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Instrumentation

INVESTIGATIONS ON THE RANQUE-HILSCH (VORTEX) TUBE

P. S. Baker
W. R. Rathkamp

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INVESTIGATIONS ON THE RANQUE-HILSCH (VORTEX) TUBE

P. S. Baker W. R. Rathkamp

ABSTRACT

Experiments in which the Ranque-Hilsch tube was used for the purpose of mass separation have been unsuccessful. An investigation of the mode of operation of the tube has led to the conclusion that the processes involved are not conducive to significant mass separation except as centrifugation, thermal diffusion, and/or other effects might enter into the picture in a secondary way. The phenomenon of the simultaneous emission of hot- and cold-gas portions from opposite ends of a tube into which gas under pressure has been introduced tangentially and at an angle seems to result from the combination of an adiabatic expansion of a portion of the inlet gas and of both a "viscous-shear" effect which transfers energy from the center of the tube to the outside layers of gas and an energy release associated with the turn-around of gas molecules at the stagnation point of the tube.

INTRODUCTION

In 1933 G. J. Ranque (1) introduced a peculiar device which "separates" gases into hot and cold fractions; he patented it (2) in 1934. His interest lay in its potentialities as a refrigerating unit, but apparently he was unable to develop it satisfactorily. Nothing more was heard of the device until 1946, when R. Hilsch (3) constructed a number of tubes and published data with respect to their operation. His work attracted rather widespread interest and, as a result, a number of relevant publications have appeared.

Among the investigations were one by Stone and Love (4) and one by Elser and Hoch (5) – both of particular significance because they reported measurable mass separation in gas mixtures and discussed theories of operation. Articles by Milton (6) and by others (7-12) mentioned the device because of its unusual characteristics, but no explanations were attempted. Most of the other reports (13-17) have dealt with the application of the tube to refrigeration.

Our particular interest lay in the potentialities of the tube as an isotope separator. Unfortunately, along with the reports of successful mass separations, there were certain reservations concerning the validity of the data. [For example, Elser and Hoch (5) present only meager data and say of their work: "... the results were poorly reproducible from a quantitative standpoint."] On the other hand, should the tube actually act as a separator, its tremendous potential throughput would make it of incalculable value. Hence a short-range program was instituted in the Stable Isotope Research and Production Division of the Oak Ridge National Laboratory for the purpose of (1) repeating and then extending the work of the earlier investigators in order to justify further development of the tube and/or (2) developing techniques and obtaining measurements designed to provide sufficient additional theory for intelligent interpretation of any data obtained while operating the tube. It was understood that the difficulties involved in trying to evaluate completely each of the large number of variables encountered would make it practically impossible, should successful separation not be achieved, to prove positively that a vortex tube will not act as a separator. For this reason, the development of a workable theory is important. (There are 14 fairly obvious variables: tube material, tube thickness, tube length, tube diameter, jet angle, jet diameter, location of jet with respect to the two ends of the tube, gas pressure, gas composition, gas temperature, hot-end baffle, cold-end baffle, time of operation, and tube temperature – e.g., cold end cooled off by water.)

THEORY

When a jet of air under pressure (ranging[1] from 10 psig to an optimum of about 10 atm) is introduced into a small tube tangentially and simultaneously at a slight axial angle, it is found that air is drawn in through the end of the tube behind the jet and blown out through the end ahead of the jet. Under these conditions the back end of the tube is very slightly cooler and the front end of the tube very slightly warmer than ambient. At pressures above about 30 psig, the velocity of the gas emitting from the jet is in the sonic range.

When the "warm" end is partially throttled by insertion of some sort of a baffle into the tube, however, the warm side becomes much warmer and the cold side colder. If the air is impeded enough by the throttle, gas is forced out the back end of the tube and becomes quite cool, whereas the gas by-passing the baffle becomes quite warm. Hilsch (3) has shown the temperature relationships of hot-end to cold-end exit gases for various exit-gas ratios. A temperature difference of 100°C between the two ends is readily attainable. Perhaps the most amazing observation is the development of a very marked "hot spot" when the warm end is shut off completely, or almost completely. The location of the hot spot – a place on the tube which is considerably warmer than the other parts of the tube in either direction from it – depends upon the inlet gas pressure and upon the tube characteristics. (Baffling is far more important than jet angle, since a hot spot may be obtained with a right-angle T-tube by proper baffling of the two ends.) The exit gas under these conditions is slightly cooler than ambient, probably partly because of the Joule-Thomson effect and partly because some of the gas expansion is adiabatic. Now, as the hot-end barrier is gradually removed or opened, the hot spot moves down the tube toward the end and eventually disappears.

Most of the investigators have proposed theories of tube operation of one sort or another, but no theory so far completely explains all the observed characteristics. Actually, there are almost as many suggestions as to how the tube operates as there have been investigators. Many of the proposals admittedly have been based upon a few superficial measurements of gas flows and temperatures of inlet and outlets; the hot spot is infrequently recognized. (It turns out, as a matter of fact, that the temperature effect itself – warm gas at one end and cold gas at the other – is difficult to avoid when high-velocity gas is introduced tangentially into any tube which has been throttled at one end.) In general, however, the explanations can be included in one of the following categories.

The "Viscous-Shear" Theory. Supported entirely or in part by Webster (*13*), Fulton (*14*), Corr (*17*), Roebuck (*18*), Taylor (*18,19*), Ashley *et al.* (*20*), and Kassner and Knoernschild (*21*), the viscous-shear theory suggests, in essence, that the gas spiraling down the tube from the jet consists of concentric layers of gas with angular velocities increasing toward the center (tending to conserve angular momentum). The result is a shearing effect by which energy is transferred from the inner layers of gas to the outer layers, resulting in a cooling of the inner layers and warming of the outer layers. Corr (*17*) presents considerable data with respect to the effect of dimensions on performance. Explanations by these investigators did not mention the hot spot, probably because the interest has usually been in the cold portion of the tube. Generally included as part of the theory, however, is the adiabatic expansion of part of the gas as contributing to the cold temperature.

The Kinetic-Molecular Interpretation. Supported by Stone and Love (*4*) and by Elser and Hoch (*5*), the kinetic-molecular interpretation suggests that there is some peculiar (and generally unexplained) effect based on a molecular distribution other than Maxwell-Boltzmann which gives rise to the peculiar temperature distribution. Stone and Love talk in terms of an "explosive diffusion" of lighter molecules, and Elser and Hoch in terms of a phenomenon with a "kinetic-molecular basis." Stone and Love claim that a counterflow system is required in which "... the jet stream selectively gathers hot molecules as it approaches the hot spot, selectively loses hot molecules as it flows on down toward the closed (or almost closed) end. The core stream flowing back from the closed end gathers the hot molecules until it reaches the hot spot and is then selectively depleted of hot molecules until it passes the jet."[2] They also suggest that a temperature

[1] Reference 5, p 28.

[2] Reference 4, p 24.

difference is prima-facie evidence of mass separation.

Specific Explanations. Scheper (*22*), basing his conclusions on probe work in which he found the static temperature of the core stream to be higher than that of the outer helix, suggests that a heat transfer results from a "forced convection" to the outer helix; however, he admits "... the required over-all heat transfer coefficient is greater than can be accounted for by conventional calculations." It is possible that he has oversimplified the fundamental relationships involved and that he has lent too much significance to small temperature differences. Scheper, like several of the investigators already mentioned, was primarily interested in the cold end of the tube.

van Deemter (*23*), in a theoretical paper, suggests that a thermodynamic-aerodynamic explanation involving an extended Bernoulli equation is quite satisfactory, since the experimental results of Hilsch and of Elser and Hoch agree, for the greater part, with the theory.

Bergner (*24*) also has written a theoretical paper in which he discusses a new method for separation of isotopes, namely, uranium. He does not refer specifically to the Ranque-Hilsch tube but rather to the "vortex principle," apparently presuming centrifugation; his report, furthermore, is rather vague as to operational details.

It should perhaps be mentioned that as far as any mass separation is concerned the separation of two different elements or compounds does not necessarily guarantee subsequent application of the tube to successful isotope separation. The differences in physical characteristics or constants (e.g., number of atoms, molecular weight, specific heat, adiabatic exponent, polar or nonpolar characteristics, kinematic viscosity, etc.) of the elements or compounds might well be of fundamental significance in their separation, whereas these factors would generally be much less important in the case of isotopes. In other words, separation of CO_2 from air or of N_2 from O_2 may not be a "mass" separation in the real sense of the word.

EXPERIMENTAL

The experimental portion of the investigation was arbitrarily divided into three parts:

1. the development of a suitable analytical method,
2. an attempt to obtain mass separation,
3. an attempt to obtain sufficient data to explain the mode of tube operation.

For the preliminary work, air was used as the gas, since previous investigators had used it and since it was readily available and of fairly constant composition.

Analytical

In order to evaluate the Ranque-Hilsch tube in terms of its ability to effect mass separation, it was necessary to devise an analytical procedure which would assure reasonable accuracy. Since different gas mixtures were expected to be used during the course of the investigation and since, even for air, the Orsat method of analysis is subject to some objection because of the difficulty in completely absorbing CO_2 and O_2 and because it is partially a differential method, it was decided to employ a method based on the use of a mass spectrometer. By relating "peak heights" of the various constituents involved, ratios can be obtained from which it is possible to determine changes in gas composition. It was believed that an analytical method which could detect 10% of the theoretically possible enrichment should be suitable for our needs. (For N_2-O_2 mixtures, the theoretical enrichment factor for diffusion, E, as calculated from Graham's law, is equal to $\sqrt{32/28} = 1.07$. If E is defined as $A_2/B_2 \div A_1/B_1$, where A_1 and B_1 are the amounts of the two constituents originally present and A_2 and B_2 are the amounts present after enhancement, then the volume ratio of N_2 to O_2 could be increased by a single-step enrichment from 3.72 normally to a theoretical value of 3.98. The mass-spectrometric method should be sensitive enough to detect one-tenth of this difference.)

For the purpose of sampling air streams passing through the vortex tube it was at first decided to use a water-filled sample flask and to draw the samples of air into the flask as the water flowed out. The design is shown in Fig. 1. A length of rubber tubing connected the top of the flask to a takeoff from the air stream to be sampled. When the stopcocks were opened, the water ran out and the sample was drawn in. Closing the stopcocks isolated the sample.

The tapered joint on the flask was next placed over the mated fitting on the inlet system of the mass spectrometer, and some of the sample was admitted to the machine, following the standard operating procedure for the spectrometer.[3] A scan over all peaks from mass 14 to mass 44 was made, and from these data ratios of nitrogen to oxygen were calculated. This procedure was repeated at least four times for each sample flask, and average values were computed. Mean deviations for the values were also determined to indicate the consistency of the ratios. Figure 2 shows a typical scan as obtained from the mass spectrometer.

[3]General Electric Analytical Mass Spectrometer, catalog No. 8665934G5.

As can be seen from Table 1, the ratios determined by use of the mass spectrometer were somewhat erratic, sometimes being consistent and sometimes not. The variation was found to result from water being used in taking samples. Apparently, considerable care must be exercised to exclude moisture from the samples. Since oxygen and nitrogen have different solubilities in water (at 20°C, N_2 = 0.0019 g per 100 g of H_2O, and O_2 = 0.0043 g per 100 g of H_2O), a slight change in the ratio of N_2 to O_2 may result merely from bringing air into contact with water. (For example, if the water in the flask being used were to become 50% saturated with N_2 and O_2 and if all the gas were to come from the sample, the N_2-to-O_2 ratio as shown by peak heights might be changed as much as from 5.00 to 5.30. Of course, such a large change is not likely but the problem could be serious.) Furthermore, the water vapor present in the air being analyzed becomes partially dissociated in the mass spectrometer and

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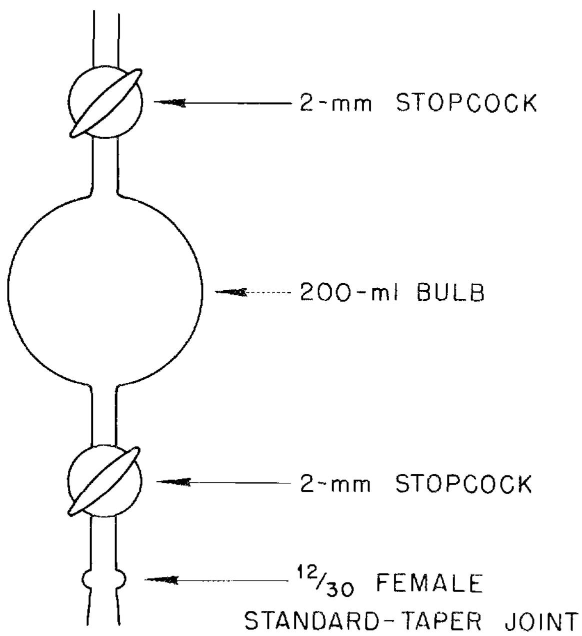

Fig. 1. Sampling Flask.

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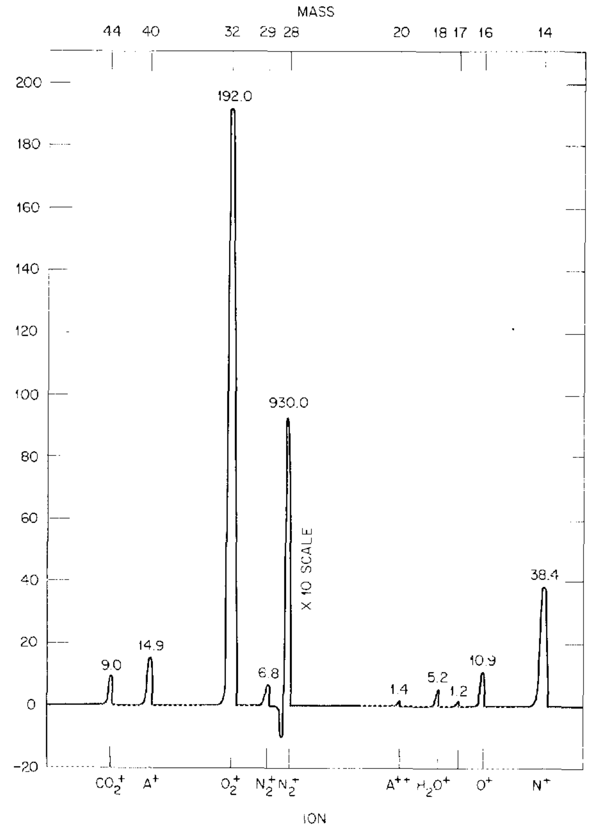

Fig. 2. Chart of Mass Spectra of Air.

thereby contributes to the oxygen peaks; this lowers the apparent value of the N_2-to-O_2 ratio. Because both these effects depend upon the quantity of water present, this quantity itself being variable, inconsistent results were obtained. (The fact that these two errors tend to cancel each other probably explains why the values are not more erratic than they are.)

The absolute value of the N_2-to-O_2 ratio is not particularly important. Owing to differences in ionization efficiencies, ionization potentials, fractionation, and molecular dissociation between the two gases involved, the calculated ratios are not the same as those based on volumes. Furthermore, there are daily variations which are much greater than the variations in successive samples run during a period of a few hours.[4] It is of interest to note, however, that where N_2^{28}-to-N_2^{29} ratios are calculated the difficulties mentioned above are unimportant, and the values are in very good agreement with the published data.

[4]See Table 4.

Table 1. Mass Ratios for Air Collected over Water

N_2-to-O_2 Ratios		
Sample A	Sample C	Sample F
4.84	5.11	4.67
4.96	5.21	4.98
	4.93	4.89
	4.95	4.88
Av 4.90 ± 0.06	Av 5.05 ± 0.11	Av 4.86 ± 0.09

In order to eliminate water as a source of error, mercury was substituted as the displacing medium. The solubility of air in mercury is negligible, and in the mass spectrometer mercury contributes peaks in the mass 200 region, which is well outside the range being investigated. This change in technique gave values repeatable to about one part in 250, as shown in Tables 2 and 3. Further experiments showed that admitting one charge to the spectrometer chamber from a given sample flask and then scanning it several times gave the same average deviations of results as the earlier procedure which involved admitting one charge, scanning, pumping out, and then admitting a new sample for scanning.[5] Obviously, this change in procedure reduced the operating time considerably, although from the standpoint of sampling theory it was somewhat less desirable.

To provide what was hoped would be a referee and perhaps a faster, alternative analytical method for the gas analyses, an Ostwald viscometer was constructed that consists of the arrangement shown in Fig. 3. The operation depends upon Poisseuille's equation:

$$\eta = \frac{\pi P r^4 t}{8Vl} ,$$

where

η = viscosity coefficient, poises,
r = radius of tube,

[5]See Table 6.

