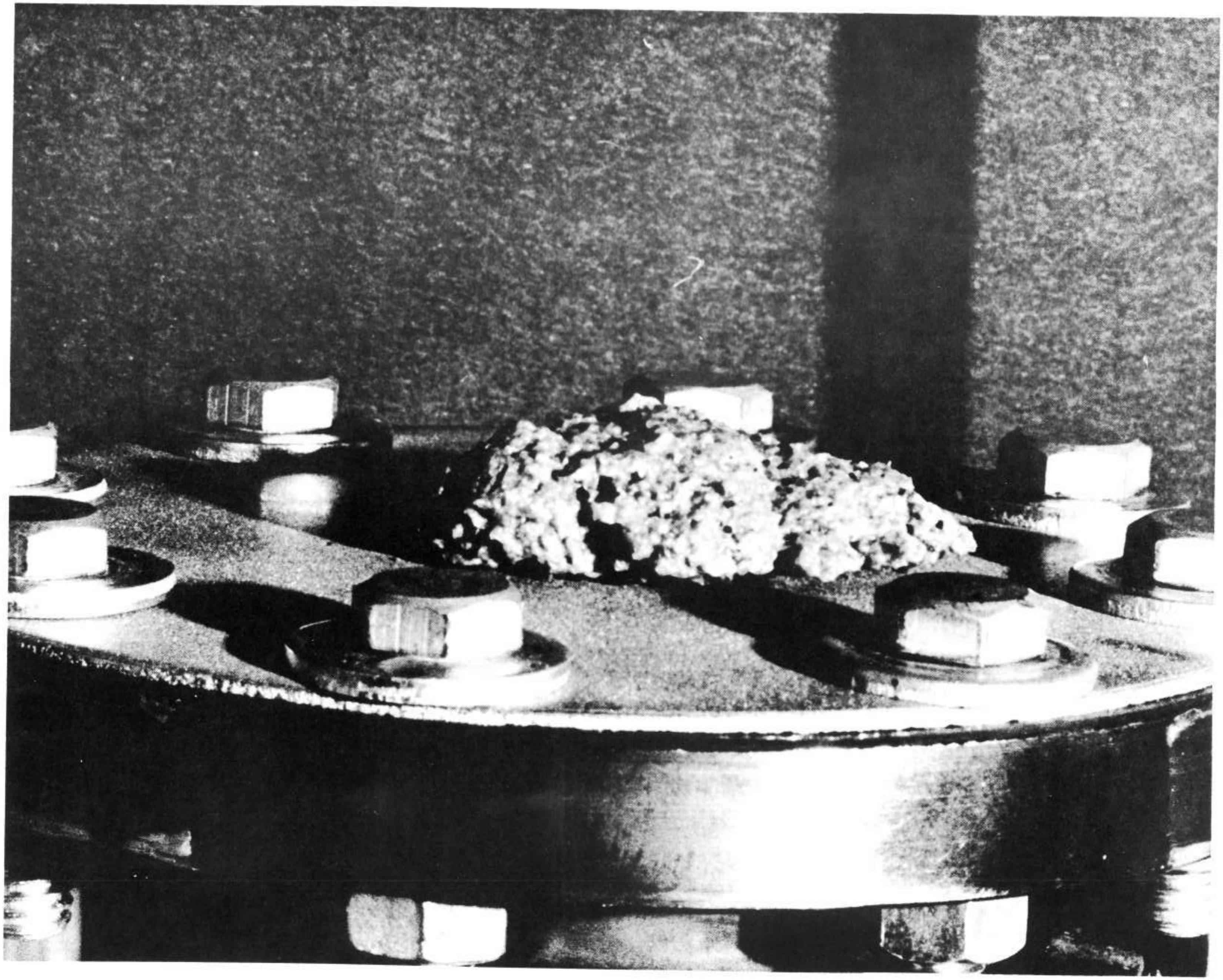


Figure 14. WET DOG FOOD SUSPENDED ABOVE 2 MICRON POROUS DISC

Water placed on the 5 micron disc with an air pressure of 180 mm Hg fragmented easily and did not form the coherent drops like those visible in Figures 11 and 12. An air pressure of 180 mm Hg with the 5 micron disc is equivalent to 260 mm Hg air pressure with the 2 micron disc (approximately 0.22 liter/sec/cm^2). This test indicated that water droplet suspension is a function of both air flow and air pressure.

Based on the above tests with the porous discs, a 2 micron pore size was tentatively selected as the most optimum.

3.1.3 Final Testing with Porous Tubes

To further evaluate the porous-pneumatic transport concept three porous stainless steel tubes of 0.5 micron, 1.0 micron, and 2.0 micron pore sizes were evaluated in the tubular test set-up. Figure 15 is a photograph of this test apparatus. The test section was approximately 11-cm long.

The dimensions of the three tubes are shown below.

Pore Size (micron)	O.D. (cm)	Wall Thickness (cm)
0.5	2.54	0.24
1.0	3.81	0.32
2.0	4.13	0.16

The 0.5 micron and 2.0 micron tubes were obtained from Mott Metallurgical Corp.; the 1.0 micron tube was obtained from New Met Products, Inc. The 2.0 micron tube was made by rolling a porous sheet and seam welding the edges together; the other two tubes were seamless.

With the 0.5 micron tube and 620 mm Hg air pressure in the annulus, some droplet suspension was noted. However, there was considerable foaming of the water and wetting of the tube wall. A high capillary action was also noted as large amounts of water were absorbed by the tube wall. When the air pressure was increased, this absorbed water was forced out of the tube wall as a corase foam.

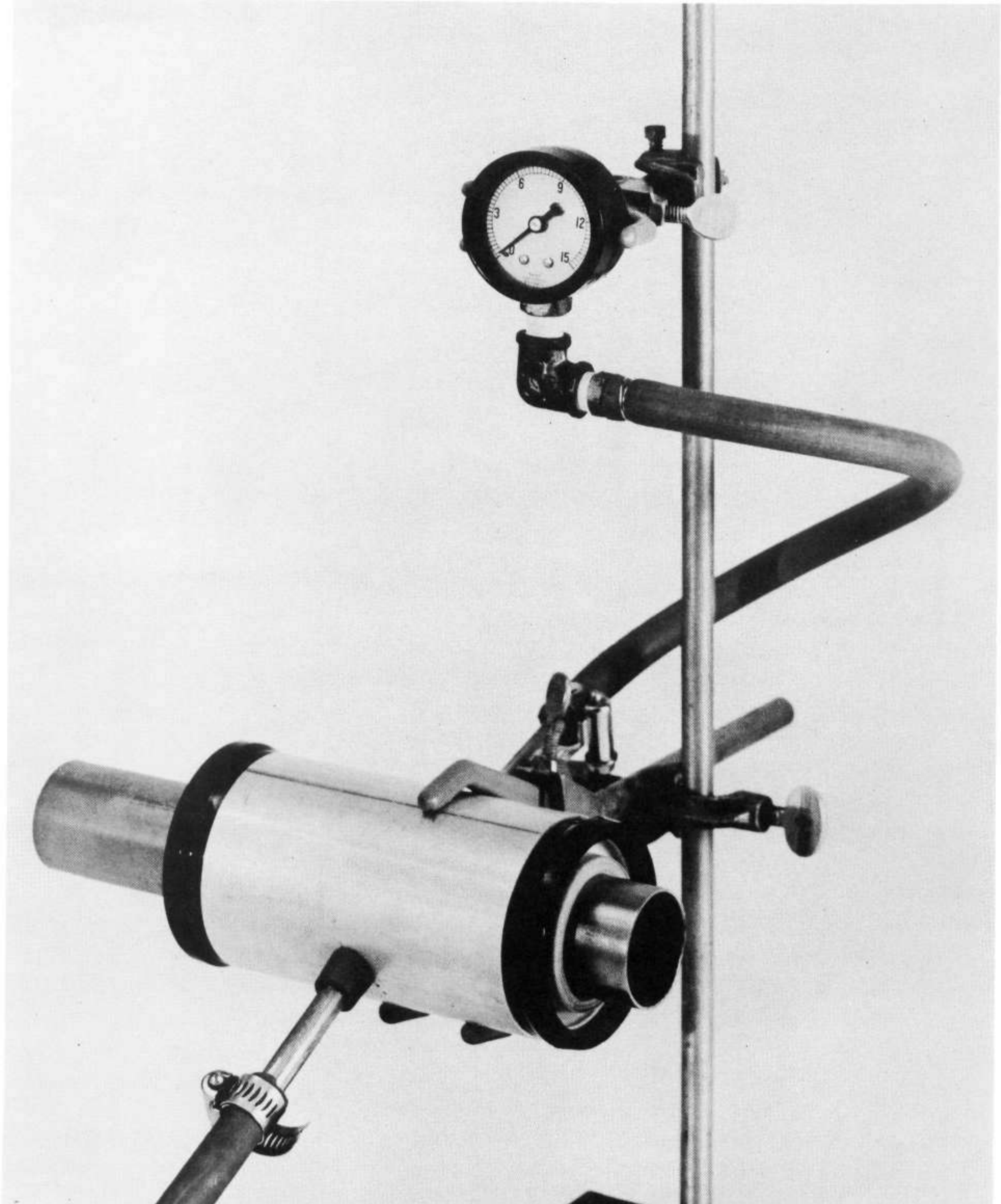


Figure 15. LABORATORY TEST APPARATUS -- POROUS-PNEUMATIC WASTE TRANSPORT SYSTEM

With the 2.0 micron tube and an annular air pressure of 300 mm Hg, water admitted to the tube formed coherent droplets that appeared to be suspended on a thin film of air. There was slight wetting of the tube surface, but little foaming was experienced. A slurry of wet dog food (approximately 25% solids) was placed in the upper end of the porous tube, which was inclined at approximately 15° from the horizontal. Dog food chunks of various sizes slid readily down the tube and did not appear to touch the tube wall.

The relationship between air flow through the porous tube and annular air pressure for the 2.0 micron tube is shown in Figure 16 for air pressures of 104, 156, 208, and 260 mm Hg. A bellows-type meter was used to measure the air flow.

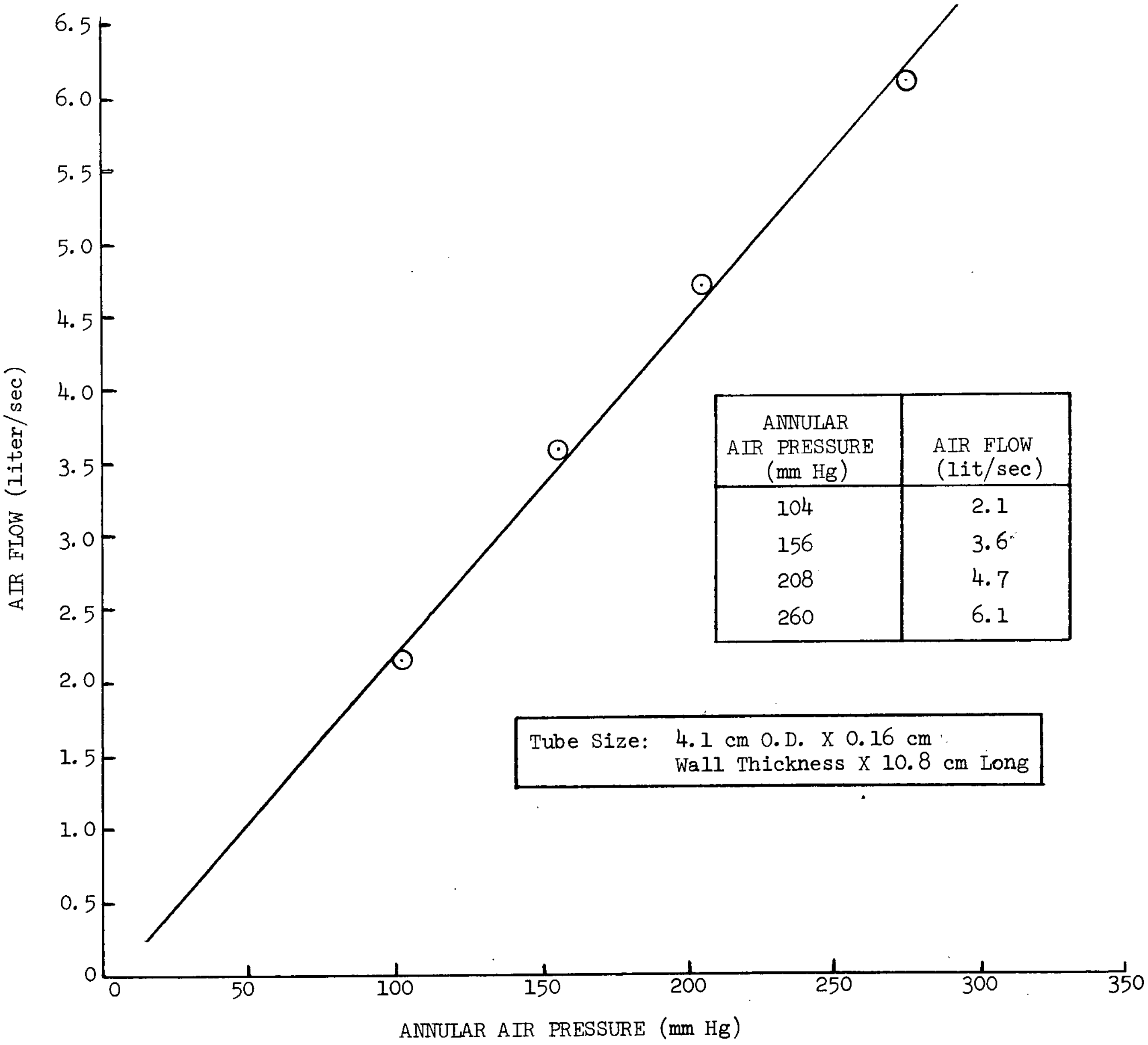
The data from Figure 16 shows that the actual air flow-pressure relation for the 2.0 micron tube was approximately 0.22 liter/sec/mm Hg. Manufacturer's data applied to this size tube resulted in an air flow-pressure relation of 1.28 liter/sec/mm Hg. Apparently the process of rolling and seam welding porous tube resulted in the closing of a portion of the pores. Despite this reduction in flow capacity, the 2 micron porous tube appeared to provide a suitable air cushion capable of suspending solids and liquid droplets.

