[redacted]

DECLASSIFIED

Classification Changed To:
By Authority Of: TID-1101
By: 10/27/56

ORNL-282
ISOTOPE SEPARATION
and Errata

LABORATORY RECORDS

AN EXPERIMENTAL STUDY OF THE HILSCH TUBE AND ITS POSSIBLE APPLICATION TO ISOTOPE SEPARATION

OAK RIDGE NATIONAL LABORATORY

OPERATED BY
CARBIDE AND CARBON CHEMICALS CORPORATION
FOR THE
ATOMIC ENERGY COMMISSION

OAK RIDGE, TENNESSEE

[redacted]

[redacted]

Report Number: ORNL- 282

This document consists of 43 pages.
Copy 7 of 99 Series A

ISSUED ______

Contract No. W-7405-Eng-26

BIOLOGY DIVISION

AN EXPERIMENTAL STUDY OF THE HILSCH TUBE AND ITS POSSIBLE APPLICATION TO ISOTOPE SEPARATION

W. G. Stone and T. A. Love

DATE ISSUED

JAN 4 1950

OAK RIDGE NATIONAL LABORATORY

operated by

Carbide and Carbon Chemicals Corporation
for the
Atomic Energy Commission
Post Office Box P
Oak Ridge, Tennessee

[redacted]

[redacted]

[redacted]

AN EXPERIMENTAL STUDY OF THE HILSCH TUBE AND ITS POSSIBLE APPLICATION TO ISOTOPE SEPARATION

Wallace G. Stone and Temple A. Love

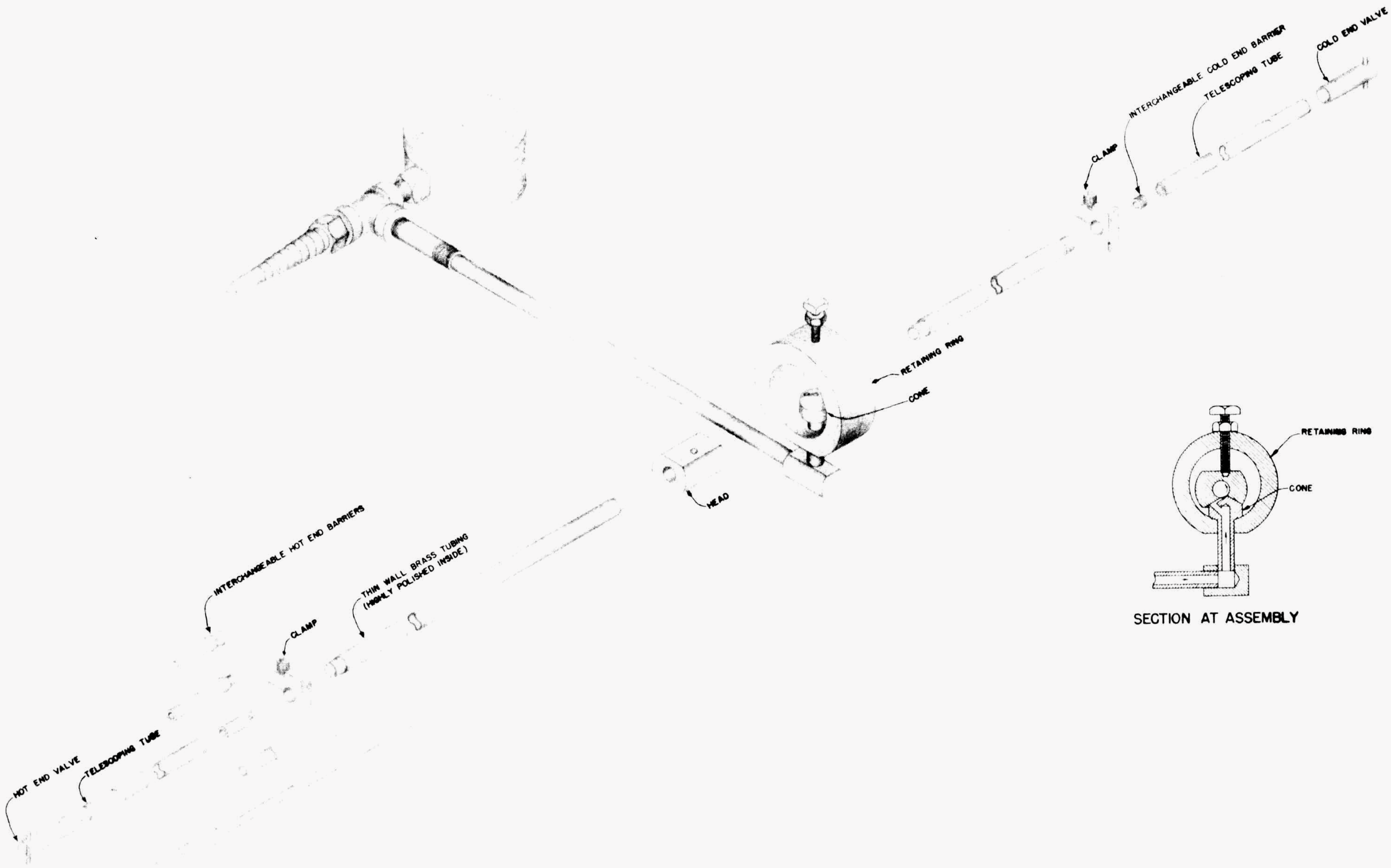
SUMMARY

It has been found experimentally that a separation of the components of a mixed gas can be obtained by the use of a modified Hilsch tube (known variously as the hot-cold tube, the "Wirbelrohre", vortex tube etc.). This separation is a function of two or more effects which interact in such a manner that variations in adjustments determine whether or not separation does occur, and if so, which of the fractions, light or heavy, is concentrated in the hot exit stream. Observations made with many modifications in design are consistent with the belief that the separation is a function of both centrifugal force and of regenerative diffusion of a special kind across a boundary maintained by the centrifugal force.

The separations definitely established at this time are small but there appears reason to believe that these can be greatly increased. All of the models which were tested were designed to determine the principles of operation, primarily by means of temperature measurements since these can be made easily and continuously. The more difficult tests of separation were done to test a tentative theory of the mode of operation which was arrived at as the result of temperature measurements and visual observations. The results of the tests for separation were consistent with the theory. This report, though final, cannot be considered a report of a completed project to investigate the possibilites of separation with this device. The pressure of other work prevents completion at least at this time. It is sincerely hoped by the authors that someone in the future will extend this investigation and that these data will be of some assistance.

[redacted]

Drawing # [illegible]



SECTION AT ASSEMBLY

FIG. I. ADJUSTABLE HOT-COLD TUBE

[redacted]

INTRODUCTION

The authors' interest in the Hilsch tube was aroused primarily by the suggestion by Carl Green at Y-12 that this device must be a separator and by his finding of a "hot spot" between the jet and the hot end barrier on a tube of his own design. It did not appear probable that other duties would allow Mr. Green to explore fully the possibilities which might be inherent in the device. The authors were awaiting the completion of laboratory facilites for other work but had available some facilities for such an investigation. Published theories of the mode of operation of the Hilsch tube were not, in our opinion, consistent with the presence of a "hot spot" and it was difficult to conceive of any mode of operation which would not result in at least some separation of a mixed gas containing components of different molecular weight. The volume of gas handled by a small device of this character is so great that only a relatively small separation factor is necessary for it to become an important tool for isotopic separation. These factors appeared to justify a critical investigation of how the Hilsch tube might really function.

DESCRIPTION OF THE BASIC MODEL

The model with which most of the temperature measurements and all of the separation measurements were made is shown in Fig. 1. This model was designed primarily for flexibility of adjustment and interchangeability of parts. The jet is defined by the space between a slot in the side of a cone, and by the inside face of a conical depression in a head, which fits tightly over the cone (see Fig. 1, section at assembly). As seen in the figure the tip of the cone just enters a transverse cylindrical hole in the head, in such a manner that the jet enters this transverse cylindrical hole tangentially. By making the cone and conical depression in the head have a large angle at their apex the jet will enter this transverse cylindrical hole almost tangentially to the wall surface even when the head is rotated 30 to 40° either way from the position shown in the figure. Each end of the transverse cylindrical hole through the head is enlarged for a distance of about one-half inch to permit the insertion of the end of a thin-walled long brass tube. After assembly of cone, head and tubes, the inside of the assembly was ground and polished to a mirror finish.

Smaller telescoping tubing carrying interchangeable restricting barriers of various kinds were made which were movable to any position along the tube. The outer ends of the larger tubes were split for a short distance and clamps were provided for locking the telescoping tubing in place. The outer ends of the telescoping tubes were plugged and they have a hole in the side near the plug. Sleeves with holes can then serve as simple valves to control the air flow. After some experimentation it was found that such valves are neither necessary nor desirable on the cold end; the annular barrier is now held in position in the larger tube; and the telescoping tube is no longer used on the cold end.

Constantan wires are soft soldered along the brass tube as desired for temperature measurements, the other end of the constantan wires going to a switch in a metal can whose temperature is measured continuously by a mercury thermometer. Copper wires are used to connect the switch and the brass air inlet tube to a galvanometer. Calibrations were done by establishing three points using ice, boiling water and melting solder of known melting point. Accuracies of various measurements are shown on the appropriate figures.

CONDITIONS FOR OBTAINING HEATING-COOLING EFFECT

With this model certain things were noted almost immediately that are not mentioned in any of the limited amount of literature we have found. With the tube completely open at both ends and jet perpendicular to the axis of tube (position shown in Fig. 1, section at assembly), air from the jet divides substantially equally between the two ends and there is no appreciable temperature effect. Obstructing the flow from one end by any means, such as a finger held lightly over the end, causes the temperature to rise in that end while the other end cools.

With both ends open and unobstructed the head may be turned a few degrees from perpendicular and the air from the jet will divide unequally so that more air flows from one end than from the other. In this position, the temperature of the end carrying the smaller volume of air may rise 30 to 35° C., while a simultaneous drop of 10 to 15° C. occurs in the end carrying the larger amount of air. At 10 to 20° of angle from perpendicular a maximum temperature difference is found, and turning the head a few degrees farther in the same direction causes a greater difference in proportion of air flowing from the two ends but a gradual decrease in temperature difference obtained. Additional turning of the head eventually results in a small amount of air from the room being drawn in one end along the axis. Under these conditions there may still be discernible a difference of 4 or 5° C. between the two ends, with the higher temperature being found on the end where air is being drawn in from the room. If now a finger is held tightly over the end from which substantially all of the air has been flowing so that most of the air must flow back and out of the other end, the temperature difference reverses and becomes much greater, so much so, that the finger may become unbearably hot.

These observations indicate that the special shapes of hot-end and cold-end barriers normally used in Hilsch tubes are merely refinements that increase the heating and cooling effect in some secondary manner but are not essential to the general mechanism. The size, shape and position of the annular ring constituting the cold-end barrier is important, however, in obtaining maximum temperature effects. The best position for this barrier is very near the jet (1/64 to 3/64 inch) and the best diameter for the hole in the barrier is dependent upon the type of action desired. This dependence will be discussed later.