Table 2. Samples Collected over Mercury

N_2-to-O_2 Ratios			
Sample 12	Sample 13	Sample 17	Sample 18
	4.98		4.94
5.29	5.03	4.98	5.01
5.29	5.02	4.95	4.93
5.32	4.97	4.98	4.96
5.31	4.94	4.96	4.90
Av 5.30 ± 0.01	Av 4.99 ± 0.03	Av 4.97 ± 0.02	Av 4.95 ± 0.03

V = volume of gas,
P = pressure difference,
l = length of tube,
t = time of flow.

The application depends upon the assumption that the changes in the viscosity of gas mixtures are proportional to the changes in the composition of the gas. Figure 4 shows the theoretical curve for the viscosities of various N_2-O_2 mixtures.

It was found after a few measurements had been made with various known mixtures of N_2 and O_2 that the sensitivity of the instrument was not sufficient for our purpose. Figure 5 is the calibration curve for the instrument. From the slope of the curve it is possible to estimate a factor of approximately 0.55 sec for each per cent change in gas composition. Table 4 shows the data for a series of runs in which ordinary air was used as the gas. It can be seen that the precision is of the order of 0.6 sec. Undoubtedly this could be improved somewhat by the use of a constant-temperature bath, but probably not to the extent that the limiting factor would be the ability to read the stopwatch. Even then, the usual error of 0.2 sec would introduce an error of more than 0.3% in composition, corresponding to $E \cong 1.04$. (Further improvement would require timing devices, and there did not seem to be justification for such a step. Should enhancement be exceptional, the viscometer might conveniently be used for routine checks.) On the other hand, changes which could be deduced from mass-spectrometer data were so much smaller than 0.3% that the Ostwald viscometer would have been useless by comparison.

Table 3. Comparison of Deviations of Samples Collected over Water with Those of Samples Collected over Mercury

Sample	Average N_2-to-O_2 Ratio	Average Deviation
	Over Water	
A	4.90	±0.06
B	4.99	±0.02
C	5.05	±0.11
D	4.71	±0.03
E	5.00	±0.01
F	4.86	±0.09
G	5.13	±0.02
		Av ±0.05
	Over Mercury	
11	5.27	±0.02
12	5.30	±0.01
13	4.99	±0.03
16	4.95	±0.03
17	4.96	±0.02
18	4.90	±0.03
31	4.80	±0.01
32	4.68	±0.02
33	4.79	±0.01
		Av ±0.02

Separation Experiments

Once the analytical techniques were considered to be suitable, it became feasible to carry out actual experiments in which the possibility of separation could be investigated. The first tube used was similar in design to that suggested by Hilsch (*3*) and by Stone and Love (*4*), with which the latter had obtained apparent separation of oxygen from nitrogen in air. Figure 6 shows several of the tubes which were used. In our experiments, also, air was used as the inlet gas, and samples were taken *at inlet, hot end, and cold end* by the procedure outlined above. Typical data for the numerous samples that were obtained are given in Table

Table 4. Ostwald Viscometer Data*

Run No.	Time (sec)	Deviation
1	481.8	−0.4
2	481.5	−0.7
3	482.4	+0.2
4	482.8	+0.6
5	482.6	+0.4
6	482.8	+0.6
7	481.6	−0.6
8	483.5	+1.3
9	481.5	−0.7
10	481.5	−0.7
11	482.4	+0.2
	Av 482.2	±0.6

*Air at room temperature used as the gas for all samples.

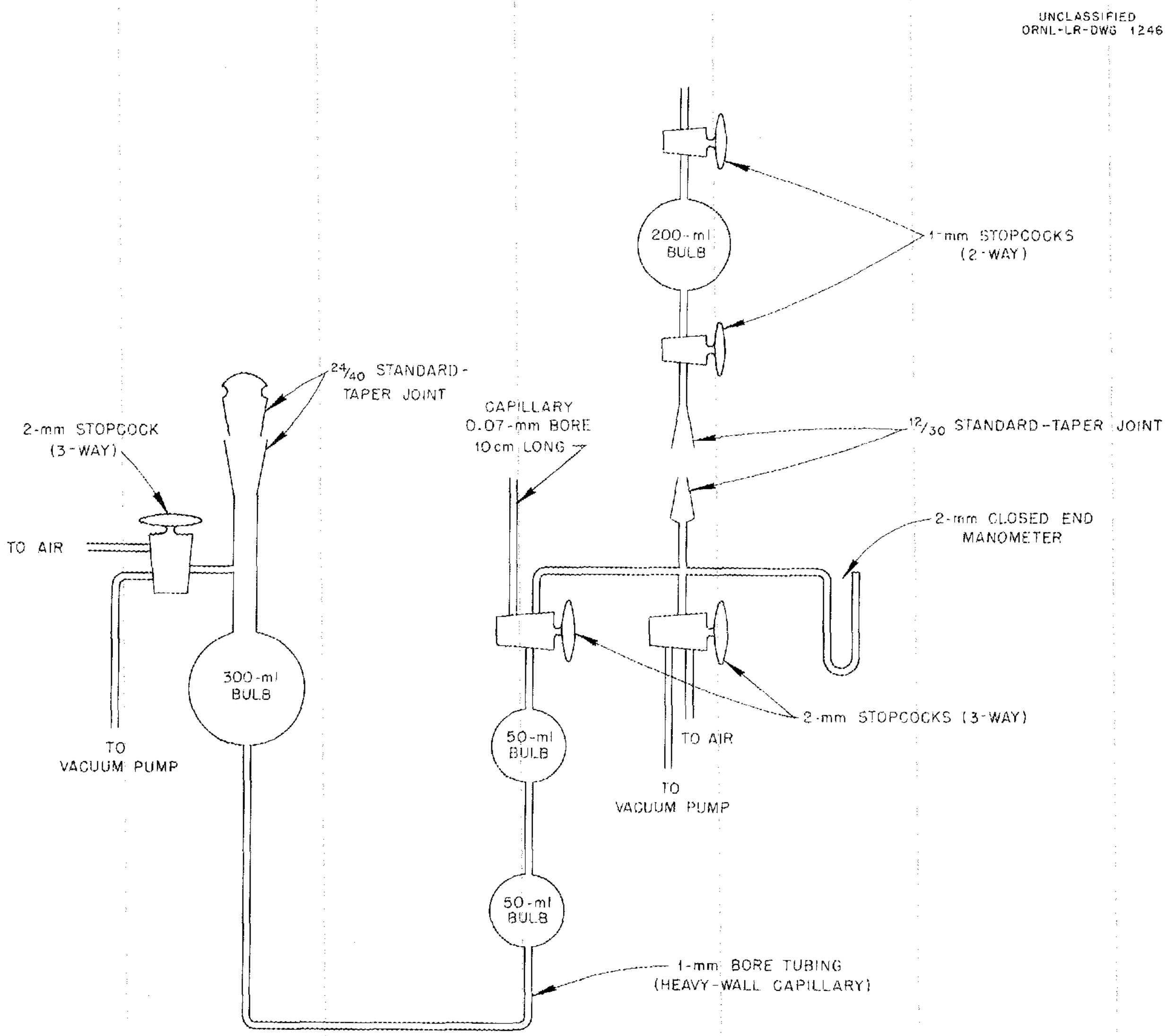

Fig. 3. Ostwald Viscometer.

5. As can be seen, any "separation" was within the limits of error inherent in the analytical method.

Table 6 shows the data obtained when control samples of ordinary air, randomly interchanged, were introduced into the mass spectrometer over a period of time which corresponded to that required for a hot-cold-inlet series of determinations. It is to be noted that the spread in values is comparable to that for samples taken from the Hilsch tube.

We found that changes in pressure, orifice opening, jet angle, inlet-to-outlet gas ratio, tube size, tube material, etc. had no appreciable effect on tube operation so far as measurable variation in mass ratios was concerned. (To eliminate possible bias, samples were always submitted in random order.) The jets were smooth and well-faired in, and the tubes were smooth inside [although Corr (17) claims that the hot ends can be rough without affecting operation]. Recycling of the hot-end effluent was considered, but the difficulties in compressing and storing are quite serious. Likewise, the engineering of a "cascade" would have been too expensive even to be considered, for the time being at least.

Several measurements were made in which a Uniflow tube (Fig. 7) was used, and it was assumed that any separation would be primarily the result of centrifugation. Again, no measurable separation was found, as can be seen in the following tabulation.

	N_2^{28}-to-O_2^{32} Ratio	N_2^{28}-to-N_2^{29} Ratio
Takeoff	4.49 ± 0.02	134 ± 1
Inlet	4.52 ± 0.03	136 ± 2

Use of a 1:1 argon-helium mixture, which has a much larger theoretical separation factor (E = 3.16) than oxygen and nitrogen (E = 1.07), did not show results any more significant than those already reported for air. (Whereas fractionation of the air samples was negligible, the helium-argon mixture fractionated severely in the system used to feed the gas to the spectrometer tube. To overcome this

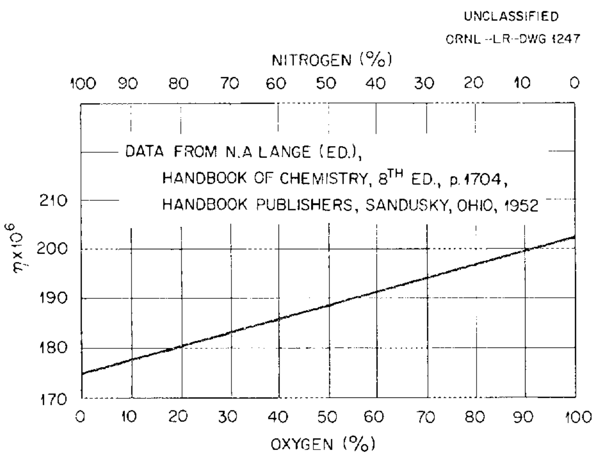

Fig. 4. Viscosity-Composition Curve; N_2-O_2 Mixtures.

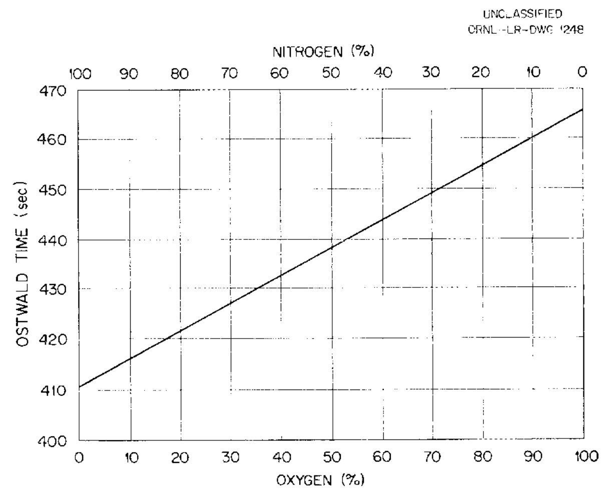

Fig. 5. Viscosity-Calibration Curve.

Table 5. N_2-to-O_2 Ratios for Separation Experiments

(Each value is an average of 3 to 6 determinations)

Sample	At Inlet	At Hot End	At Cold End	Hot Minus Inlet	Inlet Minus Cold	Hot Minus Cold
A	5.05 ± 0.03	5.08 ± 0.02	5.05 ± 0.01	+0.03	0.00	+0.03
B	5.30 ± 0.02	5.32 ± 0.03	5.33 ± 0.04	+0.02	−0.03	−0.01
C	4.99 ± 0.03	4.89 ± 0.08	4.93 ± 0.06	−0.10	+0.06	−0.04
D	4.95 ± 0.03	4.90 ± 0.03	4.96 ± 0.02	−0.05	−0.01	−0.06
E	4.83 ± 0.01	4.88 ± 0.01	4.84 ± 0.02	+0.05	−0.01	+0.04
F	4.83 ± 0.01	4.88 ± 0.03	4.85 ± 0.02	+0.05	−0.02	+0.03
		At Wall* (Hot)	At Center* (Cold)			
G		4.83	4.93 ± 0.03			
H		4.85 ± 0.02	4.83 ± 0.01			
I		4.83 ± 0.01	4.79 ± 0.02			

*Assuming wall temperature is hotter than core temperature and that lighter molecules would, through thermal diffusion, tend to be at the wall.

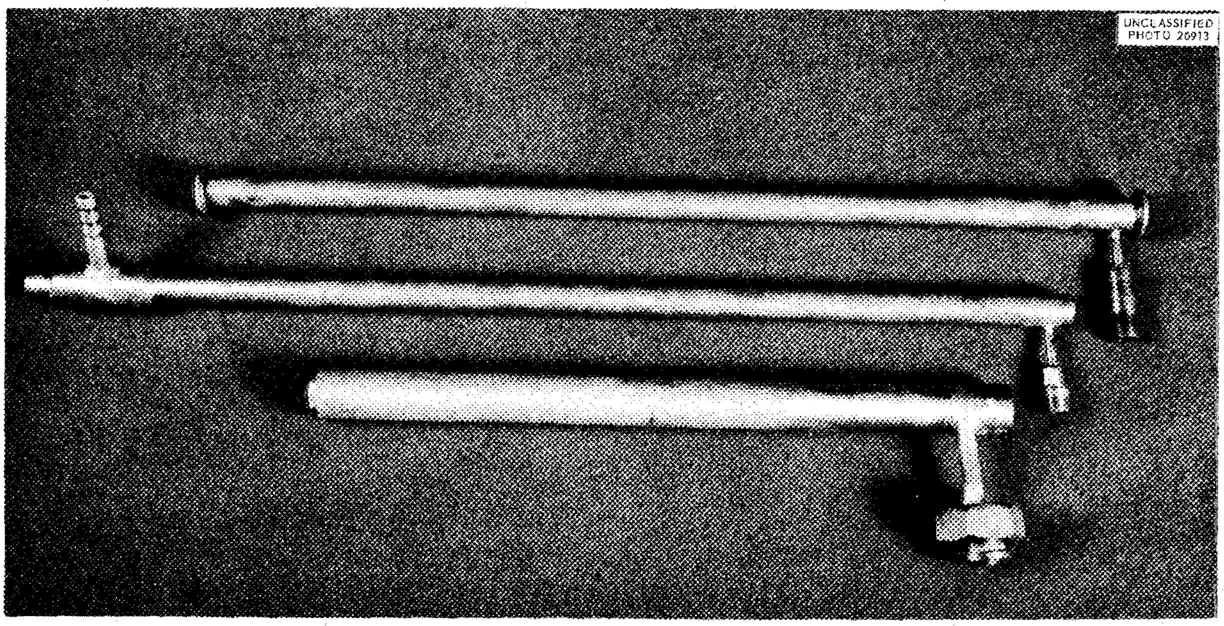

Fig. 6. Hilsch Tubes.

Table 6. Analysis of Control Samples of Air*

Sample	N_2-to-O_2 Ratio	Sample	N_2-to-O_2 Ratio	Sample	N_2-to-O_2 Ratio
A_1	5.22	A_2	5.27	A_3	5.30
B_1	5.17	B_2	5.27	B_3	5.23
C_1	Spoiled run	C_2	5.23	C_3	5.20
D_1	5.17				
	Av 5.19 ± 0.02		Av 5.26 ± 0.02		Av 5.24 ± 0.03

*Taken successively over a period of about 2 hr.

difficulty, the steps involved in admitting the gas to the spectrometer and the scans from mass 4 to 40 were carefully timed, making all runs and hence results consistent.) Typical data are shown in Table 7, and Fig. 8 shows a scan for a helium-argon mixture.

Thus, considerable work under varied conditions has produced considerable data, but apparently no matter which known variables are changed, the results are unchanged within the limits of error of the experimental method. Therefore it is extremely difficult to recommend one particular course of experimentation over any other.

Operational Experiments

As a second general phase of the experimental work, a series of tests was performed in an attempt to discover how the tube operates internally, since such information would be helpful in the planning of changes in tube design to effect and enhance separation. In general, an experimental approach similar to that of Scheper (22) and of Corr (17) was followed, but additional observations and measurements were included.