3.2 Nozzle-Pneumatic Waste Transport System

Two similar pneumatic waste transport systems, both using an inner tube containing directional nozzles, were evaluated in the laboratory. The systems were identical except for the size and number of nozzles.

3.2.1 Initial Laboratory Testing

The initial nozzle-containing tube was fabricated from a 5.1-cm O.D. x 4.5-cm I.D. clear LUCITE tube. The nozzles, which were actually small holes of constant diameter through the tube wall, were equally spaced around the circumference of the tube and along the tube's length. There were 48



ANNULAR AIR PRESSURE (mm Hg)	AIR FLOW (lit/sec)
104	2.1
156	3.6
208	4.7
260	6.1

Tube Size: 4.1 cm O.D. X 0.16 cm Wall Thickness X 10.8 cm Long

Figure 16. AIR FLOW THROUGH 2.0 MICRON POROUS TUBE AS A FUNCTION OF ANNULAR AIR PRESSURE

circumferential rows, each containing 17 holes; the axial distance between these rows was 0.64-cm. The circumferential distance between a hole in one row and a hole in the next row was 0.25-cm. The holes were approximately 0.065-cm in diameter and were positioned through the tube wall at a 15° angle from the horizontal. Figure 17 is a sketch of this initial arrangement.

The entire tube was mounted in a 6.4 cm I.D. LUCITE tube and an annular spacer/seal was fitted at each end. Air was blown into the annulus by a blower at 3.8 liter/sec and 2.8 mm Hg pressure. Water placed in the inlet-end of the tube was slowly moved along the length of the tube. A portion of the water contacted the inner surface of the nozzled tube and was given a "push" forward each time it passed over a nozzle; the remainder of the water was blown out of the tube as a mist or spray.

Due to the momentum of the air moving through the nozzles, the tube performed similar to an air ejector; that is, outside air was sucked into the opened, inlet of the nozzled tube. With 3.8 liter/sec flowing in the annulus, approximately 2.8 liter/sec of outside air was drawn into the tube.

3.2.2 Final Laboratory Testing

Since a portion of the water entering the above nozzled tube contacted the tube wall, a second nozzled tube was fabricated to overcome this problem. It was believed that there was too much space between the nozzles of the initial tube and that more nozzles of a smaller diameter would prevent water from contacting the tube surface.

The modified nozzled tube was also fabricated from a 5.1 cm O.D. x 4.5 cm I.D. LUCITE tube. As before, the nozzles were equally spaced around the circumference of the tube and along the tube's length. Each circumferential row contained 25 holes; the axial distance between each row was 0.48 cm. The circumferential distance between a nozzle in one row and a nozzle in the next

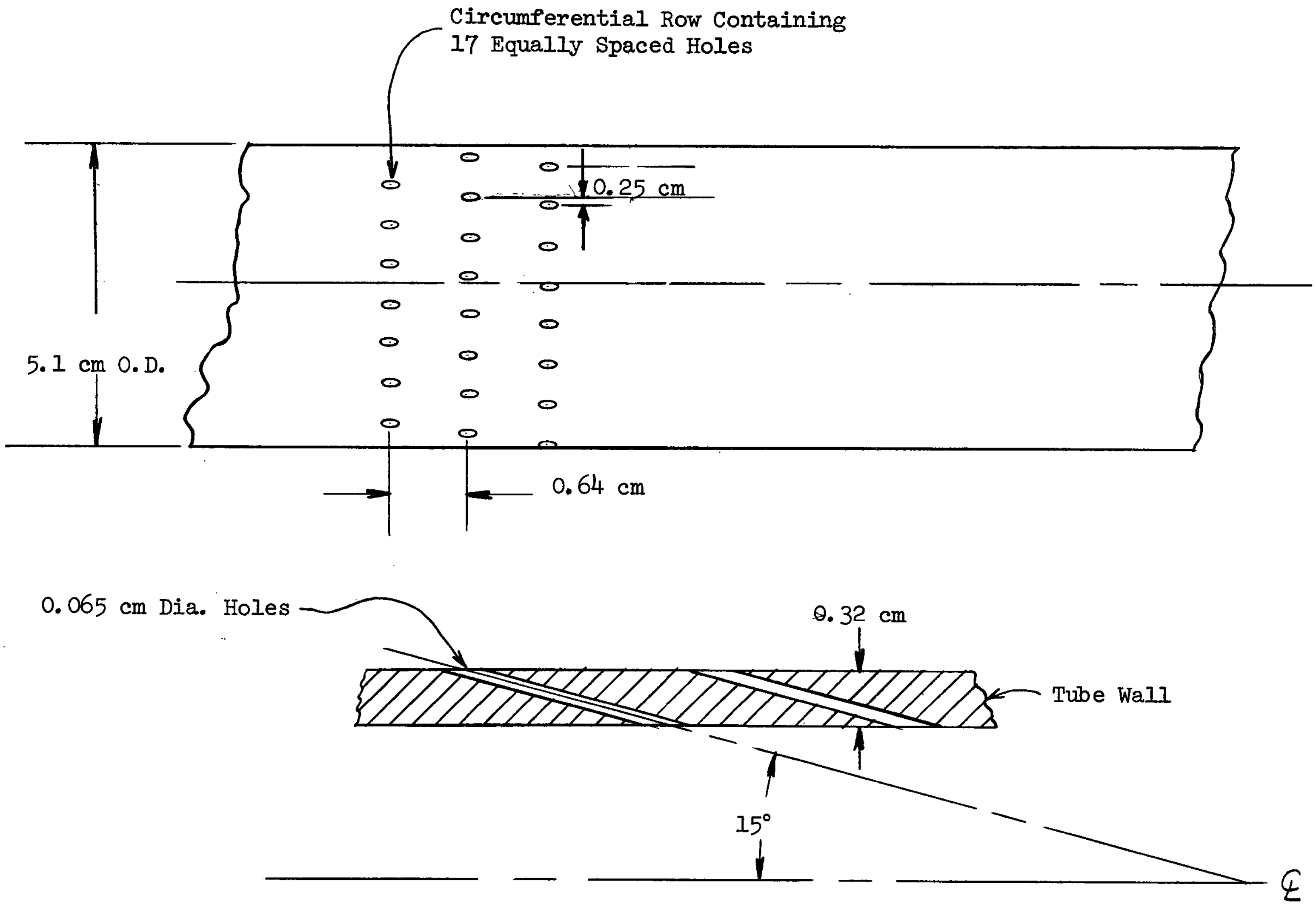


Figure 17. SKETCH OF INITIAL HOLE ARRANGEMENT FOR NOZZLE-PNEUMATIC WASTE TRANSPORT SYSTEM

row was 0.25 cm. The initial three-fourths of the nozzle length was 0.08 cm in diameter; the remaining one-fourth was 0.03 cm in diameter. As before, the nozzles were positioned through the tube wall at a 15° angle from the horizontal. A sketch of a single nozzle is shown below.

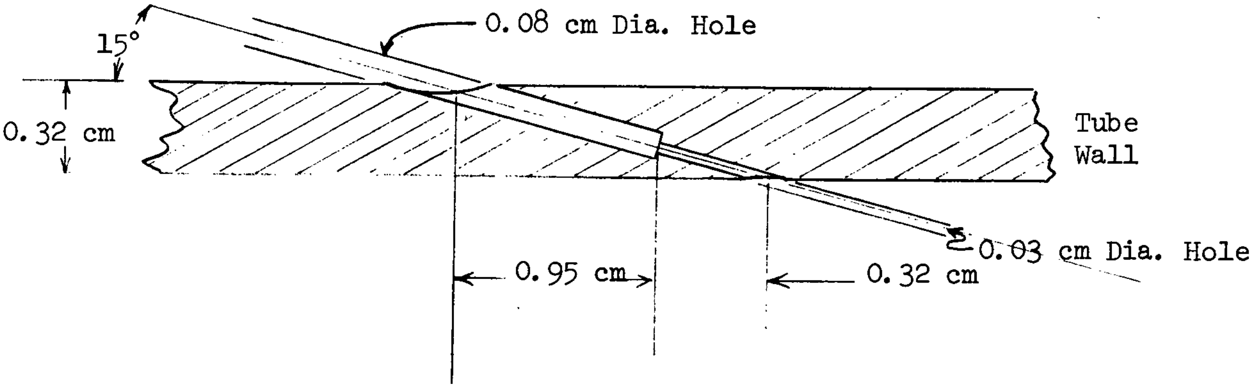


Figure 18 is a close-up view of this nozzled tube.

To determine the operating characteristics of the new nozzled tube, a series of tests were performed with the tube positioned in the test apparatus shown in Figure 15.

The first series of tests was designed to determine air flow through the nozzles as a function of annular air pressure. All but four rows (100 nozzles) were covered with tape and the inlet of the nozzled tube was stoppered. Air leaving the tube was measured with a positive displacement gas meter. Annular air pressure was varied from 52 mm Hg to 520 mm Hg. The results of these tests are summarized in Table 2 and are shown graphically in Figure 19. In Figure 19 the measured air flow was divided by 100 to obtain the air flow per nozzle.

The second series of tests was designed to measure the amount of air induced into the tube by the nozzle configuration. The induced air flow was determined by measuring the linear air velocity at the tube inlet with a hot-wire anemometer. To facilitate this measurement, a diverging cuff was positioned over the tube inlet to provide a larger cross-sectional area. Air

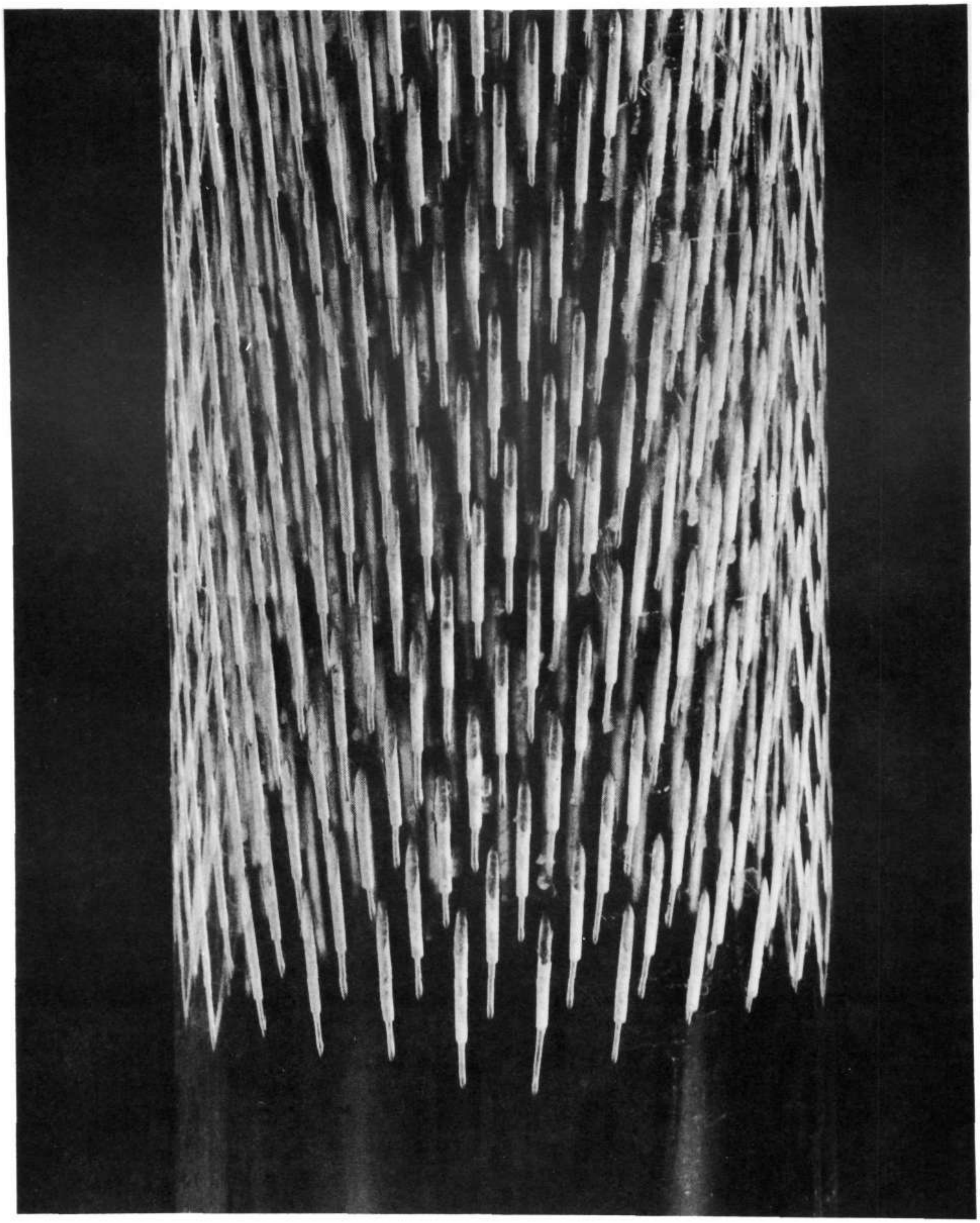


Figure 18. CLOSE-UP VIEW OF MODIFIED NOZZLE-PNEUMATIC WASTE TRANSPORT SYSTEM TUBE

Table 2. NOZZLE AIR FLOW AS A FUNCTION OF ANNULAR AIR PRESSURE FOR 100 NOZZLES

AIR PRESSURE IN ANNULUS (mm Hg)	MEASURED AIR FLOW (liter/sec)
52	0.71
104	1.42
156	1.89
208	2.20
312	2.74
416	3.31
520	3.85

