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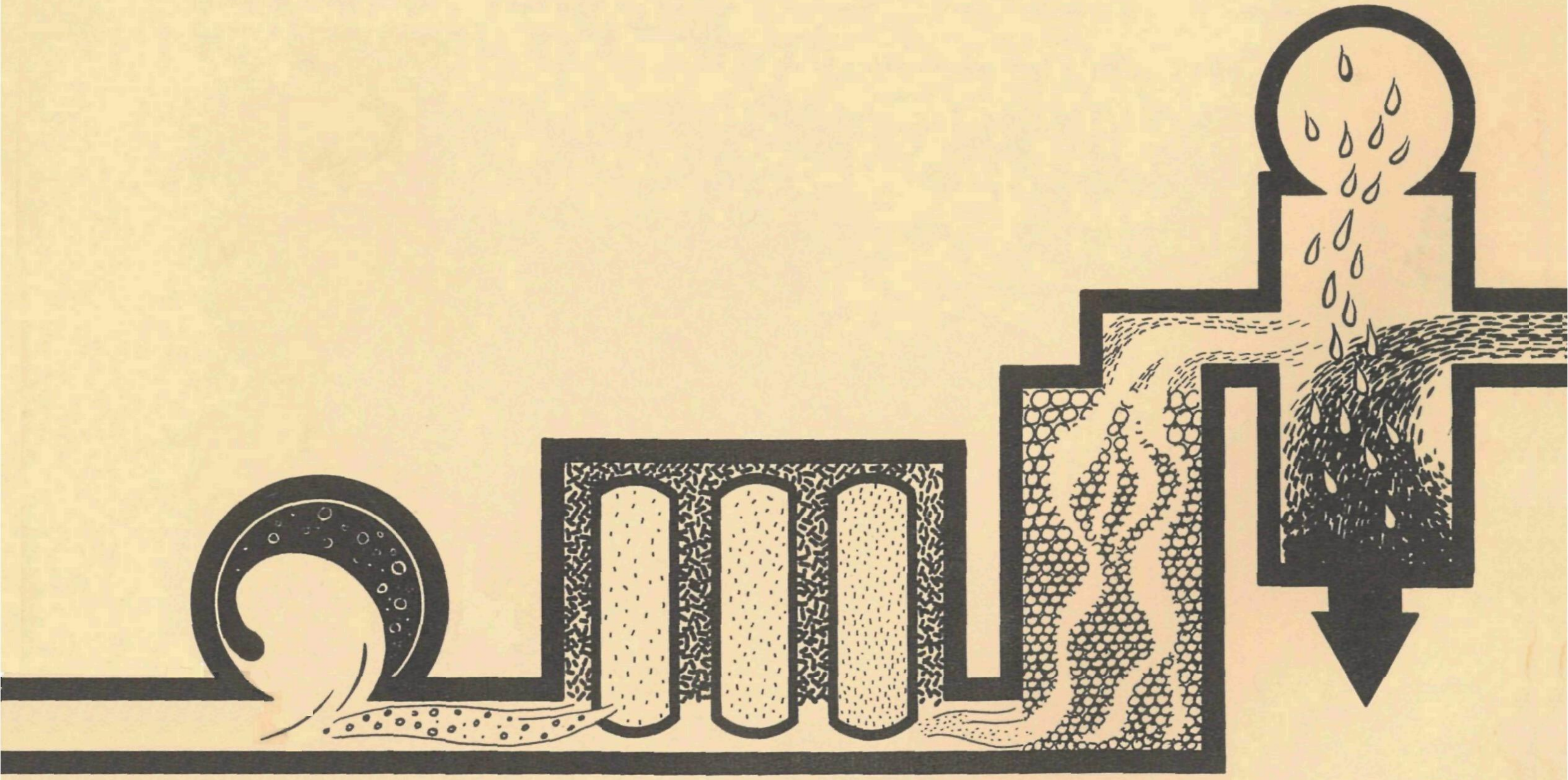
Fluidic Vortex Bubble Generator



U.S. ENVIRONMENTAL PROTECTION AGENCY

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FLUIDIC VORTEX BUBBLE GENERATOR

by

BOWLES FLUIDICS CORPORATION
9347 Fraser Avenue
Silver Spring, Maryland 20910

for the

ENVIRONMENTAL PROTECTION AGENCY

Program Number 17030 FEB
Contract Number 14-12-863

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ABSTRACT

This report contains the results of a detailed engineering investigation and evaluation of vortex devices as bubble-makers for use in the removal of suspended solids from wastewaters by flotation. The specific objective of the program was the development and test of bubble-makers useful for generating bubbles having mean diameters of about 100 microns with vortex devices having minimum liquid passageways of 1/4-inch or greater. The overall concept of the program involved testing the feasibility of improved methods for reducing the cost of generating bubbles for the flotation of solids from wastewaters.

The results of the program are summarized below:

1. Bubbles with a mean diameter of 80 to 85 microns, comparable to those produced with a pressurized air flotation system, can be successfully produced by a vortex bubble-maker.

2. Data are provided which can be used in the design of a vortex bubble-maker. This bubble-maker can produce bubbles ranging in size from 80-85 microns up to 1/8-to 1/4-inch mean diameters; with the actual size depending upon liquid pressure and the air entrained on the suction side of the pressurizing pump.

3. The minimum diameter of any internal liquid passageway within the device is 1/4 inch for a device having a region of influence 30 to 36 inches in diameter.

4. All air consumed by the device is supplied by entrainment at atmospheric pressures. No air compression or regulation is required. Pump pressure needed is 40 psig, which is comparable to that used with conventional air flotation systems.

This report was submitted in fulfillment of Project Number 17030 FEB, Contract 14-12-863, under the sponsorship of the Office of Research and Monitoring, Environmental Protection Agency.

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FIGURES

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SECTION I

CONCLUSIONS

1. As demonstrated photographically in this program, the vortex bubble-maker, as it now exists, can be used to produce bubbles having a mean diameter of 80 to 85 microns, with virtually all bubbles produced being 130 microns or less in diameter. This mean size and size range are substantially the same as bubbles produced by pressurized water processes at similar operating pressures.

2. The minimum diameter of any hole used in the best vortex device tested is one-quarter inch. Most holes are considerably larger, and no moving parts are required. Therefore, in terms of susceptibility to blockage and malfunction in actual use, these devices should perform most reliably.

3. Bubbles are produced by either of two methods: With atmospheric air aspirated directly into the vortex unit or with atmospheric air aspirated at the suction side of the pump, dissolved, and precipitated or effervesced at the vortex unit. Of the two methods, the latter gives better results in terms of numbers of bubbles produced per unit of pumping horsepower. For either case, however, no air pressurization equipment is necessary.

4. The vortex device can be used to produce bubbles larger than 80 microns mean diameter merely by increasing the amount of air aspirated at the unit. By altering an air valve setting, bubbles having a mean diameter in the range between 80 microns and 1/4-inch can be generated.

5. The best vortex device tested produced bubbles at roughly one-sixth to one-seventh the rate per horsepower of comparable pressurized water equipment. Indications are, however, that this margin may be reduced by increasing vortex gain (obtained by increasing the diameter of the vortex chamber, itself) and by aspirating air to the so-called "outside" of the vortex exit cone as well as the "inside".

6. The region of influence of a vortex device has been measured in a simulated flotation tank. Bubbles were produced uniformly over a region roughly 30 to 36 inches by 8 inches in a tank nominally 8 feet long by 8 inches wide by 45 inches in depth, with a device having a flow rate of less than 6 gpm at 40 psig. Bubbles produced over this region rose to fill the entire tank length (eight feet) from a depth of 2-1/2 feet.

7. Flotation testing was not successfully accomplished with any device or system during this program, due to test fixture problems. Sufficient

data exists, however, to design vortex bubble-makers for direct functional tests in conventional air flotation systems where a direct comparison in operating efficiency, reliability, first cost and maintenance cost can be made with conventional equipment.

SECTION II

RECOMMENDATION

Based on the conclusions resulting from this study, the following recommendation is presented:

Testing to Determine Cost Effectiveness of Vortex Bubble Generators

It is recommended that a set of vortex bubble generators be tested in a pilot processing system under conditions which conventional bubble generators operate. While not necessary, it would be useful to also include a control group of conventional generators in the test program. The pilot operation should simulate a typical flotation process or aeration process, or, if costs permit, both types of processes. The primary objective of these tests should be to evaluate the economy of the vortex generators as compared to conventional equipment.

The complete costs for a system include (1) initial costs (hardware and installation), (2) operating costs (consumables, including power, and labor), and (3) maintenance costs (replacement parts, labor, and down time losses). Regarding initial costs, it is not possible at this time to provide exact production costs for the vortex bubble generators, therefore a good comparison is not possible now. However, it is felt that there would be no significant difference between the price of vortex and conventional generators. With either approach, it is expected that the initial costs amortized over the life of a system, would be far less than the other two costs. Therefore, the study would be primarily directed toward comparing the two on the basis of operating and maintenance costs.

For this reason, an extended period of continuous operation would be required. Thus, after the test system with vortex generators is set up to yield performance comparable to a conventional system, it should be run for a period of perhaps 3 or 6 months. It is felt that this period would yield sufficient data to properly evaluate both operating and maintenance cost factors for a fair comparison with conventional equipment.

SECTION III

INTRODUCTION

DISSOLVED GAS FLOTATION

The interest of the Environmental Protection Agency in improved devices for gas bubble generation is based upon a long history of use for dissolved gas flotation processes in industrial and municipal waste treatment. Examples of industrial applications are listed in Table 1, which provides general information on a number of waste materials for which separation by gas flotation is possible.

As seen in the Table, dissolved gas flotation is an operation by which solids may be separated from a liquid phase or two or more liquids may be separated from each other. Flotation gas is introduced into the water or process liquids by a number of techniques. The choice depends upon a variety of reasons. These include the nature of the materials to be separated, possible combinations with other processes (sedimentation, for example), in-flow and out-flow concentration limitations, total flow requirements, cost limitations, etcetera. All the flotation techniques employed, however, are based on one fundamental process: that of dissolving a gas at a higher pressure and subsequent precipitation of that gas in the form of small bubbles at a lower pressure.

As reflected in Table 1, the process provides a means for separation which, for certain wastes, represents the only practical mechanism for their removal. This process also provides a mechanism by which separation can be achieved in substantially less time and with a markedly smaller facility than would otherwise be required for settling processes.

The pressure at which gas precipitation occurs will primarily depend upon the pressure at which the gas was dissolved. When solution occurs at atmospheric pressure, for example, vacuum precipitation is required. The pressure in the bubble precipitation tank must be reduced and, inasmuch as flotation also occurs in this precipitation tank, the process is called vacuum flotation. When the gas is dissolved at elevated pressures, precipitation can occur at any lower pressure. Atmospheric pressure is usually selected for such pressure flotation systems.

Assuming the applicability of Henry's Law, which states that the solubility of a gas in equilibrium with a liquid is directly proportional to the absolute partial pressure of the gas in contact with the liquid, it follows

TABLE 1

INDUSTRIAL APPLICATIONS OF DISSOLVED GAS FLOTATION WASTE TREATMENT

INDUSTRY	EXAMPLES OF APPLICATIONS OR MATERIALS SEPARATED
Chemical	Concentration and recovery of fines (e.g., carbon, $CaSO_4$, etc.) and colloids (e.g., metals).
Food Canneries	Removal of suspended organic solids from waste streams.
Laundries	Recovery of solids and fatty acids.
Meat Packing	Recovery of grease and reduction of BOD in waste streams.
Metal Finishing	Removal of suspended chips and processing oils from waste streams. Recovery of certain machining lubricants/coolants.
Metallurgical	Removal of oil and scale from mill waste streams.
Mining	Removal of fines (e.g., coal dust) that sedimentation cannot separate.
Paper- and Pulp-making	Removal of suspended solids otherwise impossible or impractical to separate.
Petroleum	Removal of free or emulsified oils from refinery waste streams.
Sugar Refineries	Separation of impurities and non-sugar solids from raw sugar melts.
Transporation	Removal of fine solids and oils from vehicle-washing waste streams.

that the pressure flotation system is superior to vacuum flotation in terms of the amount of gas which can be dissolved per unit volume of water. Of equal interest is the ratio of facilities costs required for the two types of systems. The vacuum system can be considerably more expensive to install than an equivalent pressure system.

Gas flotation can be characterized as a physical process, as opposed to a chemical process. Atmospheric air is the cheapest and, therefore, the best gas available. As a result, pressurized air flotation represents the most popular form for the fundamental dissolved gas flotation process.

Illustrated in Figure 1 is a block diagram showing the equipment requirements for a dissolved air flotation plant. Process lines are laid out to permit plant operation by pressurization of the feedwater or by pressurization of the recycled effluent with subsequent mixing with feedwater ahead of the flotation tank. The latter scheme is commonly used when chemical and biological floc particles are present in the feedwater.

The important item in Figure 1 is the equipment required for this generalized system. The vortex bubble-maker, which was evaluated during this study, represents a direct replacement for the pressure-regulation valves (usually flexible-diaphragm types) and the retention tank in effluent recycle applications.

OPERATION OF THE VORTEX BUBBLE-MAKER

Gas dissolved or entrained in the liquid is converted into bubbles by injecting the liquid into the process tank through a nozzle. To produce bubbles small enough for effective flotation (generally 100 microns or less in diameter), the conventional nozzle must have a relatively small minimum flow dimension, typically a few thousandths of an inch. This requirement for small nozzles is the source of maintenance problems in operating systems. The small nozzles clog easily and need frequent cleaning.

The vortex bubble-maker produces comparably small bubbles but with a much larger nozzle. To understand how this is accomplished it is appropriate to first consider the properties of submerged water jets and how bubbles of any size are generated by simple nozzles.

Figure 2 shows a submerged jet issuing from a nozzle in the presence of an acoustic disturbance. The disturbance is assumed to be at the characteristic frequency of the jet, thereby causing vortex shedding. This frequency is a function of jet velocity, diameter and Strouhal Number. The Strouhal Number, $S=f(d/V)$, is substantially constant for turbulent jets from geometrically similar nozzles. Thus it can be seen that the frequency

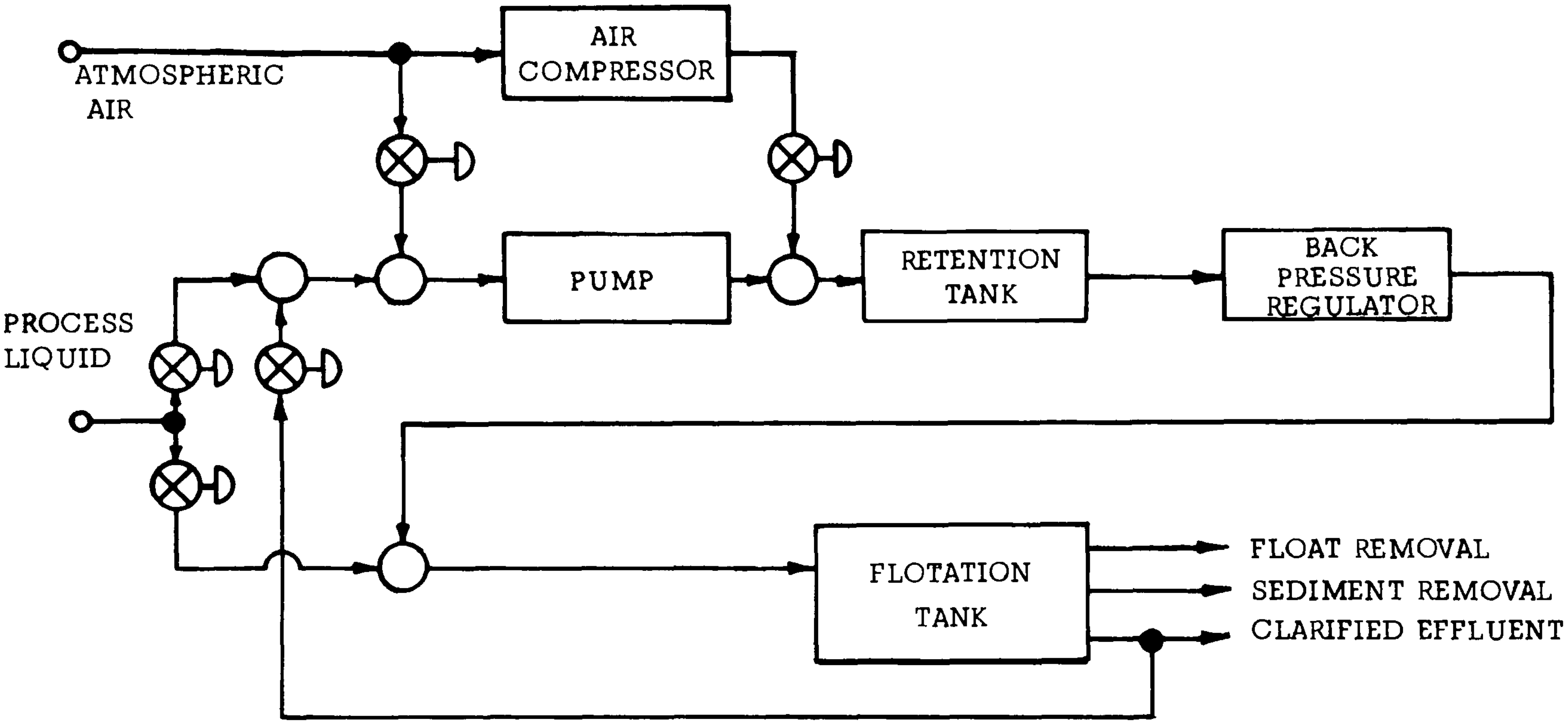


FIGURE 1

TYPICAL DISSOLVED AIR FLOTATION PROCESS
EQUIPMENT REQUIREMENTS

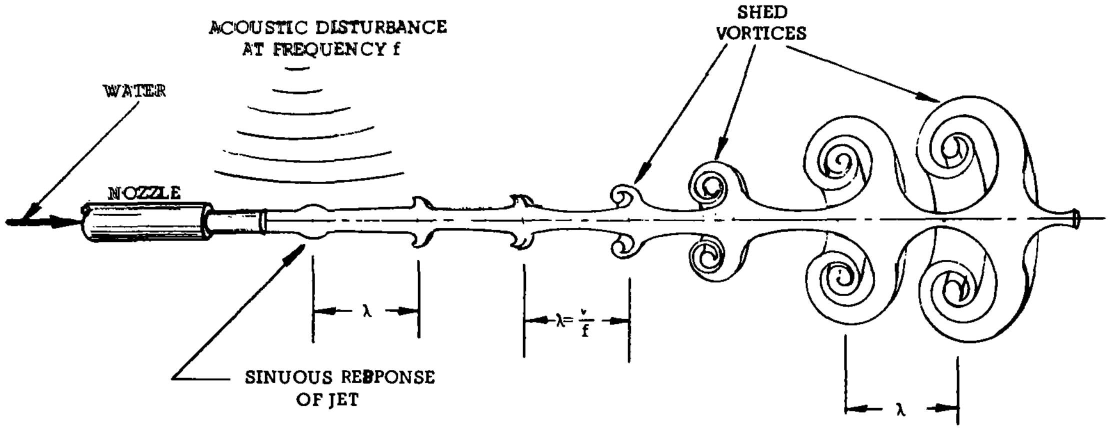


FIGURE 2

VORTEX SHEDDING FROM A SUBMERGED JET

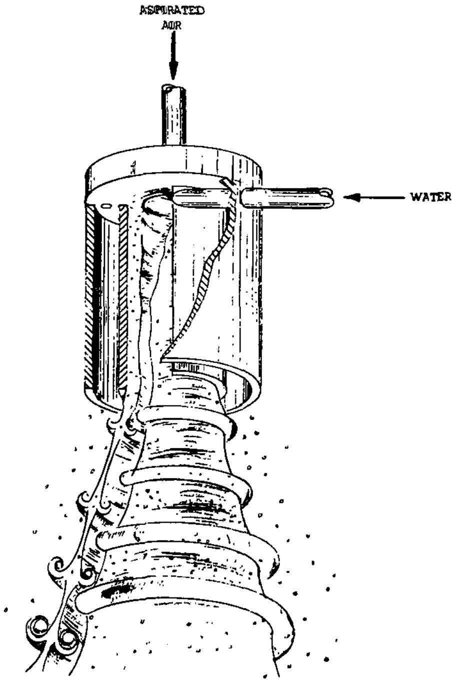


FIGURE 3

OPERATING PRINCIPLE OF
VORTEX BUBBLE GENERATOR

increases as velocity increases and as diameter decreases. In practice, acoustic exitations are always present. For a highly resonant system like a submerged turbulent jet, therefore, the shedding of regular vortices is entirely to be expected.