A number of different kinds of tubes were made by using different materials, varying the angle of the jet, changing the ratio of cold-end to hot-end

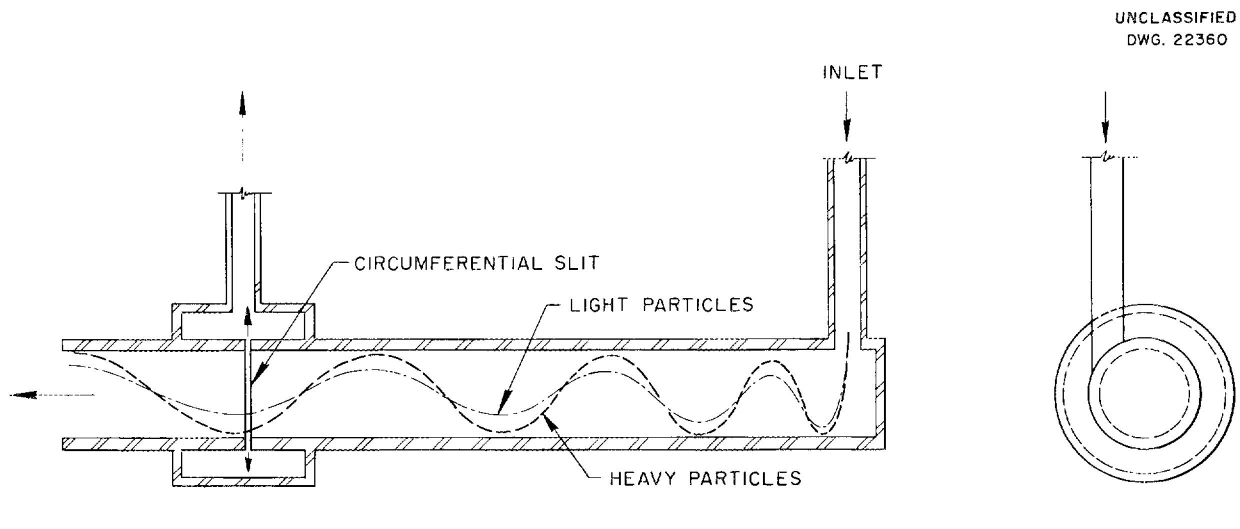

Fig. 7. Uniflow Tube.

Table 7. Argon-Helium Mixtures*

Series	Hot End A-to-He Ratio	Cold End A-to-He Ratio	Hot Minus Cold
A	6.57	6.53	+0.04
B	7.19	7.32	−0.13
C	6.39	6.34	+0.05
D	6.25	6.38	−0.13
E	7.05	6.94	+0.11

*Each value is an average of several scans of at least two different samples. Series A through D were run on different days.

outlet gas, varying the tube size, and varying the tube length. Numerous probe holes were drilled along the walls of some of the plastic tubes in order to enable measurements of pressures within. With other tubes, thermocouples were soldered along the walls at regular intervals to permit temperature measurements. With tubes of glass and of Lucite it was possible actually to see what happened inside when oil, water, and such solids as cork, plastic foam, and glass beads were introduced into the tubes during operation. In one instance it was possible to estimate the rotational velocity of glass beads by use of a Strobotac.[6]

Figure 9 shows a cutaway drawing of a typical vortex tube, including probable flow patterns.

[6]General Radio Corporation stroboscope, type No. 631BL.

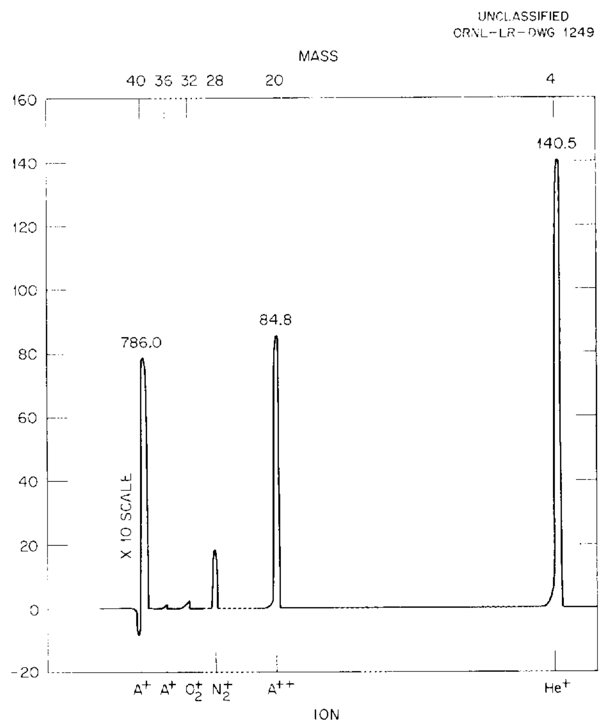

Fig. 8. Chart for Argon-Helium Mixture.

Compressed air was introduced into the jet at a pressure which depended upon both the size of the jet opening and the fluctuations in pressure in the air line. In our work, the pressure in the small tubes varied from 92 to 103 psig as a function of variation in line pressure and in the larger tubes

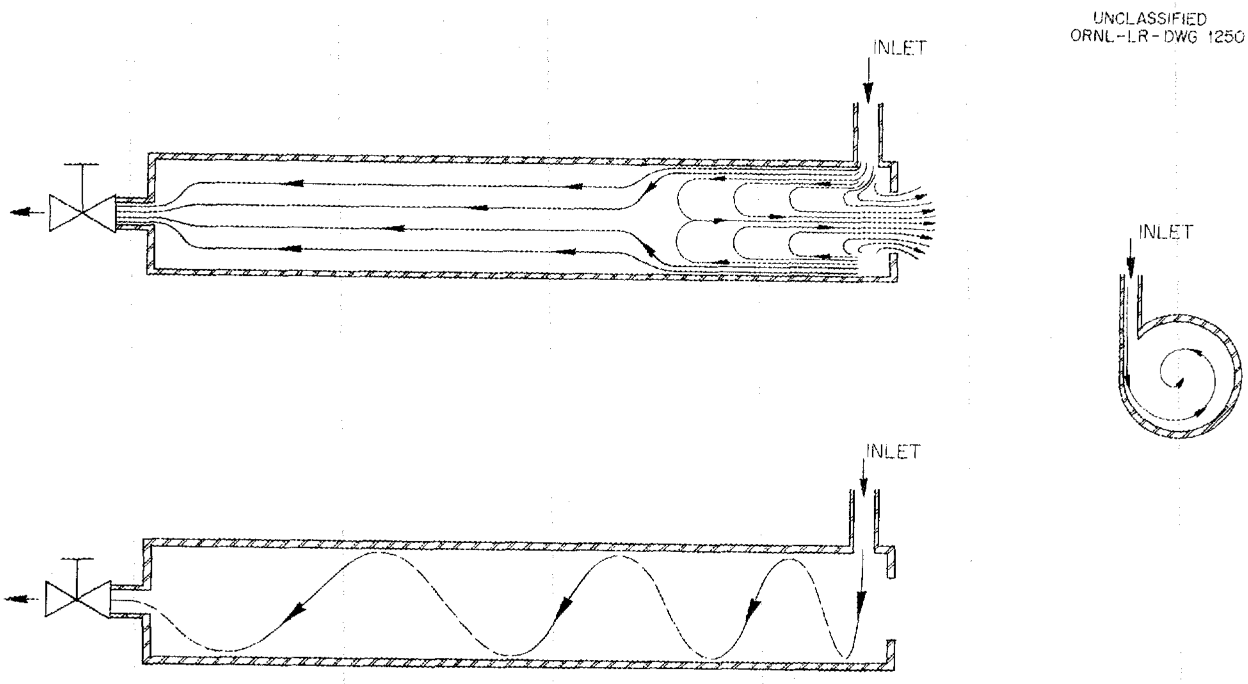

Fig. 9. Vortex Tube Flow Patterns.

from 25 to 45 psig, depending primarily upon the amount of throttling at the inlet. For any particular tube, the gas was allowed to flow for a few minutes until an equilibrium state had been reached, during which time the hot spot moved down the tube away from the jet. Then temperature measurements were made two or three times at successive 2-min intervals to ensure that equilibrium had been attained. Since there was always a fluctuation in pressure in the air line during a series of measurements, usually amounting to 2 to 3 psig in the smaller tubes, the data include average pressures.

Temperature Measurements. The thermocouples mentioned above (iron-constantan) were connected to an ordinary volt box[7] and were used to measure temperatures under different conditions of operation. The simplest experiments were those carried out with a small stainless steel tube, $\frac{5}{16}$-in.-ID with a $\frac{1}{16}$-in.-ID jet at right angles to the tube and tangential to it (Fig. 10). For the tube completely unbaffled, the data are shown in the following tabulation and in Fig. 11.

[7] Leeds and Northrup potentiometer indicator.

Thermocouple Station	Measured Temperature (°C)
1	15
2	15
3	14
4	17
5	21
6	22
7	25

Various baffling arrangements were then tried. An adjustable plug, also pictured in Fig. 10 (A), was fitted to the tube and was moved in toward the end of the tube while the latter was in operation. Tables 8 and 9 and Figs. 12 and 13 show the rather peculiar results of varying the distance of the baffle from the end of the tube. As the baffle approached the tube, there was a complete reversal of the temperature profile when the baffle reached a point about one-fourth of a turn (0.013 in.) from the end. The warm end then became cool and the cool end warm. It is to be noted that there was actually a "double reversal" in one end of the tube (occurring probably because the tube was not quite symmetrical). Thus, moving a barrier up to either end of a T-tube will effect a temperature reversal.

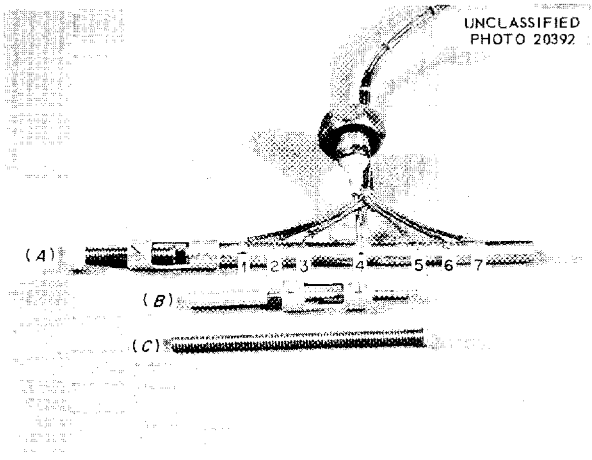

Fig. 10. Vortex T-Tube.

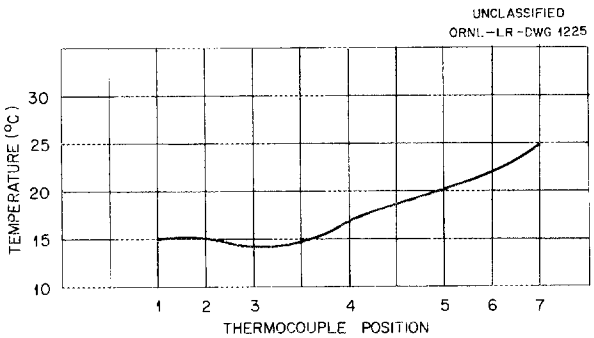

Fig. 11. Temperature Profile for Unbaffled T-Tube.

The significance of this reversal is not yet apparent. Figures 14 and 15 plot the data in another way.

A baffle was made which fit into the end of the tube just described with a minimum of clearance

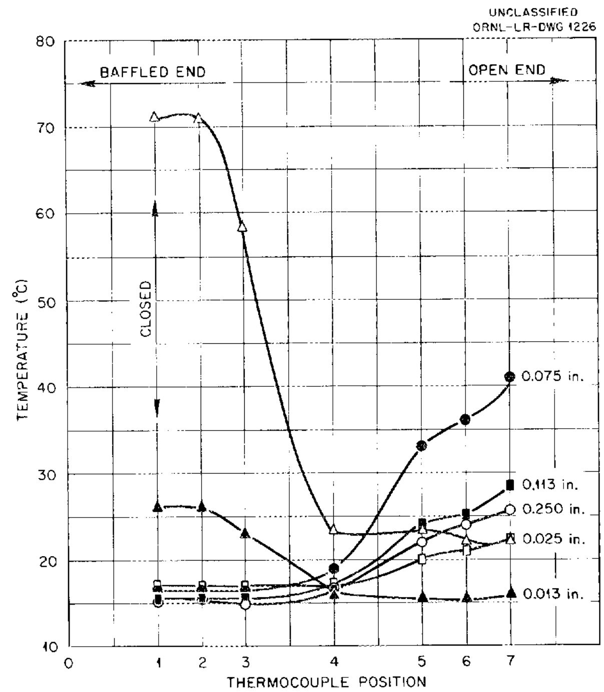

Fig. 12. Temperature Profile. Baffle adjacent to thermocouple No. 1.

Table 8. Effect of Baffle Distance at Various Thermocouple Stations

Baffle Adjacent to Thermocouple No. 1

Average Pressure (psig)	Temperature Measurements (°C) at Thermocouple Stations							Valve Opening (in.)
	1	2	3	4	5	6	7	
96.5	16	16	15	17	22	24	26	0.250
93	16	16	16	17	22	21	25	0.150
92	16	16	16	18	23	23	27	0.125
93.5	16	16	16	17	24	25	29	0.113
95.5	16	16	16	18	25	27	31	0.100
97.5	15	15	16	18	27	28	32	0.088
98.5	17	17	17	19	33	36	41	0.075
100	17	17	17	20	33	37	41	0.063
102	16	16	16	19	29	32	36	0.050
93.5	17	17	17	17	20	21	22	0.025
95	26	26	23	17	16	16	16	0.013
100.5	71	71	59	24	24	22	22	0.000*

*Closed.

Table 9. Effect of Baffle Distance at Various Thermocouple Stations

Baffle Adjacent to Thermocouple No. 7

Average Pressure (psig)	Temperature Measurements (°C) at Thermocouple Stations							Valve Opening (in.)
	1	2	3	4	5	6	7	
100.5	15	15	14	17	21	22	25	Wide open
96	16	16	15	17	21	23	25	0.400
96.5	17	16	15	17	21	23	25	0.300
100	17			17			25	0.200
100	18	17	16	17	21	23	24	0.150
100	17	17	16	17	21	23	24	0.138
100	18	17	16	17	21	22	23	0.125
100	26	27	24	17	17	15	15	0.113
101	30	30	26	18	15	15	15	0.100
101.5	33	33	28	18	15	15	15	0.088
102	33	33	28	18	15	15	15	0.075
95	31	31	27	18	15	15	15	0.063
96.5	31			18			15	0.063
98.5	29	28	25	18	16	16	16	0.050
100.5	26	25	22	18	16	16	16	0.038
95.5	20	20	19	17	18	18	19	0.025
95.5	17	16	16	18	26	28	29	0.013
100	21	22	22	24	50	57	63	Closed
98	23	25	25	26	56	64	68*	Closed**

*Hot spot seemed to be at thermocouple No. 7.

**Dropped back to 66 deg in 2 min.

but yet allowed movement of the barrier so that it could be screwed into and out of the tube (*C* in Fig. 10). The baffle was then screwed in from a position beyond the end of the tube (as had been done previously) as far into the tube as the length of the threaded portion of the device allowed. Temperatures were measured periodically; the data are shown in Table 10 and the curves in Figs. 16 and 17.

It was decided to determine what effect the introduction of a small hollow tube (*B* in Fig. 10) would have on the temperature profile of the vortex tube. The hollow probe was introduced into one end of the vortex tube to various depths while the opposite end was baffled. The baffle was adjusted to give various openings for different settings of the hollow, $\frac{1}{8}$-in. stainless steel tube; the data are shown in Table 11 and in Figs. 18 and 19. Table 12 shows the data for a repeat performance in which the probe tube was plugged up at its outer end. There are some small differences between these data and those in Table 11, but it is not known whether or not they are significant.

The experiments carried out with the small 6-in. tube were repeated with a slightly longer tube ($9\frac{1}{4}$ in.) which had 11 thermocouple stations (Fig. 20) but whose tangential jet was at an angle of about 20 deg to the perpendicular instead of at right angles to the tube. The data and curves are shown in Tables 13 and 14 and in Figs. 21, 22, and 23. Figure 21 shows the temperature profile with absolutely no baffling of any kind and, as mentioned earlier, shows that the temperature effect is almost unavoidable. The temperature reversal was not evident when the baffle was adjusted at the end nearest thermocouple No. 1 with the use of the longer tube with the angled jet. There was, however, a warm spot which occurred on what is normally considered as the cold end of the tube (*behind* the directed jet). In Fig. 22 it should be noted that the hot spot appears to occur *beyond* the barrier in some cases.

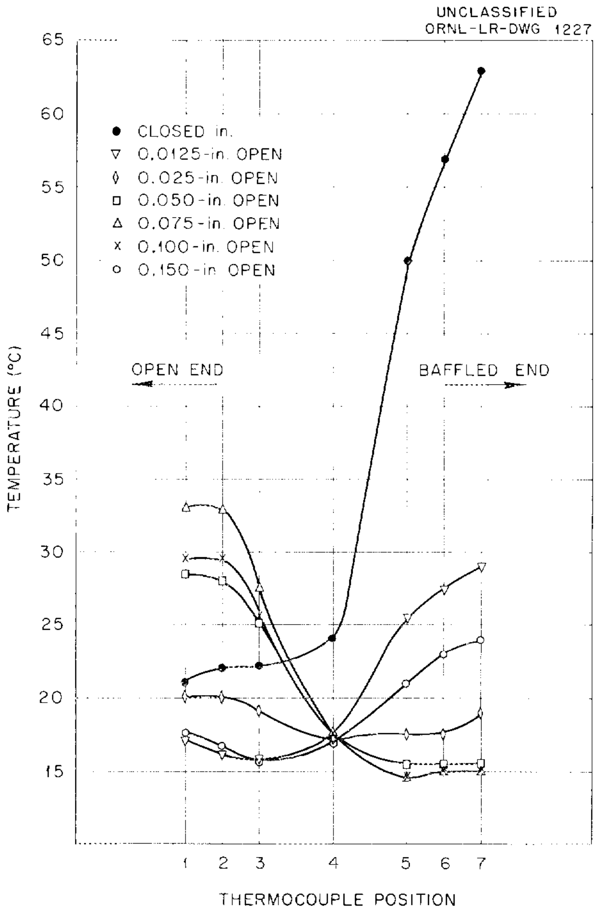

Fig. 13. Temperature Profile. Baffle adjacent to thermocouple No. 7.