The valve on the cold end appears to be unnecessary; the air flow beyond the cold-end barrier should be unrestricted. The control of the flow of the gas from the cold end is best accomplished by varying the diameter of the hole in the barrier; an iris probably being the most desirable barrier for an experimental Hilsch tube.

On the hot end, the tube should be very smooth and clean. The distance from the jet to the hot-end barrier and the total restriction of the flow of gas from the hot end are important variables and their optimum adjustment depends upon the type of operation desired. Proper adjustment for obtaining lowest temperature at the cold end consists of placing the hot-end barrier far from the jet, opening completely the hot-end valve, and leaving a small opening in the cold-end barrier. To obtain highest temperature at the hot end, the hot-end barrier is moved toward the jet, the hot end-valve partially closed, and a larger opening left in the cold-end barrier. On the other hand, maximum temperature differences are obtained by moving the hot-end barrier far from jet, closing the hot-end valve almost completely, and using a cold-end barrier of intermediate size. This adjustment produces an intensely hot spot on the tube

[redacted]

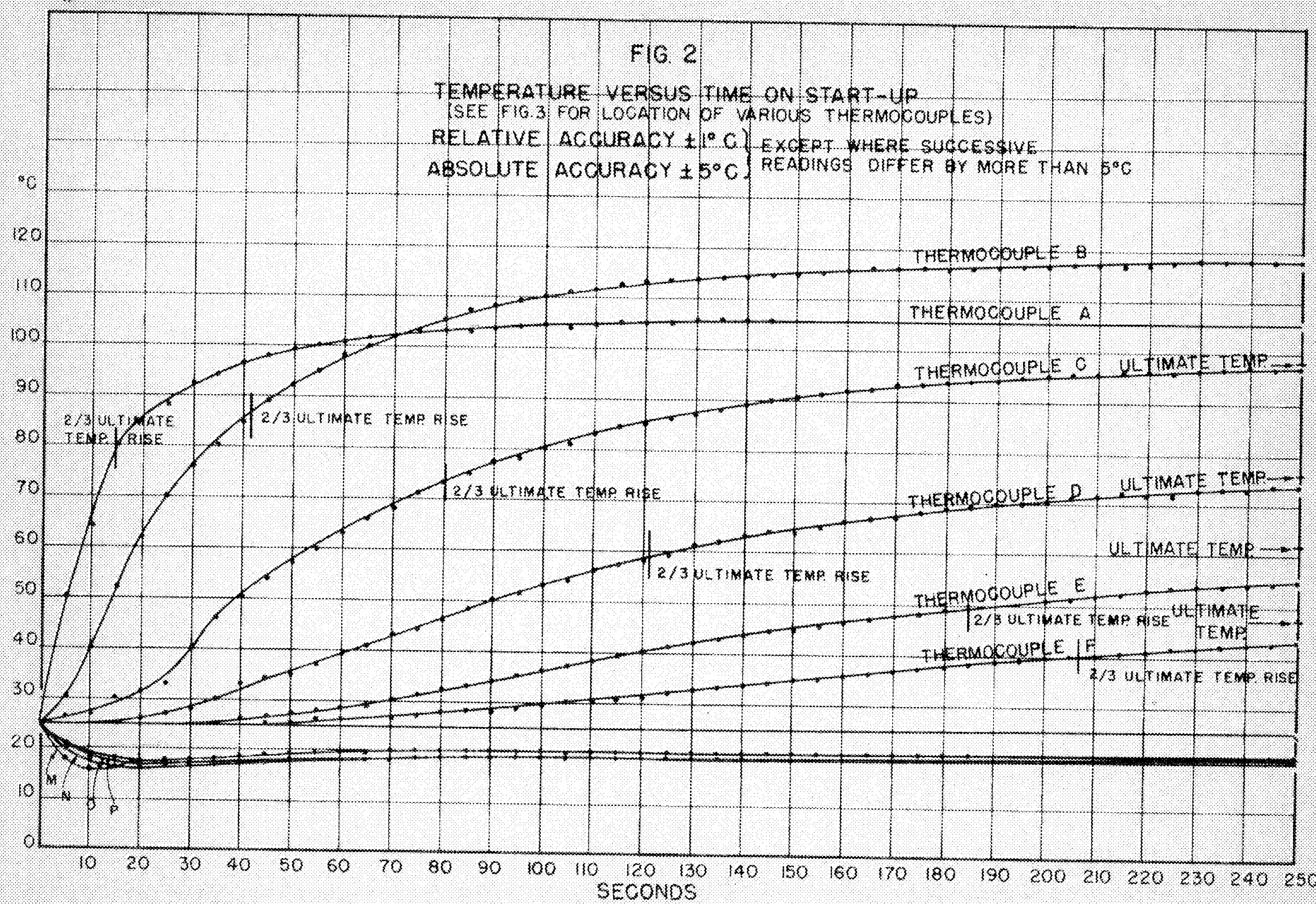


FIG. 2

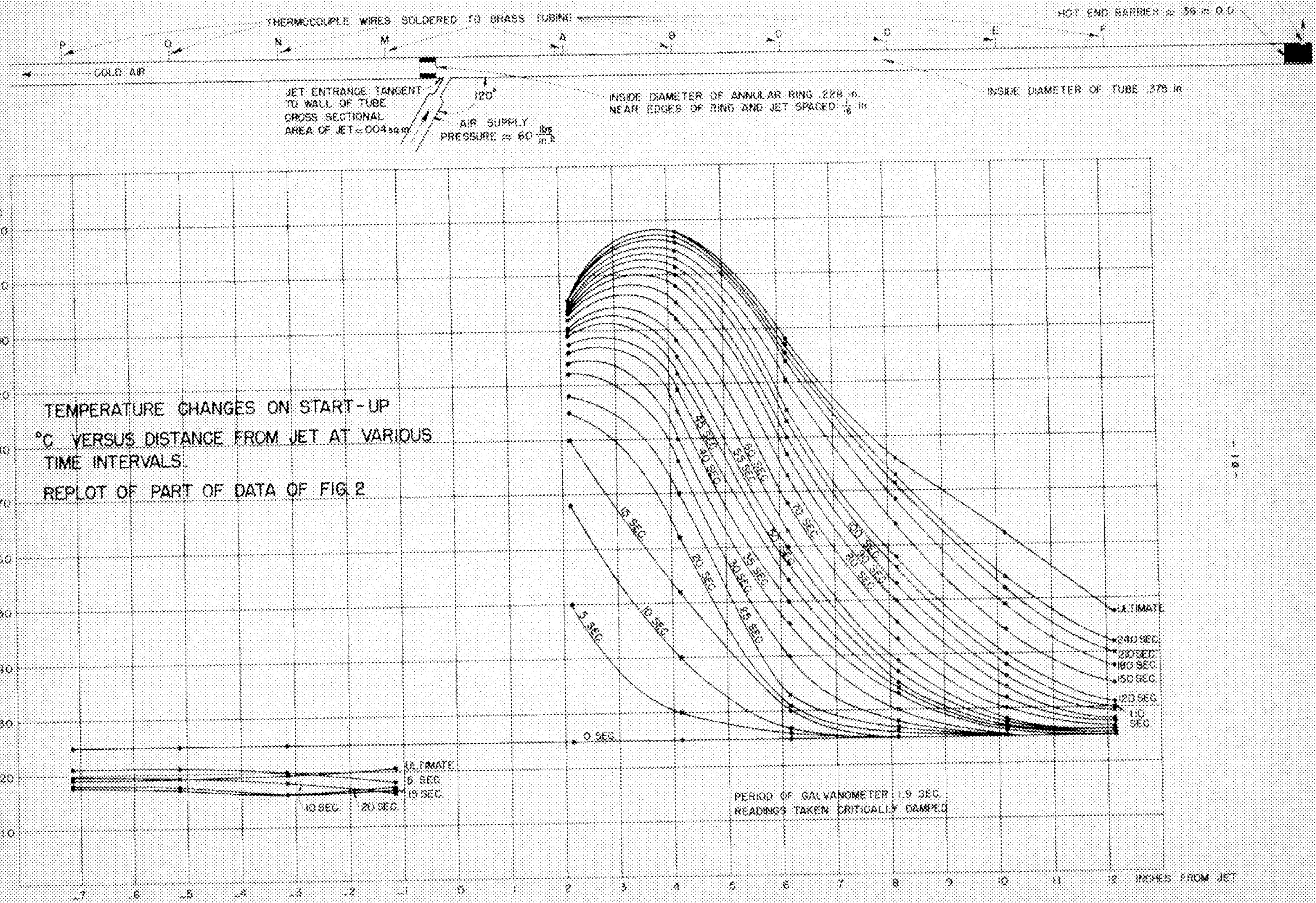
TEMPERATURE VERSUS TIME ON START-UP
(SEE FIG.3 FOR LOCATION OF VARIOUS THERMOCOUPLES)

RELATIVE ACCURACY ±1° C } EXCEPT WHERE SUCCESSIVE
ABSOLUTE ACCURACY ±5°C } READINGS DIFFER BY MORE THAN 5°C

Drawing # 7223

[redacted]

FIG. 3



THERMOCOUPLE WIRES SOLDERED TO BRASS TUBING
HOT AIR BLEED HOLE ≈ .003 sq in
HOT END BARRIER ≈ .36 in O.D.
P
Q
N
M
A
B
C
D
E
F
COLD AIR
JET ENTRANCE TANGENT TO WALL OF TUBE
CROSS SECTIONAL AREA OF JET ≈ .004 sq in
120°
AIR SUPPLY PRESSURE ≈ 60 lbs/in.²
INSIDE DIAMETER OF ANNULAR RING .228 in.
NEAR EDGES OF RING AND JET SPACED 1/8 in
INSIDE DIAMETER OF TUBE .375 in
TEMPERATURE CHANGES ON START-UP
°C VERSUS DISTANCE FROM JET AT VARIOUS TIME INTERVALS.
REPLOT OF PART OF DATA OF FIG. 2
°C
120
110
100
90
80
70
60
50
40
30
20
10
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
INCHES FROM JET
ULTIMATE
240 SEC.
210 SEC.
180 SEC.
150 SEC.
120 SEC.
110 SEC.
0 SEC.
5 SEC.
10 SEC.
15 SEC.
20 SEC.
25 SEC.
30 SEC.
35 SEC.
40 SEC.
45 SEC.
55 SEC.
60 SEC.
70 SEC.
PERIOD OF GALVANOMETER 1.9 SEC.
READINGS TAKEN CRITICALLY DAMPED