Under these circumstances if air is permitted to be entrained in the boundary layer of the submerged liquid jet, it will be broken down into isolated bubbles by the action of the vortices shedding from the jet. The higher the frequency of vortex generation, the lower will be the wavelength between successive vortices and hence the smaller will be the air bubbles formed. In general, smaller bubbles are formed by increasing the jet velocity and decreasing the jet diameter.

A similar action occurs if, instead of being entrained, the air is dissolved in the water issuing from the jet. In this case, however, the air comes out of solution inside of the individual vortices because these points are the regions of lowest static pressure. Again, the size of the formed bubbles is a function of the frequency of the shed vortices.

Bubbles are also produced by the same mechanism if the jet is in the form of a sheet instead of a circular stream. Such a jet can be formed by a slit shaped nozzle or by an annular orifice. Again the bubble size varies inversely with the frequency of the vortex shedding along the jet. This frequency is proportional to the jet velocity as with a circular jet. But in this case, the frequency is also inversely proportional to the width of the jet stream. Therefore, to generate small bubbles, less than 100 micron in size, quite narrow jets are required — again in the order of a few thousandths of an inch. As with circular jet nozzles, this leads to maintenance problems because of the tendency for small openings to clog.

The vortex bubble-maker produces a conical sheet jet which, because of its thinness, can generate small enough bubbles suitable for flotation purposes. The important advantage of the vortex bubble-maker, however, is that a thin jet sheet is achieved with a relatively large nozzle size.

The flow pattern from a vortex bubble generator is shown in Figure 3. Here, water is admitted via a tangentially-directed input pipe into a large central chamber which is open at the bottom to the liquid in which the device is suspended. Air can be entrained from the top. Although the chamber is large, the tangential-input-direction forces the entering water to assume a helical flow path that is restricted to the outer regions of the chamber. The rotation continues as the water flows downward until the chamber ends whereupon the water continues to flow in a conically-expanding jet. This jet can be given the same velocity, thickness and total area as the jet emanating from a simple annular nozzle thereby producing the same air bubble size. Because the jet dimensions are produced by vortex action, however, no small passageways are required and the vortex device is, therefore, markedly less susceptible to clogging.

Note that the vortex flow field within the vortex bubble generator is not to be confused with the vortices shed from the conical jet sheet. The latter is the flow phenomenon associated with a jet sheet from any source by which small air bubbles are produced. The former is the mechanism by which the bubble generator produces a thin jet sheet with a relatively large exit nozzle dimension.

Note also that the device shown in Figure 3 shows bubbles being generated from air entrained with the water. A low pressure exists in the central core region of the generator which allows air to be aspirated without the need of an air pump. This device also produces bubbles from air dissolved in the inlet water as described previously for a simple nozzle generator.

PROGRAM ORGANIZATION

The program reported herein was organized on the basis of preliminary development work performed by the contractor on the subject of bubble-making. During this preliminary work, the fundamentals of bubble generation through both freely-entraining and compressed-air-fed vortex devices were demonstrated. This program extends this prior work in a systematic way to develop a vortex bubble-generating device suitable for reliable, low-cost use in flotation-type waste treatment processes. Specifically, the goals were to develop a device capable of producing bubbles having a mean diameter as low as or lower than 100 microns using a simple vortex device in which no liquid passage had dimensions smaller than one-quarter inch. The device was to produce these bubbles with a minimal expenditure of total energy considering both liquid- and air-pumping requirements.

The program was organized into four tasks. These included analysis, breadboard design, evaluation and flotation testing. Section IV of this report describes the analytical work and Section V summarizes design activities, including both the design of the devices tested and the equipment used for such testing. Evaluation and flotation testing are covered in Sections VI and VII.

SECTION IV

ANALYSIS

The first requirement of the program was the preliminary optimization of the vortex device in terms of bubble size and size distribution. This requirement was based upon the fact that the devices used for earlier testing had been selected on the basis of availability rather than for reasons of optimal size or capacity. Hence, a design analysis was needed to establish the following:

1. The number and ranges of design variables appropriate for breadboarding.

2. The size of breadboard units and their scaling in relation to requirements of a probable real application.

Practical analysis of bubble formation in vortex motion is impossible because of the large number of complex, coupled phenomena occurring simultaneously. Some of these phenomena are discussed below:

1. Coupling of axial and radial velocity gradients renders a vortex core hydrodynamically unstable, i.e., tending to produce breakup, which makes the core a spiral of larger area and reduced angular velocity. The breakup is abrupt and has been described as analogous to the well-known hydraulic jump, but the analogy is in no way exact and the phenomenon is not amenable to analysis. This instability applies to the vortex core and is applicable only indirectly to free (or dissolved) air which may be carried along with the core.

2. Any air bubble which is entrained within the vortex undergoes an axial acceleration from the region of relatively static entrainment to the discharge region of the vortex. This axial acceleration has a destabilizing effect on the bubble and has been observed to produce breakup of large bubbles into smaller ones. The result, a Taylor Instability, can produce repetitive breakup of large bubbles into smaller ones.

3. There may be a sharp velocity discontinuity between the initially stagnant air entrained within the vortex and the water which surrounds it and which is swirling with very high velocity. This discontinuity would give rise to a Helmholtz Instability, which has only been studied for laminar, planar flow. The superimposed

centripetal field, however, may actually tend to stabilize any cylindrical air volumes present.

4. Rayleigh Instability is present, due partially to a surface tension effect, producing alternate swelling and contraction of a cylindrical fluid column. Superimposed rotational motions serve to enhance unstable tendencies in a manner analogous to the instability of an elastic column under the influence of compression combined with torque loading. The result is a hollow cylindrical column of air having superimposed on it surface waves which travel around this column in a helical fashion at high angular velocities. Coupling between these waves and bubble formation has been observed, but the phenomenon has not been described mathematically.

5. The presence of a severe radial pressure gradient has both a stabilizing and a destabilizing effect insofar as bubble formation is concerned. As mentioned above, the centripetal field tends to stabilize cylindrical air volumes and may, through centrifuging action, also cause bubbles present to coalesce as they travel axially through the exit tube. On the other hand, the low pressures produced at the center by this same rotation tend to precipitate air (and water vapor) out of solution at the core center in the form of small bubbles. Comparisons of the same vortex bubble-maker operated alternately as its own air entrainment unit, as a back-pressure regulator for a dissolved air system and as a combined air entrainer and regulator show this ambivalence quite clearly. These same comparisons also show the ambivalence to be related partially to the gain of the vortex device (the ratio of chamber to exit hole diameters) at a given pressure, although the precise relationship cannot be ascertained due to the complexity of the total bubble formation process.

6. The high velocity swirling motion within the water in the vortex core region has a destabilizing influence on bubbles or air volumes present in this vicinity. One of the original explanations for the behavior of vortex units as bubble-makers, in fact, was the high local vorticity that has been observed to be present in the boundary layers of wake flows. Unfortunately, this vorticity has only been analyzed for flows at Reynolds Numbers in the vicinity of unity and below, versus the four-to five-orders of magnitude larger Reynolds Numbers that prevail in the flow exiting from the vortex devices tested in this program.

In summary, a consideration of factors like those cited above makes it clear that precise analysis of bubble formation in a high-velocity vortex field is not practicable except under severely restrictive assumptions. These assumptions so limit the utility of the analysis that the results have little, if any, physical meaning.

As a result of literature review and prior testing, it was determined that the two principal variables were the vortex device gain (the ratio of vortex chamber to exit hole diameters) and water pressure. Beyond these two variables, three other geometric characteristics appeared practical to vary. Accordingly, it was decided to provide breadboard capability to vary four geometric parameters over a broad range. These geometric variables included vortex gain, water inlet impedance, air inlet impedance and total flow outlet impedance. The fifth variable was operating water pressure. Due to the desirability of minimizing capital cost requirements in any treatment plant, the air-entraining capabilities of both the vortex device and the pressurization pump were investigated. No pressurized air was used during vortex device tests.

It was necessary to design test equipment which would yield meaningful results from testing of the vortex devices. Some means for comparison testing was considered necessary involving conventional bubble-making equipment. Such equipment would provide a basis for direct comparison of the conventional and the new mechanisms for bubble-making, as to bubble size, size distributions, efficiency (bubbles released per unit horsepower) and flotation effectiveness. For this purpose, a pressurized air flotation process was selected and test equipment was designed around a dual-purpose laboratory system.

The major components of the system are shown in a block diagram in Figure 4. The system was originally designed to be operated either as a pressurized dissolved air system or as a non-pressurized system using the vortex device as a combined aspirator and bubble-maker. Bubbles were to be generated in the flow issuing from the dissolved air pressurization tank at the back pressure regulator valve, whence they would pass into the bubble-making and flotation tank for examination and test purposes. Alternatively, bubbles were formed in the vortex unit mounted directly in the same bubble-making and flotation tank. The venturi was a later addition which provided the option of air entrainment.

Sizing the vortex device for breadboarding purposes was in a sense related to pump selection and to the provision of a range of both pressures and flows over which the breadboard could be operated during testing. Based on the desire for test work at pressures up to 60 psig and variable flow

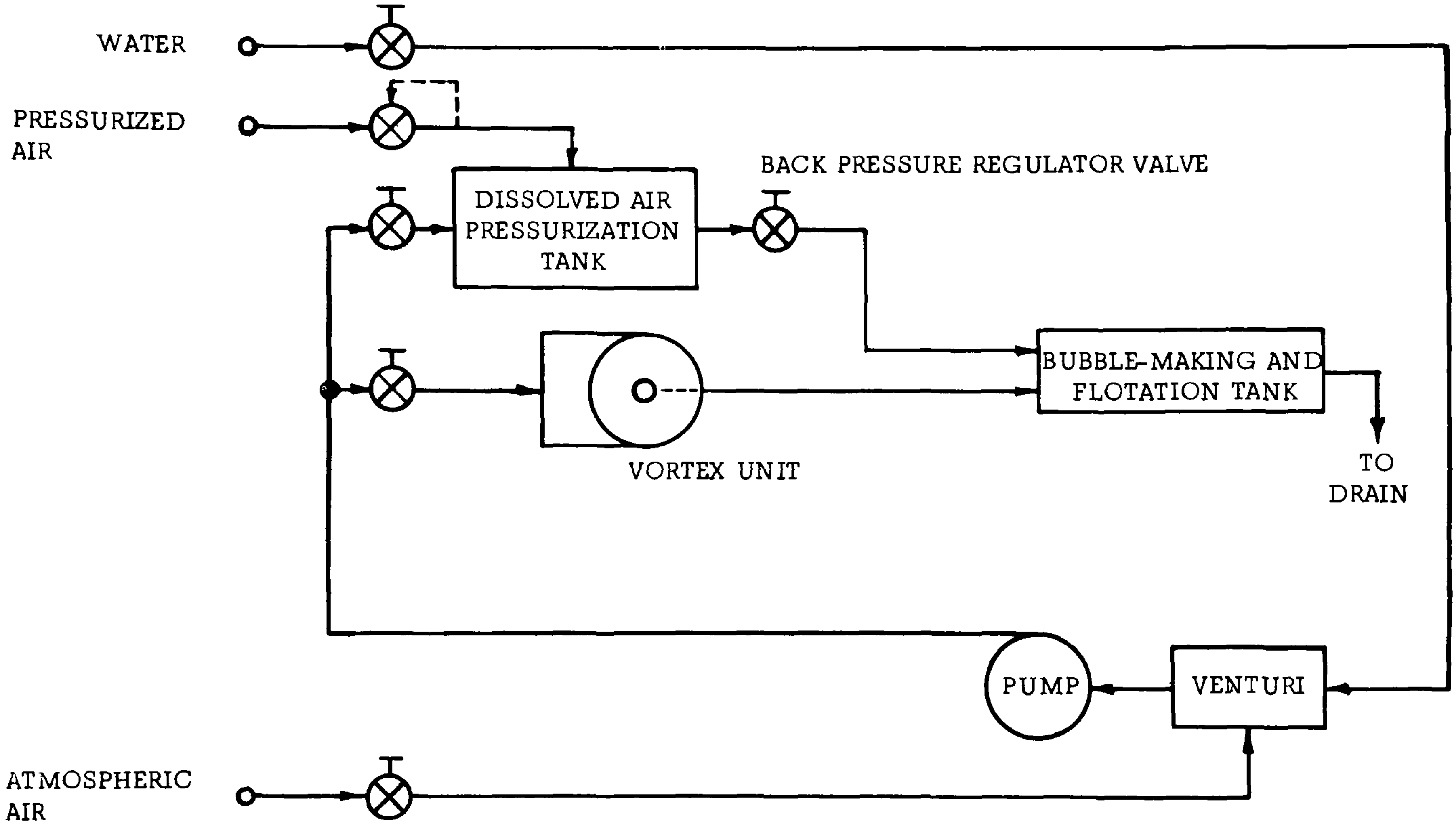


FIGURE 4

TEST EQUIPMENT

rates of less than 20 gpm, a centrifugal pump was indicated. A practical maximum rating for this pump was 1 horsepower, which would permit the desired flow variations. Based upon this pump capacity, the vortex unit was then sized to permit operation with full pump output pressure at 1/3 or less of maximum pump flow.

SECTION V

DESIGN

This section describes the design and construction of the basic vortex device to be tested and the test equipment necessary for evaluation.

VORTEX UNIT DESIGN

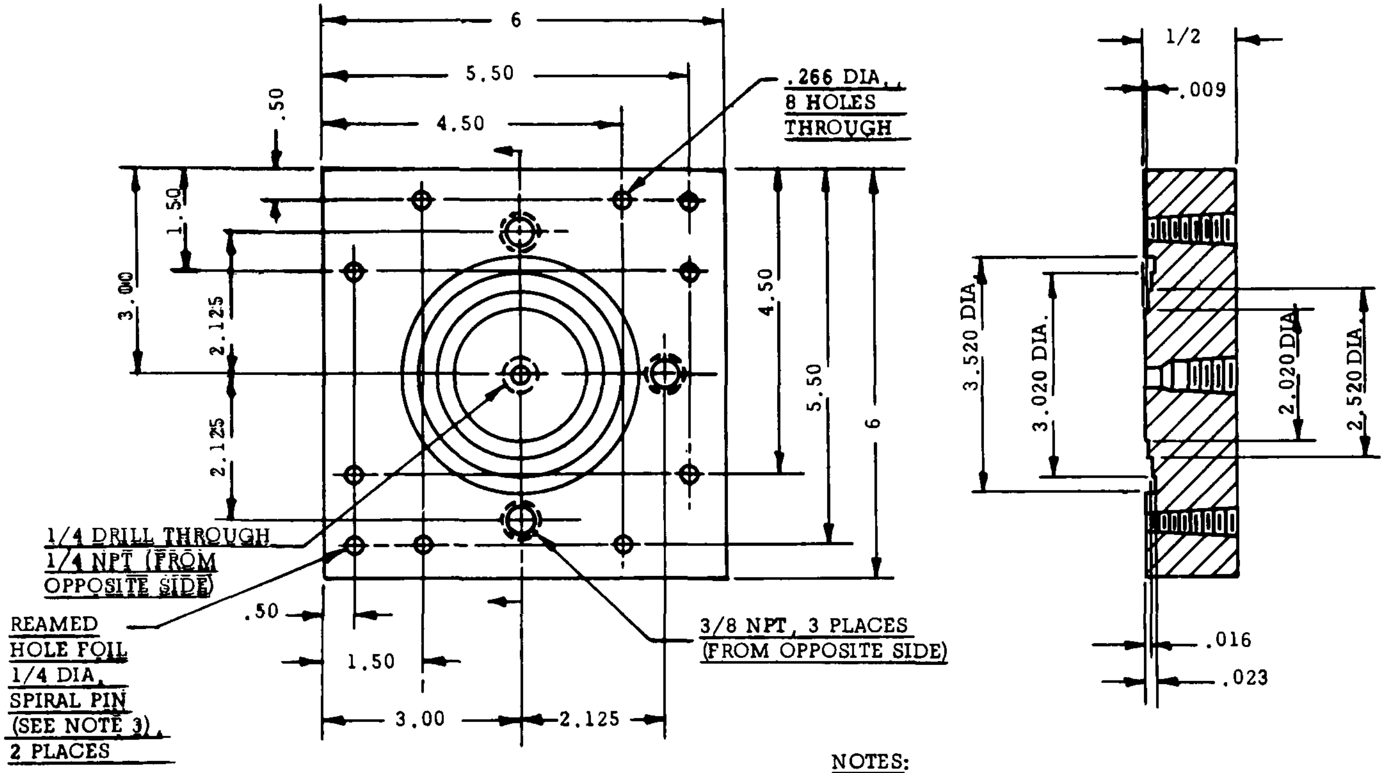
Design drawings of the basic vortex unit are illustrated in Figures 5 through 10. The basic design comprises six elements other than O-rings, hoses, pipe fittings and bolts, screws, nuts and washers. These elements are detailed as follows:

1. Top Vortex Chamber End Cover - Figure 5 -- This is the cover member through which air and water are introduced into the device. It is a flat piece of material, 6-inch square by 1/2-inch thick, containing eight bolt holes, two 3/8-inch pipe taps for water admission, one 3/8-inch pipe tap for a pressure gage, two locating pin holes and one 1/4-inch pipe tap through which air may be entrained.

2. Bottom Vortex Chamber End Cover - Figure 6 -- This is the second cover plate and also has overall dimensions of 6-inch by 6-inch by 1/2-inch, with eight bolt holes and two locating pins. At its center, however, is a 1 1/16-inch diameter through hole to accommodate replaceable exit tubes.

3. Vortex Chamber Housing - Figure 7 -- The housing is a 6-inch by 6-inch by 3/4-inch member which, with its 4 3/4-inch diameter central through hole, is clamped between the end covers where it serves as a high-pressure liquid manifold. The housing contains 8 bolt holes and two locating pins, and is equipped with an O-ring groove on both sides.