Additional tubes were prepared from polystyrene, Lucite, and glass. The diameter of the polystyrene tubes was about the same ($^5/_{16}$ in.) as that of the small stainless steel tubes; their appreciable softening and sagging shortly after startup was a distinct disadvantage. [It was quite interesting to note that with a directed jet, the cold end could be changed in length to give (1) air blown out and (2) air sucked in. Presumably at some critical length, nothing would happen.] The Lucite and glass tubes (Fig. 24), however, were of about $1\frac{1}{4}$-in.-ID material and were quite satisfactory, especially since measurements could be made at the same time that the tubes were inspected visually. Only a few temperature measurements were made with the larger tubes; most of the work involved measurements of pressure variations in the tubes. Table 15 and Fig. 25 show some of the temperature data.

It was noted with one particular baffle arrangement that the measured hot-end temperature was 94°C and that the cold-end temperature was −6°C. (The cold-end temperature seems to be somewhat dependent upon the humidity of the air, since the heat evolved in condensing or freezing moisture may be considerable. The moisture may also affect the analytical results.) The valve at the end of the tube away from the jet was an adjustable beveled screw.

Pressure Measurements. In addition to the work with temperatures, a number of measurements of pressures within the tubes were made. Probe holes were drilled into the sides of the tubes at regular intervals along the walls, and hypodermic needles were inserted to obtain values for *static head* and *velocity head* at various locations. (In making probe measurements, it was found that at some particular locations the introduction of the hypodermic needle upset the tube, apparently changing the operating conditions appreciably.) Figure 26 shows one of the Lucite tubes with the probe holes plugged with toothpicks, and Fig. 27 shows the hypodermic needles used for the pressure measurements. The needles were connected by a rubber tube to a mercury manometer, and readings were taken under equilibrium conditions. Table 16 and Figs. 28, 29, and 30 and Table 17 and Figs. 31, 32, and 33 show some of the data. It should be explained that for the earlier measurements (Table 16, Figs. 28-30) static pressures were assumed, as a first approximation, to be the average of the maximum and minimum readings, and the velocity head to be equal to one-half the difference between the maximum and minimum readings (maximum = needle facing upstream; minimum = needle facing downstream). Later on, the needle cut off at right angles was used to measure static pressures (Table 17, Figs. 31-33). Actually, probably neither is quite correct because of the vector components introduced by the vortex action.

Visual Observations. A number of experiments were performed which were intended to give some idea of the flow patterns within the tube. The copper tube, shown in Fig. 34, used to obtain the original samples for mass analysis was sawed lengthwise down the center. The striations are a result of the deposit of oil and dirt from the compressed-air line over a period of time. Their uniformity suggests that for normal operation (where

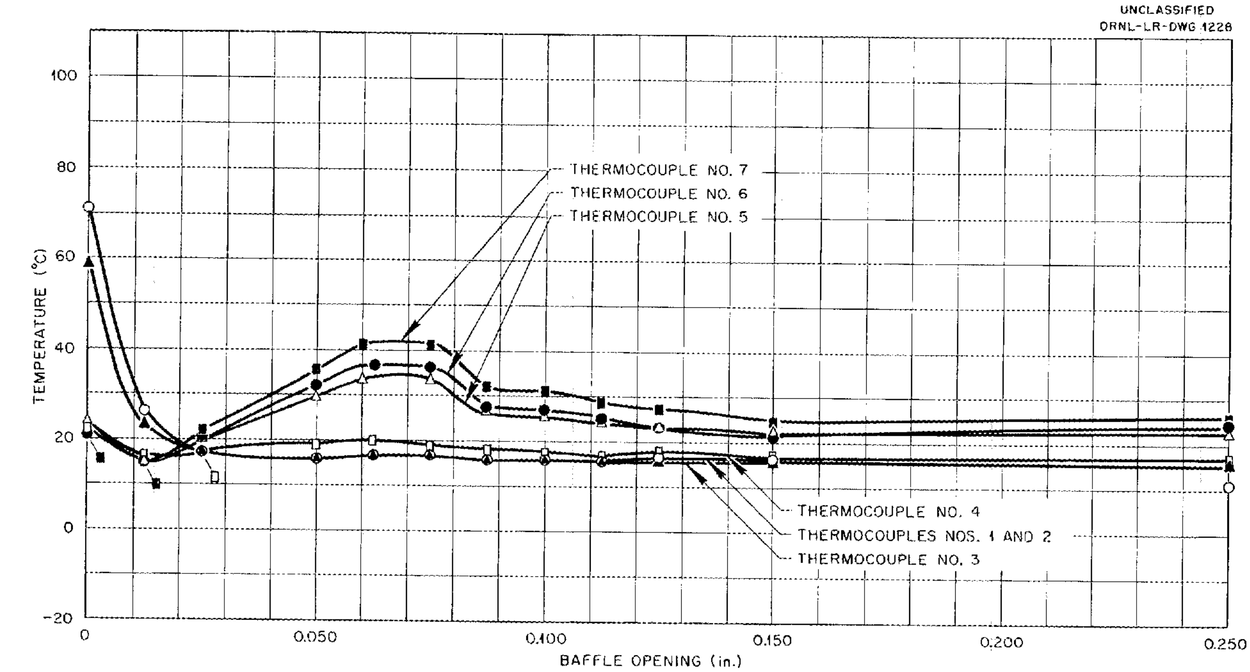

Fig. 14. Temperature vs Baffle Opening. Baffle adjacent to thermocouple No. 1.

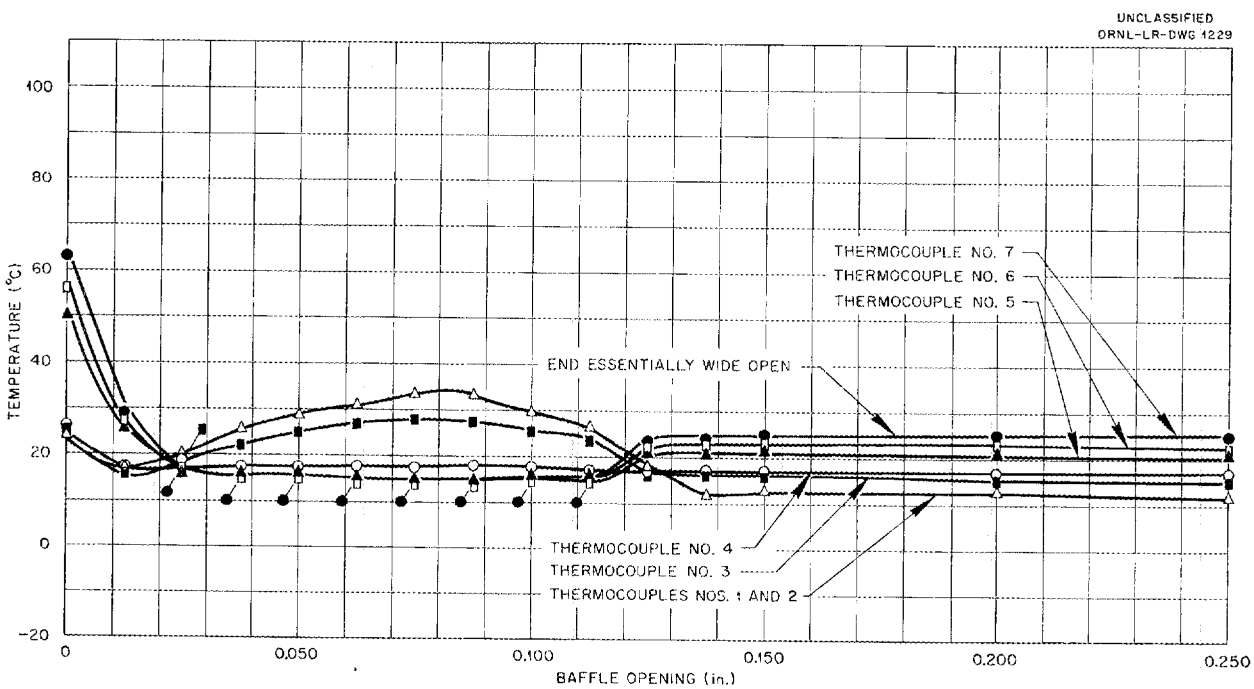

Fig. 15. Temperature vs Baffle Opening. Baffle adjacent to thermocouple No. 7.

Table 10. Temperature Measurements as Baffle Was Introduced into Tube

Baffle Adjacent to Thermocouple No. 7

Average Pressure (psig)	Temperature Measurements (°C) at Thermocouple Stations							Valve Opening (in.)
	1	2	3	4	5	6	7	
101.5	18	18	18	19	24	26	27	0.350
102	18	18	18	19	24	26	27	0.250
102	18	18	18	19	24	25	26	0.150
102.5	34	33	29	19	16	16	16	0.100
101.5	33	33	28	19	16	16	16	0.050
102	18	18	19	23	40	45	49	0.000
103	22	22	22	25	46	53	59	-0.050
95.5	22	22	23	25	46	52	56	-0.100
100.5	21	22	22	25	48	55	58	-0.150
101.5	21	22	22	24	49	56	60	-0.200
101.5	21	21	21	24	49	55	60	-0.250
93.5	21	21	21	24	47	52	56	-0.350
100	21	21	21	24	48	55	58	-0.500
101.5	21	21	21	24	51	57	60	-0.625
102	21	21	21	24	50	57	60	-0.750
103	21	21	21	25	52	60	64	-0.875
93.5	21	21	22	24	48	54	55	-1.000
96	21	21	21	25	48	54	52	-1.125
98.5	20	20	20	23	47	52	52	-1.250
101	20	20	20	24	44	50	49	-1.375
102.5	20	20	20	24	46	49	49	-1.500
94	20	20	20	25	48	50	50	-1.625
98	20	20	20	25	47	48	48	-1.750
100.5	20	20	20	25	47	49	49	-1.750*
103	21	21	21	25	48	48	48	-1.875
96.5	20	20	20	24	47	47	47	-2.000
94.5	20	20	20	24	40	40	40	-2.125
98	19	19	19	23	36	36	36	-2.250
100	19	19	18	22	36	36	36	-2.375
101.5	19	19	19	23	35	34	34	-2.500
103.5	20	20	20	24	34	33	33	-2.625
97	20	20	19	22	28	28	28	-2.750
	21	21	21	21	23	23	23	-2.875

*Repeat.

Table 11. Temperature Measurements Along Tube with Probe in End Opposite Baffle

Average Pressure (psig)	Temperature Measurements (°C) at Thermocouple Stations							Valve Opening (in.)
	1	2	3	4	5	6	7	
				No Probe				
100	23	25	25	25	52	59	62	0.000
95	25	24	23	19	19	21	21	0.025
96	32	32	28	20	18	18	18	0.050
98	37	36	32	20	17	18	17[a]	0.075
				Probe Inserted 1½ in.				
99.5	21	20	18	18	23	25	27[b]	0.075
101.5	23	22	20	18	20	22	22	0.050
103	21	19	17	19	23	25	26	0.025
94.5	23	23	23	25	51	57	62	0.000
				Probe Inserted 1 in.				
97.5	22	23	24	25	51	57	63	0.000
100.5	21	19	18	19	23	25	26	0.025
101.5	22	22	21	18	19	20	21[c]	0.050
103	23	23	19	19	20	21	22	0.075
				Probe Inserted ½ in.				
95	26	25	22	20	19	19	19[c]	0.075
97.5	26	25	22	19	19	19	19	0.050
99	21	20	18	18	21	23	24	0.025
100.5	22	23	23	25	51	58	63	0.000
				Probe Flush with End of Tube				
102.5	23	24	24	25	52	59	66	0.000
93.5	24	23	22	19	20	20	22	0.025
96.5	30	30	26	19	17	17	17[d]	0.050
98.5	35	34	30	20	17	17	17	0.075

[a]Whistle.
[b]Air sucked in; whistle.
[c]Air sucked in; no whistle.
[d]No suction; whistle.

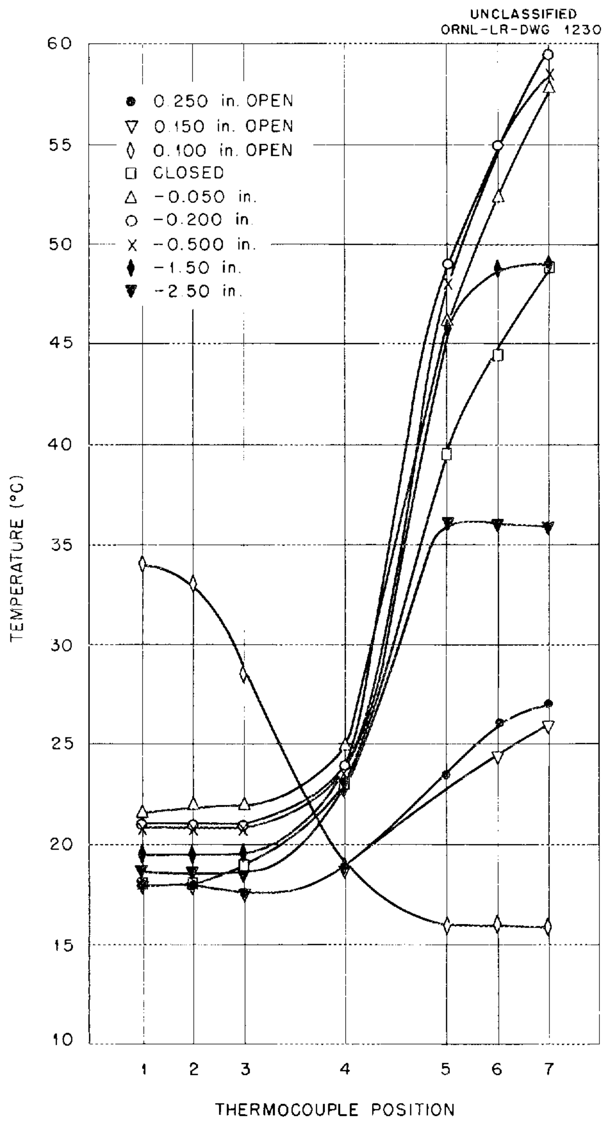

Fig. 16. Temperature Profile. Baffle into tube.

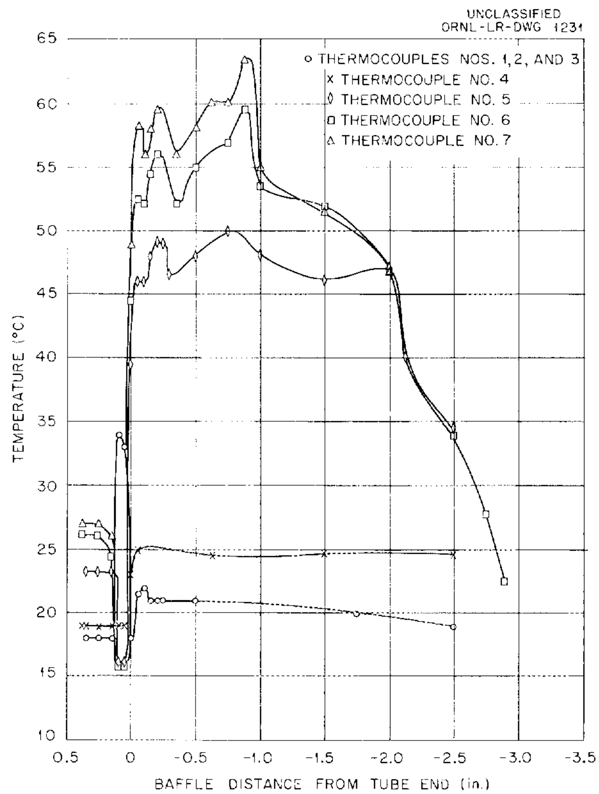

Fig. 17. Temperature vs Baffle Location.

complete baffling of the hot end is *not* involved) there is a fairly regular flow pattern.

While using the stainless steel tube with directed jet, we noticed that starch was "sucked" in at the cold end and blown out the hot end while the tube was in operation. On the other hand, when the shorter 6-in. T-tube was used, starch could not be introduced into either end.

When smoke was blown into the inlet (directed jet) of the polystyrene tube, some of it could be seen to start out the cold end and then to turn around and pass down the tube to the warm end.