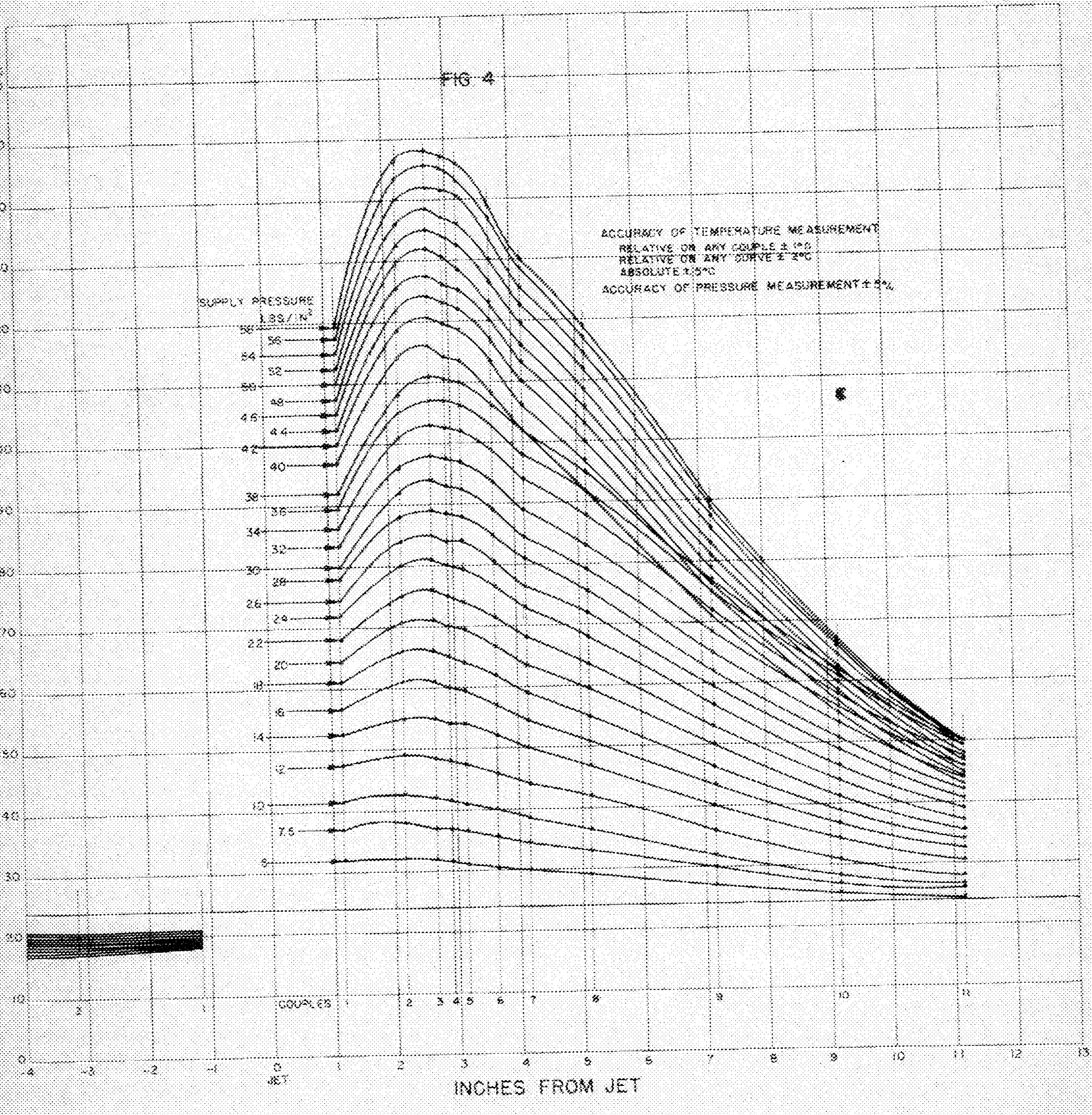
a few inches from the jet in the direction of the hot end barrier.

Measurements and Analyses of Temperature Distributions.--It was noted that thermocouples near the jet rose in temperatures much faster on start-up than those farther out, therefore, data were taken at start-up on all couples then on the tube. The results are plotted graphically in two different ways in Figs. 2 and 3, several features of which are worth careful attention. In Fig. 2 note the following: (1) Hot couple A rises very rapidly from start-up and is up two-thirds of its ultimate value in 15 seconds. (2) Couple B rises less rapidly than A; the curve of temperature versus time has a slightly sigmoid shape, reaches two-thirds of its ultimate value in 42 seconds and passes A at 75 seconds. (3) Couple C takes 81 seconds to reach two-thirds of its ultimate value and the plot of temperature versus time is definitely sigmoid. (4) Couples D, E and F take 121, 185 and 207 seconds to reach two-thirds of equilibrium. (5) All cold couples drop quickly below ultimate value and rise gradually.

In Fig. 3 it is shown that the hottest spot is initially close to the jet and moves gradually away so that it is about 3 inches from the jet in 1 minute and ultimately reaches about 3½ inches. Note also that the curve marked "ultimate" reverses curvature more than once beyond the hot spot. This appears to be characteristic of the device although the exact shape varies considerably with adjustments.

To determine the variation of temperature with air supply pressure, the data shown in Fig. 4 were taken. At each setting of pressure the temperatures were permitted to come to equilibrium before readings were taken. The data for the curves were taken in sequence starting at the highest pressure and going down. All conditions other than supply pressure were held constant from 58 to 40 p.s.i. and from 38 to 5 p.s.i. In changing from 40 to

[redacted]



[redacted]

38 p.s.i. it was necessary to open the hot-end valve slightly to keep the device working. This calls attention to a peculiarity of this Hilsch tube which may be advantageously explained at this point.

At the time this test was made there was a minimum opening of the hot-end valve for any inlet pressure at which the device would work at all. With any opening less than this critical value, an acoustic resonance was excited and the temperature effects would almost completely vanish. A "load" appeared to be necessary to reduce the "Q" of the acoustic system to a low value. Subsequent to this test the jet orifice was enlarged, smoothed and polished and the angle of entrance improved until it can now be operated with the hot-end valve completely closed. This adjustment gives a very high temperature at a place on the tube about $3\frac{1}{2}$ inches from the jet, with a steep slope of temperature on either side of this "hot spot". The temperature of the air leaving the cold end is then just about ambient temperature. With 90 p.s.i. air supply pressure, temperatures in excess of 200° C. at this "hot spot" have been obtained in this way.

Using a small probe thermocouple the radial temperature gradients in the neighborhood of the jet have been investigated. With an adjustment giving a temperature of 0° C. in the cold air stream the following facts may be noted: (1) on the axis at the jet, the temperature is a little below supply air temperature; (2) approaching the jet stream radially at a point very near the jet, the temperature drops rapidly, reaching perhaps -40° C. at a point just at the inner edge of the jet stream and rising very abruptly to about air inlet temperature within the jet stream; (3) starting from the axis and going out radially in a direction away from the jet, the lowest temperature found is about 0° C.

On the axis the temperature rises gradually as the probe is moved from a point nearest the jet toward the hot end. It was not possible to move the probe as far as the hot spot because of the large radial forces in the tube but it was possible to push it in on the axis far enough to find temperatures 30 to 40° C. higher than supply-air temperature. Within the orifice of the cold-end barrier the temperature varies a maximum of about 20° C. and outside the barrier the temperature inhomogeneity decreases rapidly, presumably due to mixing. All tests, including probe measurements, indicate that the action outside the cold-end barrier is merely one of mixing.

To check the importance of the heat loss to the metal tube several kinds of tests were made. In one test the high pressure supply air was preheated a few degrees above ambient temperature. This raised the temperatures on all thermocouples about the same number of degrees above their normal operating temperature. In another test the tube was covered with thermal insulation and operated with air at normal supply temperature. This resulted in all temperatures measured on the thermocouples being raised by 5 to 10° C. In a third test the hot end of the tube was cooled by running water. This lowered the temperature of the air leaving both the hot end and the cold end by 10 to 20° C. Inasmuch as valve adjustments easily produce temperature changes much greater than 10 to 20° C. it appears that heat losses to the metal tube play an appreciable but not an important role in the operation of the Hilsch tube.

Visual Observations of Flow Patterns.--By removing the cold end tube and leaving the hot end tube open it is possible to see that the jet produces a thin dense layer of gas around the periphery that extends a long way down the tube. It is possible to see this by looking down the tube from the cold end toward a distant source of light. Refraction differences inside and outside

[redacted]

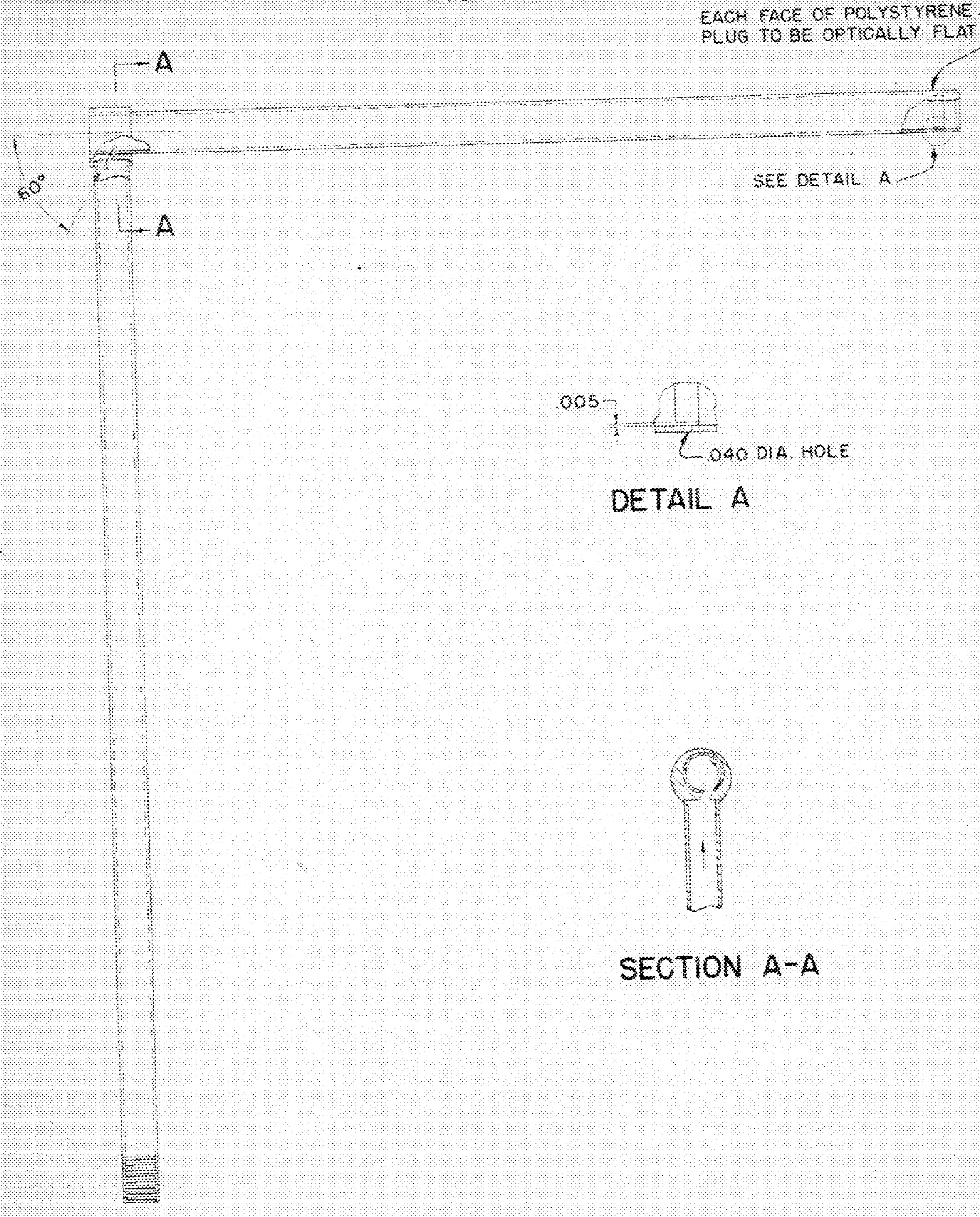


FIG.5 SIMPLE JET FOR OPTICAL STUDY

[redacted]