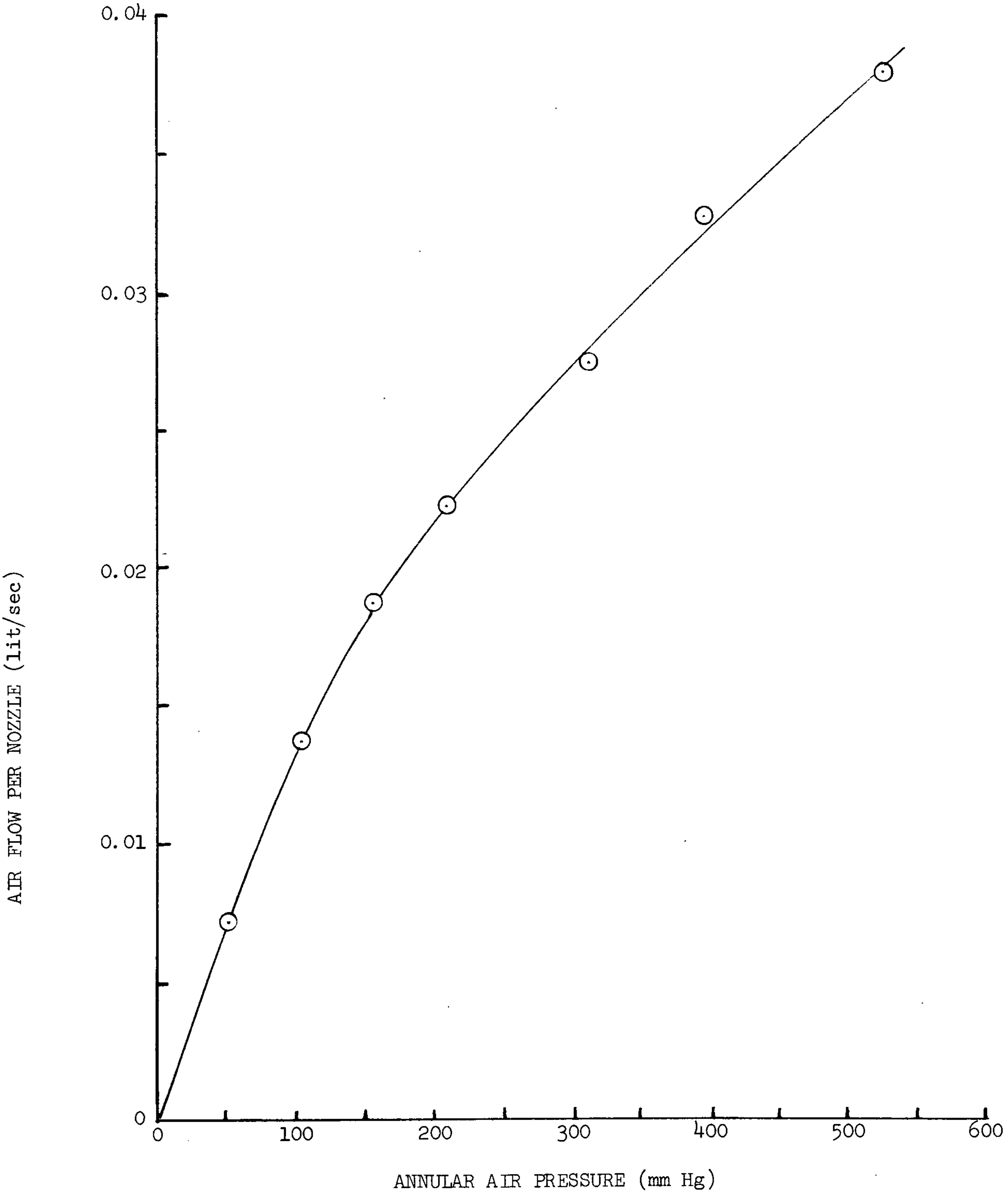


Figure 19. AIR FLOW PER NOZZLE AS A FUNCTION OF ANNULAR AIR PRESSURE

flow into the tube was calculated as the product of the cuff inlet area and the measured linear air velocity. Also, the developed suction pressure at the tube inlet was measured by stoppering the inlet and connecting the stopper to a manometer.

Measurements were made at annular air pressures ranging from 52 mm Hg to 624 mm Hg with 1, 4, and 21 rows (25, 100 and 525 nozzles) uncovered. Test results are summarized in Table 3. The previous data for air flow per nozzle were used to calculate the total air flow supplied to the annulus and entering the tube through the nozzles. The data of Table 3 are plotted in Figure 20 as total air flow induced vs. supplied air flow. Table 3 also presents a tabulation of annular pressure times supplied air flow; this provides a measure of the p-V work done in forcing the air through the nozzles. This p-V work is plotted in Figure 21 as a function of induced air flow.

The data from these tests indicate that for a given amount of induced air, a relatively large amount of air at a low pressure must be supplied to the nozzles if a large number of nozzles is used, but a small amount of supplied air at a higher pressure is required if the number of nozzles is small. Also, for a given amount of induced air, the p-V work term indicates that the tube with the fewest nozzles is the most efficient. For example, if it is desired to induce 12.75 liter/sec of air, a tube containing 25 nozzles (1 row) must be supplied air at 0.83 liter/sec and 416 mm Hg pressure, while a tube containing 100 nozzles (4 rows) requires air at 2.74 liter/sec and 208 mm Hg pressure; approximately 33% more work is done in the latter case.

The ability of the modified nozzled tube to transport water and dog food slurries was also evaluated. With an induced air flow of approximately 8 liter/sec, the entrained air was able to move water and a dog food slurry slowly along the tube; however, the air leaving the nozzles did not suspend

Table 3. OPERATING CHARACTERISTICS OF MODIFIED NOZZLED TUBE

NUMBER OF NOZZLES EXPOSED	ANNULAR AIR PRESSURE (mm Hg)	TOTAL AIR FLOW THROUGH NOZZLES (mm Hg)	INDUCED AIR FLOW (lit/sec)	SUCTION PRESSURE (mm Hg vac)	P-V WORK (Column 2 x Column 3)
25 (1 row)	52	0.18	2.12	--	9.4
	104	0.35	4.25	--	36.4
	156	0.47	6.04	--	73.3
	208	0.55	7.78	0.71	114
	312	0.68	10.30	0.94	212
	416	0.83	12.75	1.06	345
	520	0.96	14.55	1.41	500
	624	1.11	16.75	1.88	693
100 (4 rows)	52	0.71	3.73	--	36.9
	104	1.42	7.50	0.71	148
	156	1.89	9.73	1.18	295
	208	2.19	12.75	2.23	455
	312	2.74	15.25	2.35	855
	416	3.30	18.20	3.29	1370
	520	3.85	23.00	4.24	2000
525 (21 rows)	52	3.73	7.08	0.71	194
	104	7.45	13.70	3.29	775
	156	9.90	19.36	4.00	1545
	208	11.38	23.60	8.46	2360