With the $1\frac{1}{4}$-in. Lucite and glass tubes, such things as water, oil, starch, cork, Styrofoam, foam rubber, and glass beads were introduced, and the behavior was observed. For example, no matter which one of the above-mentioned substances was introduced into the tube during operation (with the hot end completely baffled), some of the material immediately moved to a point in the tube where it stopped, except for its rotational motion. The substance remained at that point as long as the tube conditions remained constant, as indicated by the stability of the sound emitted by the tube. Coincident with any change in pitch, however, there was a change in the location of this point, which we have chosen to call the "turn-around" point of the gas. A higher pitch was always associated with a point closer to the jet. The change in location of this turn-around point was almost instantaneous – faster, at least, than the eye could follow – and would frequently involve "jumps" of 12 to 15 in. The lighter substances were, of course, more responsive than the heavier ones to changes

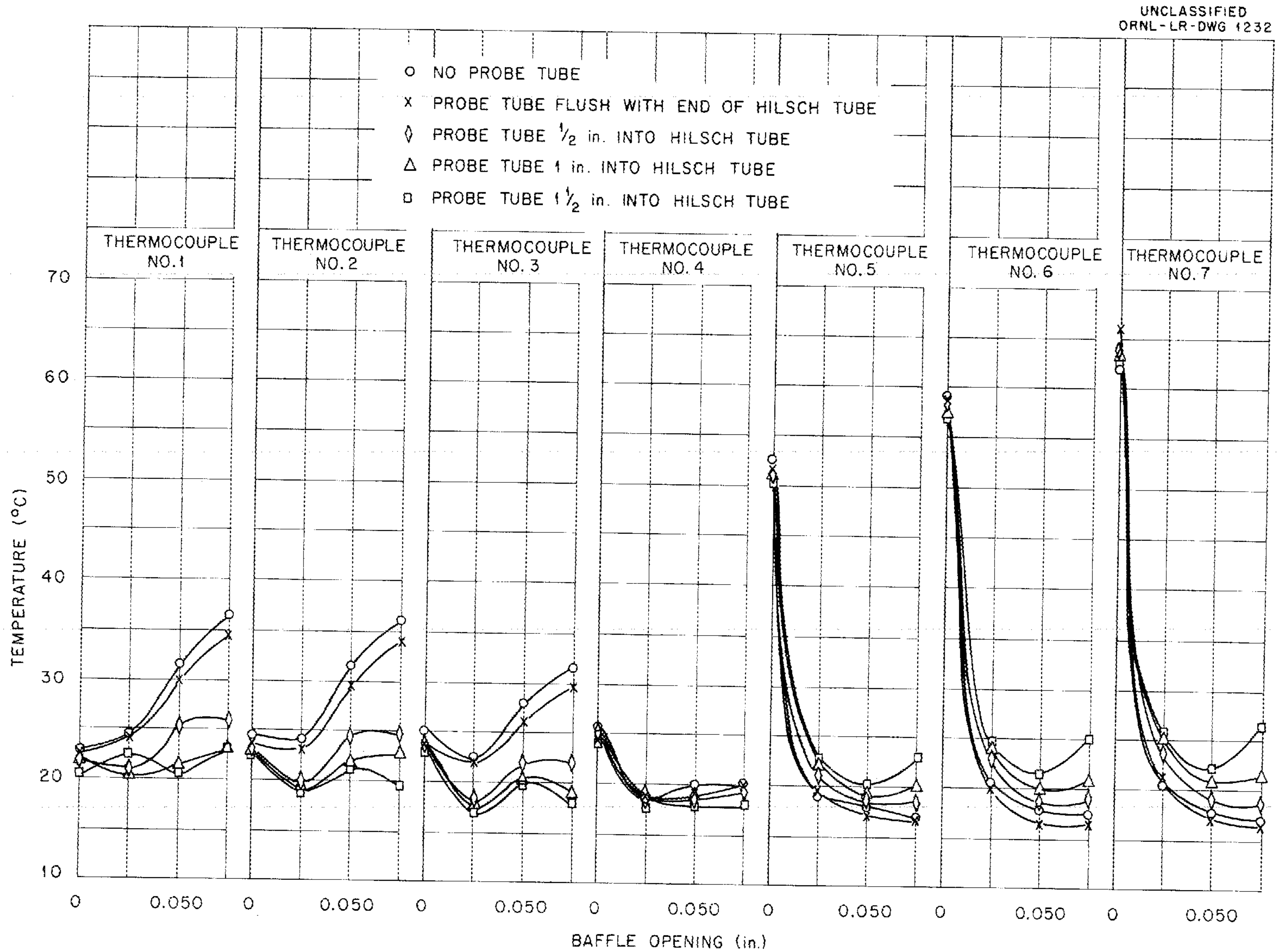

Fig. 18. Hollow Probe-Tube Effect. Effect of baffle distance.

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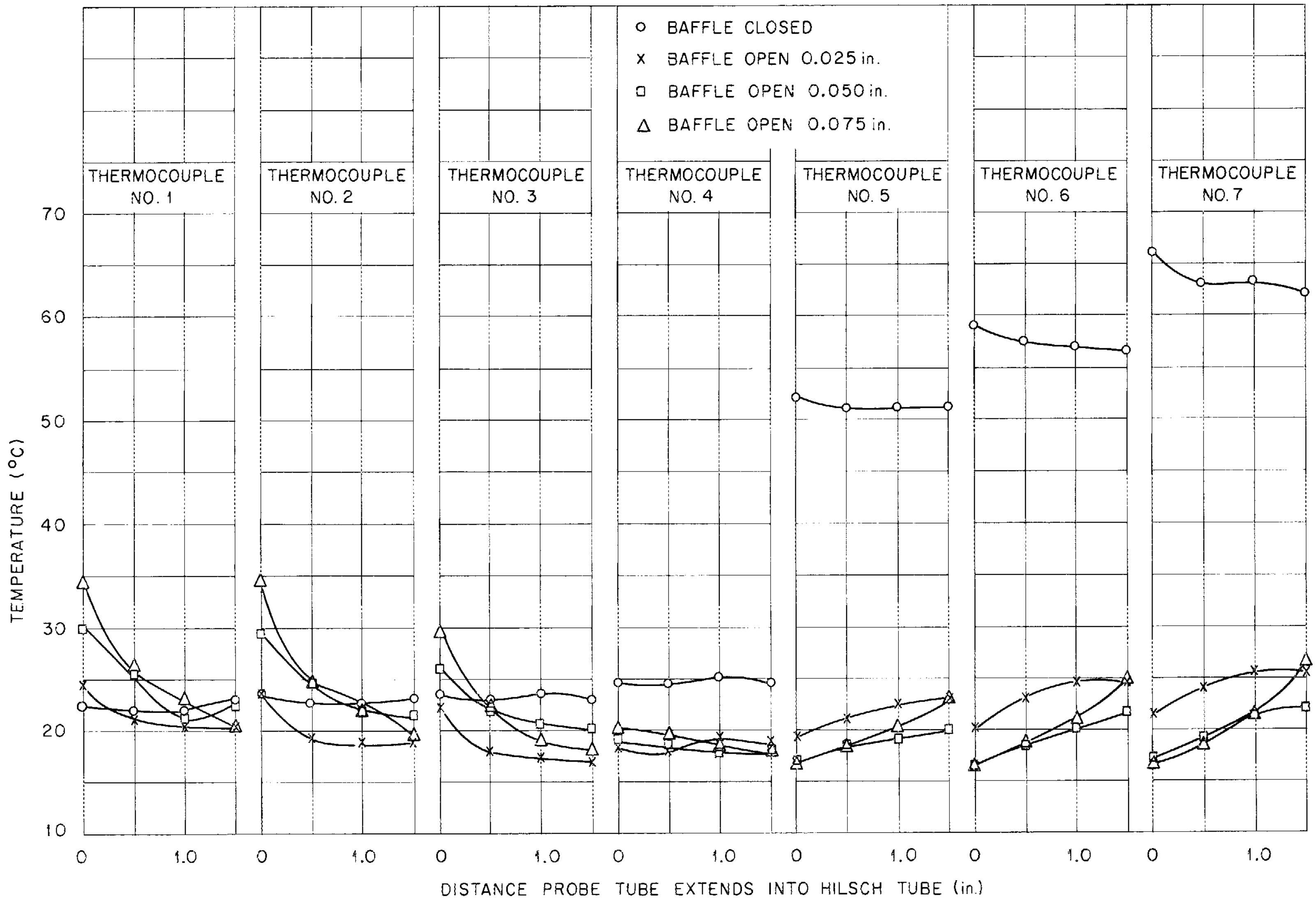

Fig. 19. Hollow Probe-Tube Effect. Effect of probe arrangement.

in conditions. Starch in the tube showed this effect very nicely. The walls were usually rather clean up to the turn-around point but were dusty beyond it, with starch swirling like a small snow storm at the turn-around. In some instances the walls were clean up to what appeared to be one turn-around point, slightly dusty up to a second,

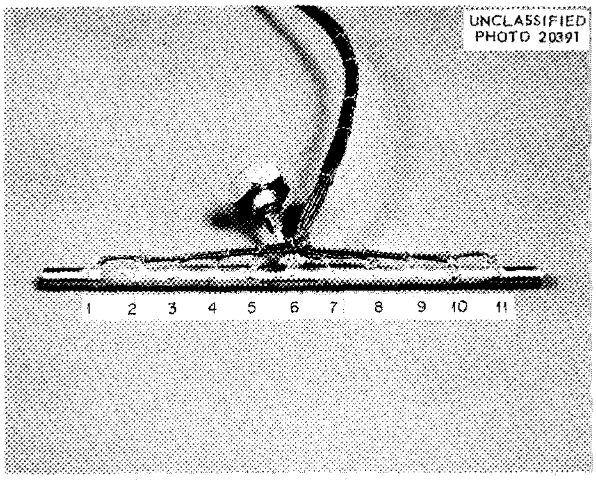

Fig. 20. Eleven-Station Vortex Tube.

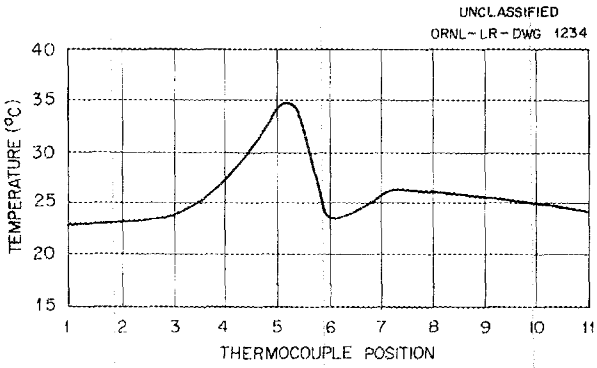

Fig. 21. Unbaffled Temperature Profile of 11-Station Tube.

Table 12. Temperature Measurements Along Tube with Probe Tube Plugged at Outer End

Average Pressure (psig)	Temperature Measurements (°C) at Thermocouple Stations							Baffle Opening (in.)
	1	2	3	4	5	6	7	
				Probe Flush with End of Hilsch Tube				
100.5	34	34	30	20	17	17	17	0.075
102.5	30	30	27	19	17	18	18	0.050
99	23	23	21	19	19	23	22	0.025
93.5	23	24	24	26	50	55	60	0.000
				Probe Inserted ½ in.				
96.5	23	23	24	25	52	59	65	0.000
98	19	18	17	19	24	26	28	0.025
99	20	19	18	18	22	25	26	0.050
100.5	19	18	18	19	23	25	27	0.075
				Probe Inserted 1 in.				
102	19	17	17	21	26	28	32	0.075
97	19	19	18	19	23	25	27	0.050
94.5	19	19	17	19	25	27	29	0.025
97.5	23	23	24	25	51	55	63	0.000
				Probe Inserted 1½ in.				
99.5	23	23	24	25	52	60	65	0.000
101	19	17	16	20	27	28	31	0.025
102.5	19	17	16	19	27	29	32	0.050
102.5	19	18	17	20	27	32	35	0.075

Table 13. Temperature Data for $9\frac{1}{4}$-in. Tube with 11 Thermocouples

Baffle Adjacent to Thermocouple No. 11

Average Pressure (psig)	Temperature Measurements (°C) at Thermocouple Stations											Baffle Opening (in.)
	1	2	3	4	5	6	7	8	9	10	11	
99	22	22	23	28	35	22	25	25	25	25	25	0.250
96	22	23	24	28	35	22	25	25	25	25	25	0.250
100.5	22	22	23	29	36	22	24	25	25	25	23	0.150
102.5	22	23	24	31	37	21	24	25	24	23	23	0.100
94	22	24	26	33	37	22	22	25	24	23	23	0.075
97.5	21	24	28	33	40	37	20	22	24	22	22	0.050
97	35	35	33	30	25	17	18	19	19	19	19	0.025
97.5	12	11	11	12	12	14	24	35	39	41	41	0.000
94.5	15	14	14	14	16	17	30	48	54	58	57	−0.050
97.5	15	16	16	16	17	18	33	54	63	68	64	−0.250
100.5	16	16	16	17	18	18	34	58	66	71	67	−0.500
102.5	17	17	17	17	18	18	34	58	67	72	68	−0.750
101.5	17	17	17	17	18	18	36	58	66	70	64	−1.000
95.5	17	16	16	16	18	18	35	56	63	67	60	−1.250
99.5	16	14	14	16	18	18	36	59	65	68	60	−1.500
102	17	16	16	17	18	18	37	62	69	70	62	−1.750
93.5	16	14	15	17	17	18	37	60	66	66	58	−2.000
96	16	14	14	15	16	18	36	58	63	62	56	−2.250
99	15	14	14	14	15	18	36	58	62	62	56	−2.750
102	16	14	14	14	17	18	37	57	60	60	54	−2.750*
96	39	46	50	47	37	20	22	23	22	22	22	+0.375
101	18	16	16	15	13	13	18	23	24	25	25	+0.125
	15	14		14	14	22	42	44	41	38	34	−4.000
101.5	23	23	24	28	35	24	26	26	26	25	24	Wide open

*Repeat.

and powdered beyond. It is not known whether this second turn-around point is a sort of harmonic or not. Between the jet and these turn-around points, the solids rotated with tremendous speeds, estimated at between 25,000 and 30,000 rpm. Gases certainly move much more rapidly.

The almost complete settling out of the powder beyond the turn-around point (other solids likewise stopped moving) indicated that the gas was essentially static beyond that point. Pressure-probe measurements seemed to confirm this observation. It was also noticed that the hot spot and the turn-around point seemed to occur in the same locality.

Another observation was that the tube would make a sharp sound like an air-brake being released when a small amount of air was permitted to escape from the hot end of the tube. The hiss would die away over a period of several seconds, and then the cycle would repeat at fairly regular intervals. Through the end of the tube it could be seen that the higher-density air which was at the wall when the hiss started was closing in toward the center and that the diameter of the "hole" gradually increased as the hiss died out. Through the walls of the tube it could be seen that the turn-around point would flip toward the hot end when the hiss started. (Steady operation of the tube should be more advantageous to secondary effects as far as separation is concerned, but even under stable conditions we were unable to obtain measurable separation.)

In general, bleeding air from the hot end would

Table 14. Temperature Data for $9\frac{1}{4}$-in. Tube with 11 Thermocouples

Baffle Adjacent to Thermocouple No. 1

Average Pressure (psig)	Temperature Measurements (°C) at Thermocouple Stations											Baffle Opening (in.)
	1	2	3	4	5	6	7	8	9	10	11	
101	24	24	24	28	35	24	26	27	26	26	25	0.250
96	23	23	24	27	34	24	26	27	26	26	25	0.150
99	23	23	23	28	34	24	26	27	26	26	25	0.100
101	23	23	23	27	35	24	26	26	25	25	25	0.075
94.5	23	23	23	28	34	24	25	26	25	25	24	0.050
98	23	24	24	30	36	24	25	26	24	24	24	0.025
100	24	26	31	38	40	23	25	25	24	24	23	0.000
94.5	25	30	36	41	39	22	24	24	24	24	23	−0.050
100.5	28	35	42	44	39	22	24	24	23	23	23	−0.250
98	29	37	43	46	40	22	24	24	23	23	23	−0.500
96.5	28	37	42	44	39	22	24	23	23	23	23	−0.750
96.5	27	39	44	47	41	22	24	23	23	23	23	−1.000
93.5	26	36	42	44	39	22	24	24	23	23	23	−1.250
101	26	36	43	45	41	23	24	24	24	24	23	−1.250*
98.5	26	35	43	45	39	22	24	24	23	24	23	−1.500
99	26	32	43	45	40	23	24	23	23	23	23	−2.000
101	28	33	40	47	41	23	24	24	23	23	23	−2.500
98.5	33	35	38	42	39	22	24	23	23	23	23	−3.000
97.5	30	32	34	35	35	22	21	21	21	22	22	−4.000

*Repeated to check effect of pressure.

cause the turn-around point to move down the tube away from the jet; as more and more air was let out, the turn-around point would eventually disappear (or move, theoretically) to a point beyond the end of the tube.