4. Vortex Chamber Spacers - Figure 8 -- These spacers, of which twelve were manufactured, were designed with two geometric variables. The variables included overall diameter, both inner and outer, and the diameter of four tangential holes which were used as high-pressure inlets for liquid supplied from the manifold chamber of the vortex chamber housing. The overall diameter changes permitted modifications in vortex gain. Variations in inlet hole geometry permitted independent changes in inlet impedance. Nominal thickness of the spacers was three-fourths of an inch and each was equipped with a

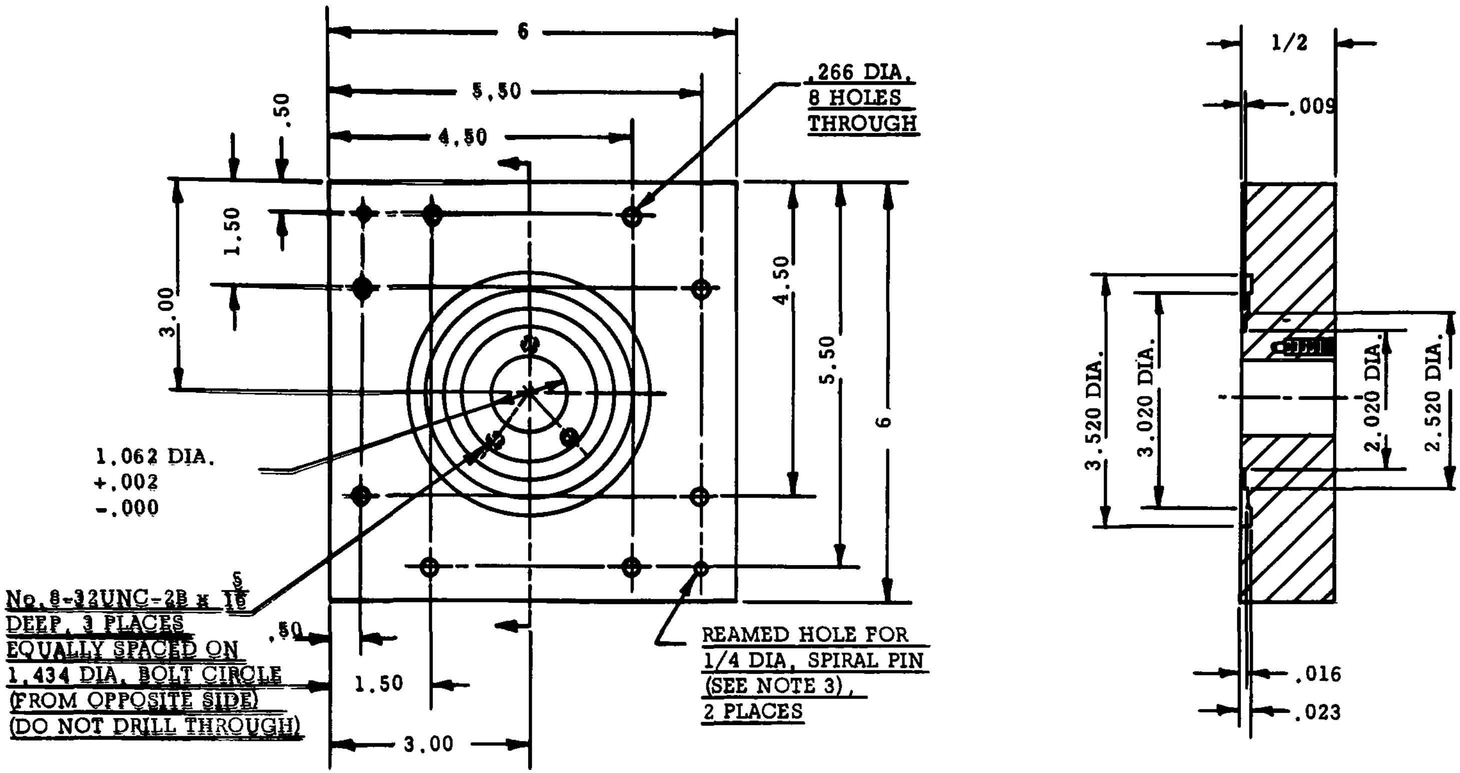


NOTES:

1. REMOVE BURRS AND SHARP EDGES
2. MATERIAL: ACRYLIC SHEET
3. SPIRAL PINS TO BE LOCATED WITH OPPOSITE VORTEX CHAMBER END COVER AND VORTEX CHAMBER HOUSING MATED TO THIS PIECE.
4. DIMENSIONS IN INCHES

FIGURE 5

TOP VORTEX CHAMBER END COVER

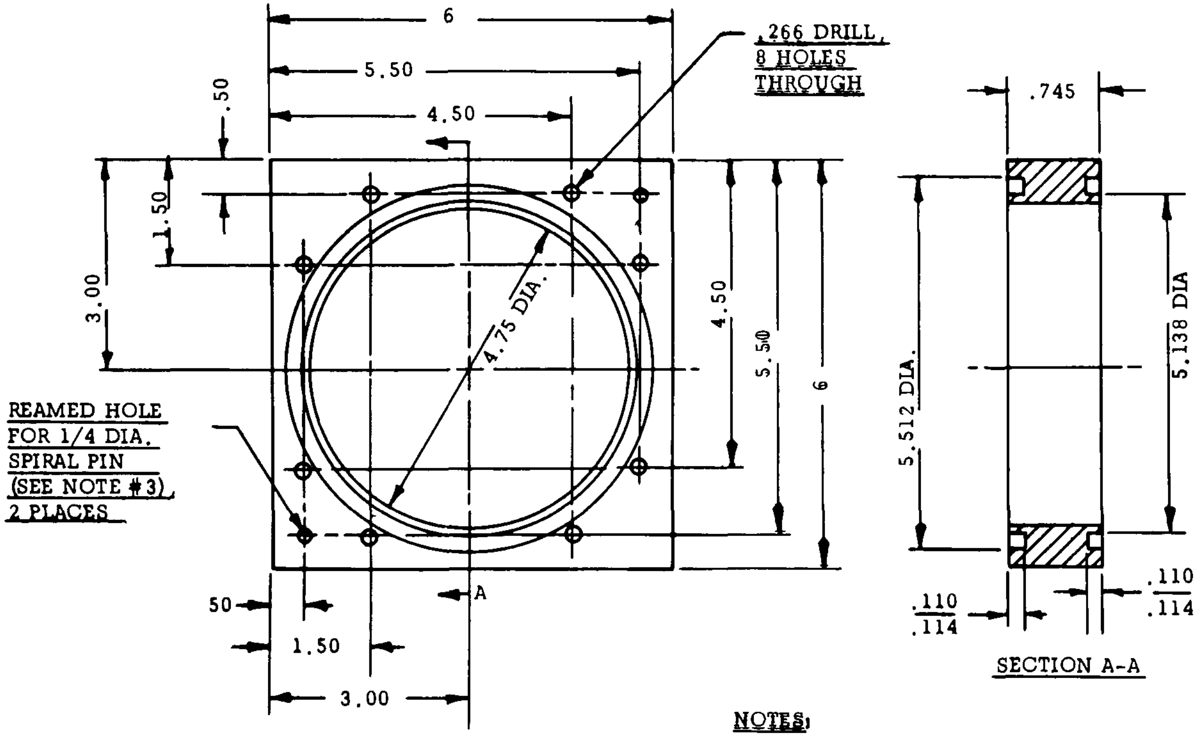


NOTES:

1. REMOVE BURRS AND SHARP EDGES
2. MATERIAL: ACRYLIC SHEET
3. SPIRAL PINS TO BE LOCATED WITH OPPOSITE VORTEX CHAMBER END COVER AND VORTEX CHAMBER HOUSING MATED TO THIS PIECE.
4. DIMENSIONS IN INCHES

FIGURE 6

BOTTOM VORTEX CHAMBER END COVER



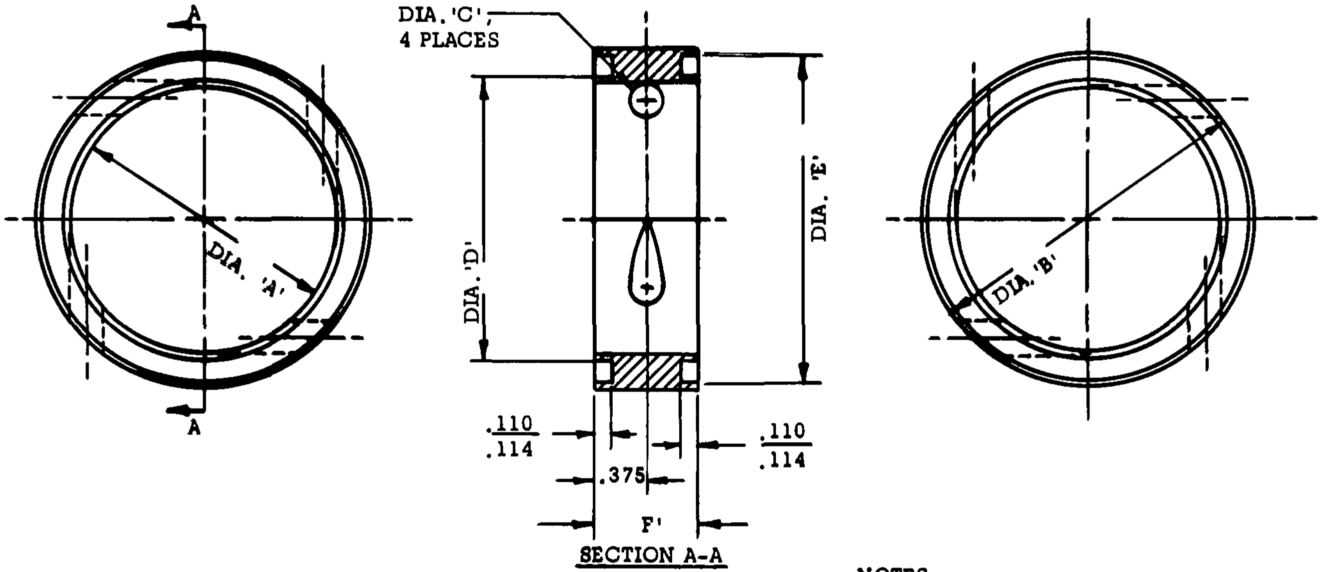
NOTES:

1. REMOVE BURRS AND SHARP EDGES
2. MATERIAL: ACRYLIC SHEET
3. SPIRAL PINS TO BE LOCATED WITH VORTEX CHAMBER END COVERS MATES TO THIS PIECE.
4. DIMENSIONS IN INCHES

FIGURE 7

VORTEX CHAMBER HOUSING

ITEM	DIA 'A'	DIA 'B'	DIA 'C'	DIA 'D'	DIA 'E'	DIM 'F'	ITEM	DIA 'A'	DIA 'B'	DIA 'C'	DIA 'D'	DIA 'E'	DIM 'F'
L-1	3.000	3.500	.277	3.087	3.387	.790	M-3	2.500	3.000	.228	2.587	2.887	.775
L-2	3.000	3.500	.250	3.087	3.387	.790	M-4	2.500	3.000	.1935	2.587	2.887	.775
L-3	3.000	3.500	.228	3.087	3.387	.790	S-1	2.000	2.500	.277	2.087	2.387	.760
L-4	3.000	3.500	.1935	3.087	3.387	.790	S-2	2.000	2.500	.250	2.087	2.387	.760
M-1	2.500	3.000	.277	2.587	2.887	.775	S-3	2.000	2.500	.228	2.087	2.387	.760
M-2	2.500	3.000	.250	2.587	2.887	.775	S-4	2.000	2.500	.1935	2.087	2.387	.760



NOTES:

1. REMOVE BURRS AND SHARP EDGES
2. MATERIAL: CAST ACRYLIC TUBE
3. DIAS. 'A' and 'B' TO BE TOLERANCED AS RECEIVED.
4. DIMENSIONS IN INCHES

FIGURE 8

VORTEX CHAMBER SPACERS

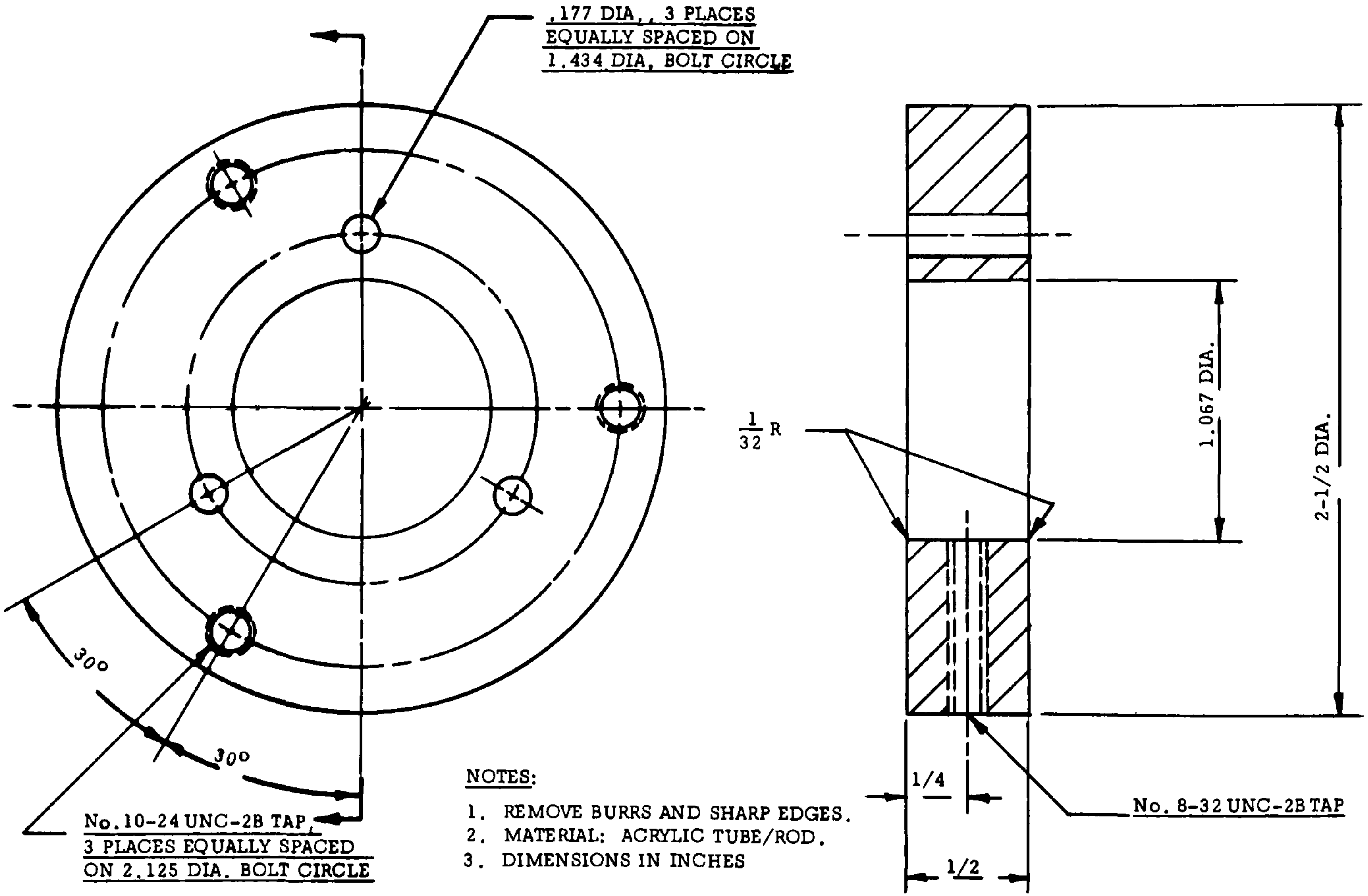
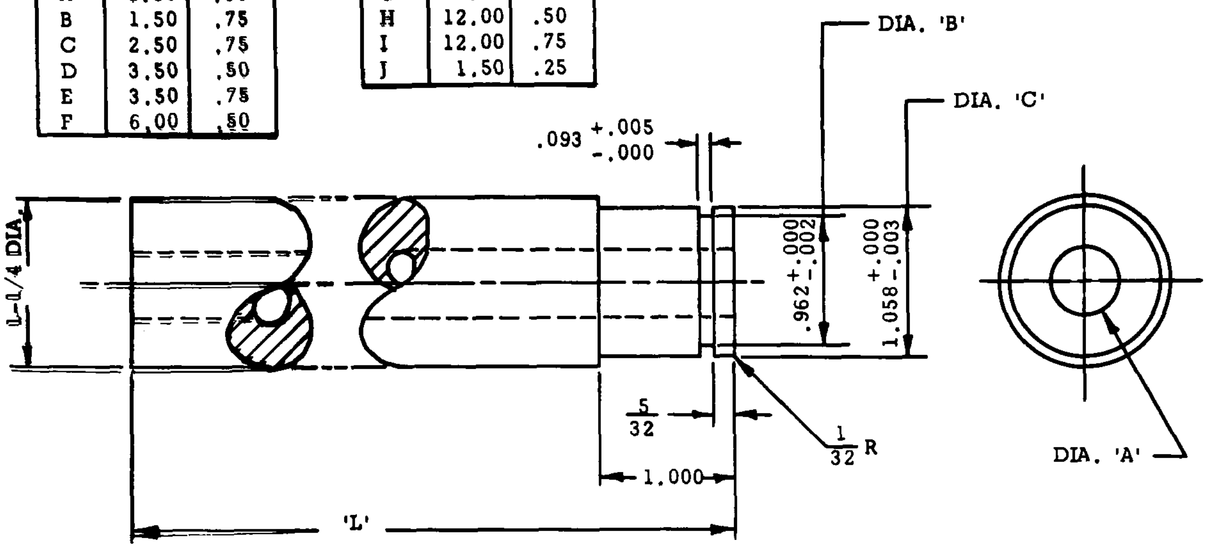


FIGURE 9

VORTEX EXIT ADAPTER

ITEM	DIM'L'	DIA.'A'
A	1.50	.50
B	1.50	.75
C	2.50	.75
D	3.50	.50
E	3.50	.75
F	6.00	.50

ITEM	DIM'L'	DIA.'A'
G	6.00	.75
H	12.00	.50
I	12.00	.75
J	1.50	.25



NOTES:

1. REMOVE BURRS AND SHARP EDGES
2. MATERIAL: CAST ACRYLIC TUBE/ROD
3. OD TO BE TOLERANCED AS RECEIVED
4. DIAS.'B' & 'C' CONCENTRIC WITHIN .005 TIR
5. DIMENSIONS IN INCHES

FIGURE 10

VORTEX EXIT TUBES

pair of O-rings for clamping and sealing between the vortex end covers.

5. Vortex Exit Adapter - Figure 9 -- The adapter is a single transition member used to hold the vortex exit tube securely in a central hole within the bottom end cover.

6. Vortex Exit Tubes - Figure 10 -- Ten exit tubes of different sizes were designed and fabricated. This array permitted relatively independent variation of vortex gain (dependent upon exit hole diameter) and outlet impedance (dependent upon exit hole diameter and length). As shown in Figure 10, each exit tube contains an O-ring groove used to seal it in position within the vortex device. A set screw in the adapter is employed to assure that the tube remains stably seated.

Figures 11 and 12 illustrate twelve vortex chamber spacers and a closeup view of one design (L-2), respectively. Figure 13 is a photograph of the vortex exit adapter together with one of the exit tubes. The complete array of exit tubes is shown in Figure 14.