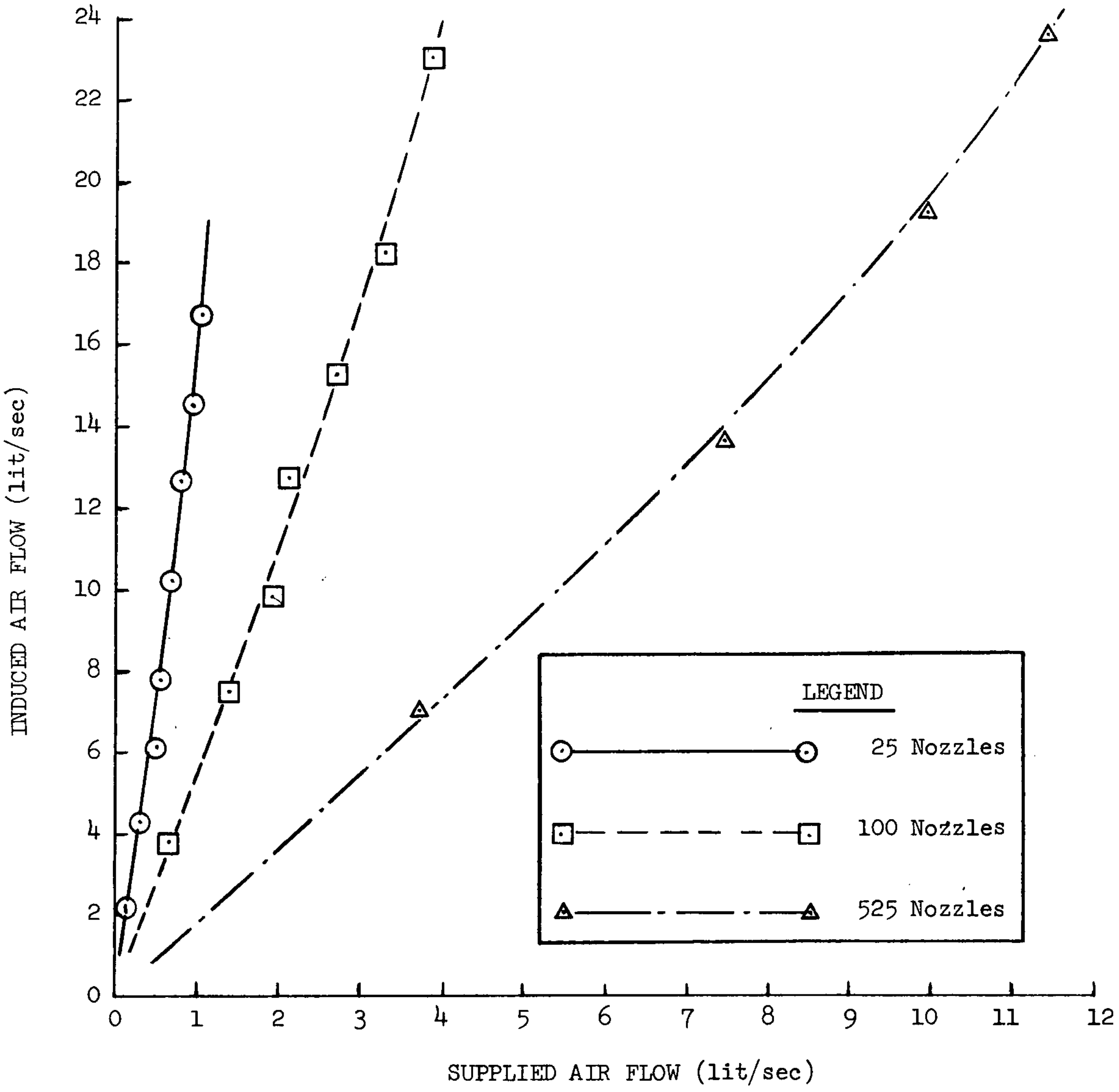


Figure 20. INDUCED AIR FLOW AS A FUNCTION OF SUPPLIED AIR FLOW AND NUMBER OF NOZZLES

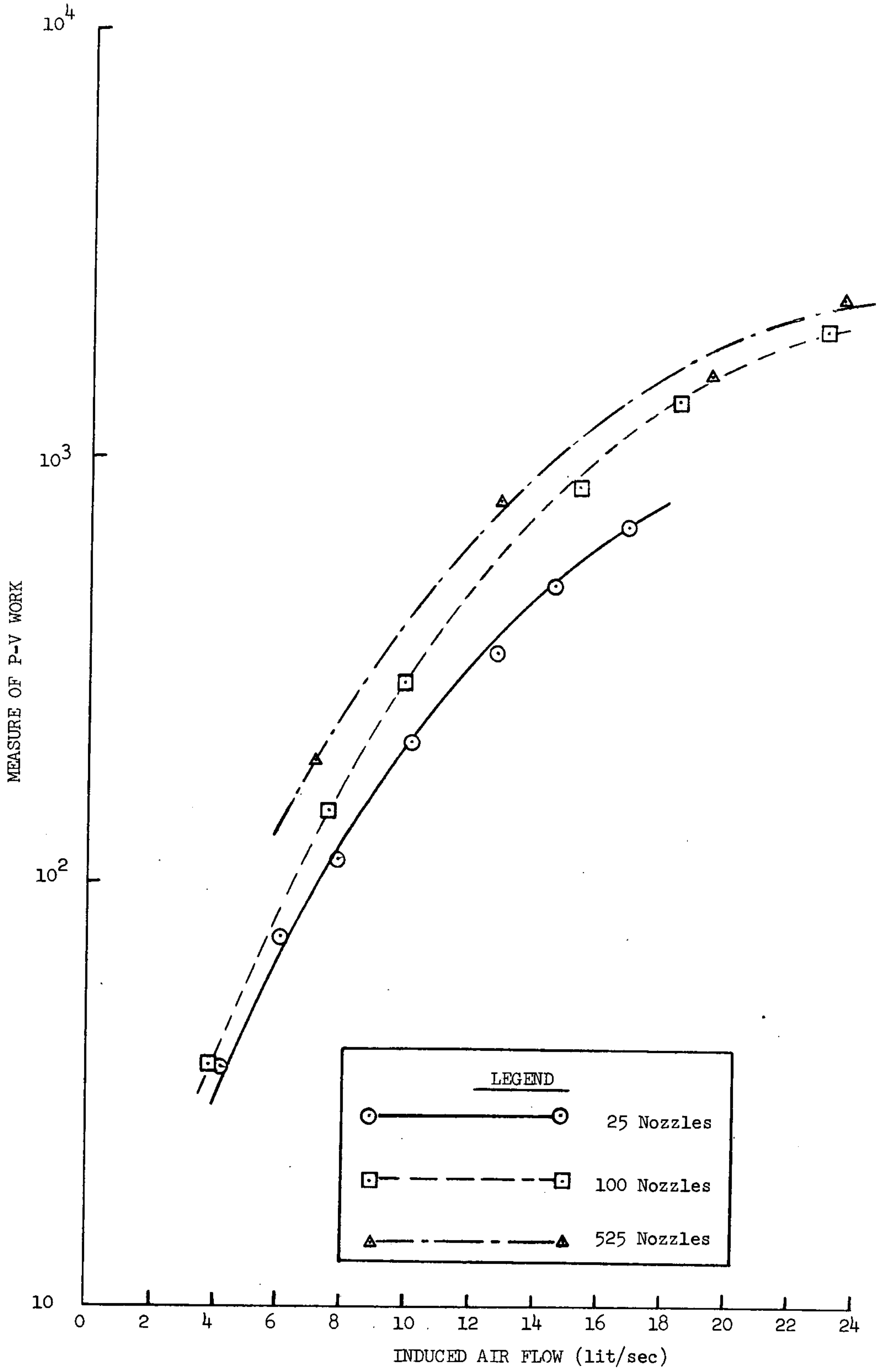


Figure 21. MEASURE OF P-V WORK REQUIRED TO OBTAIN INDUCED AIR FLOW AS A FUNCTION OF NUMBER OF NOZZLES

the feed materials, although it did minimize the amount of material adhering to the inner surface of the tube.

3.3 Screw-feed Waste Transport System

3.3.1 Design

The design of the laboratory model of the screw-feed waste transport system was changed from the modified concept described in Section 2.2.3 to a simplier version for testing and design evaluation purposes; this conserved both time and effort. The simplifications included: 1) elimination of special machined Acme screw threads, 2) placement of the rotation/drive motor outside the outer sealed container before internal temperatures were measured, and 3) use of hand-operated traverse actuating rods to move the incinerator container between hot and cold zones. Thus, temperature profile tests could be performed without building a complete system.

The screw-feed waste transport system consisted of a 50-cm long x 9.5-cm I.D. closed cylinder that was heated at one end. A smaller, concentric incinerator container (15.2-cm long x 8.9-cm I.D.) was made to move within the larger cylinder from a cool position, where wastes would normally be fed into the container, to the heated zone, where the wastes would normally be incinerated. The incinerator container was continuously rotated through a gear train and drive spline by an electric motor to impart zero-gravity capability to the system. A 2.5-cm diameter tube, positioned through the center axis of the system, was used as both a support for the rotating incinerator container, and a waste inlet tube and gas/vapor exhaust line.

Figure 22 is an assembly drawing of the screw-feed system. Figures 23-25 show the various components of the system and Figure 26 is a photograph of the assembled unit.