of the layer boundary and low angle reflection from the boundary are easily seen. Under these conditions there is very little heating effect and no hot spot. In order to determine whether this dense layer extends beyond, or is greatly modified at the hot spot, the tube shown in Fig. 5 was constructed with a transparent plug in the hot end. With 90 p.s.i. supply pressure this model has a hot spot about 3 inches from the jet, the temperature of the tube tapering off from there to the transparent plug. By looking down the tube from the cold end toward a light, 40 or more feet away, a sharply defined dense annular layer of gas can be seen to extend well beyond the hot spot with no obvious change at the hot spot. The radial thickness of this dense annular layer is about 1/32 inch, which is one sixth of the radius, and it can be seen to continue most of the way to the transparent plug.

To obtain some information in regard to direction of flow in this dense annular layer, a Hilsch tube of glass was constructed and tiny drops of heavy, colored oil were placed on the inside. The tracks of these tiny drops indicate that the gas spirals down the tube in a spiral whose pitch increases slowly from the jet to near the hot-end barrier. No unique characteristic of this flow can be discerned at the hot spot. A purely qualitative observation of the rate of flow of the tiny oil drops indicates a continually decreasing velocity of the gas from the jet to the hot-end barrier.

To definitely establish the existence of a single sharply defined hot spot and eliminate any questions as to multiple hot regions with an apparent hottest spot in between two such regions, a Hilsch tube was made of polystyrene. This plastic has low thermal conductivity and, when hit with a blast of hot air, visible surface checks appear which vanish as the surface reaches softening temperature. About 30 seconds after turning on the air to the jet a sharply defined ring of checks extending all the way around the tube appeared at the

[redacted]

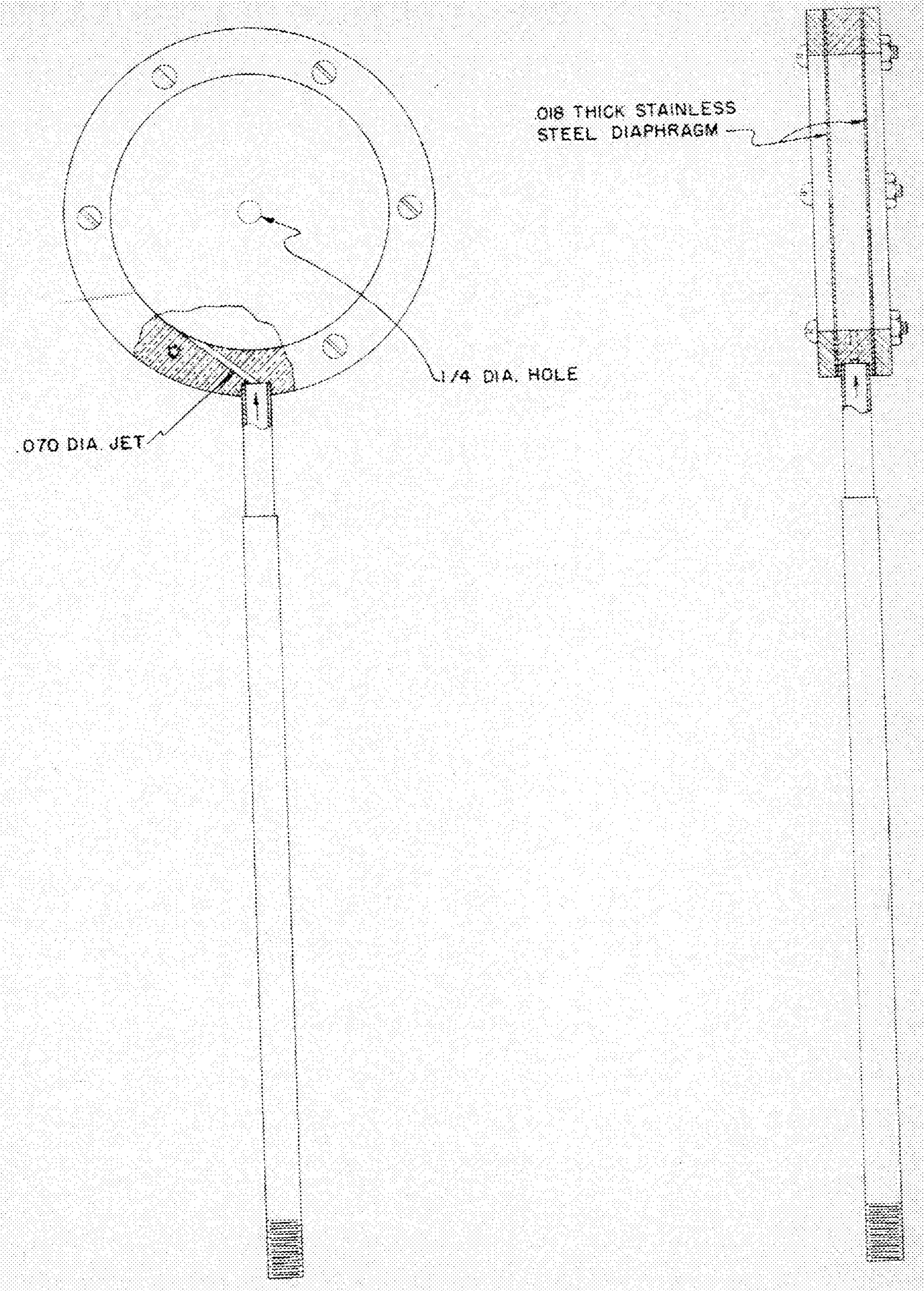


FIG. 6. FLAT SPIRAL JET

[redacted]

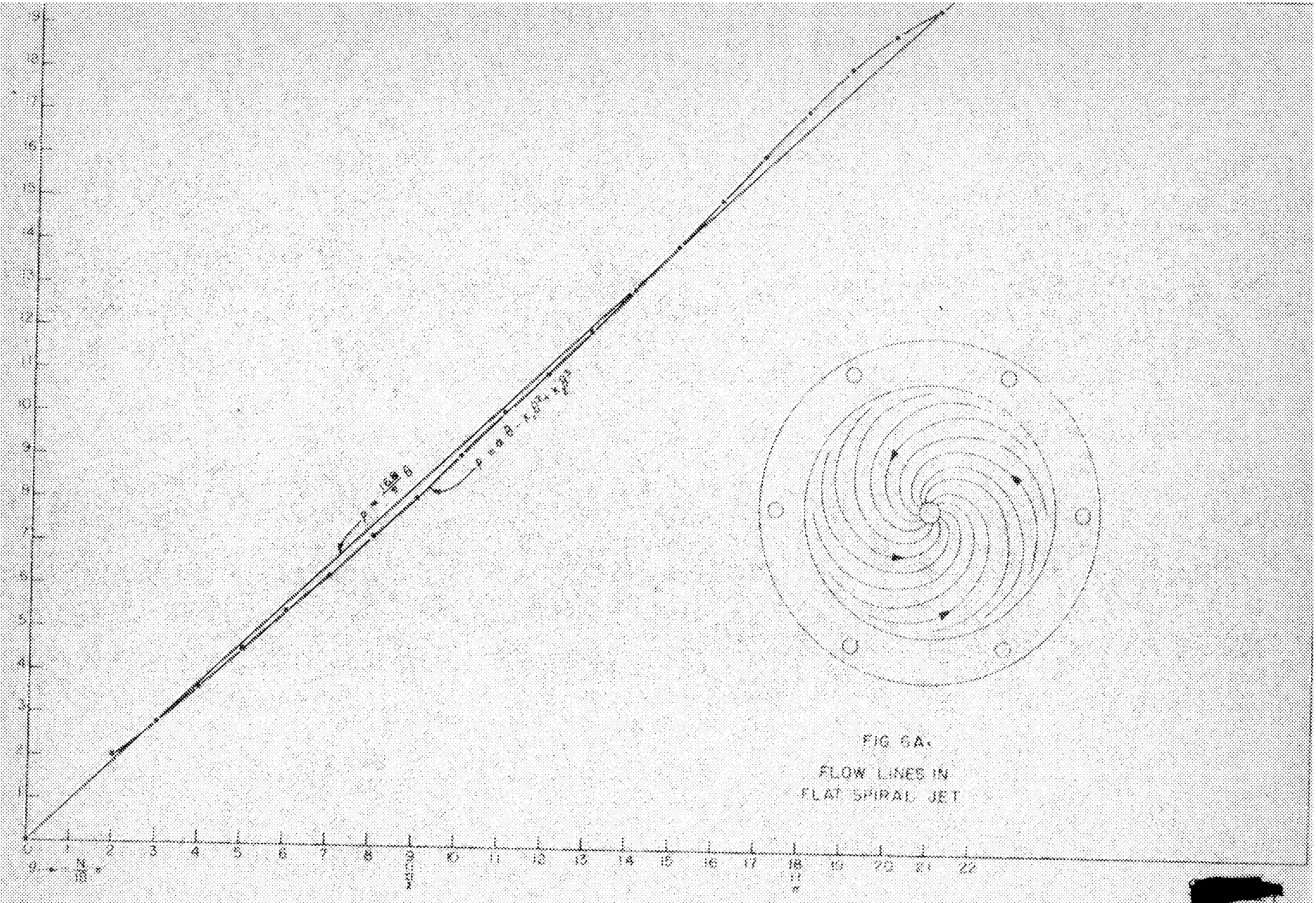


FIG 6A.

FLOW LINES IN
FLAT SPIRAL JET

[redacted]

anticipated hot spot, the checks spread in both directions along the tube and about 45 seconds from the start a ring of smooth check-free area appeared just about 1/8 inch farther out from the jet than the initial checks. This softened region spread rapidly and then the polystyrene tube slowly expanded into a bubble-like swelling before the authors lost their nerve and turned off the air.