Figure 15 is a photograph of the vortex bubble-maker set up as an exploded

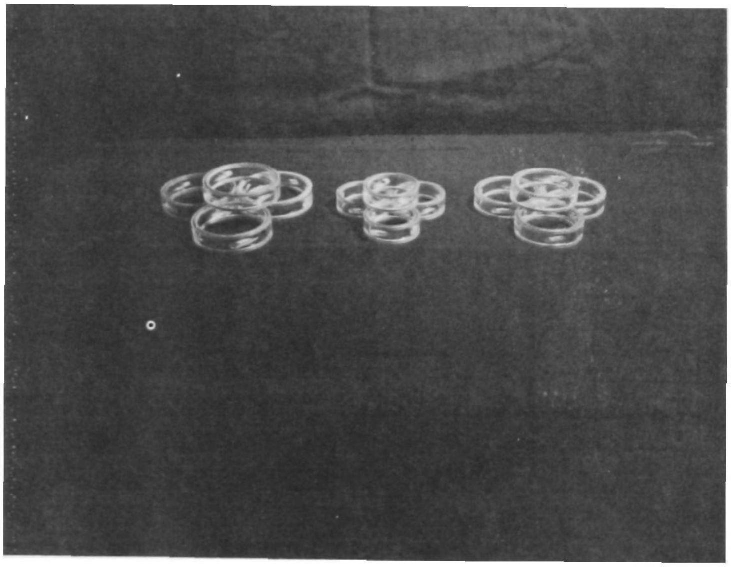


FIGURE 11

VORTEX CHAMBER SPACERS

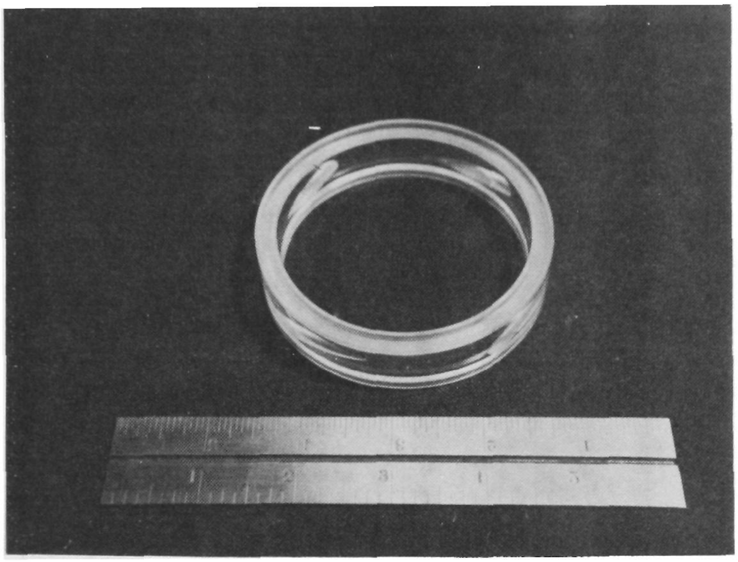


FIGURE 12

SPACER NUMBER L-2

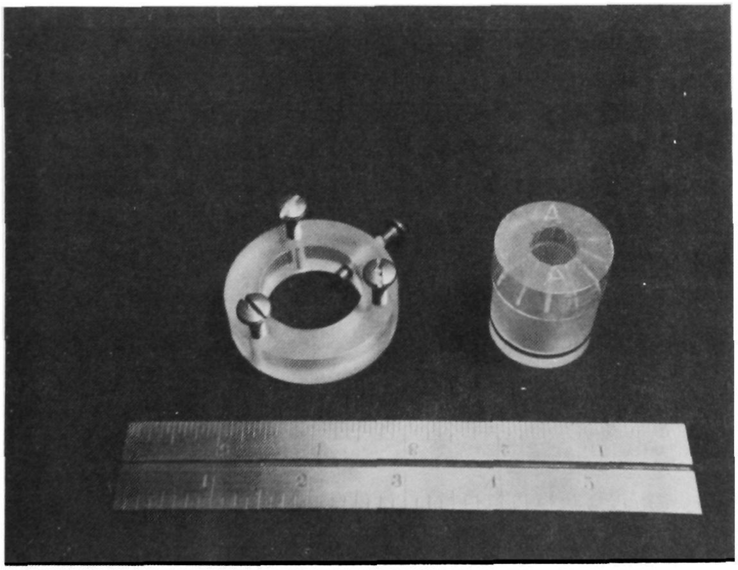


FIGURE 13

ADAPTER AND SINGLE EXIT TUBE

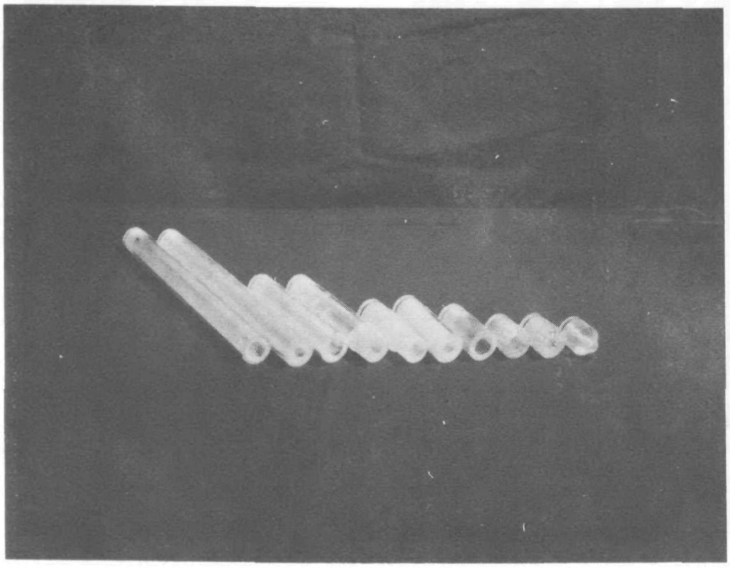


FIGURE 14

ARRAY OF VORTEX EXIT TUBES

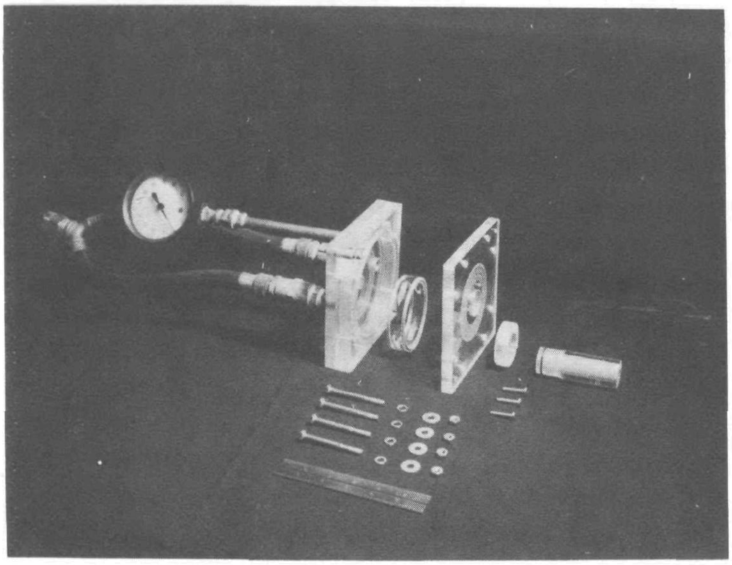


FIGURE 15

VORTEX BUBBLE-MAKER EXPLODED VIEW

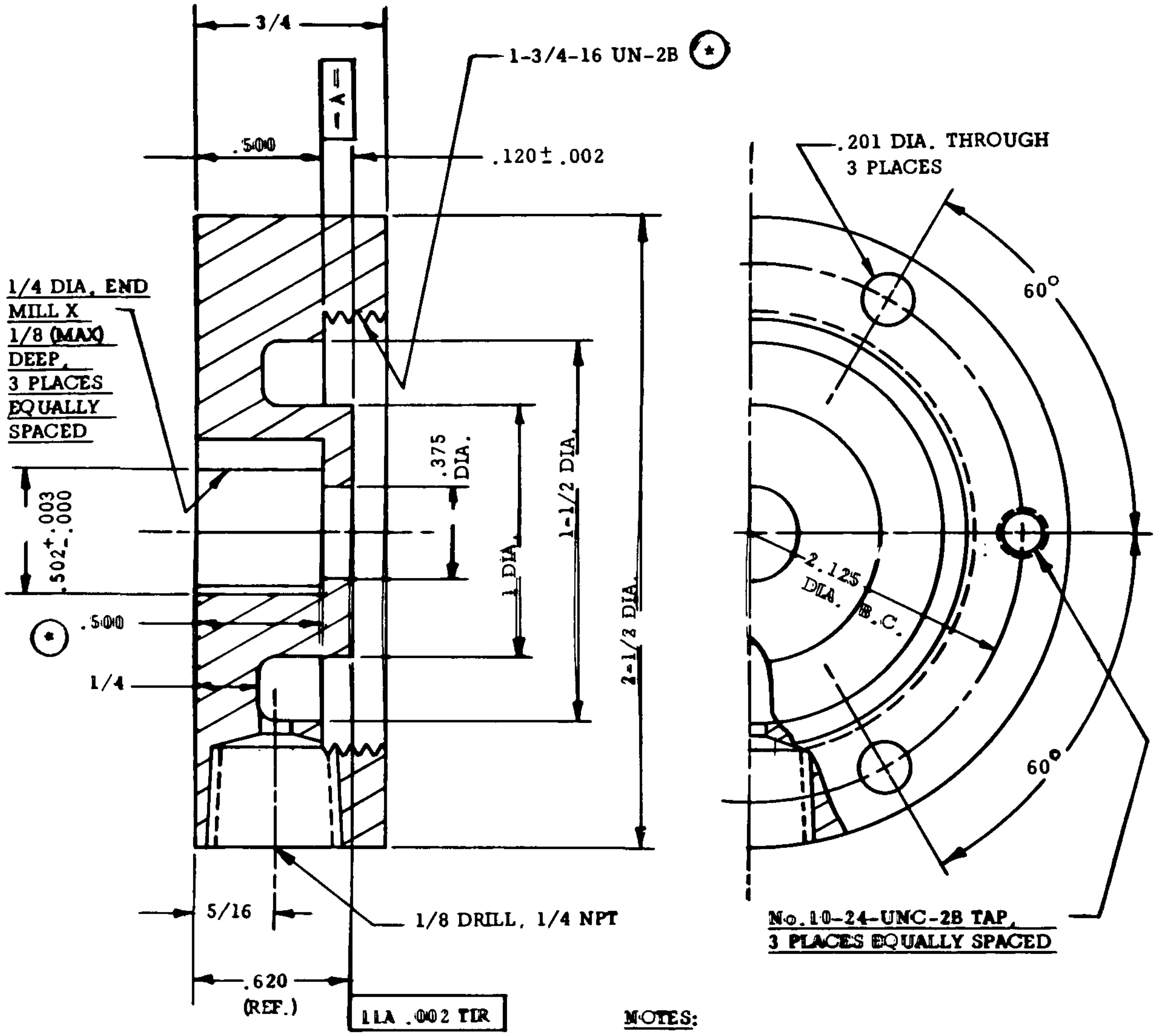
view. At the left, the top end cover (see Figure 5) is shown with high-pressure liquid lines and a pressure gage attached. Also attached to the top end cover is the housing (see Figure 6), which is held in position in this photograph by friction at the locating pins. The right side of the figure shows one of the large (L-series) chamber spacers followed by the bottom cover plate, the adapter, and the D-coded (3-1/2-inch long by 1/2-inch ID) exit tube. Also shown is the hardware used to assemble the device. Although not readily apparent in the photograph, all O-rings are in place on this unit. Most of the material selected for construction was acrylic plastic. The reason for this selection was to permit observation of the flow internal to the unit. All of the test tanks were also constructed of this material to permit easy visualization and photography.

In addition to the basic design outlined above, one other objective also required evaluation work and necessitated special design. This objective was an exploration of the possibility for doubling the bubble-making capacity of the fundamental device by permitting air to be entrained both at the "inside" and "outside" of the device. The terms "inside" and "outside" refer to the conical sheet of high-velocity swirling fluid which exits from an operating vortex bubble-maker. This sheet has an inside surface and an outside surface. The hardware shown in Figure 15 permitted air entrainment and distribution only to the inside surface of the cone. Additional hardware was needed to permit entrainment at the outside surface simultaneously.

Figures 16 through 19 are detailed drawings of the two basic devices used to evaluate this concept. As shown in Figure 19, an adaptation of the fundamental vortex exit tube design was necessary. The modification comprises a necking down of the portion of the tube which protrudes from the vortex exit adapter. This necked-down portion fits within the central holes of the adapters shown in Figures 16 and 17. These designs gave the option of operating with the outside of the vortex cone either vented or non-vented to the atmosphere. Both entrainment adapters were fitted with holes which permitted them to be stabilized with any degree of axial insertion of the exit tube from full to zero. Figure 20 illustrates the modified exit tube, together with adapter number one and its associated seal plate. As shown in the figure, the adapter is equipped with a fitting through which air can be admitted.

TEST EQUIPMENT DESIGN

Three fundamental types of test equipment were required for this program. Two of these types involved plumbing and tanks for bubble-making evaluation and flotation testing. The third involved photographic equipment and lighting suitable for high-definition photomicrographs of the bubbles formed.

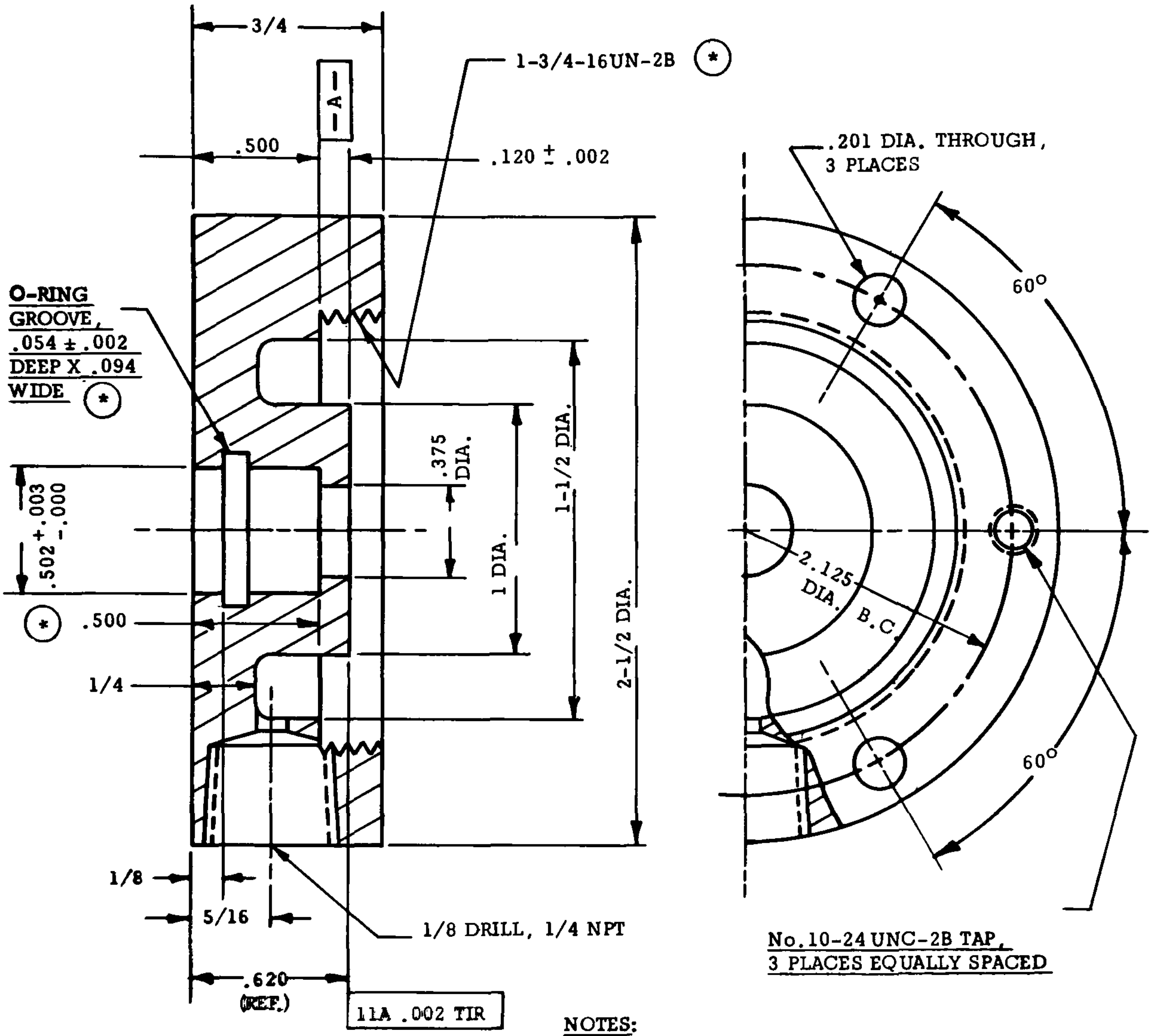


NOTES:

1. MATERIAL: ACRYLIC
2. DIAS. CONCENTRIC WITHIN .010 TIR EXCEPT THOSE WITH (*), TO BE CONCENTRIC WITHIN .002 TIR.
3. BREAK EDGES .010 R MAX.
4. DIMENSIONS IN INCHES

FIGURE 16

OUTSIDE ENTRAINMENT ADAPTER NUMBER ONE

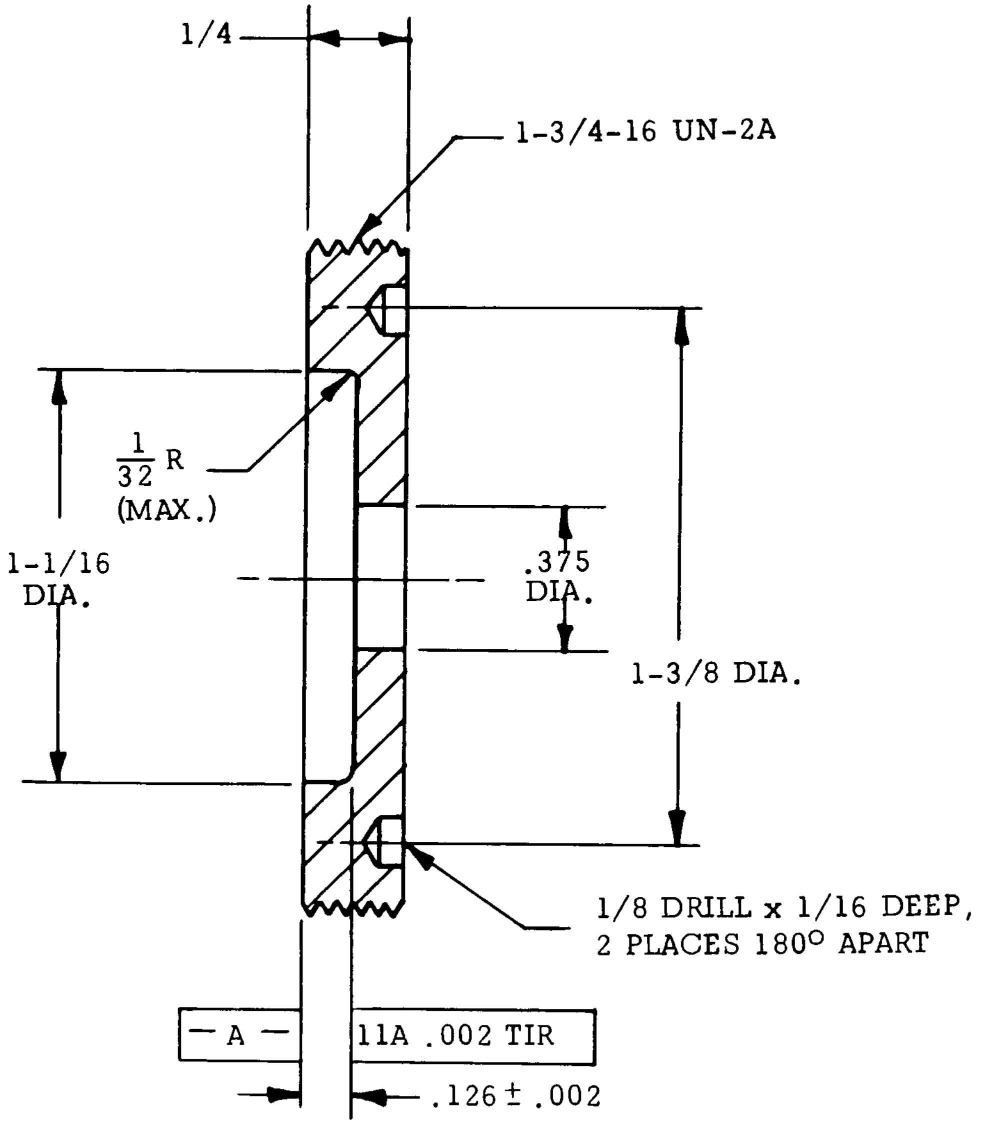


NOTES:

1. MATERIAL: ACRYLIC
2. DIAS. CONCENTRIC WITHIN .010 TIR EXCEPT THOSE WITH (*), TO BE CONCENTRIC WITHIN .002 TIR.
3. BREAK EDGES .010 R MAX.
4. DIMENSIONS IN INCHES

FIGURE 17

OUTSIDE ENTRAINMENT ADAPTER NUMBER TWO



NOTES:

1. MAKE: 2
2. MATERIAL: ACRYLIC
3. DIAS. CONCENTRIC WITHIN .010 TIR
4. BREAK EDGES .010 R MAX.
5. DIMENSIONS IN INCHES

FIGURE 18

OUTSIDE ENTRAINMENT SEAL PLATE

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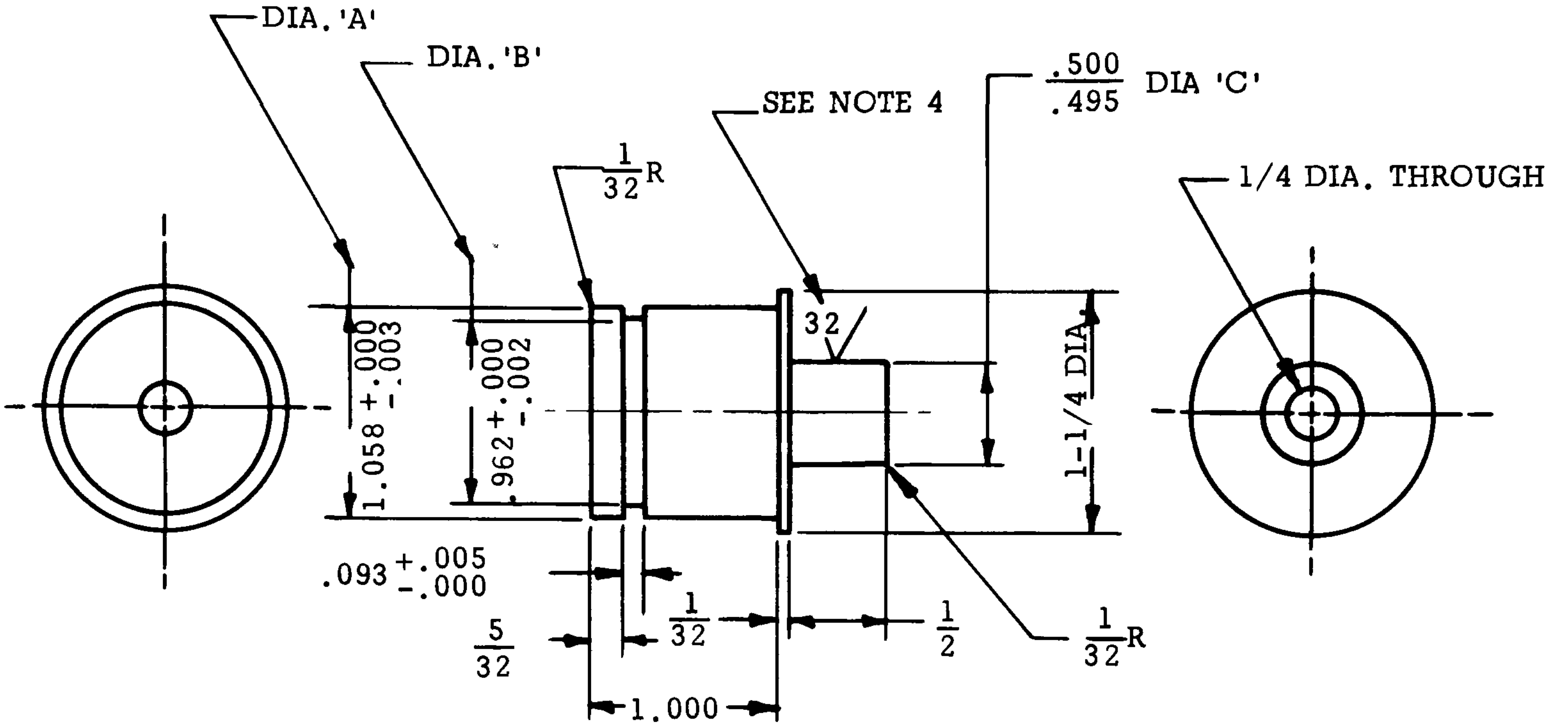

NOTES:

1. REMOVE BURRS AND SHARP EDGES
2. MATERIAL: ACRYLIC TUBE/ROD, 1-1/4 OD
3. OD TO BE TOLERANCED AS RECEIVED
4. BURNISH FOR O-RING SEAL
5. DIAS. 'A', 'B', and 'C' CONCENTRIC WITHIN .005 TIR
6. DIMENSIONS IN INCHES

FIGURE 19

OUTSIDE ENTRAINING VORTEX EXIT TUBE

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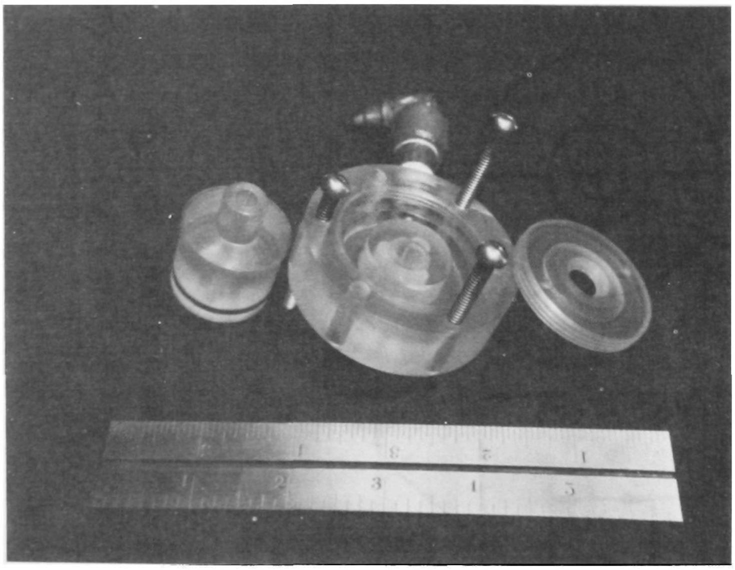

FIGURE 20

MODIFIED EXIT TUBE HARDWARE FOR
OUTSIDE ENTRAINMENT

Photographic Equipment

After some experimentation, a Nikon binocular microscope was found to be suitable as the basic image-formation device. Coupled with Nikon Microflex photographic equipment and a Polaroid sheet film adapter, the microscope was capable of linear photographic magnifications of 26.9X (with 10X eyepieces) and 53.8X (with 20X eyepieces). The microscope's focal point was situated roughly 1-1/2 inches from the objective lens, which permitted easy focusing on locations well inside any of the test tanks.