Moving of the hot-end baffle toward the turn-around point had no pronounced effect on the latter until it was very close and, even then, it seemed to move the turn-around only very slightly. When the baffle was moved completely *through* the area where the turn-around was located, the latter disappeared entirely, although a warm spot still remained.

When starch was being observed in the tube, at certain positions of the baffle a slight swirling of the starch could be seen *behind* the baffle. This was probably due to the leaking of a small amount of air between the baffle and the tube. But, at the same time, it might also help to explain the previously mentioned hot spot *beyond* the baffle.

Whether the tube was vertical, horizontal, or at an angle seemed to make no difference so far as the above-mentioned observations were concerned. The forces apparently were large compared with any effect of gravity.

It could be seen in the glass tube that oil at the turn-around point was flowing in a plane tilted perhaps 70 to 80 deg to the axis of the tube. Both oil and water showed definite flow patterns in the tube quite similar to those thought to be responsible for the deposit in the copper tube (Fig. 34). A few miscellaneous observations are listed below:

1. When the pitch is higher, the static pressure at the center of the tube is higher.

2. The static pressure behind the turn-around point seems to be relatively constant across the tube as long as the whistling occurs with constant pitch. When the whistling stops, the pressure drops simultaneously.

3. With a stainless steel, directed-jet tube,

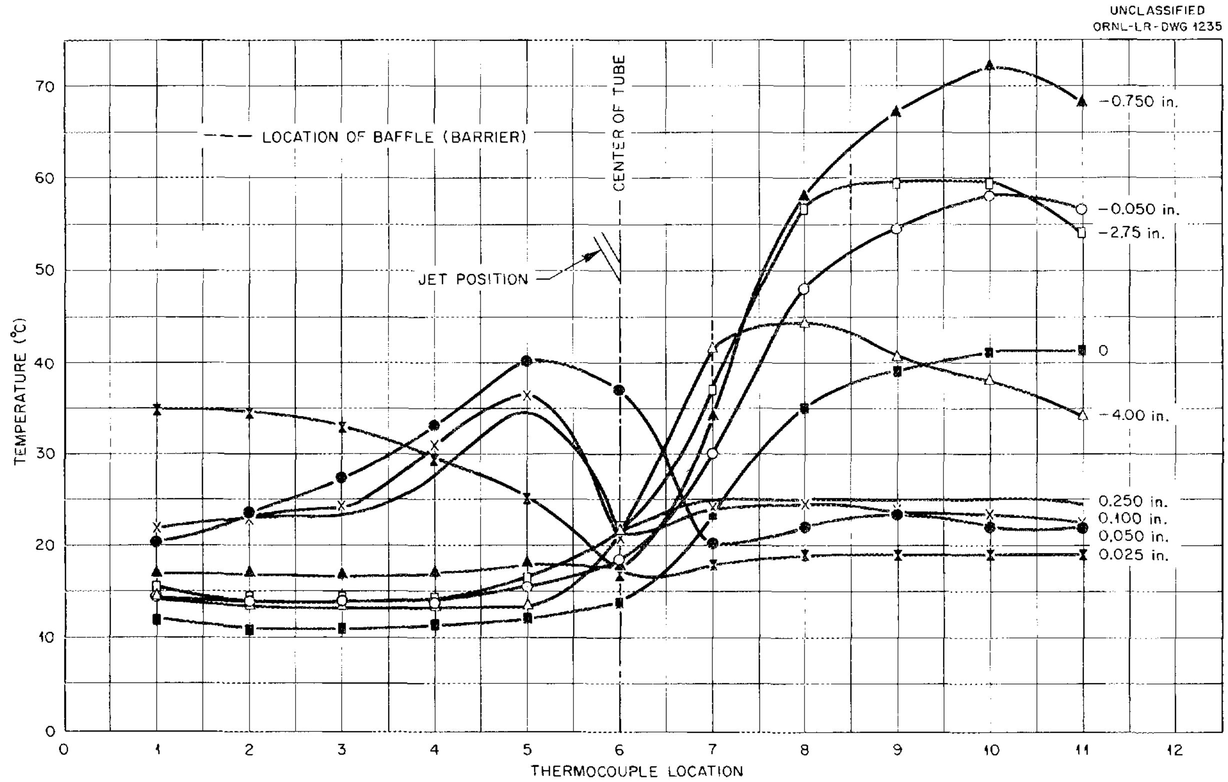

Fig. 22. Baffled Temperature Profile of 11-Station Tube. Baffle introduced from end adjacent to thermocouple No. 11.

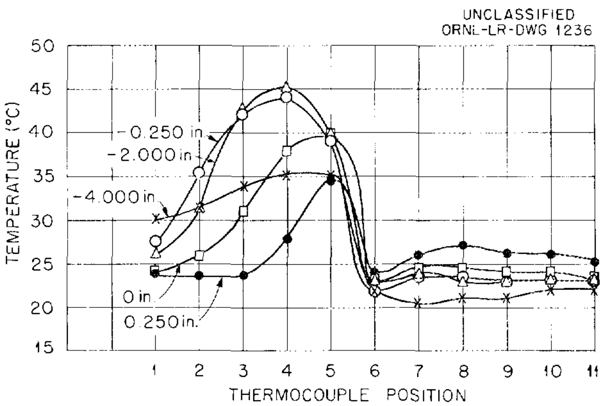

Fig. 23. Baffled Temperature Profile of 11-Station Tube. Baffle introduced from end adjacent to thermocouple No. 1.

starch is drawn into the end behind the jet. Yet, under these conditions, the tube shows a warm spot on this end (ordinarily considered the cold end). It is not clear how this can be explained by countercurrents.

4. When the turn-around is stationary, the screeching is at a minimum.

5. It seems that the hot spot with the highest temperature occurs when there is very nearly complete turn-around of the gas. Complete turn-around also gives the noisiest operation. This would lead to the belief that high temperature and good separation are not related.

6. At 35 psig jet pressure, the manometer reading of 25 (cm Hg) drops to 18 as the tube changes pitch. Simultaneously, the turn-around point moves from thermocouple station No. 13 to station No. 29.

7. There seems to be a hot spot even when there is no obvious turn-around, but this is not unreasonable. As gas is bled from the hot end, the hot spot broadens out and moves down (and eventually out) the tube; so between the two extremes there will always be an area which is warmer than the points adjacent.

Table 15. Temperature Measurements Along Lucite Tube

Average Pressure (psig)	Temperature Measurements (°C)													Remarks
	Thermocouple Stations											Hot End	Cold End	
	1 (48)*	2 (44)	3 (40)	4 (36)	5 (32)	6 (28)	7 (24)	8 (20)	9 (16)	10 (12)	11 (8)			
40	54	56	56	58	59	57	56	56	53	49	43	54	8	Hot end wide open; ~30% of gas out
	56	56	56	58	58	57	56	55	52	48	42			Same as above, 5 min later
40	64	65	66	68	69	68	66	66	62	56	46	84	10	Hot end partly closed (beveled screw 1.4 in. out)
	68	68	70	71	72	72	68	64	62	55	47			Same as above, 5 min later
41	68	66	71	74	76	76	73	71	67	59	50	73	13	Hot end closed 0.35 in. more than above
39	74	70	75	79	79	80	75	73	70	62	51			Same as above, 5 min later
38	75	72	75	79	78	79	76	72	67	59	49			Same as above, 10 min later
43	55	60	65	70	77	77	74	71	68	62	52		18	Hot end closed
38	50	57	64	68	72	72	69	68	65	59	50			Same as above, 7 min later
37.5	42	50	59	64**	71	72	68	67	64	59	50			Same, 31 min later

*Numbers in parentheses are corresponding probe points.

**Turn-around at thermocouple station No. 34.

Table 16. Pressure-Probe Data for Short Lucite Tube

Probe Stations Approximately $2\frac{1}{2}$ in. Apart Starting $\frac{1}{2}$ in. from Jet; Distance from Baffle to Jet, 17 in.

	Pressure Measurements (cm Hg ± 0.1 vs air) at Probe Stations						
	1	2	3	4	5	6	7
			Jet Pressure of 25 psig				
$Wall_{max}$	19.9	17.6	15.2	14.0	13.0	12.6	12.2
$Wall_{min}$	7.6	9.8	9.0	10.8	9.8	11.4	10.2
$R/2_{max}$	11.3	12.8	10.6	11.0	10.6	11.6	11.8
$R/2_{min}$	1.8	4.8	5.0	7.6	5.2	9.8	5.8
Center	−4.2	+3.8	−3.0	−4.6	+1.8	+5.6	5.8
			Jet Pressure of 40 psig				
$Wall_{max}$	38.0	34.8	30.0	29.9	25.0	23.0	
$Wall_{min}$	14.4	19.6	18.8	19.2	20.0	20.2	
$R/2_{max}$	20.6	24.0	20.8	21.6	19.6	20.8	
$R/2_{min}$	4.0	9.4	11.2	15.2	10.0	17.6	
Center	−7.2	+3.6	−14.4	−15.5	+5.2	+5.0	

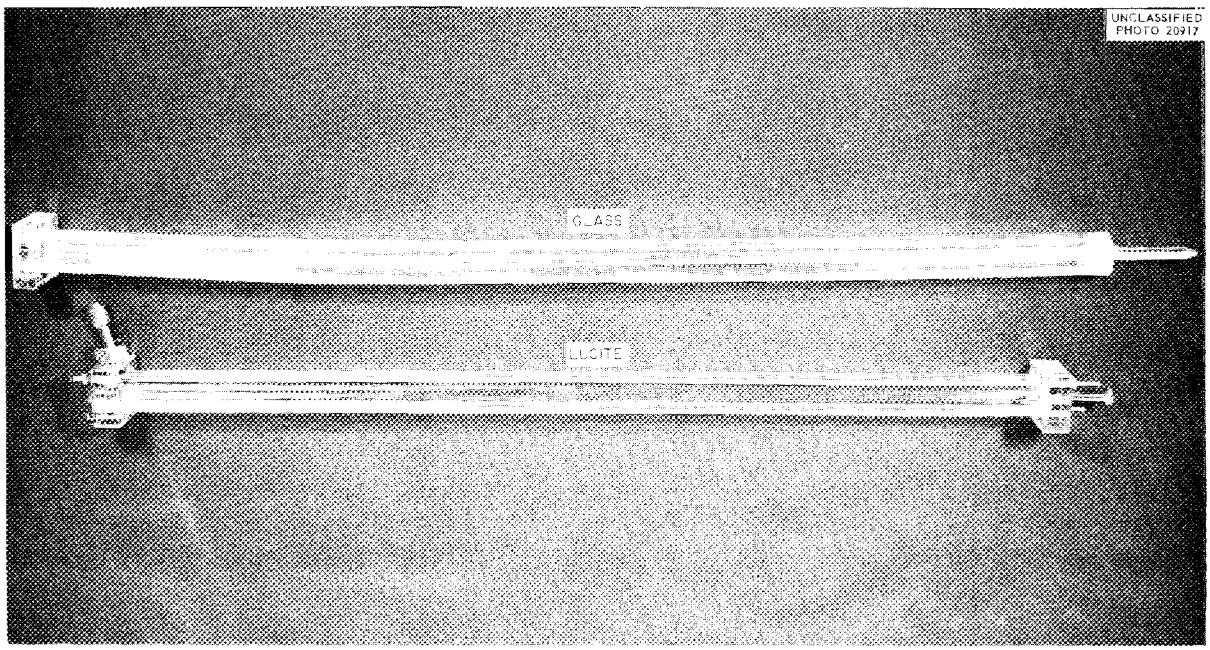

Fig. 24. Lucite and Glass Vortex Tubes.

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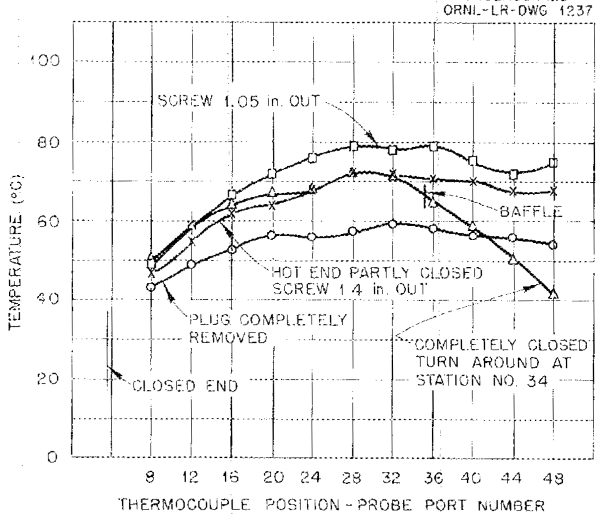

Fig. 25. Temperature Profile of Lucite Tube with Various Baffles.

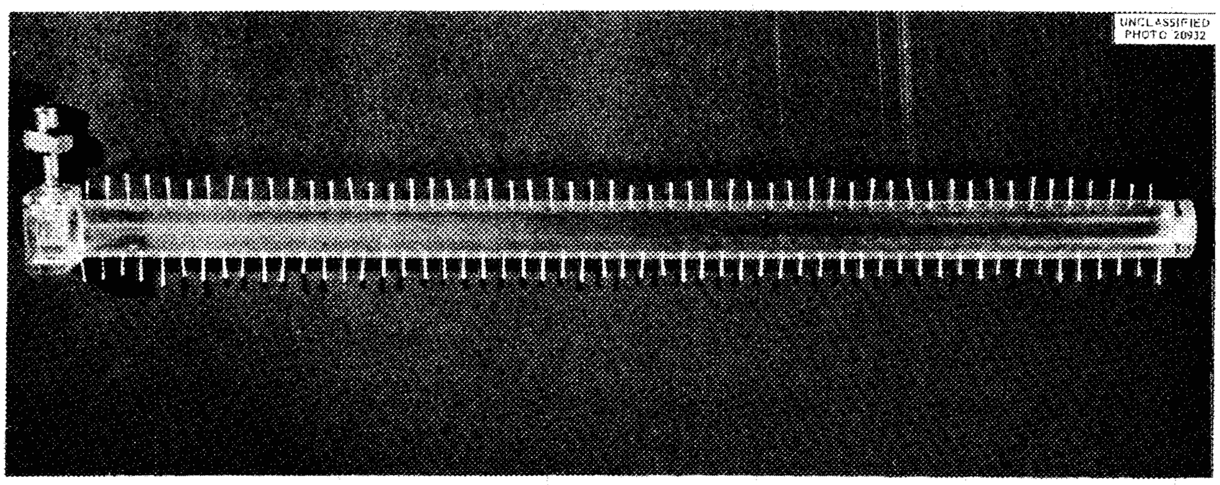

Fig. 26. Lucite Tube Used for Pressure Measurements.

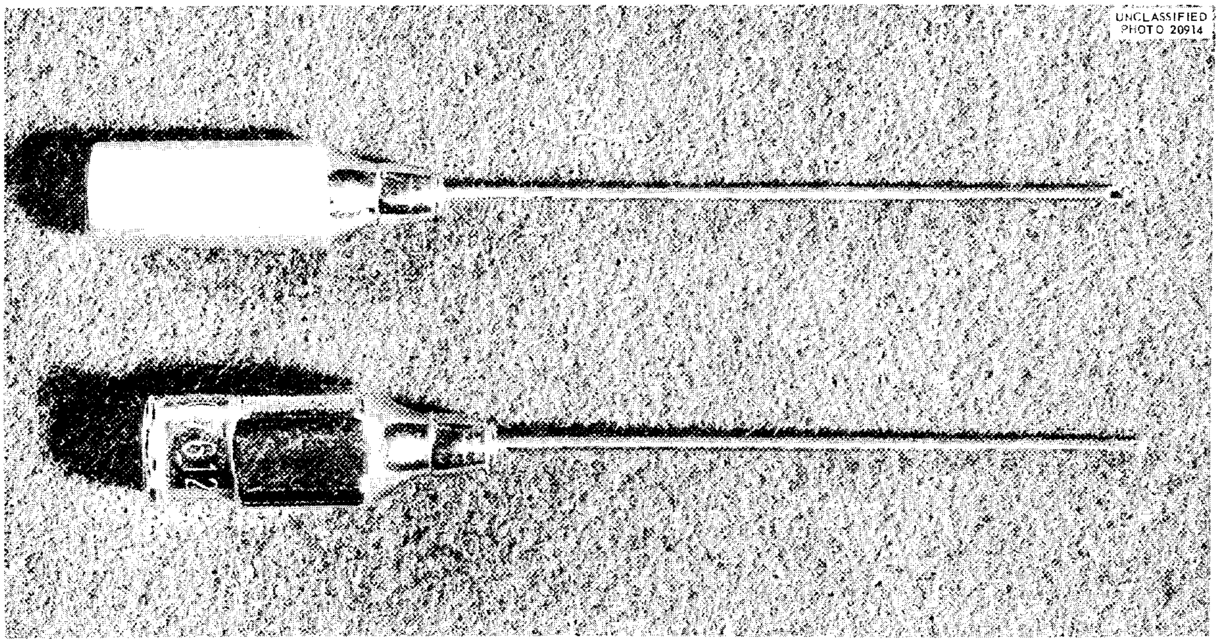

Fig. 27. Hypodermic Needles Used for Pressure Measurements.