Initially, wastes would normally be fed to the cool incinerator canister

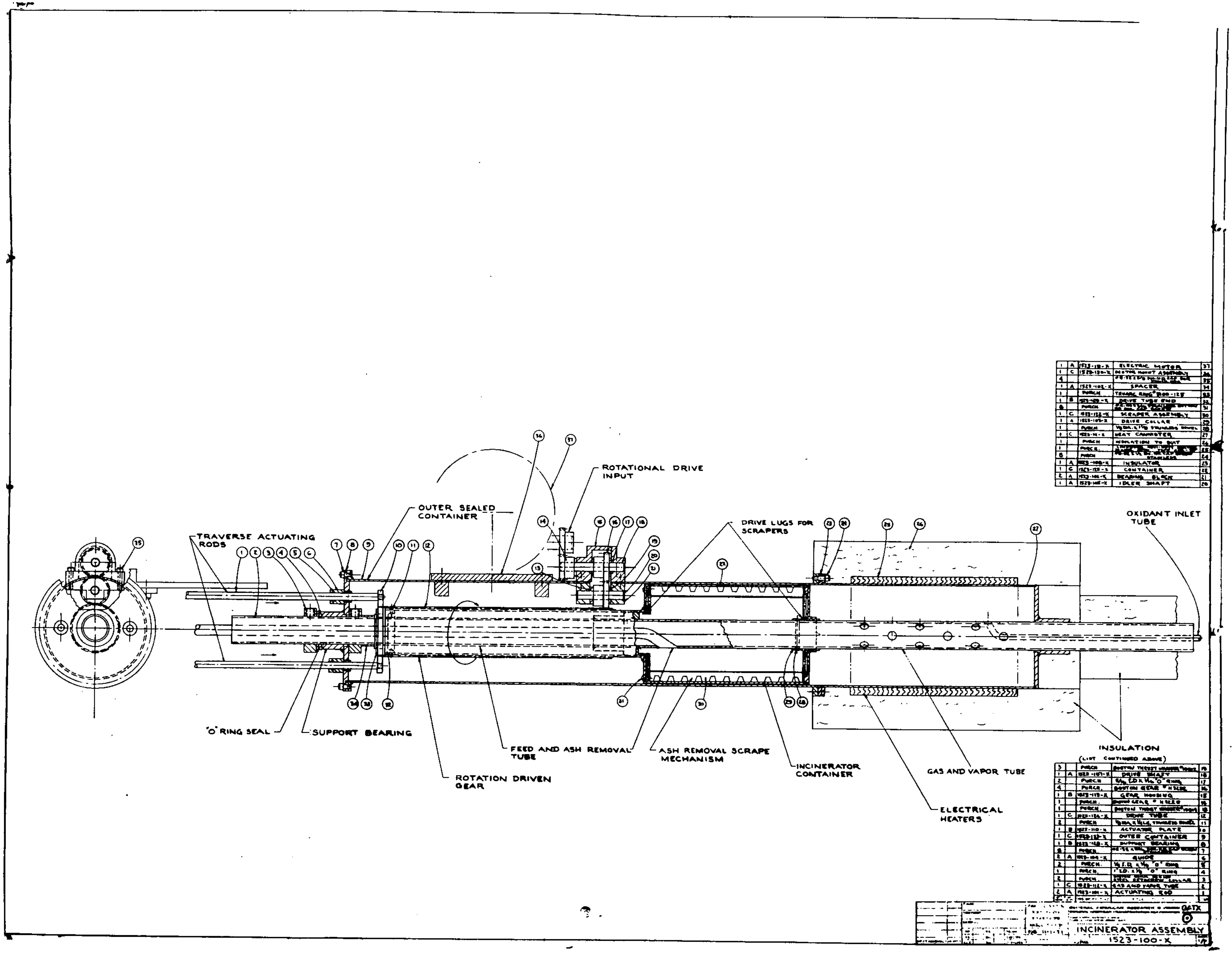


Figure 22. ASSEMBLY DRAWING OF LABORATORY SCREW-FEED WASTE TRANSPORT SYSTEM

Figure 23. SCREW-FEED LABORATORY SYSTEM:
GEAR DRIVE AND INCINERATOR CANISTER

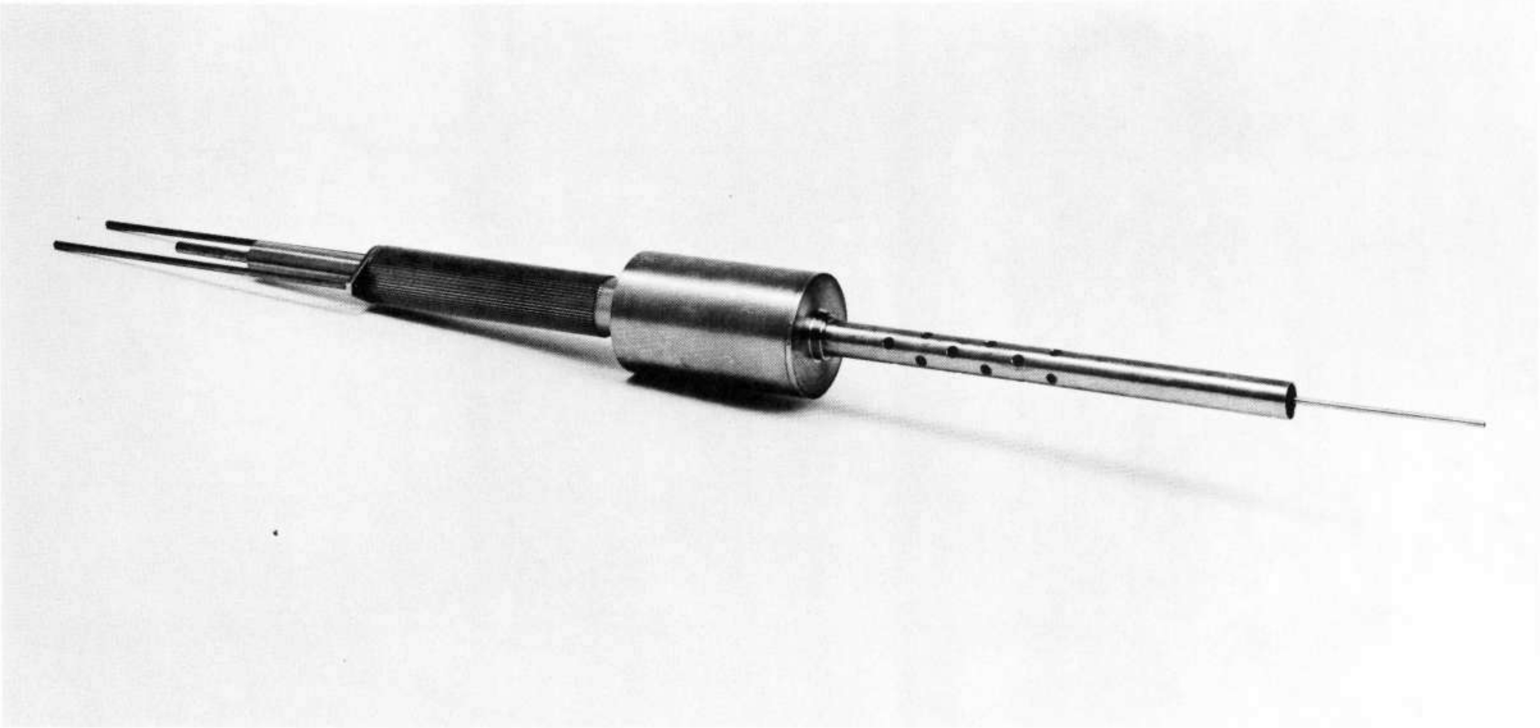


Figure 24. SCREW-FEED LABORATORY SYSTEM:
GEAR DRIVE, INCINERATOR CANISTER,
AND FEED AND EXHAUST TUBE ASSEMBLY

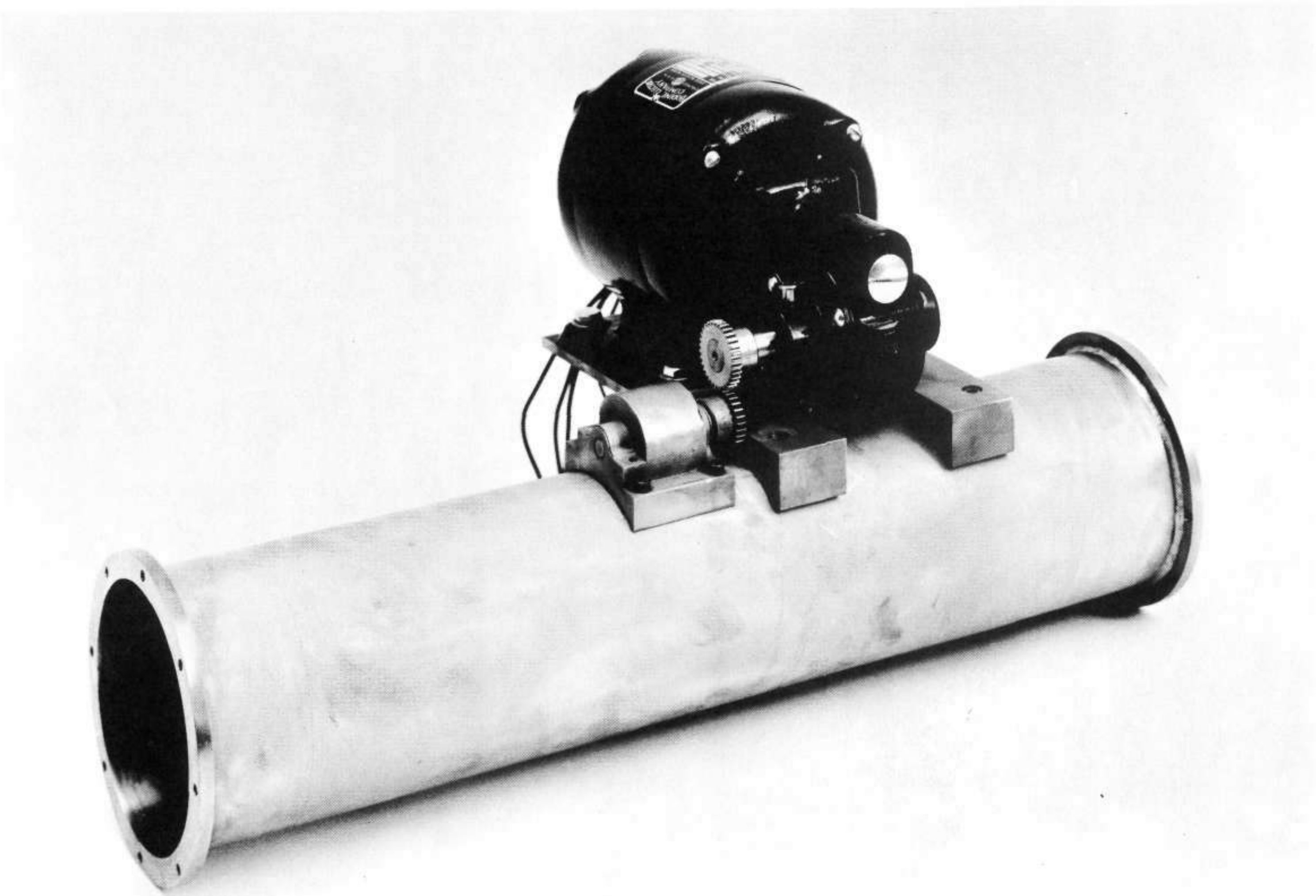


Figure 25. SCREW-FEED LABORATORY SYSTEM: OUTER CONTAINER WITH ROTATIONAL DRIVE MOTOR AND GEAR ASSEMBLY

Figure 26. ASSEMBLED SCREW-FEED LABORATORY WASTE TRANSPORT SYSTEM

through a hollow shaft. Waste feeding would normally be followed by a water rinse to clean the feed tube. The wastes would be constrained to the walls of the canister by the centrifugal force of rotation. After filling of the container, it would be pushed into the hot incineration zone by traverse actuating rods. During incineration vapors and gases would leave through a concentric gas and vapor tube. This tube contained a small internal tube for supplying oxygen to complete the oxidation of wastes during incineration. The tube arrangement is shown in Figure 27. A plug inside the tube separated the waste feed section from the exhaust section.

After incineration, the incinerator container would be pulled back to the cool zone and the ash removed by a vacuum source attached to the feed tube. Scraper blades would dislodge any ash adhering to the walls of the container. The system now would then be ready to start a new incineration cycle.

The screw-fed transport system required special materials of construction to resist corrosion from the wastes and to resist scaling from operating the incinerator at 540°C.

Stainless steel, Type 304, is an acceptable material for all parts in contact with the wastes and not heated above 450°C. Parts that operate above 450°C must be constructed from a stabilized stainless steel that resists carbide precipitation, such as Types 321 or 347. Alternately, super alloys, such as Hastelloy or Inconel, may be used.

The laboratory model screw-feed waste transport system was constructed from Type 316-L stainless steel (a low carbon version of Type 316) instead of Types 321 or 347 for the heated parts because the former was more readily available than either stabilized type and the delay that would have occurred did not justify waiting for these materials.

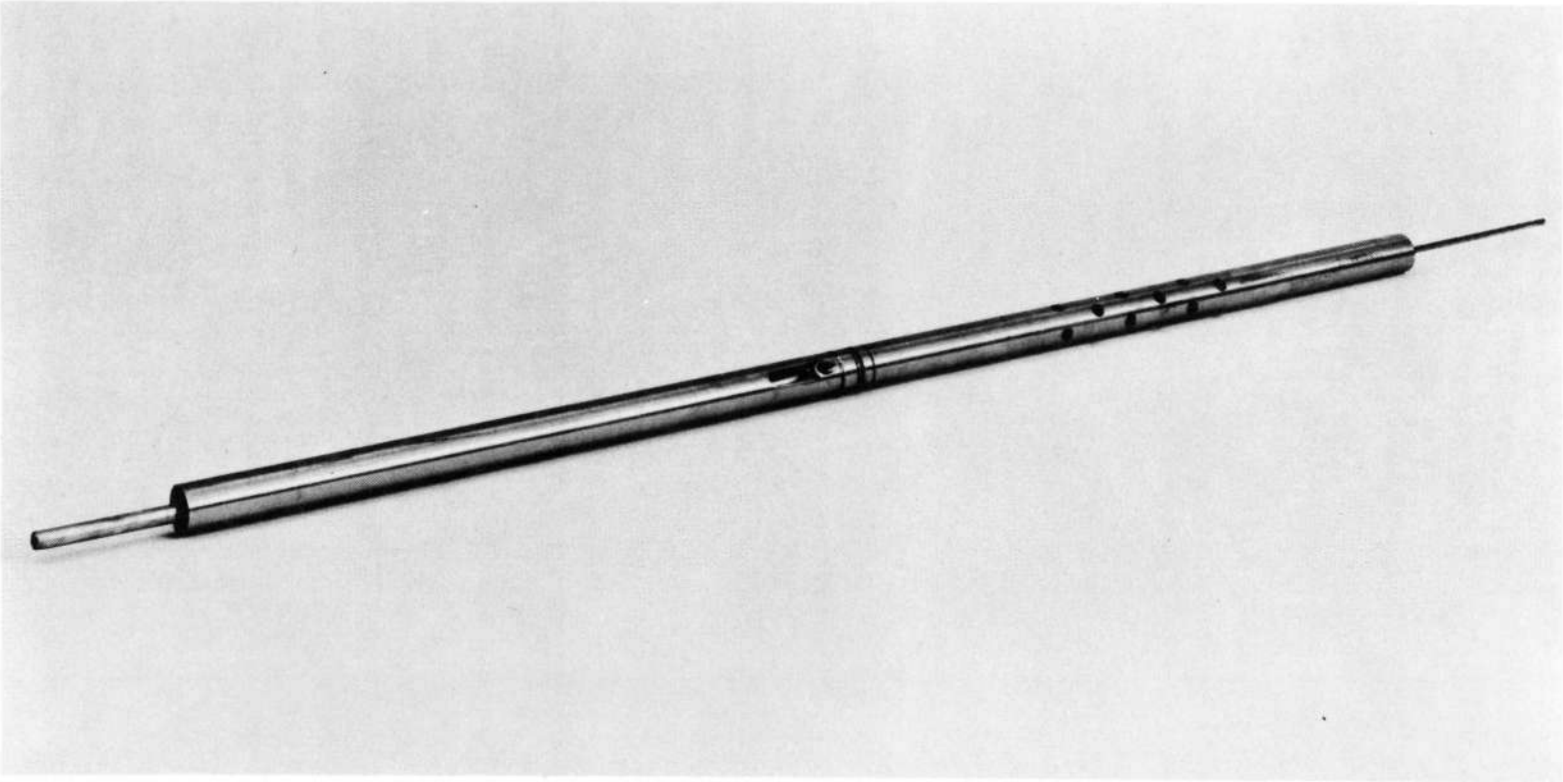


Figure 27 TUBE ARRANGEMENT FOR LABORATORY SCREW-FEED WASTE TRANSPORT SYSTEM

3.3.2 Laboratory Test Results

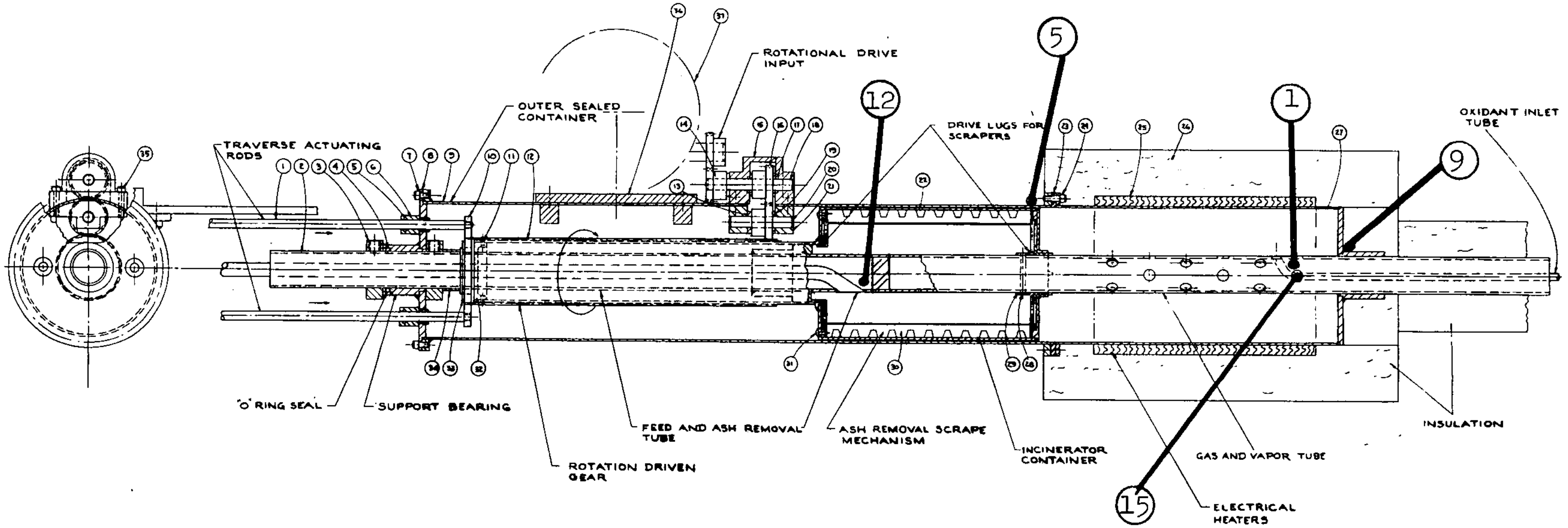
The screw-feed waste transport system was tested to verify operation when the incinerator portion was maintained at 550°C. Five Chromel-Alumel thermocouples were placed in the locations shown in Figure 28; temperatures were recorded on a multipoint recorder. Figure 29 is a photograph of the laboratory test set-up.

The test was conducted in the following manner:

1) With the incinerator container in the cold zone, the heaters and rotation drive motor were turned on.
2) After Thermocouple No. 1, located inside the gas/vapor exhaust tube, indicated 550°C, the incinerator container was pushed into the hot zone.
3) The incinerator container remained in the hot zone for 1 hour; it was then returned to the cool zone to complete the operation cycle. Then the heaters and drive motor were turned off. The operating conditions and test results are shown in Table 4.

The test verified that the screw-feed waste transport system could operate through a complete thermal cycle. However, after the system was cooled, the incinerator container could not be moved. Therefore, the system was taken apart for visual inspection. This inspection revealed that during the thermal cycle the gas/vapor tube, which was also the supporting axis for the rotating incinerator container, had warped and bowed out of shape. This warpage then restricted lateral movement of the container between the hot and cool zones of the incinerator.

To prevent a recurrence of this problem the screw-feed waste transport system must be modified to prevent warpage or to operate in a manner such that any warpage will not interfere with the lateral or rotational movement of the incinerator container.



NOTE: Numbers in large circles refer to thermocouples.

Figure 28. THERMOCOUPLE LOCATION ON LABORATORY SCREW-FEED WASTE TRANSPORT SYSTEM

Figure 29. LABORATORY TEST SET-UP -- SCREW-FEED WASTE TRANSPORT SYSTEM

Table 4. RESULTS OF LABORATORY TESTS WITH SCREW-FEED WASTE TRANSPORT SYSTEM

Operating Parameters:	
Incinerator container rotational speed	49 rpm
Heater power	400 watts
Results:	
Heat up time (T/C No. 1 25° - 550°C)	1.5 hr.
Hold time (T/C No. 1 maintained at 550°C)	1.2 hr.

Temperature profile at end of hold time

T/C No.	Temp. (°C)
1	550°
15	525°
9	465°
5	245°
12	185°

3.4 Waste Size Reduction Testing

3.4.1 Initial Laboratory Testing

To facilitate the transport of various waste materials to the incinerator it was realized early in the program that a size reduction device would be needed between the waste collection unit and the actual transport system. Considerable effort has been expended at GARD on developing similar units for aircraft and marine toilet systems. Currently, a macerator-pump is being used on GARD's Marine Evaporative Toilet System.

The macerator-pump has a four-inch inlet and accepts and shreds all types of waste materials. The macerator-pump homogenizes the wastes to a pumpable slurry and pumps them through a one-inch pipe. The pump consists of chopper section that macerates the wastes to approximately 20 mesh size particles and a centrifugal pump section that pumps the macerated slurry.

A smaller version of this macerator-pump was evaluated with water and dog food slurries; Figure 30 is a photograph of the unit. The pump required a force-feed to operate properly and the centrifugal impeller did not eject the macerated material at any significant velocity. Pressure developed by the impeller was very small (1.8 mm Hg) with air as the feed material.