One of the major photographic problems which had to be solved was in the area of lighting. Using continuous lighting, very fast shutter speeds were necessary to "stop" the moving bubbles. At such speeds, no position of the lights was possible which would provide both a visible image of the bubbles and yield enough illumination to give a visible record of that image on film, in spite of the fact that Type 57 Polaroid film having a speed of 3000 (ASA equivalent) was used.

Accordingly, emphasis was transferred to a flash lighting technique utilizing very intense lighting with a duration of a small fraction of a second. Various light sources, ranging from a Braun Hobby 200 miniature photoflash unit to an EG&G Model 502 Multiple Microflash unit, were tested. The former had an excessive exposure duration (approximately 100 microseconds). The latter unit permits control of the time intervals between successive flashes from 40 milliseconds to 10 microseconds. The unit is equippped with a high intensity flash lamp whose power pulse has a duration of 1 microsecond. Unfortunately, this appeared to be too short for effective exposure.

The ideal flash lighting source was found to be a portable stroboscopic unit, the Strobonar, produced by the Heiland Division of Honeywell. The strobe flash has a reasonably short duration, with an intensity adequate for proper illumination of the bubbles. Appropriate lighting positions were developed to yield effective microphotographs. At 53.8X magnifications, bubbles having a diameter less than 5 microns could easily be seen and sized in the photographs. Assuming that a bubble photograph as small as 0.010 inch in diameter could be easily resolved, a magnification of 50X would yield the capability of discerning bubbles as small as 5 microns in diameter.

Since 10-micron resolution was subsequently found to be adequate for the actual sizes of bubbles present, 25X magnification was used. This had the advantage that each photograph showed four times as many bubbles, thus giving a much more adequate representation of bubble size distribution than was possible with the higher magnification. With an actual magnification factor of 26.9X, each 3-1/2-inch by 4-1/2-inch photograph had a total field of view of 0.130 x 0.167 inches. Measurement resolution to 0.01 inches (approximately 9.5 microns) on these photographs was achieved with a 1:100 inch scale.

The Nikon and Honeywell equipment in position is shown in Figure 21. As indicated in the figure, reflected lighting against a black back-drop (the small rectangular object partially hidden behind the Strobonar unit) was used.

Bubble-Making and Flotation Test Equipment

The initial testing concept visualized for the program called for dual-purpose test equipment. As outlined in the block diagram of Figure 4, the original system was to have two different bubble sources, either of which would discharge into the bubble-making and flotation tank. A description of the original system is as follows:

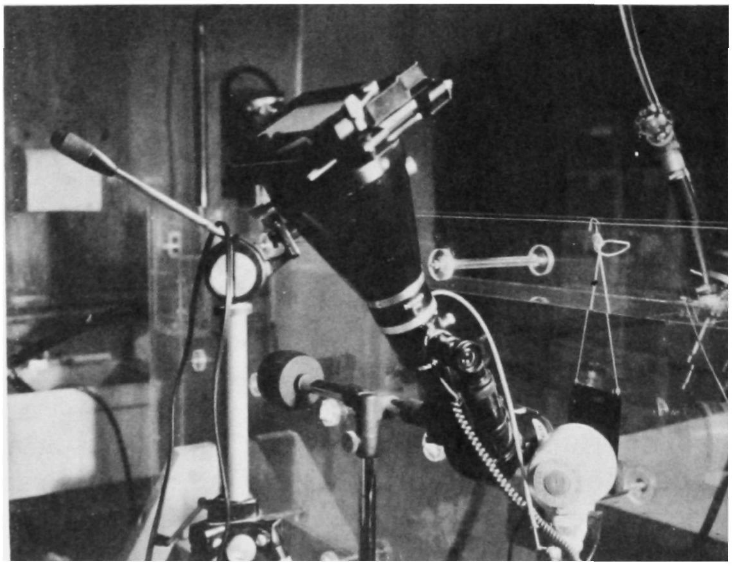

FIGURE 21

PHOTOMICROGRAPHIC EQUIPMENT

1. The dissolved-air pressurization tank was an acrylic cylinder (10-inch ID, 11-inch OD and 53 inches in length) sealed at both ends, with internal baffling to permit efficient gas transfer. The tank was equipped with a short drain line to a one-inch gate valve that served as a back pressure regulator.

2. The bubble-making and flotation tank was an acrylic cylinder (9.75-inch ID, 10-inch OD and 53 inches in length) sealed at one end, with an inlet from the dissolved air pressurization tank via the back pressure regulator valve and a water outlet via a 1-1/4-inch pipe and gate valve.

3. The pump was a Sears, Roebuck Deluxe Convertible Deep Well Jet Pump with a shallow well jet attachment, Model 390.25931, with a 1-horsepower drive motor.

4. The piping and valves consisted of one-inch pressure lines, 1-1/4-inch suction lines, flexible PVC pipe and bronze gate valves.

5. The air pressure regulator was a Fairchild-Hiller Kendall Model 30 pressure regulator.

6. The aspirator was a specially-designed venturi unit for entrainment of atmospheric air at the suction side of the pump, as shown in Figure 22.

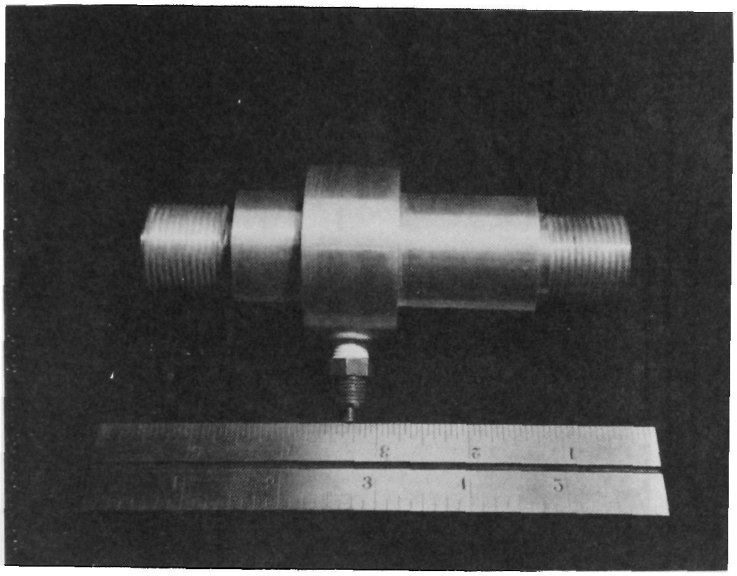

FIGURE 22

VENTURI

In the initial testing of the vortex device as a bubble-maker, this test equipment proved entirely adequate. However, the bubble-making tank lacked sufficient volume for a demonstration of the dispersion characteristics of bubbles formed by any of the bubble-makers. Moreover, successful use of the same relatively small tank for both floc generation and bubble-making during flotation tests was not possible. Hence, the test equipment as originally designed was modified to the configuration shown in the block diagram of Figure 23. In an effort to overcome the flotation problem, the floc generation function was separated from those of bubble formation and flotation. Specifically, the test equipment now included a separate new bubble-making and flotation tank that was nominally eight feet long by four feet high by 2/3-foot wide. The tank was designed so that inputs from any of three bubble sources (vortex, tank-pressurized water, and tankless pressurized water) might be introduced at one end. Also at this end, floc mixtures from a separate mixing and flocculation tank could be introduced at variable flow rates up to 10 gpm. At its opposite end, the tank was equipped with a high weir for draining of floated material and with a low drain from which effluent could be removed by pumping. The

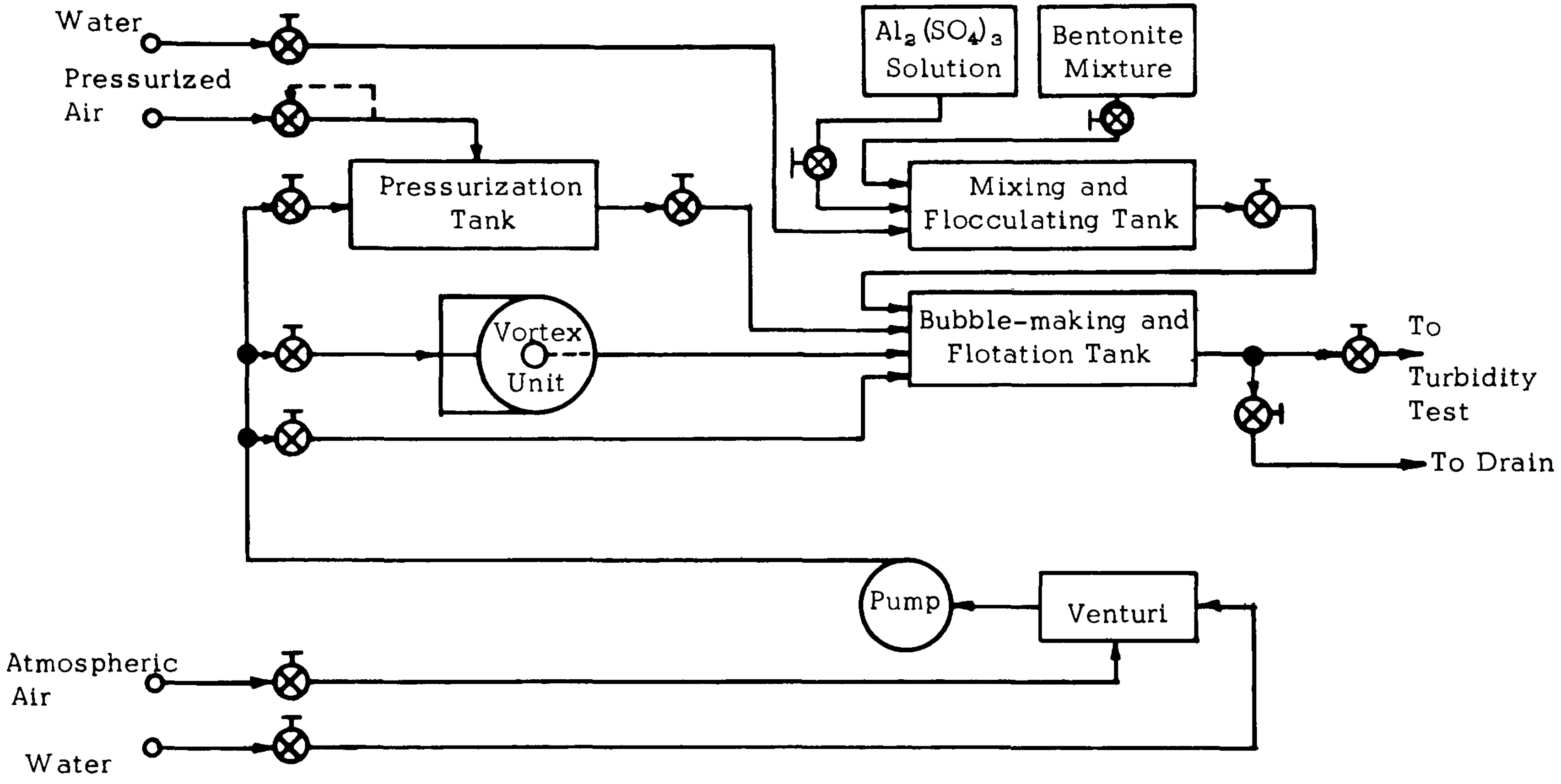

FIGURE 23

MODIFIED TEST EQUIPMENT

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new tank and some of the photomicrographic equipment are shown in Figure 24.

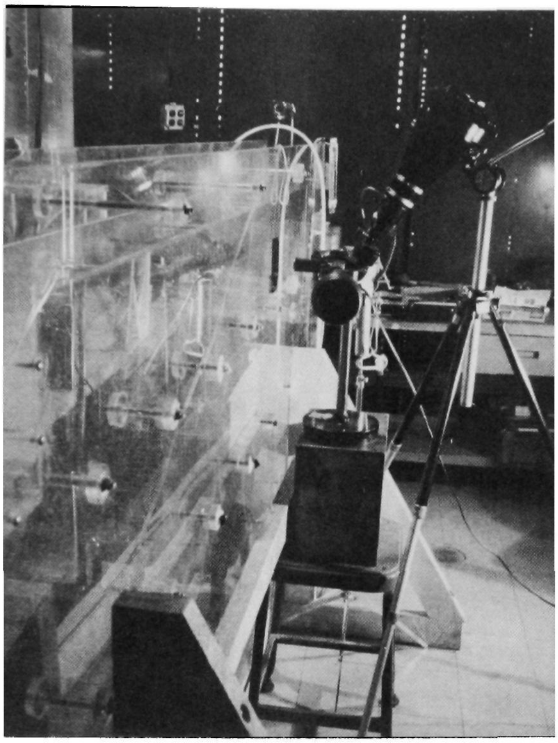

FIGURE 24

NEW FLOTATION TANK AND PHOTOMICROGRAPHIC EQUIPMENT

The original flotation tank was converted to a mixing and flocculation tank. The watér, after dosing with bentonite and alum, was stirred with a variable speed apparatus capable of rotation at rates as low as 20 rpm. The flocculated tapwater could then be introduced to the bubble-making and flotation tank at variable rates that were not dependent upon any pumping action.

Jar tests were performed to determine the optimum dose of aluminum sulfate solution for clarification of the tapwater seeded with 50mg/l of bentonite. Because local water is quite soft, a dose of 25 milligrams of aluminum sulfate per liter was found to be optimum.

It was determined that turbidity measurements would provide the best means for assessing the relative effectiveness of the flotation tests.

For this purpose, a Hach Model 2100A Laboratory Turbidimeter, capable of measurements from 0-to-1000 Jackson Turbidity Units (JTU), was purchased to permit quantitative determination of flotation efficiency.

SECTION VI

EVALUATION

The evaluation of the vortex devices as bubble generators was performed in three stages. Each vortex configuration was operated over a range of water pressures and air flow rates. Those configurations exhibiting maximum performance in terms of numbers of bubbles produced in a given size range per unit horsepower were then selected for further evaluation. Such further evaluation was designed to study the effects of chamber geometry and operation at various chamber depths.

INITIAL TEST STAGE

During initial testing, emphasis was placed on the relative operability of the various devices. At this early stage, sixty vortex geometric combinations, shown in Table 2, were available. The first objective, therefore, was to reduce this large quantity to a lesser number, more suitable for detailed testing. In this first test, each configuration was pressurized to 10 psig and 20 psig, successively, and a determination was made as to two characteristics:

1. Atmospheric air entrainment capability.

2. Minimum bubble size produced.

First, all sixty configurations developed vacuum in their vortex cores sufficient to entrain atmospheric air without the need for a separate compressed air line. Prior to program startup, certain other vortex devices had required positive pressurization in order to develop any bubbles.

Second, there was an easily observed gradation in the minimum sizes of bubbles produced. The gradation varied with pressure, i.e., minimum bubble sizes generally appeared at maximum pressure. The major effect of pressure, however, was in the quantity of bubbles produced in any given size range: More bubbles were generally produced at higher operating pressures. This is consistent with the fundamental concept of how bubbles are formed in the vortex discharge flow. An even more important part of this second observation, however, was the fact that maximum performance at any given pressure appeared to be related to geometry. Smaller bubbles, and more of them, tended to be produced by configurations having larger vortex diameters (L-units) and smaller exit tube ID's (-A and -D units).

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TABLE 2

VORTEX CONFIGURATIONS AVAILABLE
FOR INITIAL TESTING

DESIG-NATION	CHAMBER OD INCHES	CHAMBER INLET HOLE DIAMETER INCHES	EXIT TUBE INNER DIAMETER INCHES	EXIT TUBE LENGTH, INCHES
L-1-A	3.0	0.277	0.50	1.5
L-1-B	3.0	0.277	0.75	1.5
L-1-C	3.0	0.277	0.75	2.5
L-1-D	3.0	0.277	0.50	3.5
L-1-E	3.0	0.277	0.75	3.5
L-2-A	3.0	0.250	0.50	1.5
L-2-B	3.0	0.250	0.75	1.5
L-2-C	3.0	0.250	0.75	2.5
L-2-D	3.0	0.250	0.50	3.5
L-2-E	3.0	0.250	0.75	3.5
L-3-A	3.0	0.228	0.50	1.5
L-3-B	3.0	0.228	0.75	1.5
L-3-C	3.0	0.228	0.75	2.5
L-3-D	3.0	0.228	0.50	3.5
L-3-E	3.0	0.228	0.75	3.5
L-4-A	3.0	0.1935	0.50	1.5
L-4-B	3.0	0.1935	0.75	1.5
L-4-C	3.0	0.1935	0.75	2.5
L-4-D	3.0	0.1935	0.50	3.5
L-4-E	3.0	0.1935	0.75	3.5
M-1-A	2.5	0.277	0.50	1.5
M-1-B	2.5	0.277	0.75	1.5
M-1-C	2.5	0.277	0.75	2.5
M-1-D	2.5	0.277	0.50	3.5
M-1-E	2.5	0.277	0.75	3.5
M-2-A	2.5	0.250	0.50	1.5
M-2-B	2.5	0.250	0.75	1.5
M-2-C	2.5	0.250	0.75	2.5
M-2-D	2.5	0.250	0.50	3.5
M-2-E	2.5	0.250	0.75	3.5

TABLE 2 (CONTINUED)

DESIG- NATION	CHAMBER OD INCHES	CHAMBER INLET HOLE DIAMETER INCHES	EXIT TUBE INNER DIAMETER INCHES	EXIT TUBE LENGTH, INCHES
M-3-A	2.5	0.228	0.50	1.5
M-3-B	2.5	0.228	0.75	1.5
M-3-C	2.5	0.228	0.75	2.5
M-3-D	2.5	0.228	0.50	3.5
M-3-E	2.5	0.228	0.75	3.5
M-4-A	2.5	0.1935	0.50	1.5
M-4-B	2.5	0.1935	0.75	1.5
M-4-C	2.5	0.1935	0.75	2.5
M-4-D	2.5	0.1935	0.50	3.5
M-4-E	2.5	0.1935	0.75	3.5
S-1-A	2.0	0.277	0.50	1.5
S-1-B	2.0	0.277	0.75	1.5
S-1-C	2.0	0.277	0.75	2.5
S-1-D	2.0	0.277	0.50	3.5
S-1-E	2.0	0.277	0.75	3.5
S-2-A	2.0	0.250	0.50	1.5
S-2-B	2.0	0.250	0.75	1.5
S-2-C	2.0	0.250	0.75	2.5
S-2-D	2.0	0.250	0.50	3.5
S-2-E	2.0	0.250	0.75	3.5
S-3-A	2.0	0.228	0.50	1.5
S-3-B	2.0	0.228	0.75	1.5
S-3-C	2.0	0.228	0.75	2.5
S-3-D	2.0	0.228	0.50	3.5
S-3-E	2.0	0.228	0.75	3.5
S-4-A	2.0	0.1935	0.50	1.5
S-4-B	2.0	0.1935	0.75	1.5
S-4-C	2.0	0.1935	0.75	2.5
S-4-D	2.0	0.1935	0.50	3.5
S-4-E	2.0	0.1935	0.75	3.5

SECONDARY TEST STAGE

It should be noted that these tests were in the nature of a coarse screening. Photography was concurrently attempted, but without successful high-resolution results. Moreover, the limited flow capacity of the pumps at high pressure made it impossible to obtain comparable data for all configurations at all conditions of operation. For example, data for the relatively high-impedance configurations could be obtained at operating liquid pressures as high as 28 psig. For the lower-impedance units such as S-1-B and S-1-D, however, testing was limited to pressures of 20 psig and below. Accordingly, the evaluation up to this point was somewhat subjective.