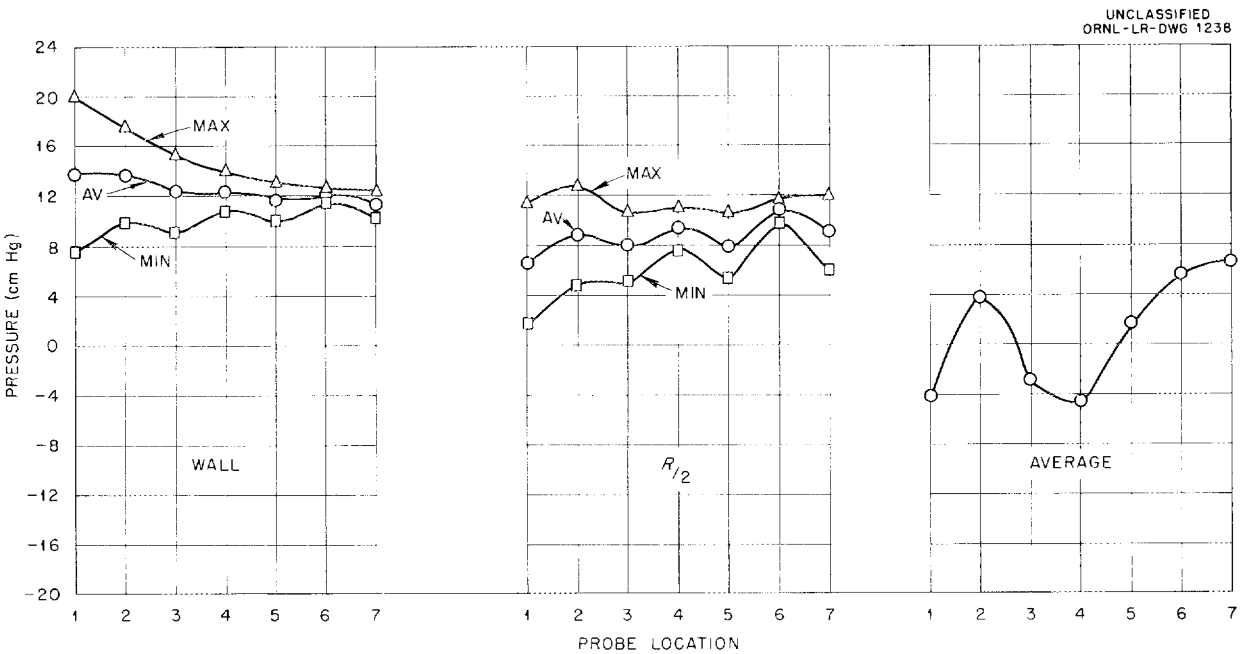

Fig. 28. Pressure Profile Along Tube. Jet pressure, 25 psig; baffle, 17 in. from jet.

Table 17. Pressure-Probe Data for Long Lucite Tube

Probe Stations Approximately $\frac{1}{2}$ in. Apart

Probe Station	Pressure Measurements (cm Hg ± 0.1 vs air)								
	Static					Dynamic			
	Jet Pressure (psig)								
	40[a]			37.5[b]		37.5[c]			
						Wall		R/2	
	Wall	R/2	Axis	R/2	Axis	Maximum	Minimum	Maximum	Minimum
1	33.8			−2.0	−4.7	60.0	8.8	11.2	−1.4
2				−4.0	−3.1	52.7	7.7	7.4	−2.8
3	28.0			−4.6	−3.5	53.4	5.5	6.0	−2.6
4				−3.6	−3.8	46.0	8.0	7.6	−3.0
5	27.0			−1.2	−2.0	45.4	10.6	11.1	−2.9
6				−0.5	−3.6			14.8	−0.2
7	26.0			+0.5	−3.5	39.0	13.7	12.6	0.0
8				0.7	−3.0			10.5	0.0
9	23.7			0.2	−3.0	33.7	11.5	9.8	−0.8
10				2.2	−1.0			11.0	−0.4
11	24.4			4.6	+0.8	32.0	13.5	14.0	+0.4
12				5.7	0.0			15.8	2.3
13	23.8			5.6	−0.4	28.9	15.4	16.2	3.8
14	22.0			5.5	+0.3			14.3	3.7
15	21.8			4.8	0.8	25.7	14.2	11.4	3.7
16	20.6			4.6	1.3			10.4	3.2
17	22.2			6.0	3.0	24.4	14.1	12.8	4.2
18				8.0	3.4			15.2	5.7
19	21.4			9.0	3.6	22.8	15.2	16.8	7.6
20				9.4	3.8			17.2	8.4
21	20.5			8.9	4.0	20.9	14.5	15.2	8.0
22	18.8			8.4	4.4			14.1	7.4
23	17.9			8.7	5.4	20.3	14.0	13.2	6.8
24				11.6	6.4			14.4	7.8
25	18.6	12.9	8.6	12.6	8.5	20.7	15.5	15.8	9.8
26	18.0	12.7	8.3	12.8	8.4			16.0	10.5
27	17.6	12.2	8.0	12.3	7.0	19.6	15.7	15.7	10.6
28	17.0	11.4	8.4	11.8	6.8			15.0	10.2
29	16.4	11.2	8.0	11.6	6.8	18.8	15.6	14.1	10.0
30	16.2	11.4	8.3	11.4	7.0			13.9	9.8
31	16.2	12.3	9.0		9.3	18.9	15.4	14.5	10.2
32	16.0	12.8	9.6					14.5	10.8
33	16.2	12.6	9.2			18.5	15.7	14.5	10.9
34	16.2	12.6	8.6					15.2	12.0
35		12.5	8.4			17.9	16.0	14.6	12.4
36	16.1	12.4	8.3					14.8	12.2
37		12.3	8.6			17.5	15.5	14.8	11.6
38	16.0	12.8	11.0					15.1	11.2
39		13.5	13.3			17.6	15.8	14.8	10.8
40	16.2	14.0	10.8					15.4	12.8
41		14.4	10.0			17.3	16.0	15.8	13.5
42	16.2	14.5	9.8			17.0	15.8	15.7	14.0
43		14.4	8.8			16.7	15.7	15.7	14.1
44	16.2	14.0	8.0			16.8	15.7	15.3	12.9
45		13.8	11.4			16.5	15.5	15.2	12.0
46	16.0	14.0	10.8			16.2	15.2	15.2	11.0
47		15.0	13.6			16.1	15.0	14.8	11.6
48	16.3	15.4	10.6			15.7	15.1	15.0	13.1
49		15.7	12.0			15.5	15.0	14.7	14.2
50	16.5	15.7	13.0			15.5	14.7	15.3	14.2
51		15.4				15.8	15.2	15.0	13.7
52	16.4	15.0				16.1	15.5	15.0	13.3
53		14.6				16.0	15.5	15.0	11.6
54	16.6	14.8				16.0	15.4	15.3	11.0
55		15.0							

[a] About 5% of inlet air out hot end; needle cut off at right angle.

[b] Other conditions same as those for 40-psig test.

[c] Needle with directed tip.

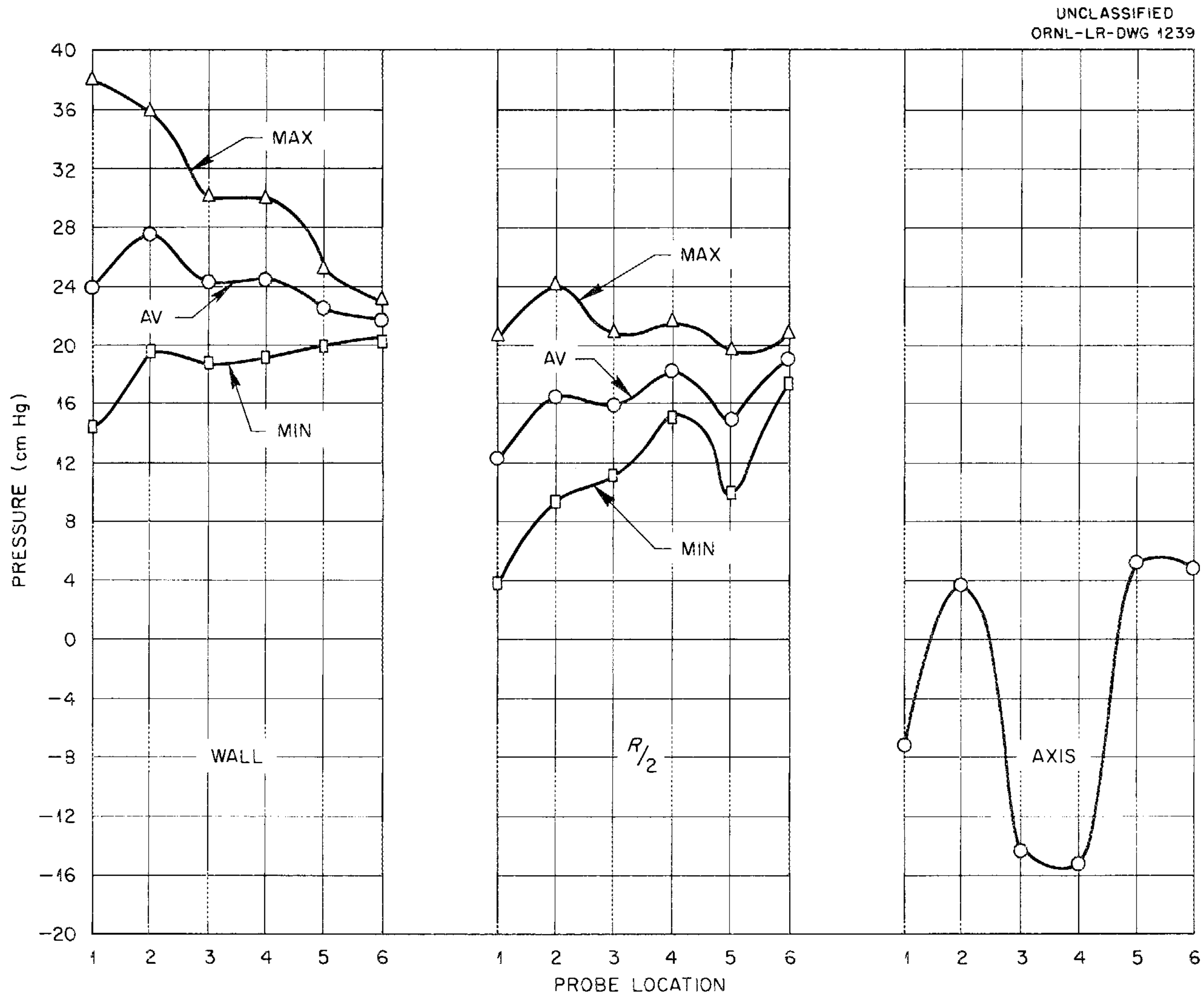

Fig. 29. Pressure Profile Along Tube. Jet pressure, 40 psig; baffle, 17 in. from jet.

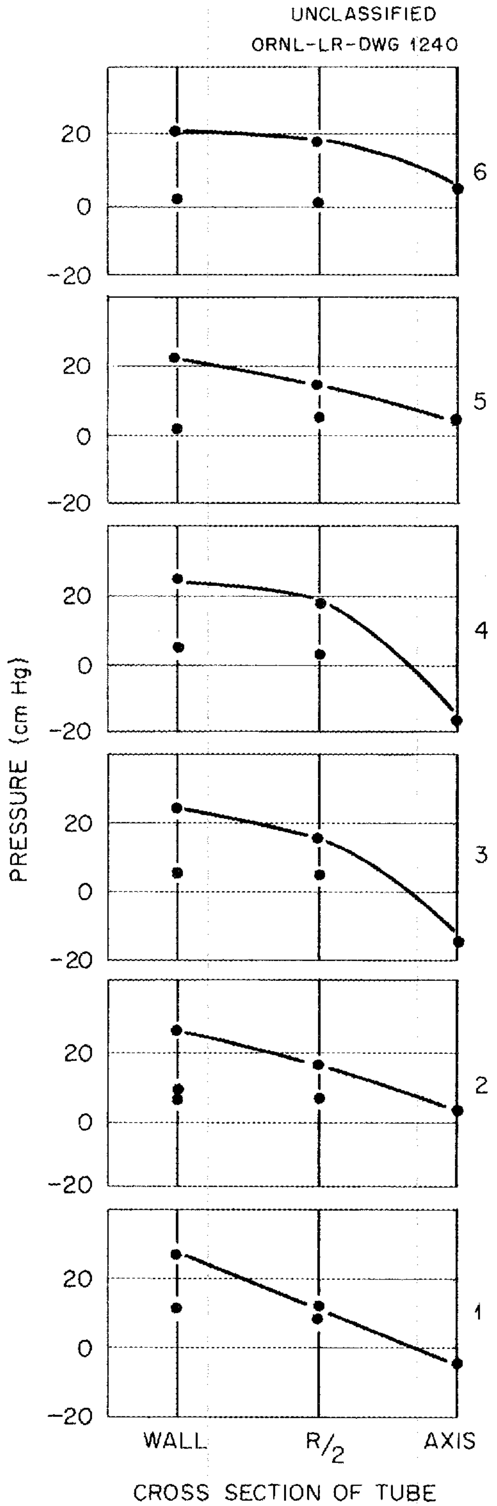

Fig. 30. Pressure Profile Across Tube at Various Stations.

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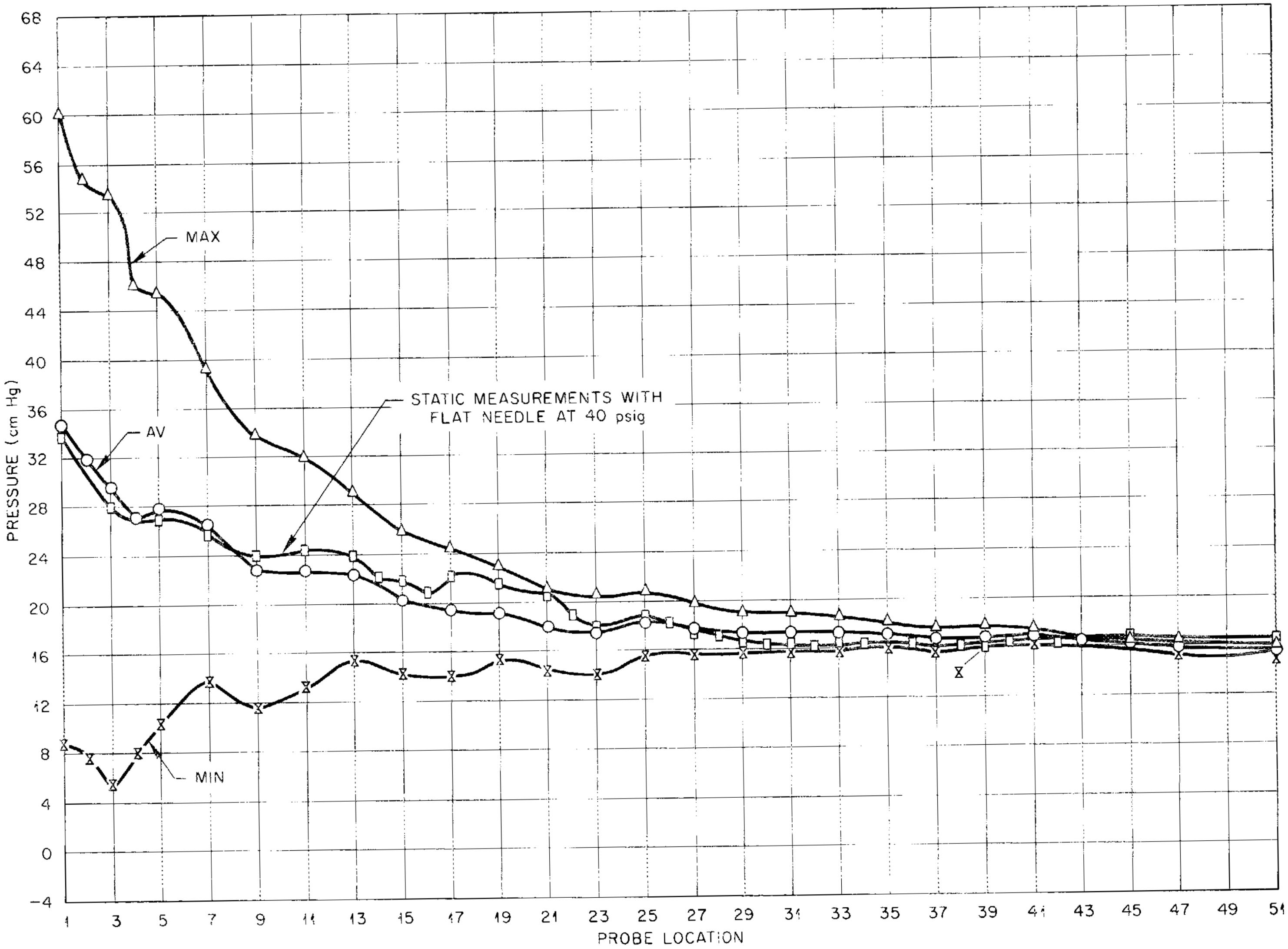

Fig. 31. Pressure Profile for Long Lucite Tube at Wall. Jet pressure, 37.5 psig; about 5% of air out hot end.