When a thick mixture of dog food and water was gravity-fed into the pump, it became entrapped in the impeller section with resulting overload on the motor. Plain water was easily pumped and pressures of 11 to 15 mm Hg were generated at the outlet, provided no air entered the pump.

When a porous tube with a pressurized annulus was attached to the pump outlet, a portion of the air entering the porous tube through the pores exhausted back through the pump and feed section.

To circumvent this back-pressure, the nozzled tube was substituted for the porous tube. The nozzled tube sucked air into the pump and created a

Figure 30 MACERATOR-PUMP (0.5 HP MOTOR)

slight, negative pressure at the pump inlet. A slurry of dog food and water was then gravity-fed into the pump. The slurry was readily macerated with little splash-back but 100-200 grams of slurry was required to prime the centrifugal section of the macerator pump. The macerated slurry was expelled from the pump at a low rate; this caused a build-up of material at the pump outlet, eventually plugged the tube and cutting off the air suction. Flushing the system with water provided a sufficient liquid head above the feed material to "push" the feed through the macerator-pump.

Since the macerator-pump did not pump air and required a liquid pressure head to force-feed the wastes, it was decided to study an alternate technique of size reduction.

3.4.2 Final Laboratory Testing

A commercial household blender was purchased and modified to provide a macerating unit capable of handling high air flows and preventing a build-up of macerated wastes in the tube outlet. The blender's variable-speed motor and chopper-blade assembly were removed from their housing and fitted at the base of a transparent acrylic feed tube. The nozzled tube arrangement was fitted at the blade assembly at right angles to the feed tube. Figure 31 is a photograph of the laboratory system with the feed material directed downward on top of the spinning blades. Figure 32 is a close-up view of the chopper-blade assembly.

Pressurized air at 200 mm Hg in the annular space around the nozzled tube was used to induce outside air into the system. A 25%-solids mixture of dog food and water was then gravity-fed into the spinning blades. Although some material was chopped and blown out the nozzled tube, much of the feed was retained between the blades and walls of the feed tube, as well as beneath the blades.

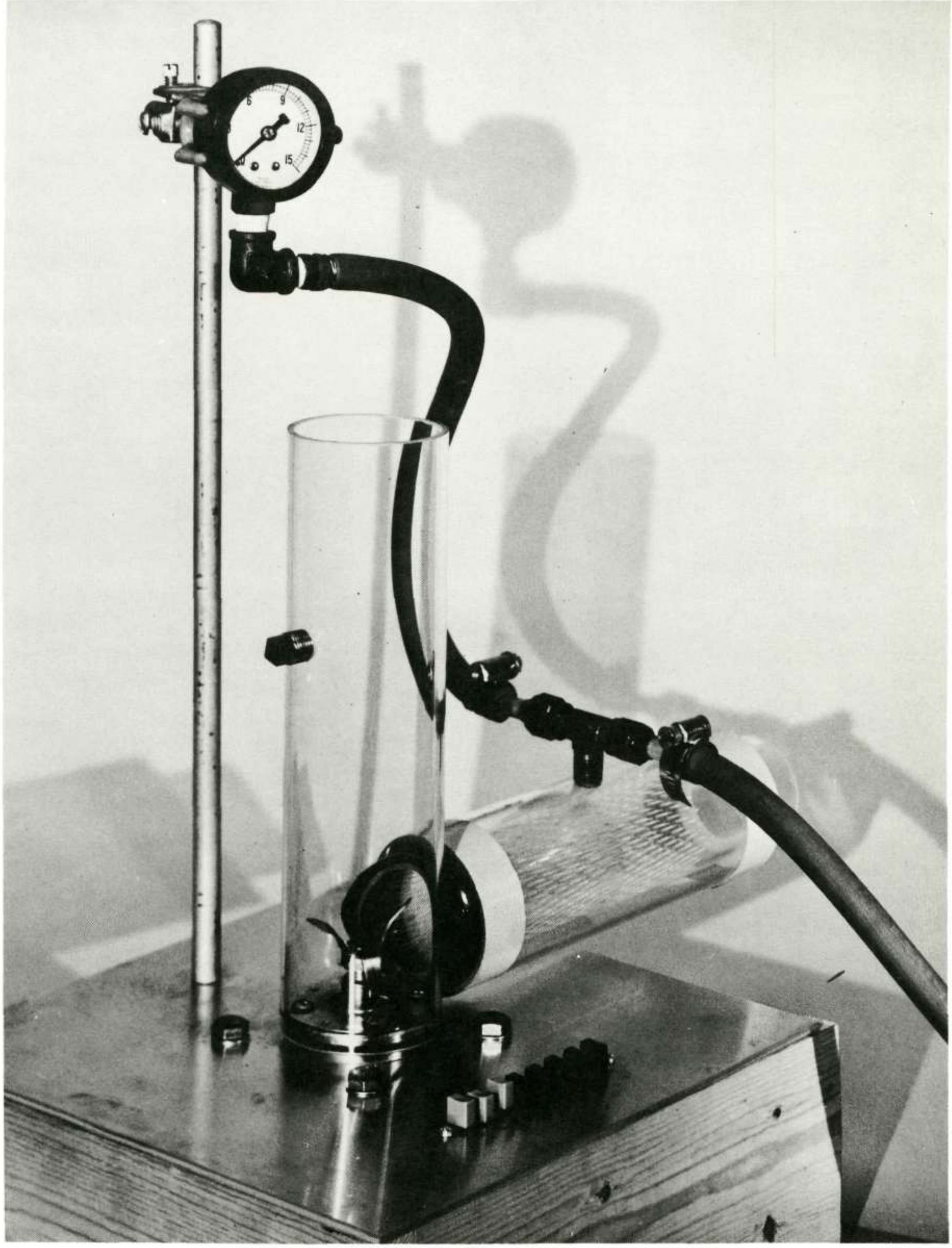


Figure 31. LABORATORY TEST APPARATUS -- CHOPPER-BLADE ASSEMBLY WITH NOZZLE-PNEUMATIC DISCHARGE TUBE (VERTICAL POSITION)

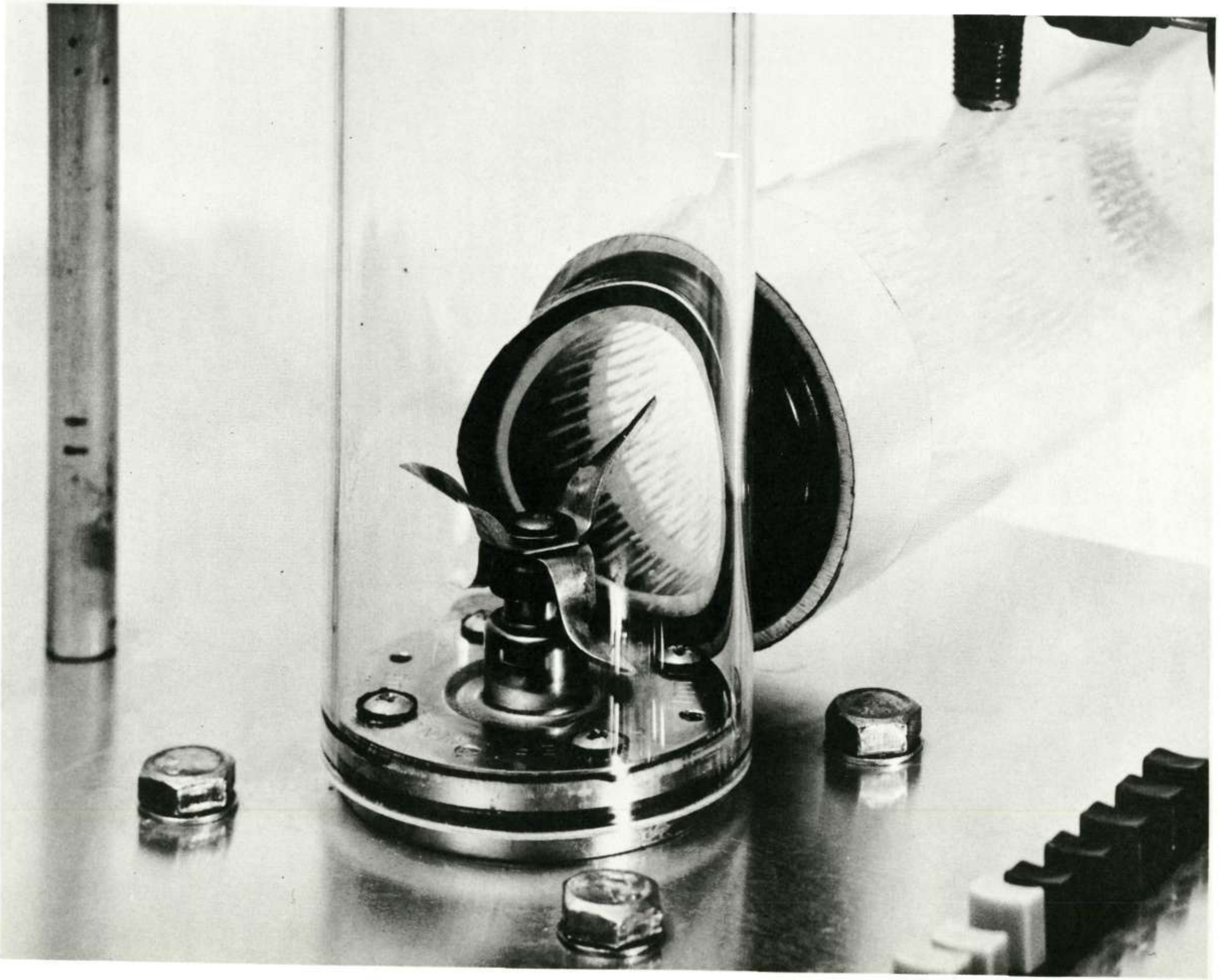


Figure 32. CLOSE-UP VIEW OF CHOPPER-BLADE ASSEMBLY

To prevent this build-up of feed material below the chopper-blades, the apparatus was re-arranged to allow the material to be gravity-fed into the sides of the spinning blades. This arrangement is shown in Figure 33. With this configuration, feed material was thrown back against the base of the blade assembly and almost none entered the nozzled tube. This was caused by the pitch of the blades, which is normally designed to direct material downward in the commercial household blender.

An attempt was then made to reverse the pitch of the blades by bending them. This apparatus was tested with viscous dog food in both of the above feed configurations; results were only slightly better. Flushing of the system with water washed out most, but not all, of the retained feed material.

The apparatus was then modified by employing the first nozzled tube with a pressurized outer tube as the feed tube to the chopper-blades. This configuration is shown in Figure 34. With both the inlet and outlet fitted with nozzled tubes, dog food was fed onto the top of the spinning blades; little retention of material was noted around the base of the blades. Although most of the material was rapidly blown through the system, a small portion did remain around the base of the blades. When toilet tissue was fed into the system, it was temporarily retained around the blades, but spinning with the blades. This resulted in a very effective wiping action that cleaned the base of the blades, removing almost all of the previously retained material. A small water flush then cleaned out the remaining material. Dry and wet paper towels fed into the spinning blades were shredded and rapidly transported through the system.

These test results showed that a very effective transporting and size reduction system is obtained when the inlet and outlet sections of the chopper-blade assembly are fitted with the nozzled tubes. It is anticipated that a further reduction in waste retention around the base of the blades

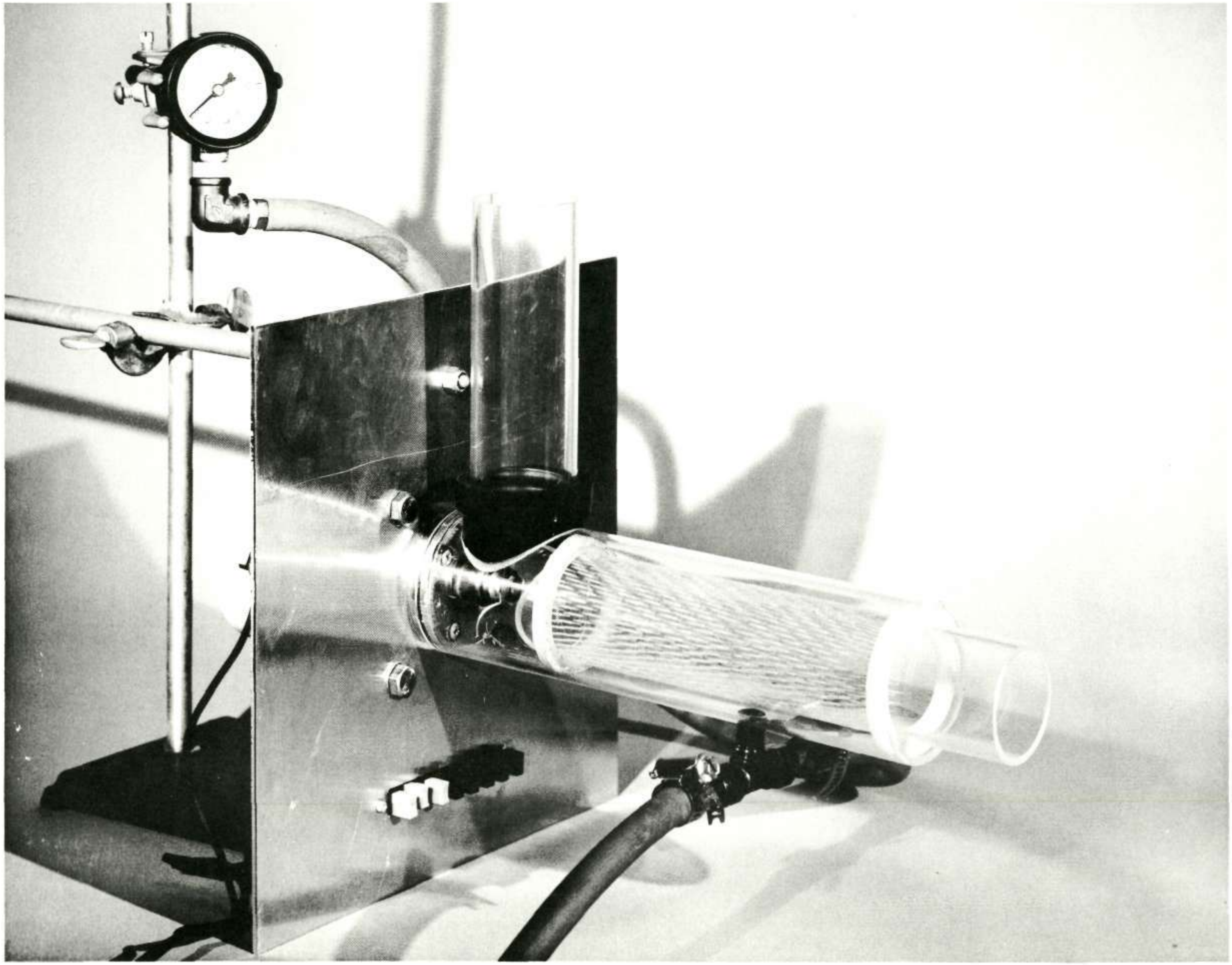


Figure 33. LABORATORY TEST APPARATUS -- CHOPPER-BLADE ASSEMBLY WITH NOZZLE-PNEUMATIC DISCHARGE TUBE (HORIZONTAL POSITION)