The model shown in Fig. 6 was built to study the flow pattern of air spiraling inward and to determine whether this mechanism by itself produced a radial temperature gradient in accordance with the heating mechanism proposed by Hilsch (6) and further analyzed by von Gerd Burkhardt (13). No radial heating or cooling effects of appreciable magnitude can be observed on this model. By using a thin film of stopcock grease on the inside of the diaphragms, flow lines were made visible and clear enough to be carefully measured. These flow lines seem to result from the stripping of grease from the stainless steel somewhat similar to the effect of a snowball rolling down a snow-covered roof.

The general form of the flow lines is shown in Fig. 6A although they did not occur in any regular pattern as shown. All the grease was stripped from the extreme outer edge but, just inside this edge, the streaks were narrow, going in spirally as shown. One of the clearest and sharpest of these streaks was carefully measured and is plotted in Fig. 6A as ρ versus θ. Note that the curve departs very little, though probably significantly, from an Archimedes spiral defined by the equation

$$\rho = \frac{16.8}{\pi} \theta .$$

A somewhat closer fit might be obtained by an equation of the form

$$\rho = a\theta - k_1 \theta^2 + k_2 \theta^3 .$$

[redacted]

Drawing # 7224

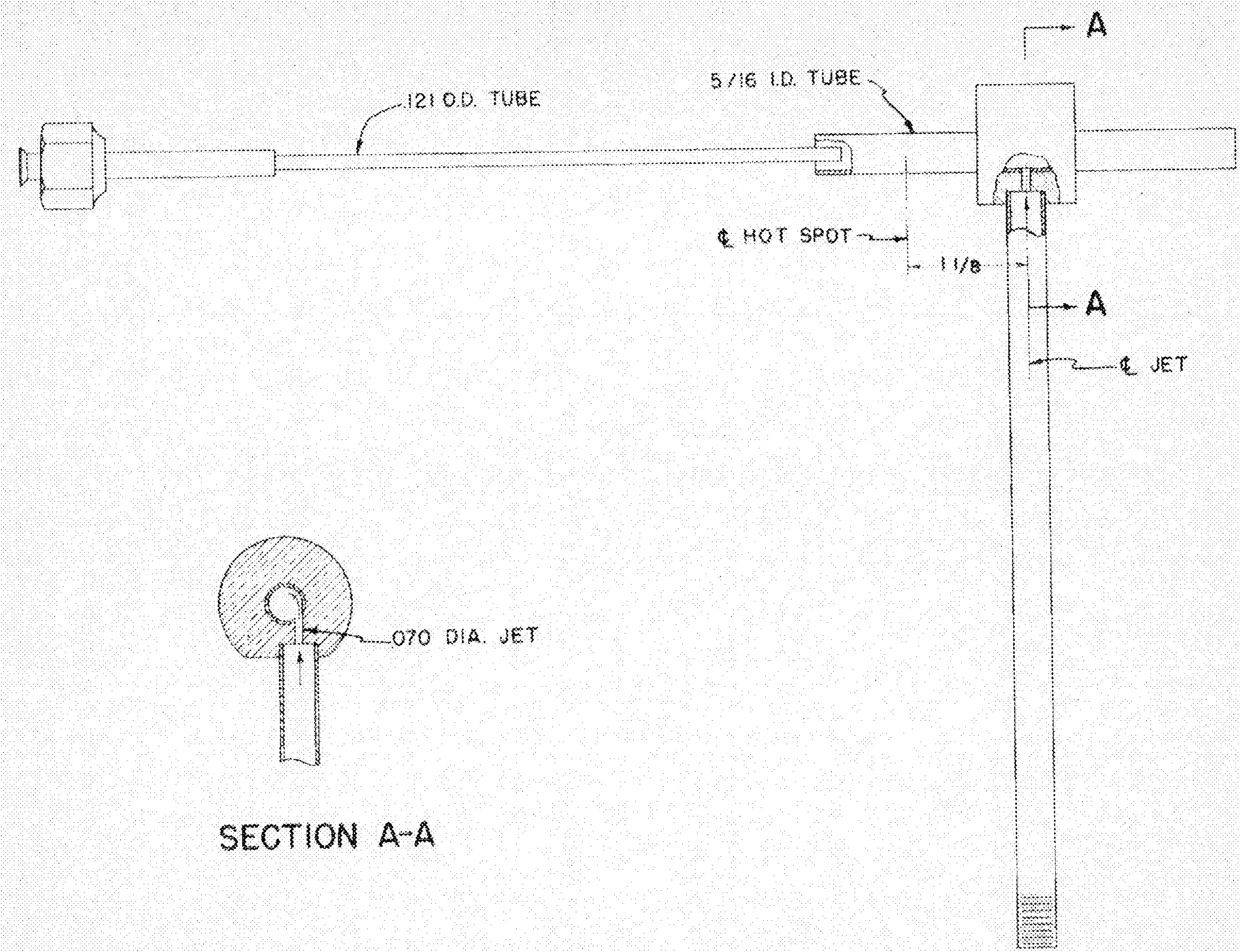


FIG. 7. DEMONSTRATION OF COUNTER FLOW PRINCIPLE

[redacted]

The static pressure at the periphery with 90 p.s.i.* inlet pressure is 38 p.s.i. The density at the periphery is therefore more than three times atmospheric density, perhaps much more than three times atmospheric density, because the Bernoulli effect at such velocities as exist here reduces the static pressure by a considerable amount.

Theory of the "Hot Spot".--Analyzing all models described and many others, the authors reached the conclusion that a "hot spot" always occurs where a dense outer layer of gas progresses spirally one way down a tube while an inner core of gas moves back the other way, and that a "hot spot" never occurs unless these conditions are met. The counter flow can be produced by the angle of the jet inlet, by baffles of various kinds, by valve adjustments or by tapering the bore of the tube, with results which are the same qualitatively, though they may differ in temperature produced and in distance from the jet to the "hot spot". To check as directly as possible the theory that the counter flow is the essential requirement, the mechanism shown in Fig. 7 was constructed. This jet is symmetrical and the tubes are quite short as shown so that the air from the jet divides about equally and goes out either end with only two or three complete turns of the spiral from jet to open end. The air leaves the open ends tangentially with high velocity forming an almost complete sheet of radially moving air. By centering carefully, the small tube shown can be inserted a short distance into one end without perceptibly altering the air flow. No appreciable heating or cooling effect can be found until air from a low pressure source (4 to 5 p.s.i.) is blown in through the small tube. This low pressure air does not greatly modify the flow of air from either end but a "hot spot" (15 to 20° C. above ambient) appears at the point indicated and the air leaving the opposite end drops in temperature, especially on the axis of the tube.

* All pressures are expressed as pounds per square inch above atmospheric pressure.

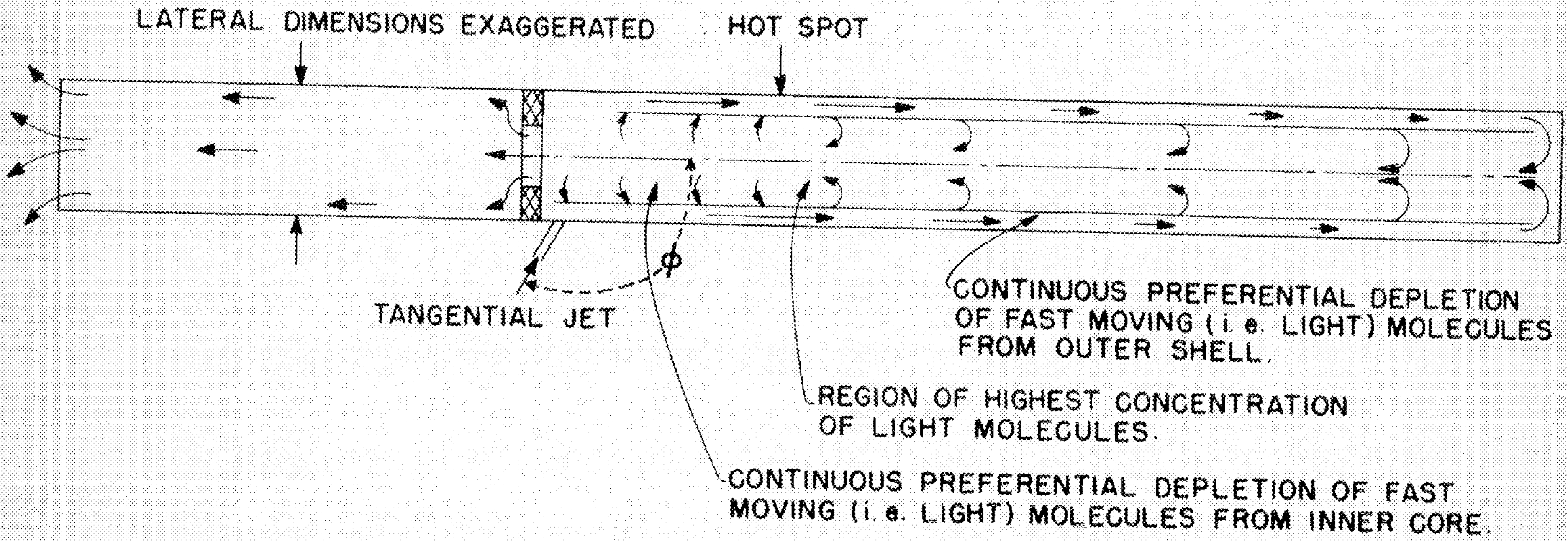
[redacted]

FIG. 8

Drawing # 7286

SUGGESTED GAS FLOW DIAGRAM IN HILSCH TUBE WHEN HOT END IS ENTIRELY CLOSED

ROTATORY MOTION NOT SHOWN IN DIAGRAM



[redacted]

As was observed optically in the mechanism shown in Fig. 5 there is a sharp boundary between the rapidly moving outer layer of gas and the inner core. The outer layer is the jet stream, which in a visible sense maintains its integrity as a spiraling stream most of the way from the jet to the hot end. Near the jet the familiar Bernoulli Effect produces a low pressure on the the side of the stream which results in air from the core being drawn into the stream. Referring to Fig. 8 it is obvious that at some distance from the jet sufficient air from the core must be incorporated into the stream to raise the effective radially-inward pressure on the inner face of the stream to equal the effective radially-outward pressure of the core. It is obvious that this incorporation of gas from the core may modify the jet stream as to direction, velocity, density, temperature and composition, depending upon the gas in the core and its velocity, direction, density, temperature and composition. Less obvious is the fact that the counterflowing core may be modified by this action as much as, or more than, the jet stream. To explain the measurable temperature gradients in the core one is logically forced to consider a temperature-selective action of some kind by which hot molecules* are preferentially removed from the core and incorporated into the jet stream. Ordinary diffusion in which rapidly moving molecules transfer across any boundary more rapidly than slow moving molecules, simply by virtue of their higher velocity, would give an effect of the right sign but, as will appear later, this effect is too small by about an order of magnitude unless some special kind of action is in operation.