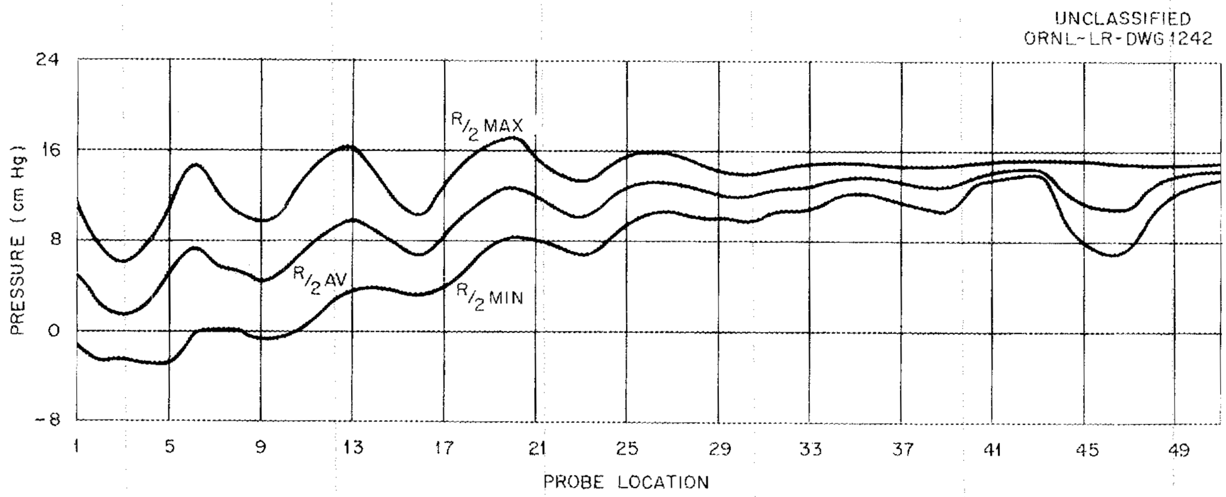

Fig. 32. Pressure Profile for Long Lucite Tube at *R*/2.

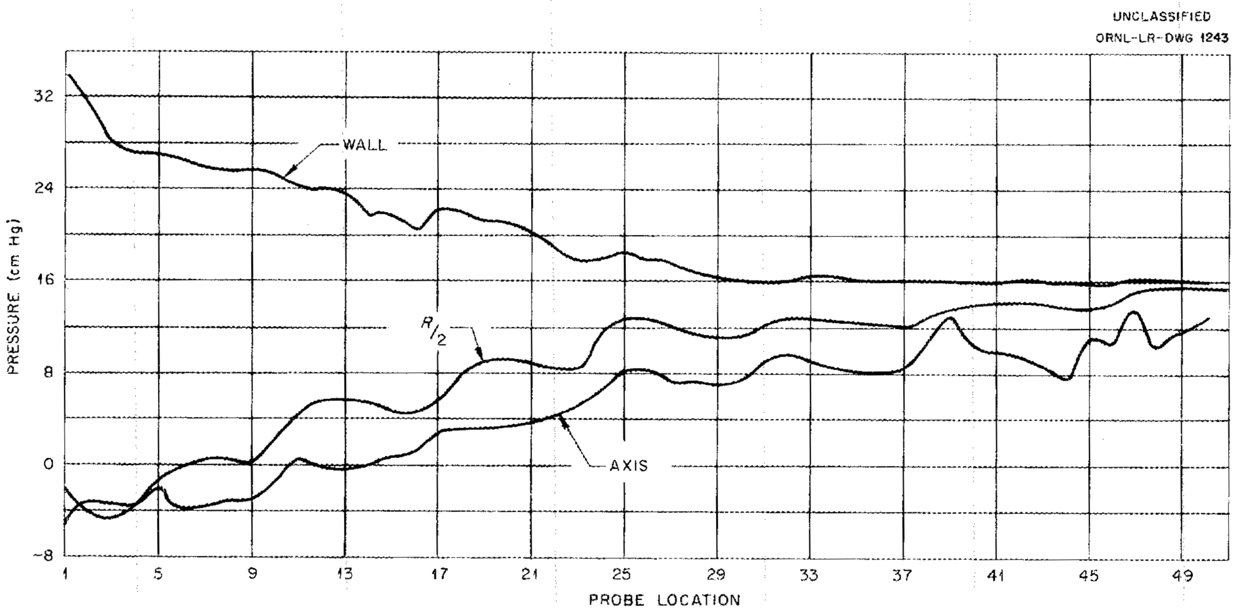

Fig. 33. Static Pressure Profile for Long Lucite Tube at Wall, *R*/2, and Axis.

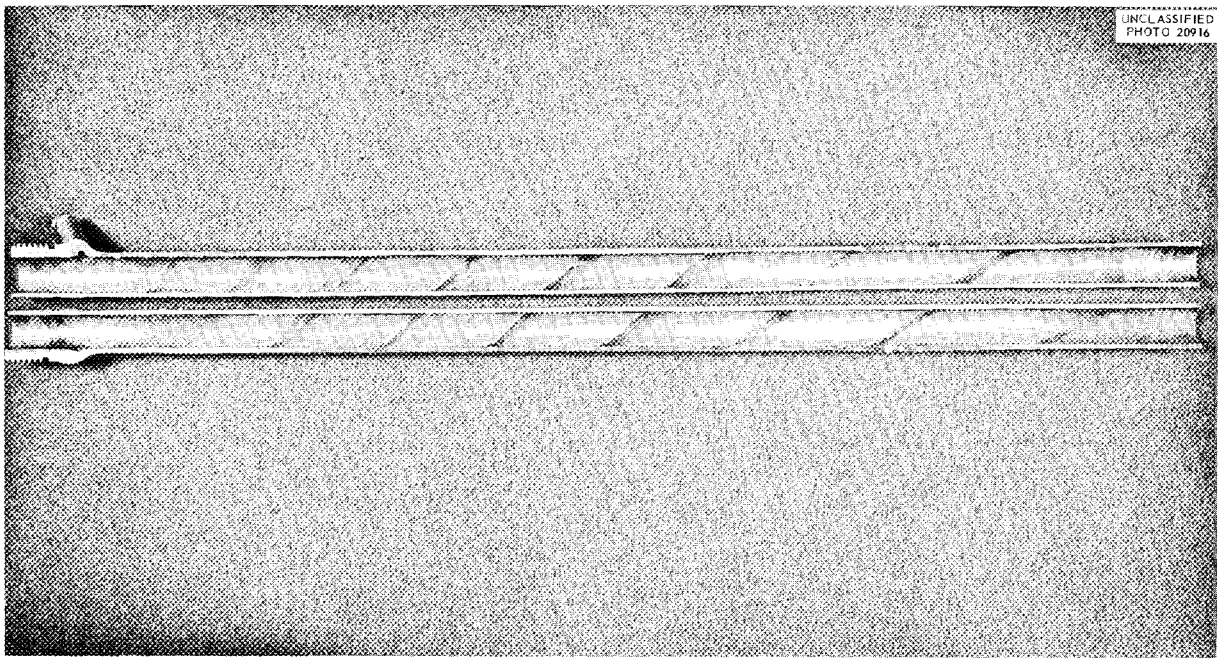

Fig. 34. Copper Vortex Tube Sawed Lengthwise.

RESULTS

The compilation of considerable information has not, frankly, made it possible for us to determine exactly which data are significant and which are not. However, most of the data have been included in the hope that they will ultimately lead to a more complete picture of the manner in which the vortex tube operates. At the same time, a consideration of the data we do have has led to the development of the following general theory of tube operation – a combination theory comprising three parts – which seems to explain satisfactorily the various phenomena observed.

1. An adiabatic expansion of a portion of the gas is responsible for much of the temperature drop at the cold end of the tube,[8] although some cooling results from the loss of energy to the outer layers of gas as it moves down the tube. The Joule-Thomson effect may contribute to or detract from this effect, depending upon the sign of the Joule-Thomson coefficient.

2. The viscous-shear theory (modified to include a multistage heat-transfer concept) explains the increase in temperature along the tube.

3. The complete turn-around of the gas at the stagnation point when the far end of the tube is completely baffled and the partial turn-around of a portion of the gas under other conditions result in sufficient energy exchange to account for the temperatures of the warm or hot spots. Any shock waves which may occur in the region of the hot spots (since the gas is known to be traveling with near-sonic velocity, shocks are probable) may also contribute to this effect.

In connection with item No. 3, the work of Nuttall (26) is of interest. He has shown qualitatively by means of dyes introduced into swirling liquids flowing through a circular plastic pipe that reverse flow occurs in the center of the pipe for certain rates of swirl and discharge.

The conditions inside the tube seem to be largely turbulent, as Corr (17) also has found, although his suggestion that complete throttling of the hot end

[8]Reference 14, p 475.

destroys the temperature differential has not been borne out.

It has not been shown that there is any relationship whatsoever between the temperature effect and the separation effect, even where the latter is claimed. On the contrary, the conditions for maximum temperature seem, on the basis of pressure-probe measurements and visual observations, to be those least expected to give good mass separation.

Any "explosive diffusion" effect is difficult to visualize in view of the very short, mean free path of the molecules at the usual operating temperatures; and the fact that the gas apparently is not laminar beyond the stagnation point seems to rule out the necessity of a countercurrent extraction of hot molecules to explain the hot spots. Furthermore, the apparent turbulence in the region of the turn-around would, seemingly, tend to give homogeneity to the system, thereby lessening the possibility that any marked deviations from Maxwell-Boltzmann distribution are responsible for the observed effects.

It is not believed that the theory of Scheper is contradicted, since any "forced convection" would be in the right direction. Any disagreement can probably be traced to a misunderstanding of terminology.

Elser and Hoch, as well as Stone and Love, suggest that hot air is at the rim of the vortex. This is probably quite true between the jet and the turn-around, but beyond the turn-around point all the air seems to be hot, and we were unable to find any temperature difference at all between the center and the periphery (probably because the gas in this area is quite turbulent). Fulton (25) also seems to have encountered this difficulty.

Samples taken at the hot spot during tube operation do not show results any more promising than do any of the other samples (Table 18). If temperature differences and mass separation are related, as far as vortex tube operation is concerned, then the greatest mass separation presumably occurs at the hot spot (assuming a relatively low axial temperature at that point). Stone and Love predict this effect by their suggestion that light molecules are depleted beyond the hot spot and are enriched when approaching the hot spot.

It seems particularly significant that combined averages of all separation data show the following values, with no trend significant enough to be greater than the analytical limits of error.

	N_2-to-O_2 Ratio ($\pm$0.03)
Inlet	5.00
Hot end	5.01
Cold end	4.98

(A consideration of the data included in Table 5 is of interest in this connection, also. If separation is occurring as predicted, then the N_2-to-O_2 ratios should be hot > inlet > cold; and hot minus inlet, inlet minus cold, and hot minus cold should all be positive values. A glance at the table will show that this is true only about as often as it is not true.) Further, the cold-end fraction of effluent gas averaged between 0.8 and 0.9; so the more noticeable enhancement should be at the hot end. These values show that 80 to 90% of the air is being depleted twice as much as the other 10 to 20%

Table 18. Samples Taken at Hot Spot

Probe Location	Mass Ratio			
	N_2^{28} to N_2^{29}	N_2^{28} to O_2^{32}	N_2^{28} to A^{40}	N_2^{29} to A^{40}
Hot end	145	4.88	56.9	0.393
Inlet	140	4.83	65.1	0.466
Cold end	140	4.85	65.3	0.469
At wall	145	4.83	60.2	0.414
One-half distance to axis	138	4.79	64.9	0.467
Two-thirds distance to axis	139	4.85	59.7	0.430
At axis	141	4.93	64.7	0.459

is being enriched. In other words, if the differences are real, the figures belie the usual expectations with regard to material balance.

Another interesting interpretation of the data can be made from the results in Table 18, which includes several mass ratios in addition to the N_2-to-O_2 ratio. It appears that light nitrogen is being concentrated at the hot-spot wall and at the hot end with respect to heavy nitrogen; but it also appears that argon likewise is being concentrated at the hot-spot wall and at the hot end with respect to the same nitrogen. Further, light nitrogen is being concentrated at the axis with respect to the heavy nitrogen, and this is contrary to theory. In other words, under fixed conditions of operation of a particular tube, it is not expected that some heavy molecules or atoms will be separated in one direction and other heavy atoms or molecules in another direction, although some property of the gases might conceivably allow this. Elser and Hoch[9] were unable to correlate what they found with *any* obvious gas characteristic; Johnson (16), on the other hand, thinks ΔT is mass-dependent.

Even if this slight trend *could* be construed as real, the enhancement factor is so small (hot end, 1.002; cold end, 1.004) that improvement of tube operation would be absolutely essential if its use is to be feasible. However, correlation of data so far apparently has shown no trends; therefore a long-range program would be necessary for evaluating the variables and/or developing a workable theory.

[9]Reference 5, p 29.

CONCLUSIONS

At present, the status of the Ranque-Hilsch tube from the standpoint of its application to mass separation is as follows:

1. On the basis of the data obtained to date, interpretation does not indicate that such a tube is a good mass separator; furthermore, any separation which may occur would probably result from secondary effects such as centrifugation or from thermal diffusion associated with the hot part of the tube.

2. It is not denied that there may possibly be conditions under which the tube will operate satisfactorily, but so far our arrangements have not been fortuitous. As a matter of fact, we cannot even point to trends.

3. To rule out positively the vortex tube as a mass separator could well involve a long-time program for accumulating sufficient data for an ironclad theory of operation to be formulated. On the other hand, any particular experiment might happen to involve the right combination of variables to effect separation. Our brief program has indicated no readily observable trends and has produced sufficient data to support our belief that separation is not likely. On this basis, further work at present seems to be unwarranted.

Two quotations sum up very nicely our observations. Johnson[10] says: "Samples of air taken from the two ends were analyzed and the results gave no indication of any separation of the air into its components in passing through the heat separator." Corr[11] says: "With such high (centrifugal) fields one would expect centrifuging effects on water vapor, or perhaps the gas molecules themselves. Humidity measurements made on the hot air indicated a slight enrichment of the hot air, but such differences were well within the limit of experimental error and not regarded as significant. Dr. F. J. Norton analyzed some samples of hot and cold air using the mass spectrograph and found no apparent separation of the component gases."

[10]Reference 16, p 301.

[11]Reference 17, p 34.

ACKNOWLEDGMENT

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APPENDIX

Should it be desirable to continue work on the vortex tube, a few experiments which have been suggested during our investigation are listed here for what they may be worth. Certainly other ideas will occur to those reading this report.

1. Measure pressures in front of and behind turn-around when tone of tube changes.

2. Use a porous alundum or porous carbon tube. See if a hot spot still occurs when some of the gas is allowed to seep through the tube. Also get mass analyses of both outer and inner gas.

3. Recycle or cascade the effluent from the hot end and analyze.

4. Explain why the hot spot moves down the tube after startup.

5. Explain how the apparent hot spot occurs *beyond* the barrier in some cases.

6. Find the exact location where the static pressure changes sign (1) along the tube and (2) from wall to axis.

7. Get samples for analysis just beyond turn-around (where centrifugal effect should be great).

8. Try a tube threaded on the inside to control the spiral.

9. Try a copper coil inside a larger tube, with the jet directed so that the gas passes through the coil. Perforate the coil to let molecules escape. Check for hot spot.

10. Make as short a tube as possible which still shows turn-around. Introduce a very small tube into the hot end and extend it beyond the turn-around to determine whether or not air is sucked in; according to pressure measurements, there should be some locations where the air should be drawn in.

11. Put a thin-walled concentric tube which can be rotated at velocities approaching those of the gas inside another tube. Check for hot spot, and if there still is one comparable to that without the inside tube, the viscous-shear theory will be supported and the kinetic-molecular theory disproved.

12. Find out exactly how the "reversal" of the warm spot is related to the tube length.

13. Study further the flow characteristics within the tube by introducing Freon at various points in the tube and testing for it at other points; using fluorescent gases to study flow patterns; using radioactive tracers as a possible aid; using HCl-NH_4OH as a possible aid, that is, placing a piece of cotton soaked in HCl at the hot end of the tube and introducing NH_4OH into the inlet stream; note where NH_4Cl is formed.