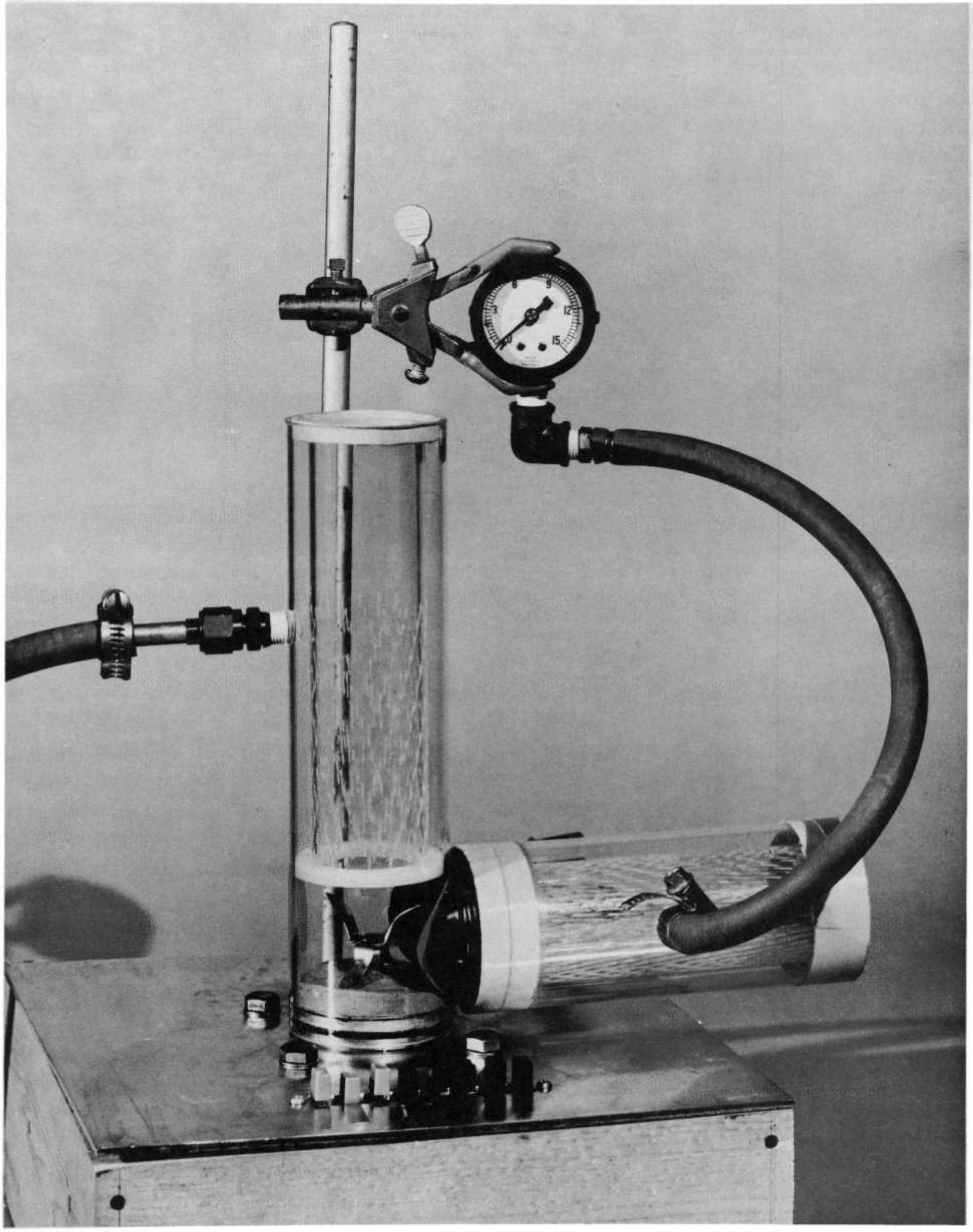


Figure 34. LABORATORY TEST APPARATUS -- CHOPPER-BLADE ASSEMBLY WITH NOZZLE-PNEUMATIC FEED AND DISCHARGE TUBES

is possible if a porous tube is used around the blades. The combination of the nozzled and porous tubes fitted with a pressurized outer tube should also eliminate the need for a dynamic seal around the chopper motor shaft. Thus, an ordinary bearing may be used, since the pressurized air in the annulus will prevent the escape of wastes and/or odors around the shaft bearing.

SECTION 4

FINAL CONCEPT SELECTION

The results of the design verification testing presented in the previous section were thoroughly evaluated to determine the merits and shortcomings of each of the three waste transport system concepts. The objective of this evaluation was to select the most effective transport system. This system will then be further developed by designing, building, and testing a six-man prototype system. This evaluation is presented below and is followed by a preliminary design of the prototype system.

4.1 Overall Concepts Evaluation

4.1.1 Pneumatic Waste Transport System Concepts

The laboratory test results showed that porous stainless steel having an average pore size of 2.0 microns is able to provide a suitable air cushion for supporting solids and liquids. A minimum air pressure drop through this porous material of 260 mm Hg, which is equivalent to an air flow of 0.22 liter/sec/cm^2 of porous surface, is required to obtain the cushion effect. Pore sizes less than or greater than 2 microns were not effective for suspending liquids, even at air pressures providing a comparable air flow rate through the pores. Although solids could be readily suspended with other pore sizes, water wetted these porous surfaces and merely foamed. This porous material, however, was not effective for imparting momentum to the liquid or solid feed materials.

The laboratory test results also showed that a tube containing numerous directional nozzles was effective for inducing outside air into the tube and creating an air drag effect. The nozzles performed similar to an air ejector pump creating a suction upstream of the nozzles and imparting momentum to materials fed into the tube. Tests with the modified nozzled tube revealed that more air is induced into the tube per nozzle when fewer nozzles are employed;

also, a measure of the p-V work expended was less with fewer nozzles. This can be seen by comparing the data of Table 3 (Section 3.2.2). Dividing the induced air flow by the supplied air flow for each pressure level and number of nozzles, as shown in Table 3, and averaging these values results in the following values:

Number of Nozzles Exposed	Average Ratio of Induced Air Flow To Supplied Air Flow
25	15.3
100	5.5
525	2.0

Thus, from a practical standpoint, the number of nozzles used should be kept to a minimum. Although a higher pressure is required to obtain a large induced air flow with fewer nozzles, the volume of air that must be supplied to the nozzles is minimal.

Since the porous tube created an adequate air cushion but could not impart momentum to the feed materials, and since the nozzled tube was able to transport the wastes but not suspend them, a suitable system design should incorporate both concepts. Thus, a few nozzles, positioned at the upstream end of a porous tube, will transport waste materials through the tube without the wastes contacting the tube walls.

The laboratory tests also showed that a chopper-blade assembly, combined with nozzled feed and discharge tubes, was an effective method for shredding waste materials without creating an excessive build-up of wastes around the blade assembly. Any residual wastes around the blades were readily removed when toilet tissue or paper towels were fed into the system; momentary retention of the spinning paper effectively wiped and cleaned this area. If the tube walls around the blade assembly were made of the porous material, no retention of the wastes is anticipated.

Finally, by placing a sealed housing around the chopper-blade drive motor and shaft and allowing the compressed air from the annulus to enter this housing, no waste materials will come in contact with the motor or the shaft support bearings.

4.1.2 Screw-Feed Waste Transport System Concept

Laboratory test results of the screw-feed waste transport system concept verified that the system could operate through a complete thermal cycle. However, the gas/vapor tube and rotational supporting axis warped and bowed out of shape. The close tolerances between the tube and mating portions of the incinerator canister prevented the canister from being easily returned to the cool zone due to this warpage.

The canister rotation and lateral motion of the rotating canister were performed without difficulty, indicating the feasibility of this approach. The feasibility of using an automatically actuated scraper mechanism within the incinerator for ash removal was also demonstrated.

The two basic shortcomings of the laboratory model were the tube warpage and the location of the rotational drive motor. With the drive motor located outside of the outer sealed container, a gear assembly through the container wall was required. Proper sealing of this arrangement can be obtained by fitting a sealed housing around the motor and gear assembly. However, a better arrangement is to position the motor inside the container and use a single shaft, direct drive to rotate the canister; this arrangement eliminates the need for a gear assembly and a common feed/exhaust tube and support axis.

4.2 Preliminary Prototype System Design

Since both the porous and nozzle pneumatic and screw-feed concepts appeared to be feasible techniques for transporting waste materials to an incinerator unit, it was decided that a prototype system based on both designs should be evaluated further. Both methods have certain merits and shortcomings that, when combined and analyzed as a whole, appear equal in the two systems. Elimination of one technique in favor of the other did not seem justified, as no meaningful basis of comparison was possible. Thus, no one system could be isolated as the most effective. GARD has therefore decided to subject both systems to prototype development and testing. This appears to be the best approach for the development of a waste transport system suitable for aerospace applications. A brief description of the preliminary design for each concept is presented below.

4.2.1 Pneumatic Waste Transport System

The preliminary design of the prototype pneumatic waste transport system is shown in Figure 35. As shown in Figure 35, the pneumatic transport arrangement is located at the commode outlet. At this point and/or a short section, directional nozzles are fitted through the walls of an inner acrylic plastic tube. The nozzled section is followed by a porous metal tube, approximately 7.5 cm in diameter. The porous section is then formed into a reducing elbow into which is fitted a chopper-blade assembly. The chopper-blade assembly is positioned at a 30° angle from the vertical to provide more efficient shredding action with less possibility of waste retention and to prevent any short-circuiting of the wastes. The motor is contained in a sealed housing.