Beyond the region where the effective pressure of the jet stream and core are equal, the jet stream continues to flow as a definite stream with a visible sharp boundary. The density of the jet stream is still visibly greater than the core. Any action which slows the stream down, such as friction, conversion

* The term "hot molecule" is used in this report to designate any molecule having an instantaneous velocity with respect to other molecules in its vicinity appreciably greater than the root mean square velocity of these molecules.

of velocity head to pressure head, etc., raises the effective pressure of the jet stream above that of the core so that flow takes place from stream to core. Here again the temperature evidence indicates that the molecules leaving the jet stream carry more than their proportionate share of thermal energy. Here also ordinary diffusion would produce an effect of the right sign but of insufficient magnitude.

Referring again to Fig. 8, 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. The relatively long time constant on start-up as seen in Figs. 2 and 3 is indicative of a regenerative effect by which the average temperature of the "hot spot" builds up to such a point that the thermal energy of the gas finally leaving the device is consistent with the energy of the inlet gas despite the fact that both the jet stream and the core are selectively depleted of hot molecules as they flow away from the "hot spot" and toward an exit.

One of the most interesting and significant things about the "hot spot" is that the distance between it and the jet is almost independent of (1) angle of entrance of the jet, (2) supply pressure of the gas, (3) the distance of barriers from the jet and (4) the valve adjustment (as long as 10% or less of the air leaves the hot end). On start-up, however, the "hot spot" is very close to the jet and takes about 40 seconds to move out two-thirds of the way to its ultimate position. With valve adjustments which allow more than 10% of the air to leave at the hot end, the "hot spot" broadens greatly and moves farther from the jet. With about 30% of the air allowed to leave at the hot end the "hot spot" is no longer a spot but, as seen in Fig. 10, the temperature rises from inlet temperature according to an equation of the form

$$T = a(1-e^{-bd}) - c$$

where T = ^{o}C. above inlet temperature

d = distance from jet toward hot end

a, b and c are constants.

In contrast to the relative independence of the position of the "hot spot", its temperature rise above inlet gas temperature is dependent upon many things. If all conditions other than supply pressure are held constant

$$T_{h.s.} = k\ P_i$$

where $T_{h.s.}$ = ^{o}C. of "hot spot" above temperature of supply gas

P_i = supply pressure of gas

k = a constant .

When adjustments are varied it is found that k is a function of the angle of the jet, having a maximum when Ø is between 100 and 120^{o} (see Fig. 8), the exact angle for maximum varies between these limits as other adjustments are varied. k is also a function of the ratio of the quantity of gas entering through the jet to the quantity of gas flowing from the cold end, being a maximum when this ratio is 1. k is likewise a function of the positions of the barriers and the size of the opening in the cold-end barrier.

To recapitulate: the evidence clearly shows that in a tube such as shown diagramatically in Fig. 8, the stream from the jet spirals down the inside of the tube, rising rapidly in temperature for a short distance and then dropping almost as rapidly as it continues on down the tube. As it approaches the closed end the stream becomes slower and finally looses its visible boundary. The gas from the stream is turned back in some manner and flows back along the axis of the tube inside the spiraling stream. As the gas flows back its temperature rises by some amount not accurately measured and then falls until it passes the jet, finally leaving the tube at about the same temperature as that of the supply gas.

It is deduced that the rapid rise in temperature of the jet stream is due to incorporation of gas from the counter-flowing core stream by some, as yet unspecified, mechanism which preferentially selects molecules having an average velocity that is more than r.m.s. velocity. It is further deduced that the subsequent drop in temperature of the jet stream is due to the flow of molecules from the jet stream toward the axis and that the same or some similar mechanism preferentially selects molecules having more than r.m.s. velocity for this flow.

No alternative explanation has been found for the observed facts in a Hilsch tube of this kind where the hot end is completely plugged, and all the gas is forced to leave by the cold end. In view of the very high temperature obtainable at the "hot spot" in this model, it seems to be logical to assume that the basic mechanism necessary to explain the action in this model is responsible for the heating and cooling effects obtainable in various other models.

PROPOSED THEORY OF THE HEATING-COOLING ACTION

At some of the gas supply pressures which have been used, the veolcity at the jet must be approximately equal to sonic velocities*. With air as the gas this amounts to about 330 m/sec. With the jet coming in at an angle

* About 30 p.s.i. drop at an orifice is necessary to accelerate air to sonic velocity. This may require as much as 45 p.s.i. at the gauge because there is some friction between the gauge and jet and there is some back pressure at the outlet end of the jet.

of 120°* with respect to the axis on the hot end, the jet stream travels about 18 cm. going from the jet to the "hot spot". At 330 m/sec. this would require only .55 milliseconds. The axial component of this velocity cannot decrease by any large factor before it reaches the "hot spot" because it was observed that the cross section of the jet stream perpendicular to the axis does not greatly change from jet to "hot spot". Even with considerable slowing up in this distance it probably requires less than 1 millisecond for the air to travel from the jet to the hot spot. In this interval of time the jet stream rises in temperature something like 100° C. This rise in temperature requires between 17 and 24 calories per gram. This is too large to be a friction effect even if the over-all operation of the device admitted this interpretation of the heating. The only explanation of this rise in temperature that is consistent with the observations is the incorporation of hot gas from the core. The gas from the core must be selected by a mechanism giving preference to the hot molecules because that gas in the core which runs the gantlet from "hot spot" to jet without being captured emerges with a temperature equal to or lower than the inlet gas temperature.

If the heating is due to incorporation of hot gas the temperature changes must proceed according to the equation**

$$\frac{m_1}{m_2} = \frac{t_2 - t_3}{t_3 - t_1}$$

* The angle of the jet does not control the pitch of the spiral as much as the size of the jet orifice controls it. This angle of 120° is just about the angle of the natural pitch for this particular Hilsch tube.

** This equation assumes negligible difference in composition of jet stream and core stream.

where m_1 = mass of gas entering tube from jet

m_2 = mass of gas transferred from core to jet stream

t_1 = inlet temperature of m_1 $^\circ K$

t_2 = average temperature of m_2 $^\circ K$

t_3 = final temperature $^\circ K$

It is obvious from this equation that either $t_2 - t_3$ must be equal to or greater than $t_3 - t_1$ or m_2 must be greater than m_1. In the case just given where the rise is 100° C. the average temperature of the gas removed from the core must be at least 220° C.* unless m_2 is greater than m_1. With an inlet pressure of 100 p.s.i. this becomes even more striking, requiring average temperatures of the entrained gas from the core stream approaching 400° C. or an entrained gas mass greater than the mass of gas from the jet. It was difficult to reconcile the possibility of m_2 being greater than m_1 with the observation that the jet stream, as seen in the mechanism shown in Fig. 5, was not obviously thicker radially at the hot spot than it was near the jet.

The axial velocity of the core stream must be at least one-third the axial velocity of the jet stream, in the case where the hot-end valve is completely closed and all the gas is forced to flow back and out of the cold end, because the cross-sectional area of the core stream perpendicular to the axis is only about three times that of the jet stream. The density of the jet stream is visibly greater than that of the core stream so the axial velocity of the core stream must be more than one-third the axial velocity of the jet stream. This means that the selection mechanism must remove the hot molecules from the core stream in less than 5 milliseconds, perhaps in less than 1½ milliseconds. Ordinary diffusive processes are too slow to transfer the thermal

* Assuming an inlet temperature of 20° C.

energy from the axis to the boundary layer in this length of time unless the temperature at the boundary is assumed to be much lower than measured. Three possibilities present themselves here: (1) Turbulence operates to keep a uniform thermal distribution from axis to boundary layer, selection of the hot molecules occurring at the boundary layer. (2) A selection mechanism or a boundary condition (or both) exists under these conditions, which makes possible the transporting of thermal energy radially outward several times as fast as in ordinary diffusion. (3) Some combination of turbulence and selection or boundary condition accomplishes the transfer.

The first possibility is eliminated by the probe measurements which show a temperature gradient from axis to boundary layer. No data taken by the authors permit a definite choice between (2) and (3). The essential clue to the only mechanism which appears to be capable of producing the effect observed is the time element. In less than .003 seconds the average temperature of the gas in the core drops by about 100° C., the greatest drop in temperature occurring at the periphery. The speed with which this drop occurs is essentially "explosive" and the action must be comparable to an "explosion". Let us assume that one has a cylindrical vessel filled with gas at some pressure P and temperature T suspended in a vacuum and revolving rapidly on its axis. Now let us assume that one is able to completely remove the confining cylindrical wall for a very short interval of time τ, and then restore the confining wall and measure the instantaneous temperature distribution in the gas which has not escaped. The rapidly moving molecules near the cylindrical wall have a larger chance of escaping in this short time than do the rapidly moving ones at the center or the slower moving molecules. These rapidly moving molecules will carry more than their proportionate share of energy and thus the temperature of the remaining gas will be lowered.

A good mathematical treatment of this is beyond the scope of this paper but approximate calculations indicate that τ should be small as compared to a millisecond to get an average temperature drop such as is obtained in the Hilsch tube and the general pattern of temperature distribution would be somewhat as observed; i.e., a much larger drop in temperature at the periphery than at the axis. The fact that τ is smaller than a millisecond may be interpreted as indicating that not every molecule reaching the boundary of the core enters and is incorporated into the jet stream, i.e., the effective pressure at the boundary is not zero.

This "limited explosion" process provides a possible explanation of the action occurring between the jet and the "hot spot". Except for the complications resulting from the rotation of the gas in the core, this becomes a diffusion problem with the external boundary conditions determined by the velocity and effective inward pressure of the jet stream rather than by the composition and temperature of the gas within the jet stream. Beyond the hot spot the action must be similar except that the action is an "implosion", the back pressure at the boundary is much greater and centrifugal force tends to counteract the inward pressure of the jet stream and make quite specific requirements as to direction and magnitude of thermal velocities of the molecules which are able to go inward toward the axis.

Proposed Theory of Mass Separation.--In calculating the heating effects between the jet and the "hot spot" a reasonable approximation of the action in the core might consist of assuming no collisions within the core during the period τ in which the peripheral boundary is assumed to be removed. This is comparable to, although not as well justified as, the same assumption made in the simple derivation of the ideal gas law. In any calculation of the separation of molecules as a function of mass, the assumption of no collisions may not be a reasonable approximation. At the end of the period τ in the hypothetical revolving cylinder illustration, the change in density ratios of two gases would be a function of their relative mobilities, the speed of revolution of the cylinder and the length of time τ during which the boundary is totally removed*. The separation obtained in this way must be reduced by the centrifuge effect which tends to increase the concentration of the light molecules on the axis prior to the start of the period τ.

Without going into the details of the mechanism of separation, certain predictions can be made in regard to what should happen to a mixed gas if the proposed theory has any validity.

(1) Faster moving (i.e., light and hot) molecules will tend to become a greater proportion of the population at the "hot spot" than elsewhere because both streams tend to gather these faster moving molecules as they approach the "hot spot" and lose them as they leave.

(2) Centrifugal force will tend to concentrate heavy molecules on the outside of the whirling mass.