The initial tests were all performed with pumps of limited capacity and without the availability of a useful photographic technique. As a result, while it was obvious that no advantage lay in retention of mid-range sizes of vortex configurations (e.g., M- units and -C units), there was sufficient question as to the relative importance of vortex gain versus vortex inlet and outlet impedance to warrant continuing the relative evaluation of L- and S- units at higher operating pressures. Accordingly, some sixteen of the configurations listed in Table 2 were selected for such continued testing. These sixteen are listed in Table 3.

Secondary testing utilized the test setup described in Figure 4. Also, development of the final photographic technique and lighting arrangements had progressed so that a quantitatively recorded evaluation could be made.

The secondary evaluation phase of testing comprised operation over a range of pressures with photography of the bubbles formed at each of the operating pressures. Each of the configurations listed in Table 3 was operated at pressures of 10, 20 and 30 psig, and some of them were operated at pressures as high as 40 psig. At each of these pressures, photographic calibration of bubble output was made, with photographs like the one shown in Figure 25. Several photographs were taken for each configuration at each operating condition. Each photograph was then examined and the diameters of all bubbles in focus were individually measured to a resolution of 0.01 inch on the photograph, which was adjudged adequate for the bubble sizes actually present.

At this time, it had become apparent that there was actually a choice of operating methods for the basic vortex device. The device could be operated as its own air entrainer or aspirator, or it could be operated as a back pressure regulation device with air being supplied via the pump. The basic technique for the latter method has been worked out with a crude aspiration device on the earlier pumps.

TABLE 3

VORTEX CONFIGURATIONS SELECTED
FOR SECONDARY TESTING

DESIG-NATION	CHAMBER OD INCHES	CHAMBER INLET HOLE DIAMETER INCHES	EXIT TUBE INNER DIAMETER INCHES	EXIT TUBE LENGTH, INCHES
L-2-A	3.0	0.250	0.50	1.5
L-2-B	3.0	0.250	0.75	1.5
L-2-D	3.0	0.250	0.50	3.5
L-2-E	3.0	0.250	0.75	3.5
L-4-A	3.0	0.1935	0.50	1.5
L-4-B	3.0	0.1935	0.75	1.5
L-4-D	3.0	0.1935	0.50	3.5
L-4-E	3.0	0.1935	0.75	3.5
S-2-A	2.0	0.250	0.50	1.5
S-2-B	2.0	0.250	0.75	1.5
S-2-D	2.0	0.250	0.50	3.5
S-2-E	2.0	0.250	0.75	3.5
S-4-A	2.0	0.1935	0.50	1.5
S-4-B	2.0	0.1935	0.75	1.5
S-4-D	2.0	0.1935	0.50	3.5
S-4-E	2.0	0.1935	0.75	3.5

For this round of testing the venturi shown in Figure 22 was designed and built. A direct comparison with operation of each vortex configuration in each of these two modes clearly showed the superiority of air entrainment and pressurization via the pump over air entrainment in the vortex itself. This is understandable inasmuch as the amount of air in solution at the high output pressure of the pump is considerably greater than that entrained at the reduced pressure in the vortex core. The margin of superiority in terms of numbers of bubbles of a given size range per photograph averaged approximately two-to-one for pump entrainment over vortex entrainment. Hence, from this point forward, all further vortex measurements were made with the "inside" air supplied by the venturi located at the suction side of the pump.

Results for the second-round tests are summarized in Table 4. The more promising performance levels are underlined. Considering the ranges of

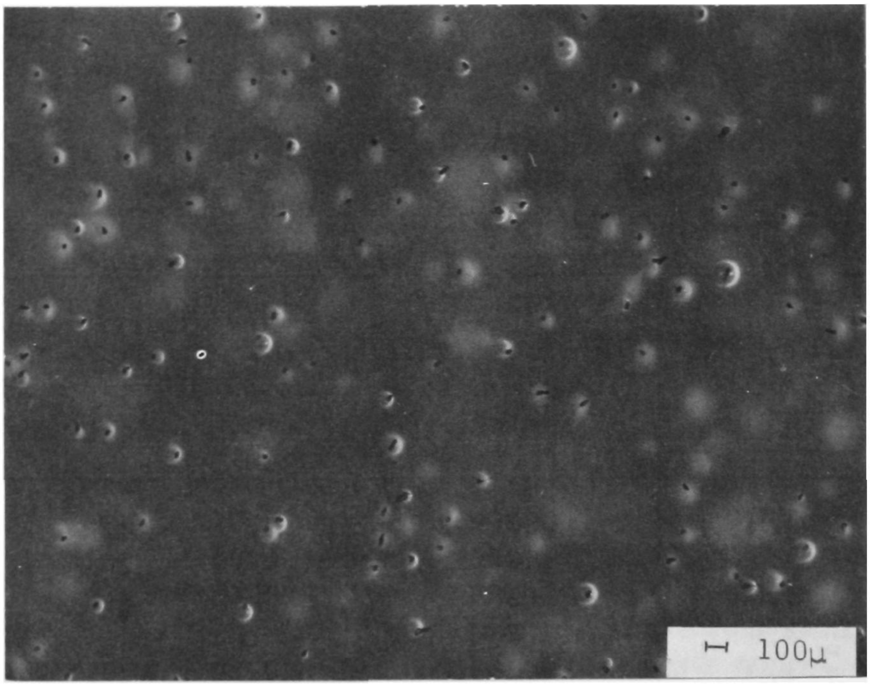

FIGURE 25

TYPICAL BUBBLE PHOTOMICROGRAPH
UNIT L-2-D AT 26.9X MAGNIFICATION, 36 PSIG

parameters over which tests were conducted, the results in terms of both bubble sizes and number of bubbles produced per unit volume were quite flat, with mean bubble size varying over a range from approximately 85µ to 120µ. Not surprising was the superiority of the larger vortex units (Code L) over the smaller ones (Code S) in producing small bubbles, but the margin of superiority was lower than anticipated and data were scattered. Likewise, smaller bubbles were usually obtained at higher operating pressures, but again data showed scatter. The scatter in the data was due to the fact that local bubble velocity in some photographs was clearly higher than in others, making accurate measurements more difficult.

In general, the better combination of vortex geometry and pressures yielded very similar results in terms of small bubble size (around 85 microns diameter). In terms of the number of bubbles produced per unit volume of water in the bubble-making tank, the number of countable bubbles shows a considerable spread. The spread amounts to more than 3 to 1 between the maximum and mean numbers for the approximately 100 photographs taken. However, for those photographs exhibiting a mean bubble diameter of 90 microns or less, the mean bubble count is roughly 20% higher than that of the entire array. Data in the form of a histogram for the best configuration are given in Figure 26.

TABLE 4

SECONDARY TEST RESULTS

VORTEX DESIG-NATION	20 PSIG		30 PSIG		40 PSIG	
	MEAN BUBBLE DIAMETER MICRONS	BUBBLES/ HORSE-POWER	MEAN BUBBLE DIAMETER MICRONS	BUBBLES/ HORSE-POWER	MEAN BUBBLE DIAMETER MICRONS	BUBBLES/ HORSE-POWER
L-2-A	118	616	112	510	***	***
L-2-B	97	432	*	*	***	***
L-2-D	94	381	103	389	86 **	758 **
L-2-E	89	342	*	*	***	***
L-4-A	90	854	84	447	84	616
L-4-B	*	*	104	432	94	288
L-4-D	100	644	86	461	96	566
L-4-E	91	230	110	369	103	187
S-2-A	85	685	106	565	***	***
S-2-B	*	*	*	*	***	***
S-2-D	*	*	*	*	***	***
S-2-E	110	376	88	166	***	***
S-4-A	*	*	81	534	***	***
S-4-B	90	360	*	*	***	***
S-4-D	*	*	*	*	***	***
S-4-E	99	632	105	320	***	***

* Unsatisfactory bubble size or concentration

** 36 PSIG

*** Inoperable or unsatisfactory bubble concentration.

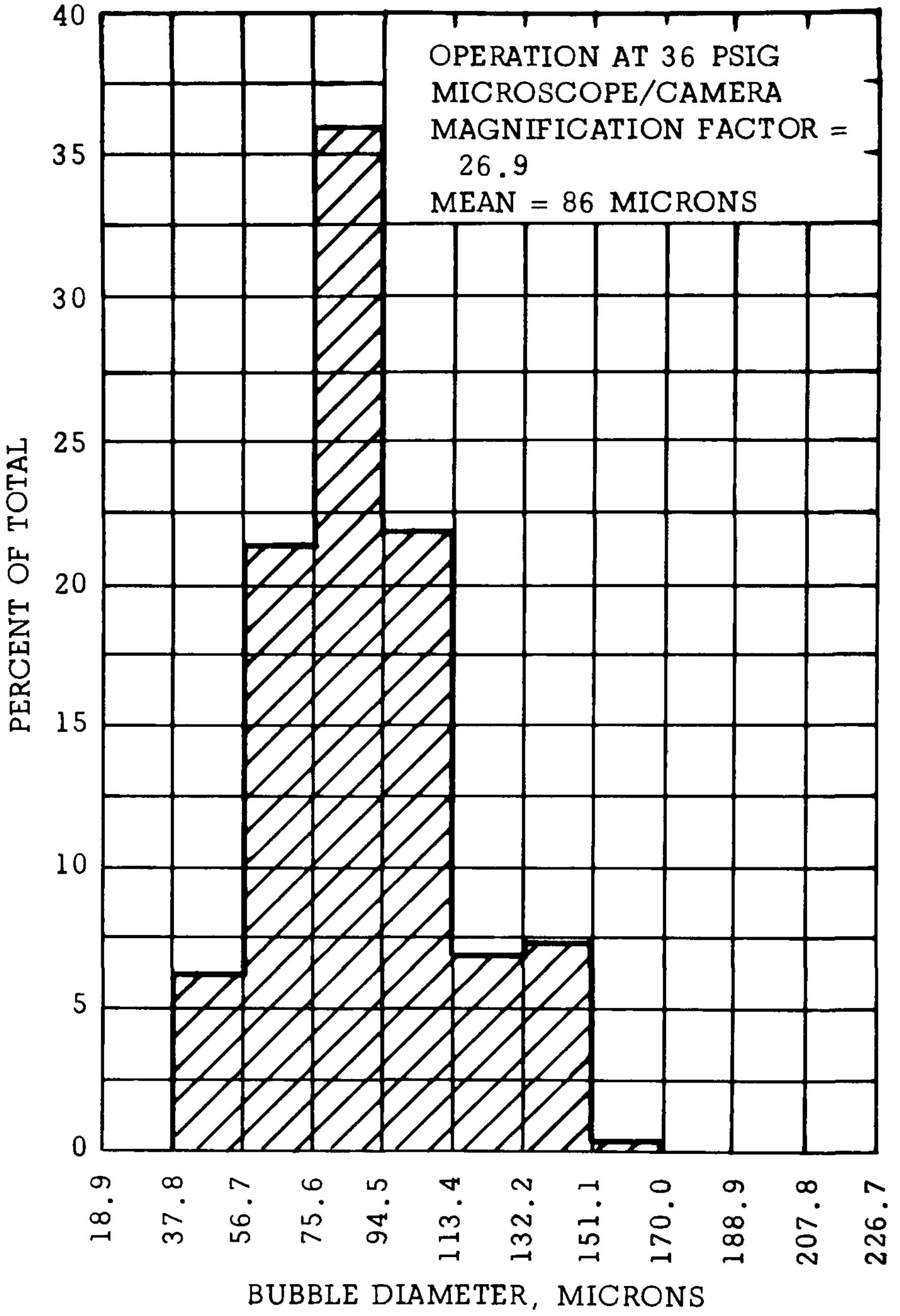

FIGURE 26

HISTOGRAM OF BUBBLE SIZES
FOR VORTEX UNIT NO. L-2-D

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In order to get comparative data between the performance of the vortex device and a more conventional system, the pressurization fixture was operated and produced the histogram shown in Figure 27. The data are not significantly different from that of Figure 26. The main point is, however, that the data tend to confirm the relationship between minimum bubble size and pressure: Mean bubble size from this entirely different process was roughly 80 microns and the histogram shows a scatter similar to that of Figure 26. In terms of a subjective evaluation, both aerated containers of water were milky but that of Figure 27 was considerably milkier than that of Figure 26. The bubble count for Figure 27 was, however, only 35% higher than that for Figure 26.

Based upon the scatter in the data shown in Table 4, some of the tests required repetition under conditions more favorable for the necessary photographic work. As observed previously, local bubble velocities in certain of the photographs were higher than in others, sometimes making accurate measurements impossible. A considerable portion of the problem lay in the fixturization: Specifically, in the combined bubble-making and flotation tank. This tank was too small for many of the tests, as demonstrated by the relatively high turbulent velocities with which bubbles would intermittently swirl through the camera field of view. In addition, this tank was too small for measurements of the dispersion of bubbles formed by any of the techniques and devices available. Hence, the test equipment modifications described in Section V were introduced for all further testing.

TERTIARY TEST STAGE

The first requirement in the third stage of testing was to determine whether further improvement in vortex bubble generator performance (i.e., that aspect of performance relating quantity of bubbles produced per unit of water pumped) might be obtained by increasing the output impedance of the device alone or whether a change in vortex gain (i.e., the ratio of inlet to outlet diameters) was the primary factor. For this purpose, four additional vortex exit tubes (-F, -G, -H and -I in Figure 10) were built and tested, each one consisting of a hollow cylinder designed to be inserted into the basic vortex device. Each cylinder had an inner diameter of either 1/2 or 3/4-inch and was identical to the existing outlets except for overall length. Values for this dimension of 6 and 12 inches were used, versus the 1-1/2- and 3-1/2-inch values selected previously. Selection of length alone as the means of modifying impedance was based upon the fact that a change in the diameter of the outlet hole would change both impedance <u>and</u> gain. A change in length alone was, therefore, the easiest means for checking the effect of impedance independent of gain.

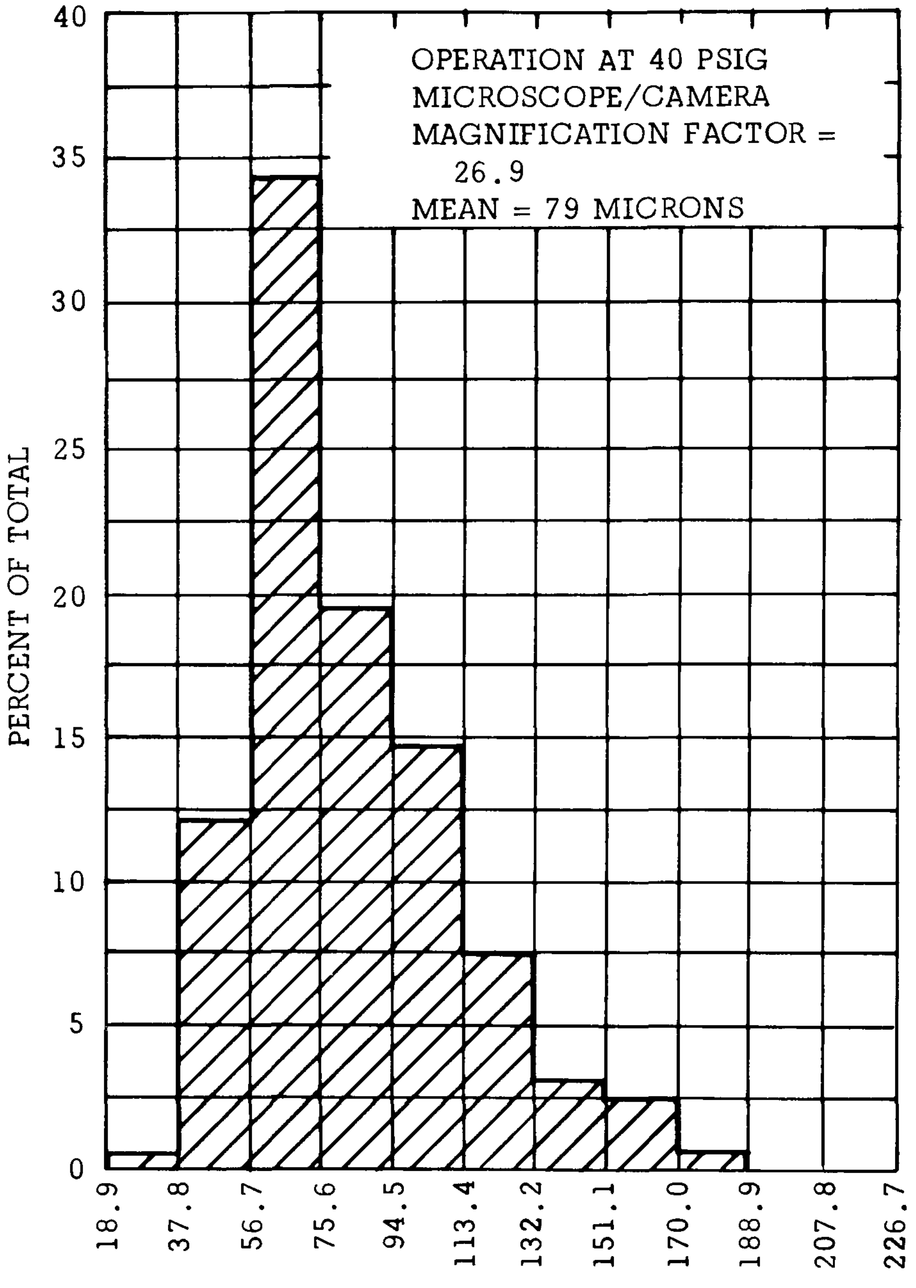

FIGURE 27

HISTOGRAM OF BUBBLE SIZES
FOR PRESSURIZED WATER
SYSTEM WITH TANK

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The vortex unit, equipped with these new outlets, was restested, and results were compared with those obtained from earlier tests. With the longer exit tubes, the small changes in performance noted previously between, for example, L-4-A and L-4-D became much more evident. A visibly greater number of bubbles was produced per unit volume of water using the shorter outlet nozzles. Also, cross-comparison of performance between long and short outlet nozzles of the two inside diameters shows that performance is definitely improved with smaller nozzle ID. This, coupled with earlier observations of better performance in terms of bubble size with large values of the vortex diameter, indicates that vortex gain is a major factor in establishing total performance of the vortex device. To confirm this finding, a comparative test was made between some of the original vortex units and similar units incorporating modified gains. For this purpose, a new exit tube arrangement (-J in Figure 10) was designed, built, and tested. This arrangement provided a reduced ID (1/4-inch) exit for the vortex flow, while length was maintained at 1-1/2 inches. Tests were run with the two nozzles using the same four vortex rings that had been subjected to previous tests. The tests were performed in the new flotation tank, and four photographs were taken for each of the configurations. Water flow rate and delivery pressure were also recorded for each. Data are given in Table 5. Photographs for the best two combinations are shown in Figures 28 through 35.