Following the tapered elbow is another plastic section containing several rows of directional nozzles, which is followed by a porous metal tube having a diameter of approximately 4 cm. The entire length of nozzled and porous tubes, as well as the tapered elbow, are fitted within a larger outer pressurized tube,

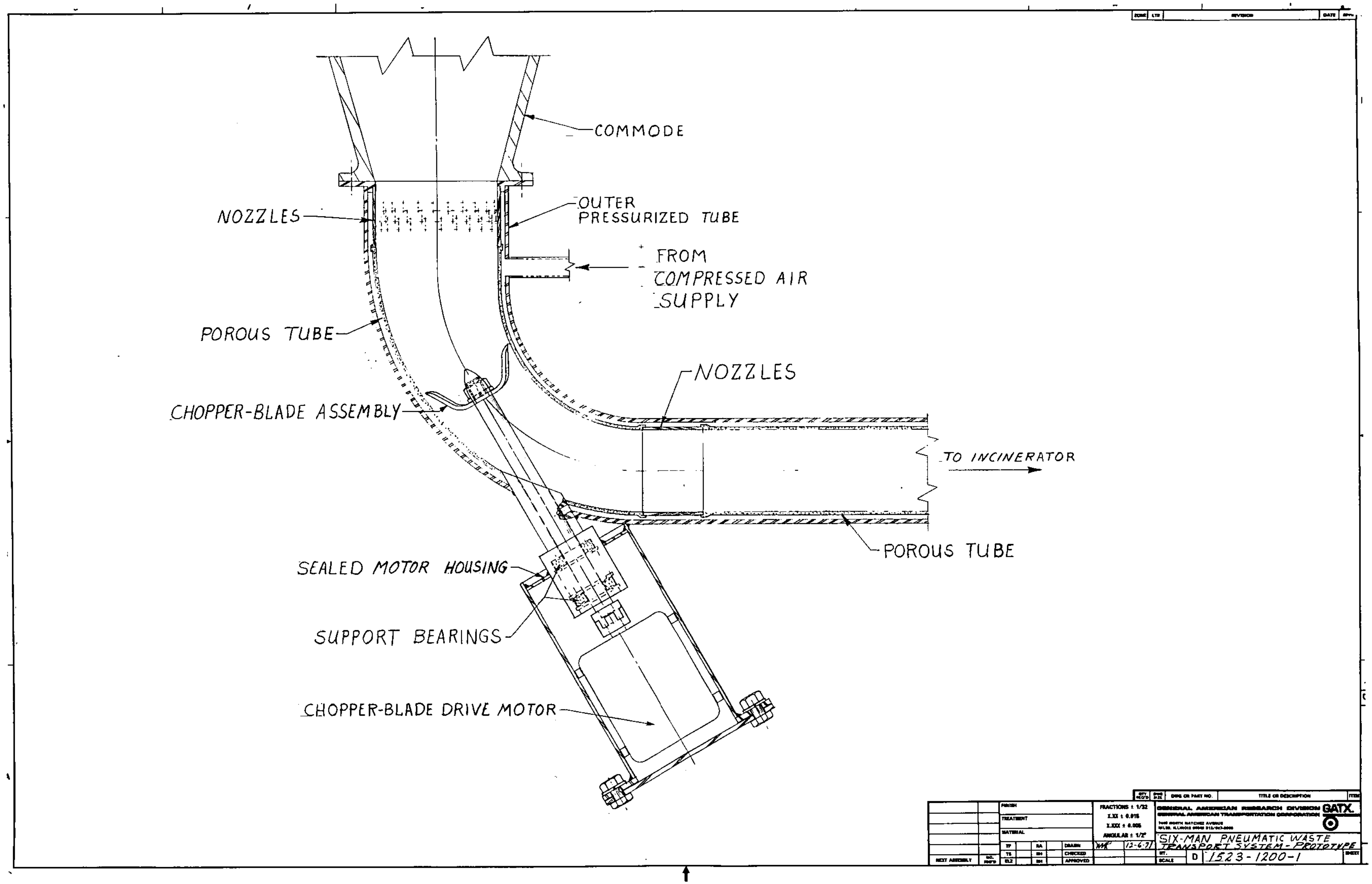


Figure 35. PNEUMATIC WASTE TRANSPORT SYSTEM -- PRELIMINARY PROTOTYPE DESIGN

which is connected to a compressed air supply. The resulting annular spacing is approximately 0.2 cm wide.

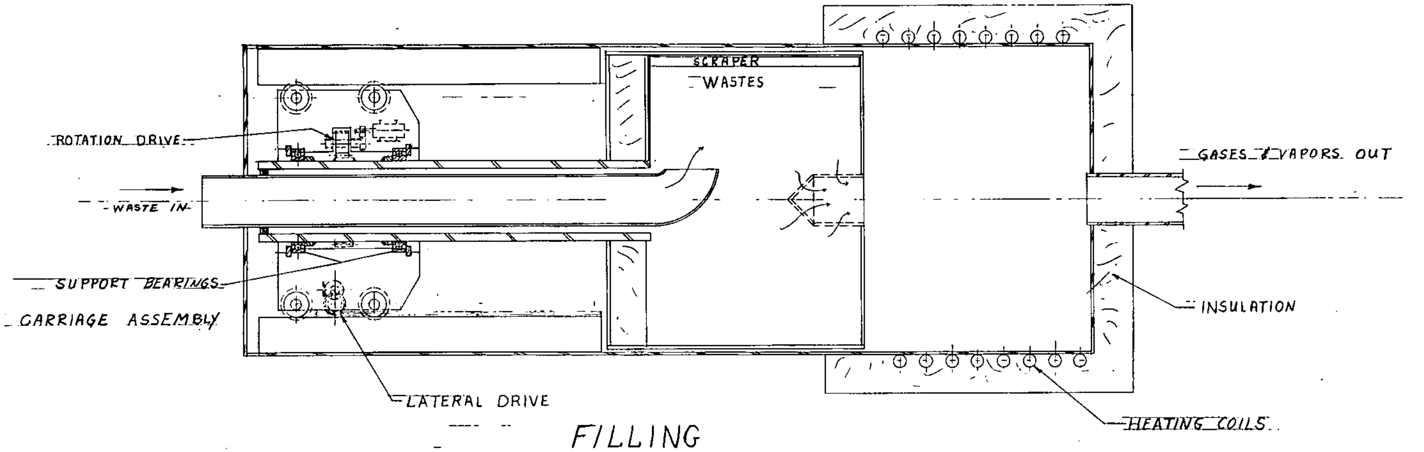
A short tube, connecting the pressurized annulus with the sealed motor housing, allows the compressed air to flow around the motor shaft, through loosely fitted ball bearings, and into the inner tube. This arrangement prevents any waste materials from contacting and contaminating the ball bearings or motor.

4.2.2 Screw-feed Waste Transport System

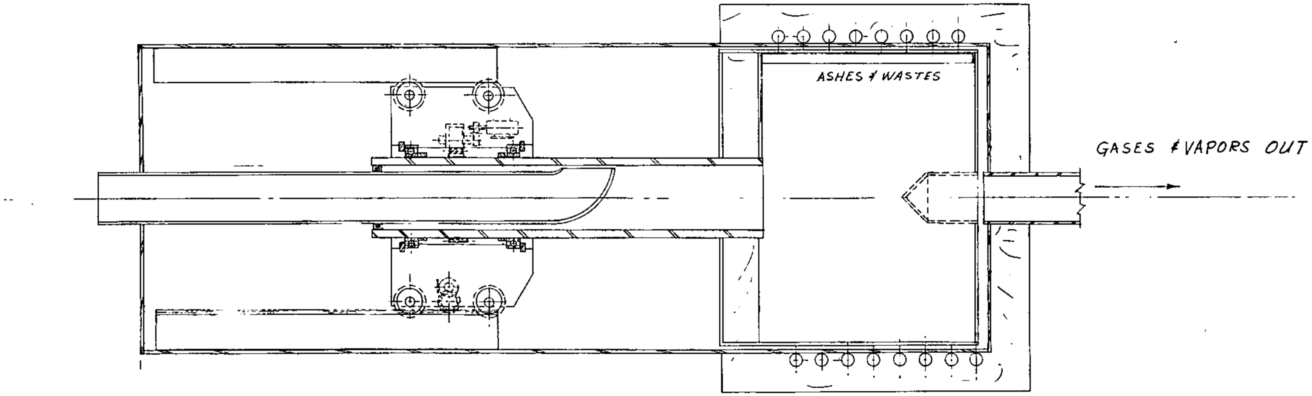
To prevent the interference with movement incurred with the laboratory screw-feed waste transport system, the design of the support and drive mechanism for the incinerator container will be modified as shown in Figure 36. The following modifications have been made.

First, the incinerator canister will be supported on one end only. Thus, all bearings and drive mechanisms will be positioned in the cool zone and will not be exposed to thermal cycling. Second, wastes are fed directly into the canister through a straight feed tube and are deflected to the walls of the canister. This design change also facilitates any required flushing of the feed tube. A screen arrangement within the incinerator canister allows air to escape but prevents any wastes from escaping. Third, the rotational drive-motor has been relocated inside the outer sealed container. Thus, no gear assembly through the container wall is required. Also, an internal lateral drive-motor will replace the traverse actuating rods. This configuration for the drive-motors eliminates all dynamic seals from the system.

In operation, wastes will be fed through the feed tube and will be deflected to the walls of the incinerator canister by a bend in the end of the tube. A rotational drive-motor will continuously rotate the incinerator canister. The resulting centrifugal force of rotation will confine the wastes to the walls of the canister in zero gravity. The filled canister will then be driven into the hot zone by a lateral drive-motor rack and pinion assembly.



FILLING



INCINERATION

Figure 36. SCREW-FEED WASTE TRANSPORT SYSTEM -- PRELIMINARY PROTOTYPE DESIGN

In the hot zone the wastes will be burned to gas, water vapor, and ash. At the completion of the pyrolysis phase of incineration, oxygen will be admitted to the canister for the final combustion phase. After incineration has been completed, the incinerator canister will be driven back to the cool zone. Here a scraper mechanism will loosen ash from the canister wall; the ash will be removed from the incinerator through the feed tube by a vacuum source. After the ash has been removed and the incinerator canister has cooled, the system will be ready to receive a new batch of wastes.

Figure 36 shows the incinerator canister in both the filling and incinerating position.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

On the basis of the tests conducted during this phase of the program, the following conclusions have been reached concerning the automatic transport of wastes for spacecraft.

(1) Solids and liquids can be readily suspended on an air cushion by forcing compressed air through a porous substrate.

(2) Solids and liquids can be made to flow through a tube without touching the tube walls by employing a porous metal tube, positioned concentrically within a larger, solid tube, and by admitting compressed air to the annular space between the tubes.

(3) The air cushion effect is a function of both pressure drop and air flow rate through the porous tube, which, in turn, are a function of the pore size and pore spacing.

(4) A 2 micron stainless steel tube, manufactured by Mott Metallurgical Corp., was able to provide the air cushioning effect better than tubes of different pore sizes.

(5) A minimum pressure drop of 260 mm Hg through this 2 micron metal material, which is equivalent to an air flow rate of 0.22 liter/sec/cm^2 of porous surface, is required to obtain the air cushion effect.

(6) Porous materials with pore sizes less than or greater than 2 microns were not effective for suspending solids and liquids, even at comparable air flow rates.

(7) Although the porous-pneumatic tube was able to suspend waste materials, it was not able to impart momentum to the wastes.

(8) Waste materials can be readily transported through a tube by providing small directional nozzles through the tube's wall, by positioning the tube concentrically within a larger, solid tube, and by admitting compressed air into the annular space between the tubes.

(9) The initial pressure energy of the compressed air is converted to kinetic energy within the nozzles. Air thus leaves the nozzles in the form of a jet, reducing the pressure at the inlet of the tube.

(10) The nozzled tube performs similar to an air ejector pump, sucking several times more outside air into the tube; this creates an air drag effect capable of rapidly transporting solid and liquid feed materials.

(11) With a small number of nozzles, a higher annular air pressure is required to obtain a specific induced air flow than when a large number of nozzles is used.

(12) The induced air flow per nozzle is inversely proportional to the number of nozzles.

(13) At comparable induced air flows, the expended work varies directly with the number of nozzles.

(14) Positioning the nozzles at a 15° angle from the horizontal and employing the smallest nozzle diameter obtainable, provides a suitable air drag effect with minimal expended work.

(15) A macerator-pump is not effective for macerating and pumping semi-solid wastes, even if an air drag is used to feed the pump.

(16) A chopper-blade assembly, similar to that used in a commercial household blender, combined with nozzled feed and exhaust tubes, is a suitable technique for reducing the size of the wastes and transporting them through the system.

(17) A small amount of waste material is retained around the chopper-blade assembly due to the centrifugal force created by the spinning blades and the sticky nature of the wastes.

(18) Admitting toilet tissue or paper towels to the chopper-blade assembly results in momentary retention of the spinning paper, which effectively wipes and cleans out most of the retained wastes. A small amount of flush water will then remove all remaining waste and shredded paper particles.

(19) Transporting a continuously rotating incinerator canister into and out of a heated incineration zone is feasible.

(20) Rotating the incinerator canister on a long tube is not feasible as heat warpage and bowing of the tube restricts lateral motion of the canister.

(21) Use of an automatically actuated scraper mechanism within the incinerator canister is an effective means of dislodging incineration ash from the walls of the incinerator.

(22) Of the three waste transport systems evaluated, no one could be singled out as the most effective. All had merits and shortcomings, which, taken as a whole, could not be used as a suitable basis of comparison.

5.2 Recommendations

Based on the observations and conclusions drawn from this phase of the program, the following recommendations are made concerning the use, operation, evaluation, and future testing of an automatic, zero "g" waste transport system.

(1) The porous and nozzled tubes should be combined into a single system to provide an effective pneumatic waste transport system.

(2) A 2 micron porous metal tube, fitted with several small directional nozzles at its inlet end, should be used to provide both waste transport and waste suspension.

(3) Only a small number (≤ 100) of nozzles of the smallest diameter obtainable should be used to create an air drag and these nozzles should be positioned through the tube wall at a 15° angle from the horizontal.

(4) A chopper-blade assembly, similar to that used in a commercial household blender, should be incorporated into the above pneumatic transport system to reduce the size of the waste materials and facilitate their transport.

(5) The chopper-blade assembly should be positioned in the transport tube at an angle to provide more efficient shredding of the wastes and to prevent any short-circuiting of the wastes around the blades.

(6) Compressed air should be supplied to the annular space around the porous and nozzled tubes to provide a minimum pressure drop of 260 mm Hg across the porous section.

(7) The wall thickness of the porous tube should be selected to provide a minimum air flow rate through this wall of 0.22 lit/sec/cm^2 of porous surface at the minimum pressure drop.

(8) The porous tube should be fabricated of 2 micron porous stainless steel as manufactured by Mott Metallurgical Corp. or equivalent material.

(9) The rotational gear assembly and incinerator canister of the screw-feed waste transport system should be driven by a single-shaft, direct-drive motor positioned within an outer sealed container.

(10) Suitable materials of construction are required for the screw-feed system to withstand large temperature cycles and the corrosive nature of the wastes and incineration products.

(11) Suitable insulation should be provided between the incinerator canister and the drive motor to afford ample protection to the motor.