(3) At the cold-end exit the separation may be zero or may proceed either way, depending upon competing effects. This results from the fact that the gas flowing back toward the jet from the hot spot comes from a population high in light molecules and then undergoes preferential depletion of light molecules by "explosive" diffusion until it passes the jet and the cold-end barrier.

* This might be treated as a kind of diffusion problem in which the concentration of both gases at the boundary is zero during the period τ. The initial rotation of the gas which may give the gas a linear velocity at the periphery appreciable compared to the average thermal velocity, and the rapid acceleration of the medium through which the diffusion must occur, makes a complete mathematical treatment very difficult. There aren't enough data available to know what approximations are justified. A very rough treatment seems to indicate, however, that the period τ, necessary to produce such separations as have been obtained, is less than .003 seconds.

(4) At the hot end the change in concentration of the components must be of opposite sign to the change in concentration at the cold end and must balance the cold end quantitatively taking into consideration the ratio of the quantities of gas leaving the two ends.

(5) The greater the distance between the hot-end barrier and the hot spot (within some undertermined limits), the greater the separation effect should be, other conditions being the same.

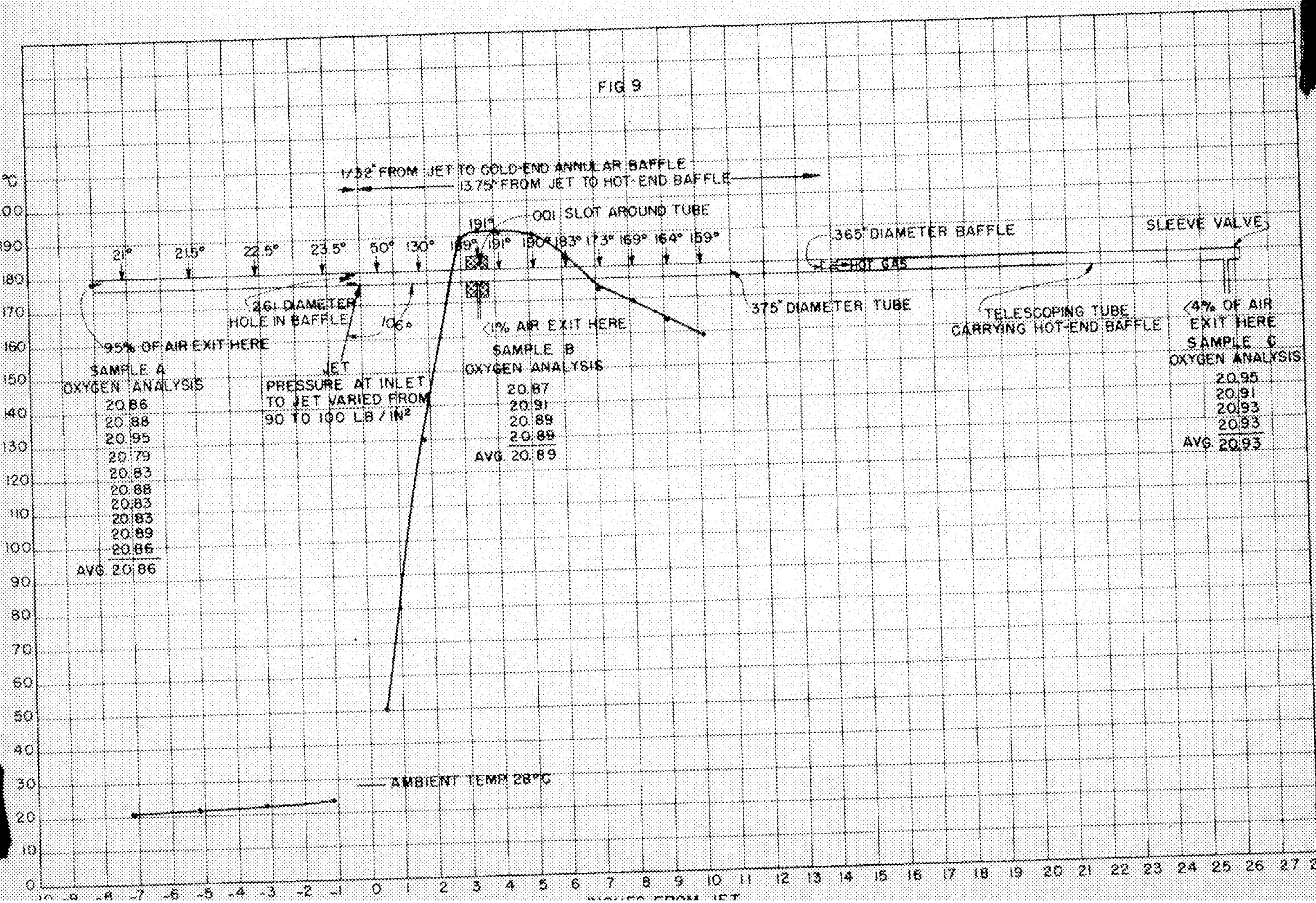
EXPERIMENTS ON MASS SEPARATION

The first tests for concentration were done before it was suspected that there might be competing effects such that either the light fraction or heavy fraction might be concentrated in the hot end. Unfortunately the significant data as to angle of jet, temperature curves, etc. were not kept as their importance was not realized at that time. Samples of the air from the compressed air line were taken at the hot end and control samples at the inlet simultaneously. These were analyzed for carbon dioxide by Dr. D. S. Anthony. The controls checked with an average deviation of .0016%, the samples showing an average deviation of .0029% (this is percentage of the total air mixture), and indicated enrichment factors from 1.039 to .76. When completed the experiment was discarded as valueless because of the apparently erratic results, in spite of the fact that statistical analysis indicated less than one chance in 1000 that the control analyses and the sample analyses differed merely because of random errors.

After arriving at a tentative theory of operation a series of four experiments were devised to check the predictions enumerated. Twelve 8-liter flasks of air were sent to Mr. D. B. Trauger at K-25 for analysis. The results of these analyses and the set-ups used are shown in Figs. 9 to 12.

Drawing #7272

FIG 9



Drawing # 7273

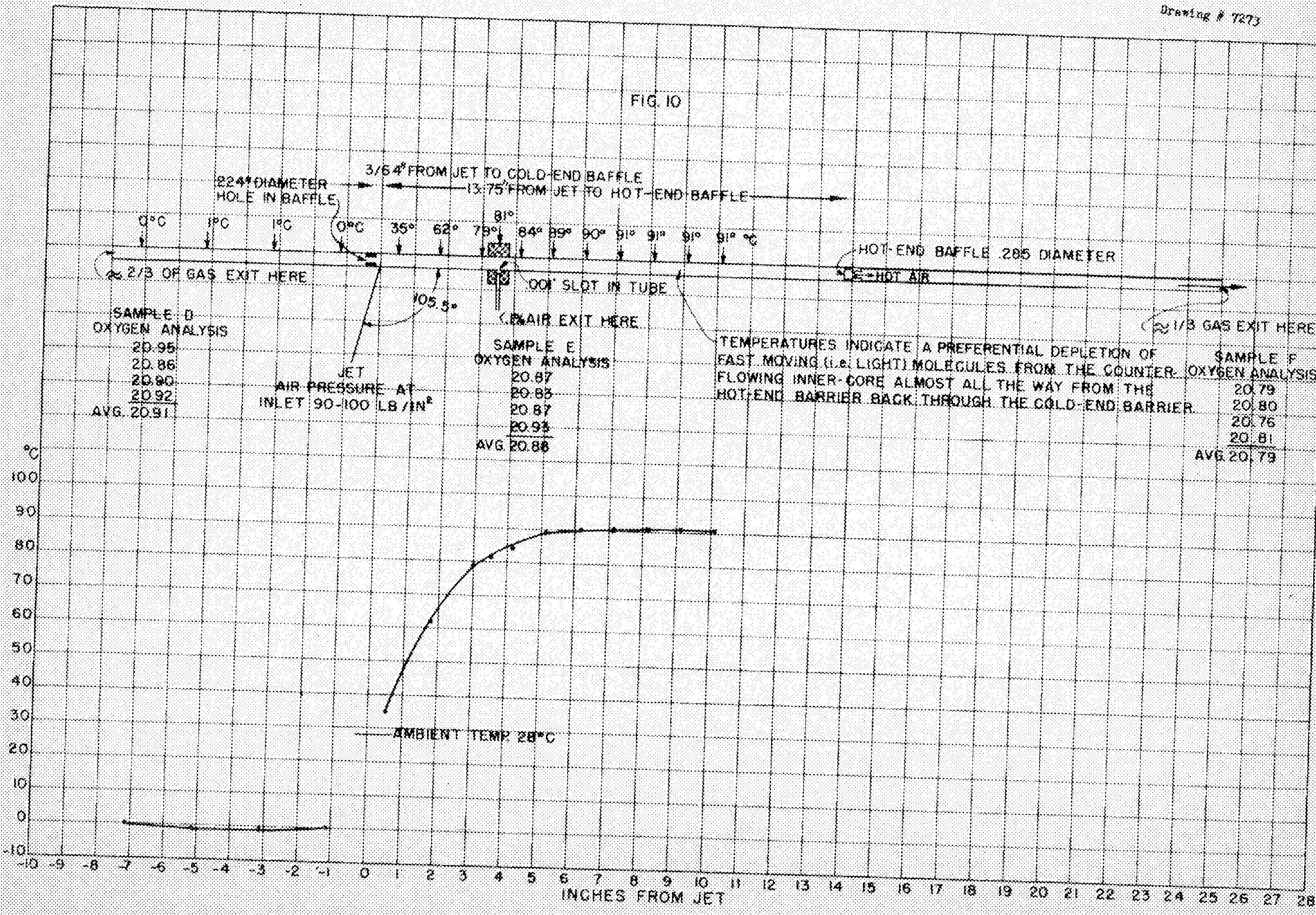
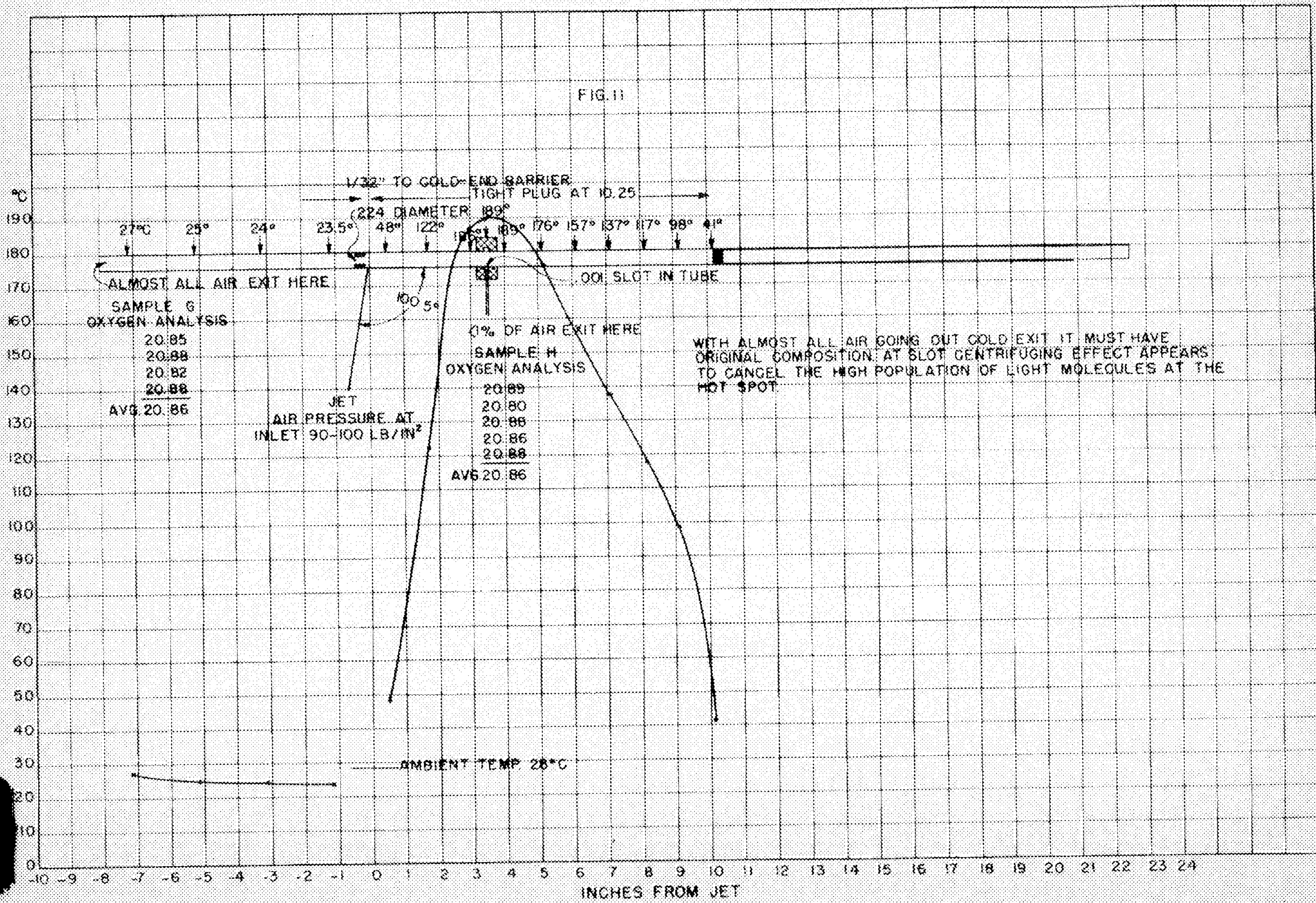