TABLE 5

TERTIARY TEST RESULTS

Unit No.	Vortex Diameter, Inches	Exit Diameter, Inches	Supply Pressure, PSIG	Mean Bubble Diameter, Microns	Number of Bubbles Photographed	Bubbles Photographed Per Input Horsepower
L-2-A	3	0.50	33.0	<u>81</u>	93	680
L-2-J	3	0.25	40.0	<u>88</u>	<u>169</u>	<u>1400</u>
L-4-A	3	0.50	38.0	108	90	740
L-4-J	3	0.25	42.5	97	<u>137</u>	<u>1510</u>
S-2-A	2	0.50	31.0	<u>77</u>	63	560
S-2-J	2	0.25	41.0	<u>83</u>	<u>124</u>	930
S-4-A	2	0.50	35.5	96	<u>130</u>	<u>1100</u>
S-4-J	2	0.25	36.0	99	91	760

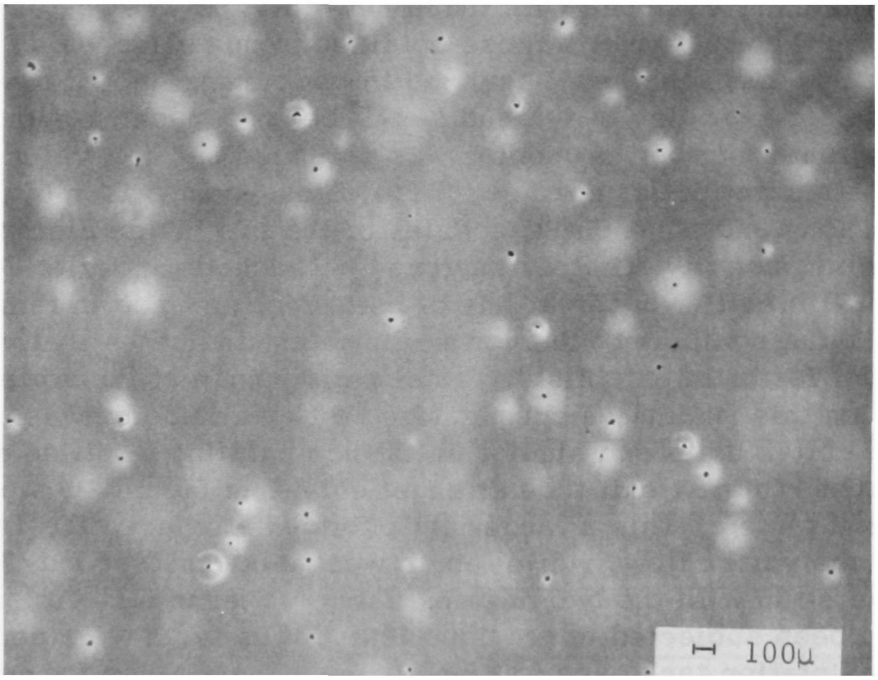

FIGURE 28

PHOTOMICROGRAPH, L-2-J @ 40 PSIG and 0.48 SCIS

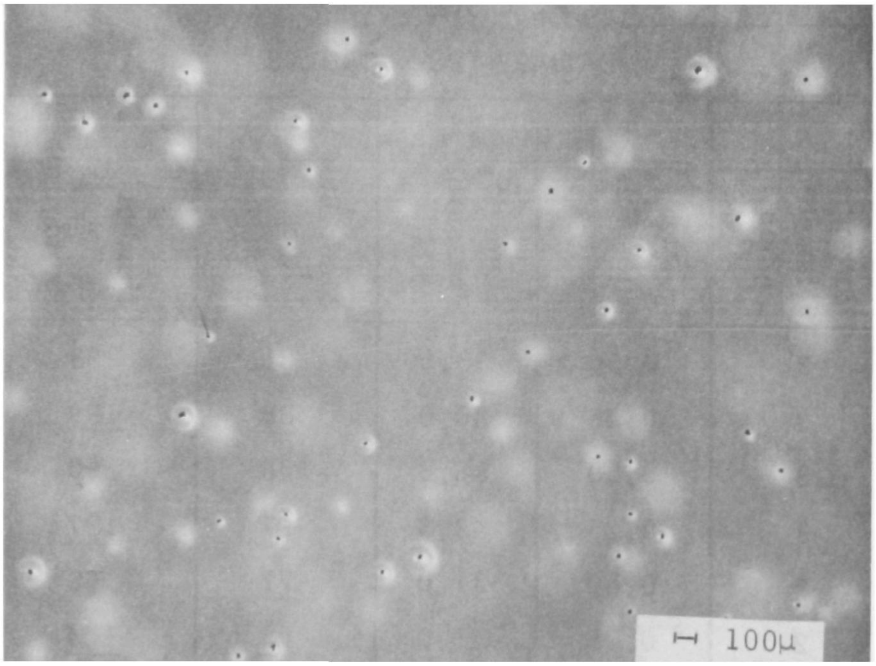

FIGURE 29

PHOTOMICROGRAPH, L-2-J @ 40 PSIG and 0.48 SCIS

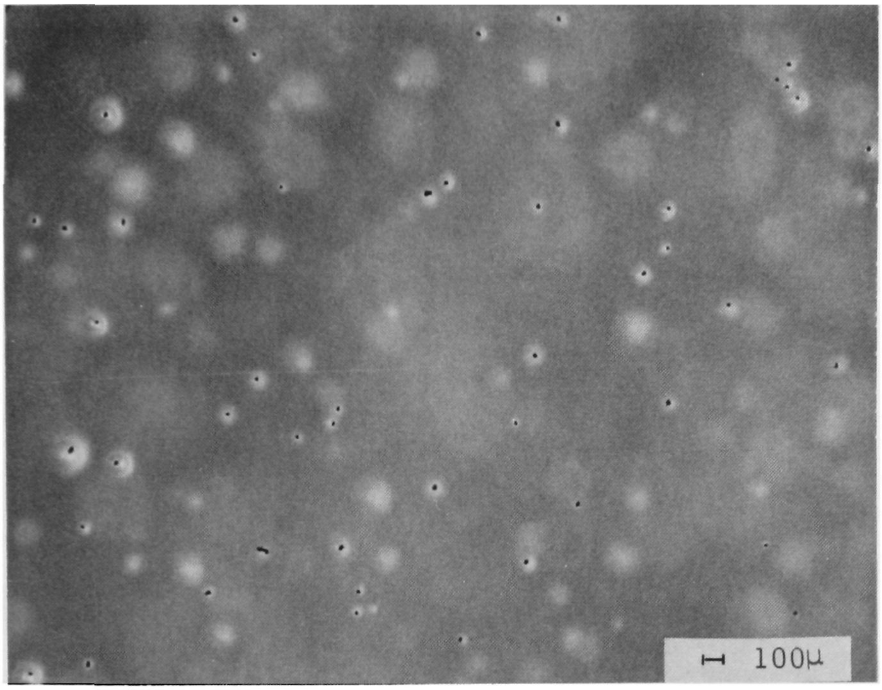

FIGURE 30

PHOTOMICROGRAPH, L-2-J @ 40 PSIG and 0.48 SCIS

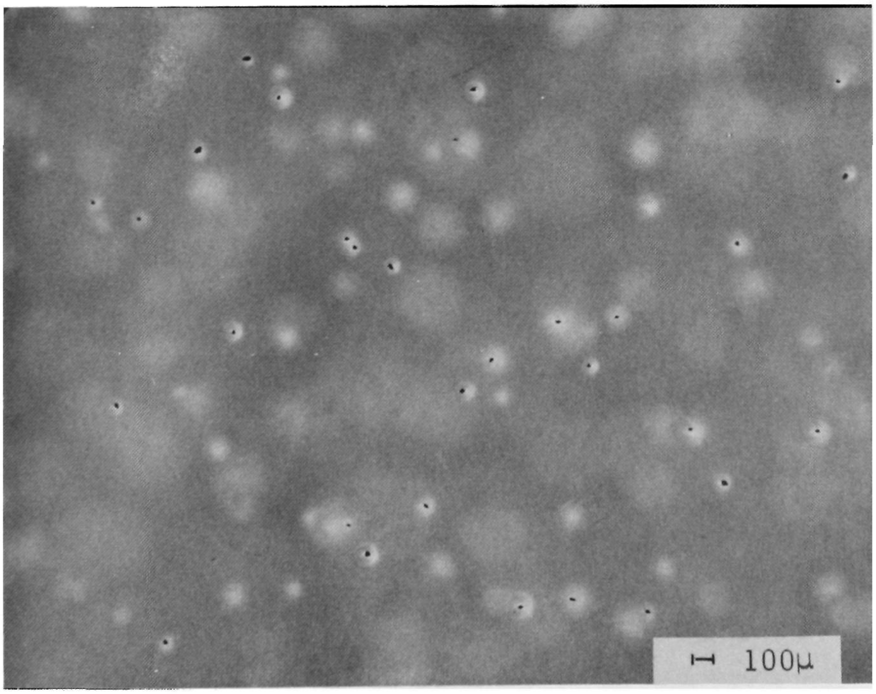

FIGURE 31

PHOTOMICROGRAPH, L-2-J @ 40 PSIG and 0.48 SCIS

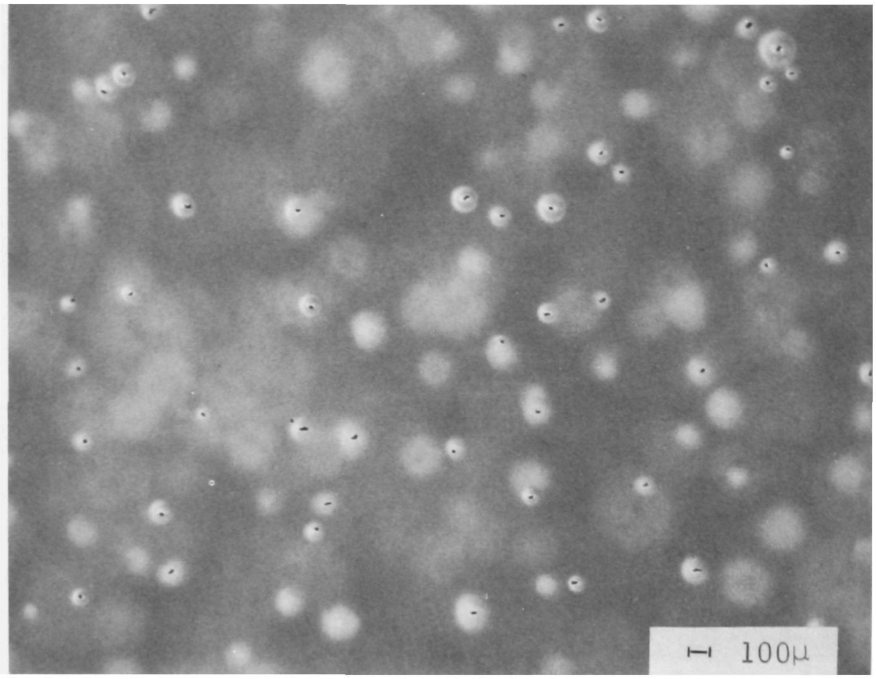

FIGURE 32

PHOTOMICROGRAPH, L-4-J @ 42.5 PSIG and 0.47 SCIS

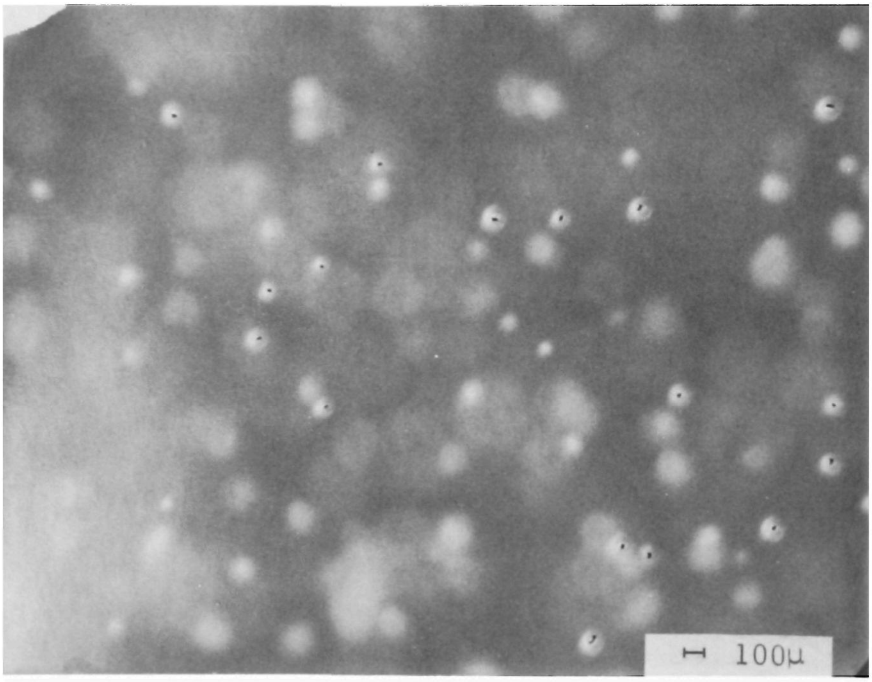

FIGURE 33

PHOTOMICROGRAPH, L-4-J @ 42.5 PSIG and 0.47 SCIS

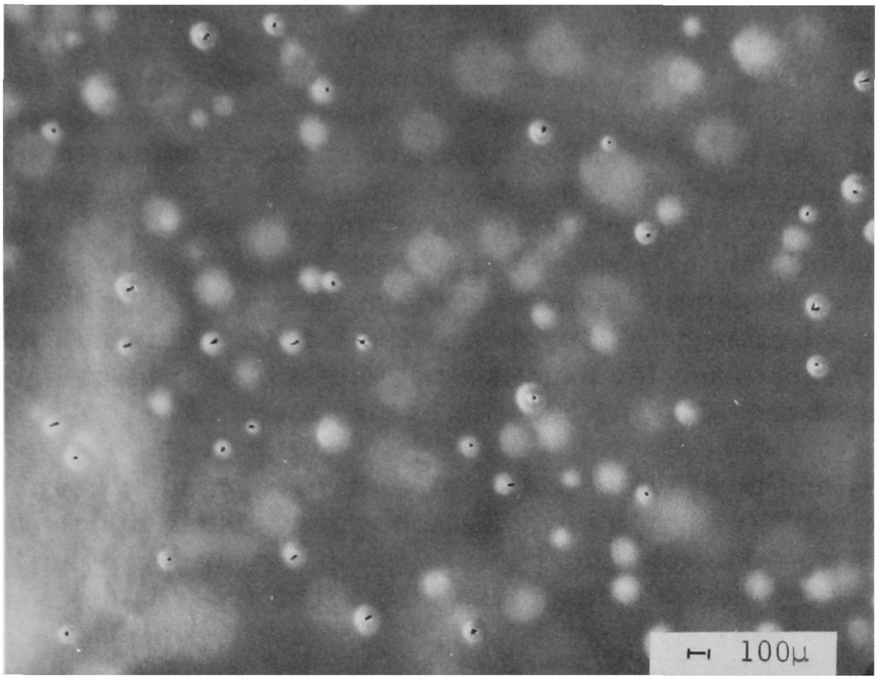

FIGURE 34

PHOTOMICROGRAPH, L-4-J @ 42.5 PSIG and 0.47 SCIS

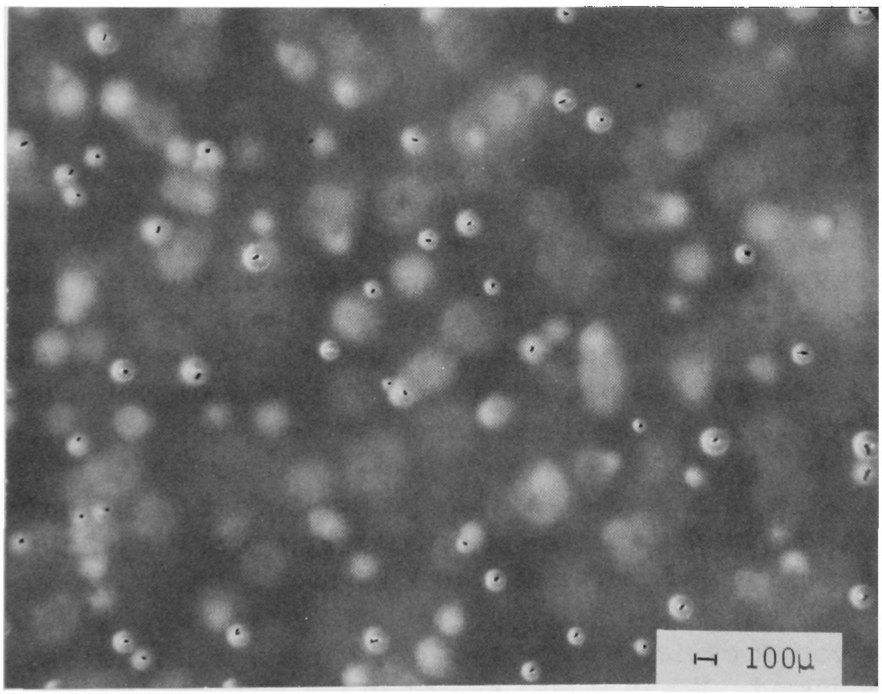

FIGURE 35

PHOTOMICROGRAPH, L-4-J @ 42.5 PSIG and 0.47 SCIS

Small bubble diameters, high numbers of bubbles photographed and high values of bubbles photographed per input horsepower were the evaluation parameters. The better data are underlined in the table. From the table, bubble sizes are roughly the same for the large and small group of vortex units, with an increase in bubble diameter occurring as one goes from a low to a high input impedance device (e.g., L-2-A to L-4-A or S-2-J to S-4-J). In terms of bubble size alone, there is relatively little to choose between units having a mean output of 80 and 90 microns. The major point of comparison is, therefore, the number of bubbles produced and the power expended in producing them. The L-units, with their high gain, are generally superior to the S-units and, within each size category, the high-gain-J units are generally superior to the -A units.

The L-2-J configuration operating at 40 psi is judged to have the best performance. It is the only configuration which yielded a high relative bubble count, had a relatively high bubble-per-horsepower gain, and produced bubbles with a mean diameter less than 90 microns.

It is noted that the L-4-J configuration had a somewhat higher gain (bubbles-per-horsepower) than the L-2-J unit although the bubble count at about the same supply pressure was lower. This is because the L-4-J unit required less pump power due to a lower flow resulting from the smaller vortex chamber inlet diameter of the L-4 units compared to the L-2 units, 0.1935 and 0.250 inches, respectively (see Table 2).

DISPERSON PATTERNS

For those vortex configurations producing an adequate supply of bubbles in the tank, the pattern of bubble dispersion was startlingly uniform. Shown in the line drawing of Figure 36, this pattern comprised (for the vortex device position shown) a relatively invariable distribution in which the thirty-inch wide region to the right contained what relatively small turbulence was present due to the vortex outflow. The region to the left was a relatively quiet zone having a uniformly high concentration of bubbles with an average size slightly smaller than those on the right.

The dimensions and location of the clear zone remained relatively unchanged for both vortex units and pressurization testing (inlet shown in the lower, right-hand corner of Figure 36).

When the vortex device was moved to the right, no significant change in pattern occurred. When it was moved to the left, the clear zone narrowed by almost exactly as much as the vortex device was moved. For leftward movements of the vortex unit beyond about six inches, a clear zone began to appear on the right as well as on the left. This indicates that the zone

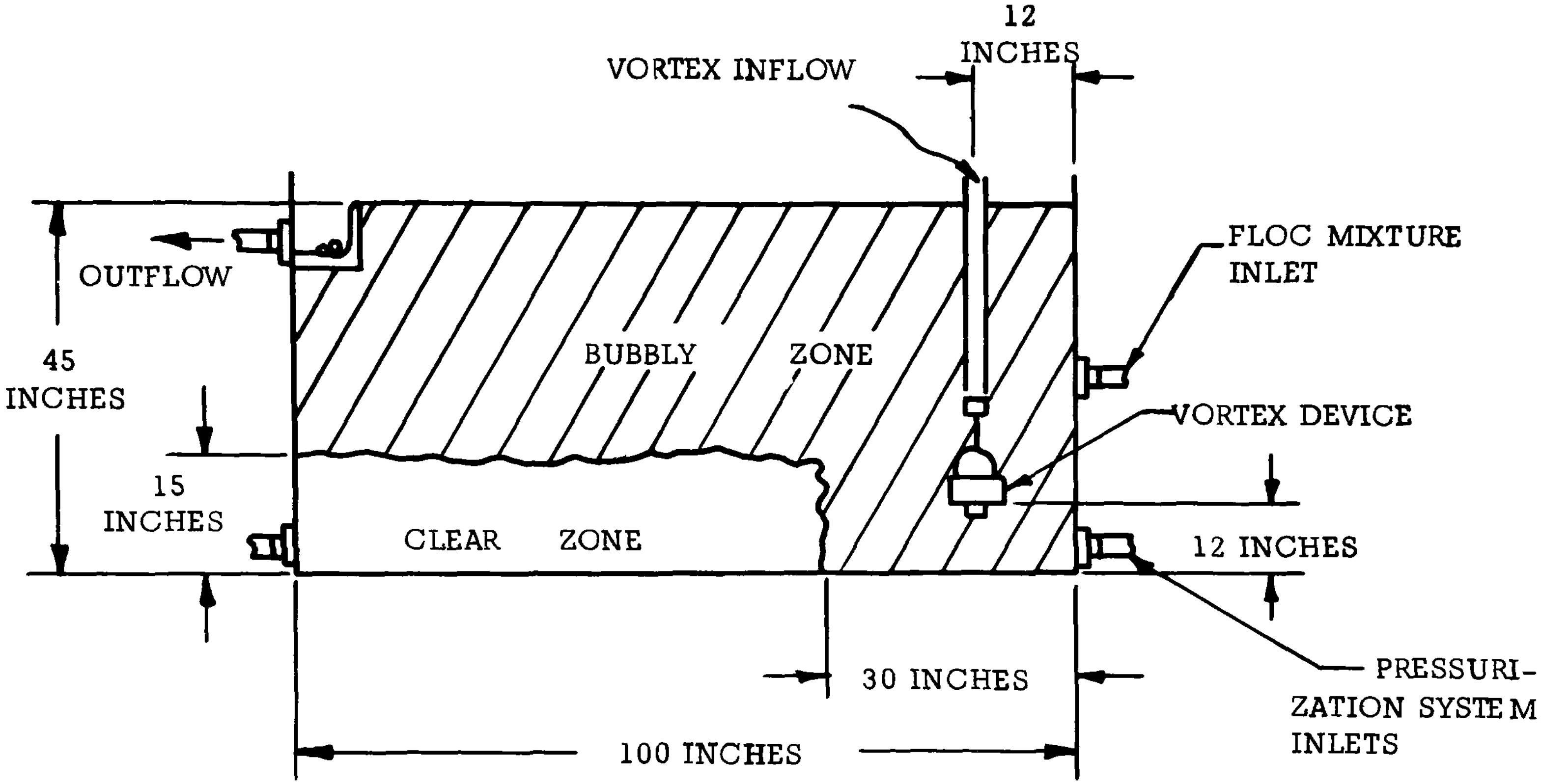

FIGURE 36

TYPICAL BUBBLE DISPERSION PATTERN

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of total influence of the most effective vortex devices is a circle of approximately 30 to 36 inches in diameter. No significant change in pattern occurred as the depth of the vortex unit within the tank was changed as much as 1-1/2 feet.

"OUTSIDE" AIR ENTRAINMENT

The question of air entrainment on the outside of the conical sheet of swirling fluid exiting from a vortex device was introduced previously. Figures 16 through 20 describe the equipment used to evaluate the concept. As pointed out in Section V, two devices were actually involved, one of them permitting the outside cone of the vortex to be vented to ambient pressure and the other one inhibiting this venting.

Initially, the non-venting device was tested and was found to have substantially only one axial position in which it would entrain atmospheric air. All other positions resulted in the device blowing water out of the aspiration tube. At the point where aspiration was possible, so little air was entrained that a negligible quantity of bubbles were produced in comparision with those generated by "inside" aspiration.

When the vented device was substituted, it was found to be operable as an entrainer of atmospheric air over its whole range of axial positions. Moreover, a valve was required to throttle inlet air flow to the point where only small bubbles would be produced at all operating conditions. Accordingly, the vortex unit with this device was operated over a range of liquid pressures and at various depths to determine whether any one or more combinations of axial position, depth and pressure would result in a significant quantity of small bubbles being generated.

Unfortunately, no such combination was found which would in any way compare with bubbles produced by "inside" aspiration for the vented unit. Measurements of the air intake flow were of the order of 0.01 to 0.03 SCIS, or well under the entrainment levels of the "inside" aspiration. This comparison becomes moot in light of the superior performance demonstrated by aspiration on the suction side of the pump over "inside" aspiration.

PRESSURIZATION PROCESSES

During the course of the program, an opportunity presented itself to evaluate a form of the pressurization process which excludes a retention tank in its design. This process was essentially identical to that which was used for final evaluation of the vortex device, except that the back pressure regulator replaces the vortex unit. In essence, the process makes use of air aspirated on the suction side of the pump; the air passes through the pump where it is dissolved; the resulting pressurized solution goes directly to a gate valve (back pressure regulator) and thence to the bubble-making tank. If wastewater had been used instead of tapwater, the solids could have clogged the gate valve, necessitating the use of a more sophisticated back pressure regulator. Subsequent information supplied by EPA revealed that a similar system in South Africa is employed in a wastewater renovation plant. It was decided to determine whether the process was effective, and how it compared in bubble-making efficiency with both the tank pressurization process and the vortex bubble-makers.

Although equipment for the tank process existed, the only work done during initial testing to compare tank and tankless processes directly involved two different bubble-making tanks and valve-piping arrangements. As a result, photography was not attempted, and the two processes could only be qualitatively judged as "comparable". The modified test equipment built for final test purposes had comparable valving and a common inlet from both processes to the bubble-making and flotation tank. During the only test of the tank system with this modified equipment, the pressurization tank ruptured before photographs could be taken. Therefore, no further work with the tank process was attempted and subsequent evaluation consisted solely of a comparison between the tankless process and the various vortex bubble-makers.

The tankless pressurization process was tested at various operating water pressures and input air flow rates. A gate valve was used to simulate a conventional bubble-making nozzle. As anticipated, best performance was attained at maximum available water pressure with maximum air flow short of that which caused pump binding. Using the same photographic site employed in the tertiary tests of the vortex devices, 9900 bubbles per input horsepower were recorded at a water pressure of 40.5 PSIG and an air flow of 0.60 SCIS. The mean bubble size was 67 microns in diameter. Photomicrographs of bubbles formed by this process are shown in Figures 37 through 40. The test was run continuously for 1-1/2 hours without need for any readjusting or trimming of the gate valve once the correct setting had been made.

The set-up for this tankless pressurization test included several branch lines off of the pump line feeding the gate valve. These had been in the system for other test purposes. It was recognized that these lines provided a volume which might be functioning as a pressurization tank. If so, the test would not be a true representation of a tankless pressurization process. Therefore, the piping was rearranged to provide a close-coupled

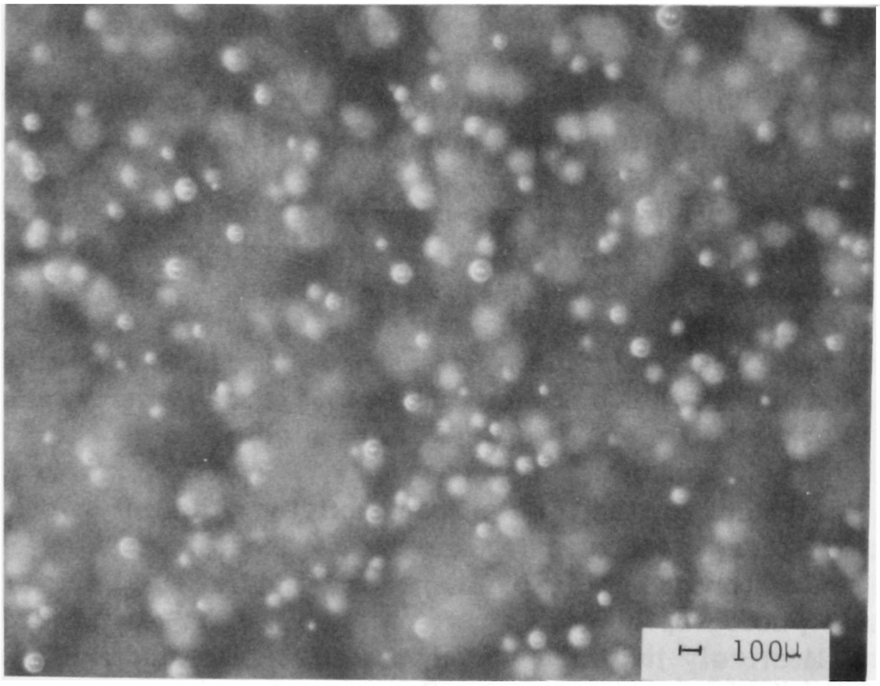

FIGURE 37

PHOTOMICROGRAPH, TANKLESS PRESSURIZATION @ 40.5 PSIG & 0.60 SCIS

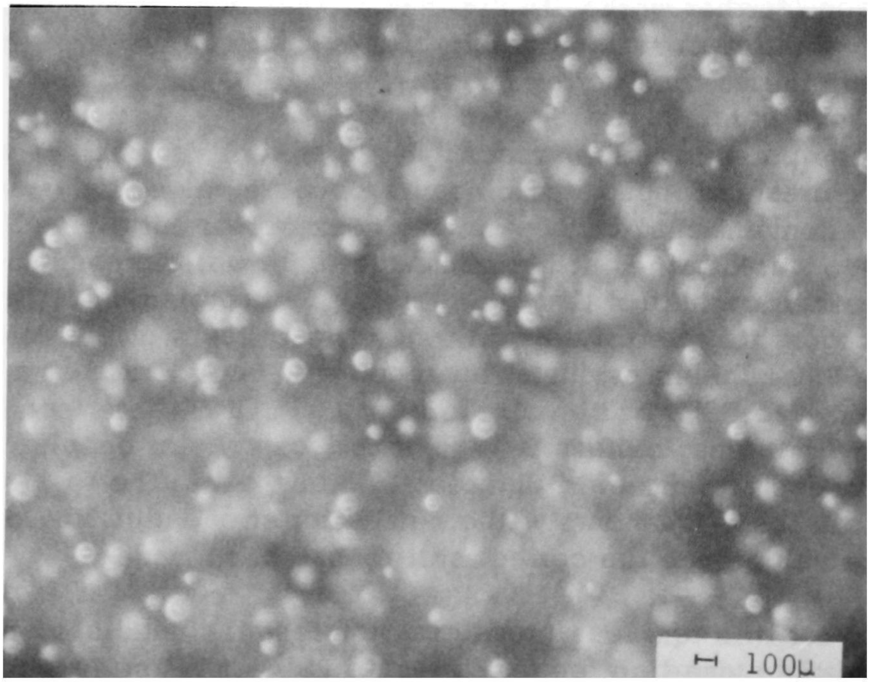

FIGURE 38

PHOTOMICROGRAPH, TANKLESS PRESSURIZATION @ 40.5 PSIG & 0.60 SCIS

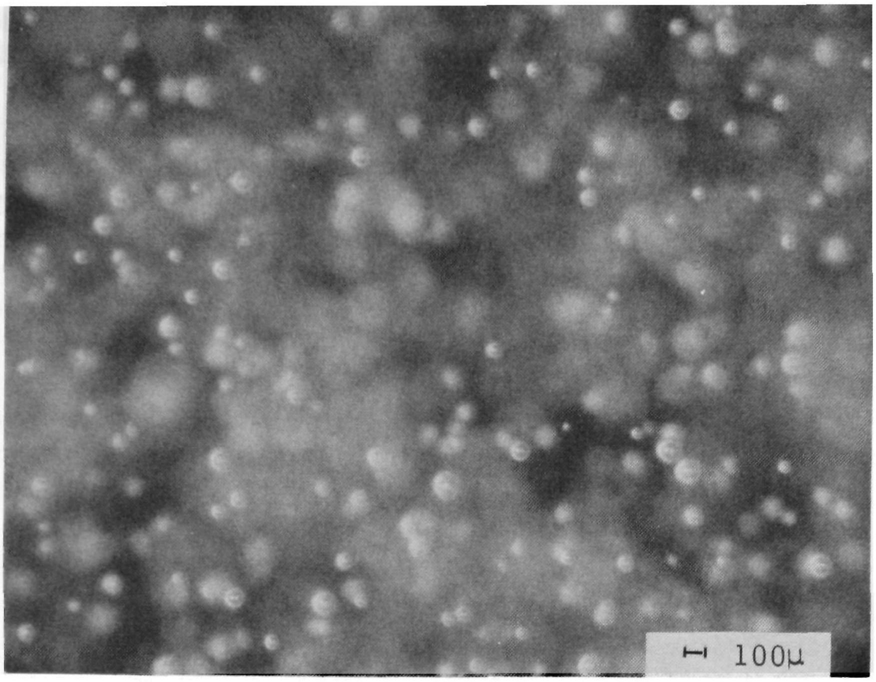

FIGURE 39

PHOTOMICROGRAPH, TANKLESS PRESSURIZATION @ 40.5 PSIG & 0.60 SCIS

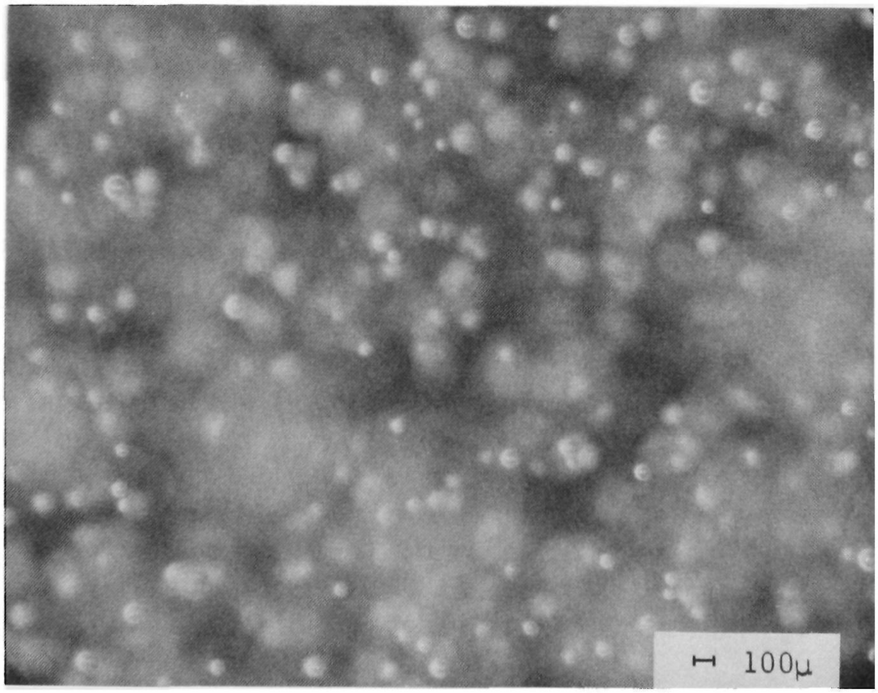

FIGURE 40

PHOTOMICROGRAPH, TANKLESS PRESSURIZATION @ 40.5 PSIG & 0.60 SCIS direct line from the pump to the gate valve. With this arrangement, the system was operated for more than an hour, again without breakdown or the need for readjusting or trimming once the correct valve setting had been made. A detailed analysis of the bubble formation of this second run was not made. However, no apparent differences were noted in either the general bubble formation or photomicrographs of this run. From these tests, it is concluded that the tankless pressurization approach for dissolving air in water can be used in dissolved gas bubble-making processes.

SECTION VII

FLOTATION TESTING

Flotation screening tests were desired as part of the final evaluation of vortex devices being developed under this program. Such tests were regarded as a suitable climax to the evaluation which made up the major share of planned program work. The testing was to be performed under procedures supplied by the EPA, using at least three mean bubble sizes (50, 100 and 200 microns diameter). The main objective of these tests was to be the determination of optimum bubble size for clarification. Measurements of air flow and of water pressure and flow were also to be taken to assist in the evaluation.

Using the concentrations of bentonite and aluminum sulfate described in Section V, a mixture was prepared and placed in the initial, cylindrical flotation tank. Initially, the mixture was stirred by circulation through the pump. This was found to be unsuccessful, however, as any floc which tended to form was broken up by the impeller of the centrifugal pump and subsequent attempts to float this floc were unsuccessful. After this, the mixture was stirred by hand, using paddles, followed then by another attempt at flotation. This second attempt was at least partially successful in that a small amount of relatively stable foam was rapidly formed in the first two minutes.

Accordingly, the test system was modified as described in Section V of this report. When tested as a bubble-making site, the new bubble-making and flotation tank arrangement was highly successful, as outlined in Section VI. When tested as a flotation tank, however, no float was generated. Neither the vortex device nor the pressurized process produced a float when the various floc mixtures were introduced into the new flotation tank. The problem was due to the fact that the flotation tank was roughly nine times larger than the flocculation tank, which was capable of only batch operation. Conversion of this latter tank to a continuous system would have constituted the major portion of the solution to the problem. Unfortunately, these extensive modifications to the flocculation and mixing system were not possible within the time and funds remaining on the program. Since the flotation testing actually represented a small portion of the program, further work toward flotation testing was abandoned.

SECTION VIII

DISCUSSION

GENERAL APPLICABILITY

The experimental results of this study verified that the vortex bubble generator can produce small gas bubbles of less than 100 microns in diameter. It should be possible to use these devices in any process which requires bubbles of this size for its operation.

The same vortex units can generate bubbles larger than 100 microns if needed for any of these processes. By increasing the air flow, larger bubbles, up to 1/4-inch in diameter, can be formed. The ability to conveniently change bubble size over a wide range without mechanically adjusting numerous units in an installation may be another advantage over some of the conventional generators.

These devices should also be able to find application in aeration processes where gas is bubbles through liquid for the purpose of dissolving a portion or all of the gas into the liquid. Air bubbles, for example, can be used to oxygenate water in this manner.

OPERATING METHOD

The vortex bubble generator has two possible methods of operation. In both methods water under pressure enters the unit tangentially which sets up the vortex motion within the unit. In one of the possible operating methods atmospheric air is aspirated into the center of the unit through a separate inlet tube. No air pump is needed because sufficient vacuum exists to draw the air in. In the second method of operation the air enters the device dissolved in the pumped water. No separate air tube is needed. Also, no air pump is needed if the air is added at the inlet to the pump.

This second method proved to be more efficient than the first in terms of producing more bubbles per pumping horsepower. In addition to this advantage, it has important installation advantages. Most obvious of these is that only one supply pipe is needed. The first operating method would require an additional inlet pipe for each unit. It is likely that an air valve adjustment would be needed on each unit, particularly if the quantity of air or if bubble size were to be changed. Therefore, the second method is preferred for operating the vortex bubble generator. It provides a dissolved gas bubble-making technique using devices which need no adjusting when first installed or after long periods of operation and are virtually free from clogging.

COST ESTIMATES

The vortex bubble generator is quite simple in its basic design and therefore can be produced at a relatively low cost. It can be made in two pieces and bolted together with an O-ring or gasket providing a static seal. No moving parts are used. In quantities of 20 to 100, the cost per unit is estimated at $50 to $70. In higher production quantities the cost could be reduced to under $20.

It is expected that a hardware cost comparison of conventinal dissolved gas bubble generators and vortex generators will not reveal a significant difference in initial cost. The more important differences are expected to be revealed in a maintenance and operating cbst comparison.

Tests conducted in this study show that a modified conventional pressurization system produces more bubbles per water pump power than the vortex generator. Further development may improve the vortex performance in this regard but at this point it must be viewed as a potential disadvantage when comparing operating costs with those of conventional devices. On the other hand, the vortex unit has a potentially lower maintenance cost advantage. No situation can be foreseen which would require replacing, adjusting or cleaning these devices.

The result of a cost trade-off probably depends to some extent on the particular application. In some processes it may be convenient to conduct routine maintenance at very little cost. In other cases it may be very important for production reasons to run for a long period without disruption. For these reasons it would be appropriate to conduct a pilot cost evaluation program on an actual process.

SECTION IX

ACKNOWLEDGMENTS

The program was performed during 1970 and 1971 by the Bowles Fluidics Corporation of Silver Spring, Maryland. Bowles personnel participating in the program included L. W. Pearson, Project Manager; R. J. Range and R. F. Turek, Principal Engineers; L. R. Moore and V. F. Neradka, Senior Engineers; and J. S. Sims, Jr., Vice President. Special thanks are due to Mr. T. O'Farrell of the EPA facility at the Blue Plains Treatment Plant of the District of Columbia. The assistance of Mr. J. F. Kreissl, Project Officer, Environmental Protection Agency, Advanced Waste Treatment Laboratory, Cincinnati, Ohio, is gratefully acknowledged.

SECTION X

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SECTION XI

PUBLICATIONS AND PATENTS

No publications, patents or pending publications or patents have been produced as a result of this project.

SECTION XII

GLOSSARY

Term	Definition	Units
GPM	Water flow rate	gallons per minute
PSIG	Pressure	pounds per square inch gage
SCIS	Air flow rate	standard cubic inches per second
μ	micron	10^{-6} meters
d	Diameter	inch
f	Frequency	hertz
v	Velocity	feet per second

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16. Abstract

This report contains the results of a detailed engineering investigation and evaluation of vortex devices as bubble-makers for use in the removal of suspended solids from wastewaters by flotation. The specific objective of the program was the development and test of bubble-makers useful for generating bubbles having mean diameters of about 100 microns with vortex devices having minimum liquid passageways of 1/4-inch or greater. The overall concept of the program involved testing the feasibility of improved methods for reducing the cost of generating bubbles for the flotation of solids from wastewaters.

17a. Descriptors

*Waste Treatment, *Flotation, *Separation Techniques

17b. Identifiers

*Bubble Generation, *Vortex Devices, Bubble Sizes, Bubble Densities

17c. COWRR Field & Group 05 D

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