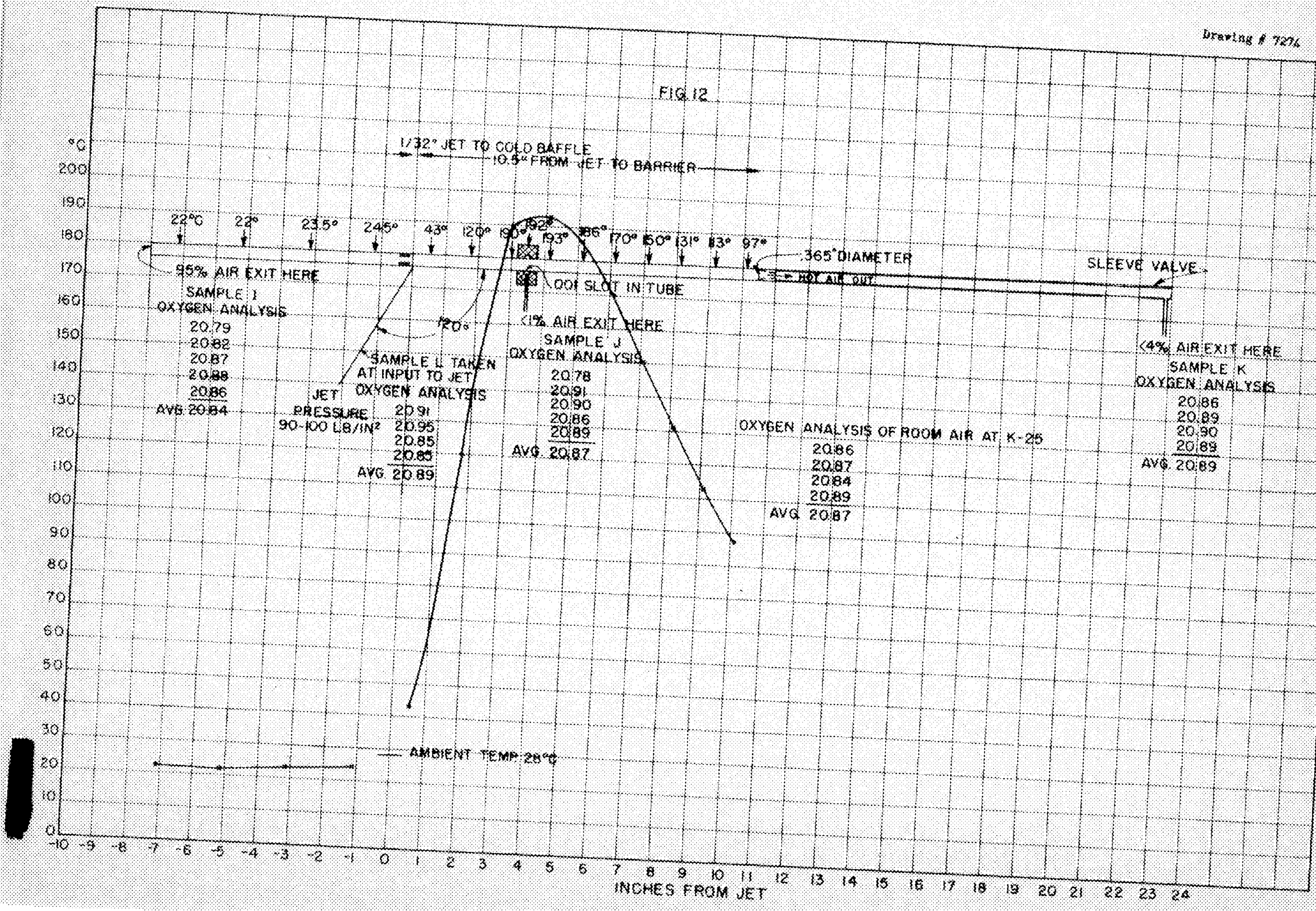
FIG. 10

Drawing # 7275

FIG. 11



-35-



Drawing # 7274
1/32" JET TO COLD BAFFLE
10.5" FROM JET TO BARRIER
°C
22°C
22°
23.5°
24.5°
43°
120°
190°
192°
193°
186°
170°
150°
131°
113°
97°
.365" DIAMETER
SLEEVE VALVE
HOT AIR OUT
95% AIR EXIT HERE
SAMPLE I
OXYGEN ANALYSIS
20.79
20.82
20.87
20.88
20.86
AVG 20.84
.001 SLOT IN TUBE
120°
SAMPLE L TAKEN
AT INPUT TO JET
OXYGEN ANALYSIS
20.91
20.95
20.85
20.85
AVG 20.89
JET
PRESSURE
90-100 LB/IN²
<1% AIR EXIT HERE
SAMPLE J
OXYGEN ANALYSIS
20.78
20.91
20.90
20.86
20.89
AVG 20.87
OXYGEN ANALYSIS OF ROOM AIR AT K-25
20.86
20.87
20.84
20.89
AVG 20.87
<4% AIR EXIT HERE
SAMPLE K
OXYGEN ANALYSIS
20.86
20.89
20.90
20.89
AVG 20.89
AMBIENT TEMP 28°C
INCHES FROM JET

FIG 12

Fig. 9 shows the jet at an angle of 106° to the axis on the hot side with the hot baffle at 13 3/4 inches from the jet. With this set-up the centrifugal effect plus the depletion of light molecules from the outer sheath beyond the hot spot resulted in an excess of oxygen at the hot end. The excess of oxygen was slight and inasmuch as the gas bled out there and at the hot spot was so small, the air going out the cold end differed negligibly from inlet air.

In the experiment shown in Fig. 10 conditions were radically changed. Here approximately one-third of the gas leaves through the hot end, most of the remaining gas returning in the core and undergoing continuous preferential depletion of fast moving molecules for almost the full length of the active portion of the tube. There is no sharply defined hot spot but the hot-end barrier is in the broad hot region. This test shows an oxygen deficiency at the hot end and an excess of oxygen at the cold end. Quantitatively the results may be somewhat confused by the water vapor, carbon dioxide, and argon present in the air, as these may be altered to a greater degree than the oxygen-nitrogen ratios.

Fig. 11 shows no hint of separation. None could be expected at the cold end because almost all of the gas must go out there, and apparently the centrifugal force effect exactly cancels the effect of the high population of light particles at the hot spot. In all other experiments where a "hot spot" existed at the "hot spot" bleeder (Figs. 9 and 12) a slight, though perhaps not significant, excess of oxygen appears. This may be interpreted as indicating a higher excess of light particles at the "hot spot" in this experiment than obtained in the other experiments.

Fig. 12 shows a set-up similar to Fig. 9 except that the jet points more toward the hot end and the hot-end barrier is nearer the jet. Less oxygen is shown at the hot valve than in Fig. 9, which is according to prediction (5).

This slight excess of oxygen is in fact not significant from a statistical viewpoint.

The analyses on the control flask consisted of only four points and had a rather high deviation and so they were combined with the cold air analyses shown in Figs. 9, 11 and 12 to get a reliable mean and standard deviation of the tests. This appears to be justified physically, due to the fact that the small percentage (less than 5%) of the gas leaving at the hot end and the hot spot did not show a change in concentration large enough to alter appreciably the composition of the 95% fraction. The assumption was made that the air from the compressor remained constant in composition.

The results shown were analyzed mathematically by Mrs. Palmiter under Dr. A. S. Householder's supervision. By an analysis of variance, Mrs. Palmiter found that there is less than one chance in a hundred that the results shown at the hot end in Figs. 9 and 10 were due to random errors. Some other methods of analysis indicate an even smaller chance than this.

Dr. Harold C. Urey called attention to the admitted fact that such analysis does not rule out the possibility of systematic error. However, inasmuch as the bottles of gas analyzed by Mr. Trauger's group bore no labels indicating the grouping of the tests, which might have unconsciously influenced the results, and the results do support the theory of operation previously arrived at by temperature measurements, it seems probable that the results are qualitiatively valid.

Other tests have been made at K-25, using tanks of oxygen and helium, which apparently showed some separation but which were somewhat inconsistent. Some of the inconsistencies were of such a nature that they may only be explained by assuming rather large random errors in analysis or by assuming that the gas coming from the tanks varied in composition as a function of

Drawing # 8046

[redacted]

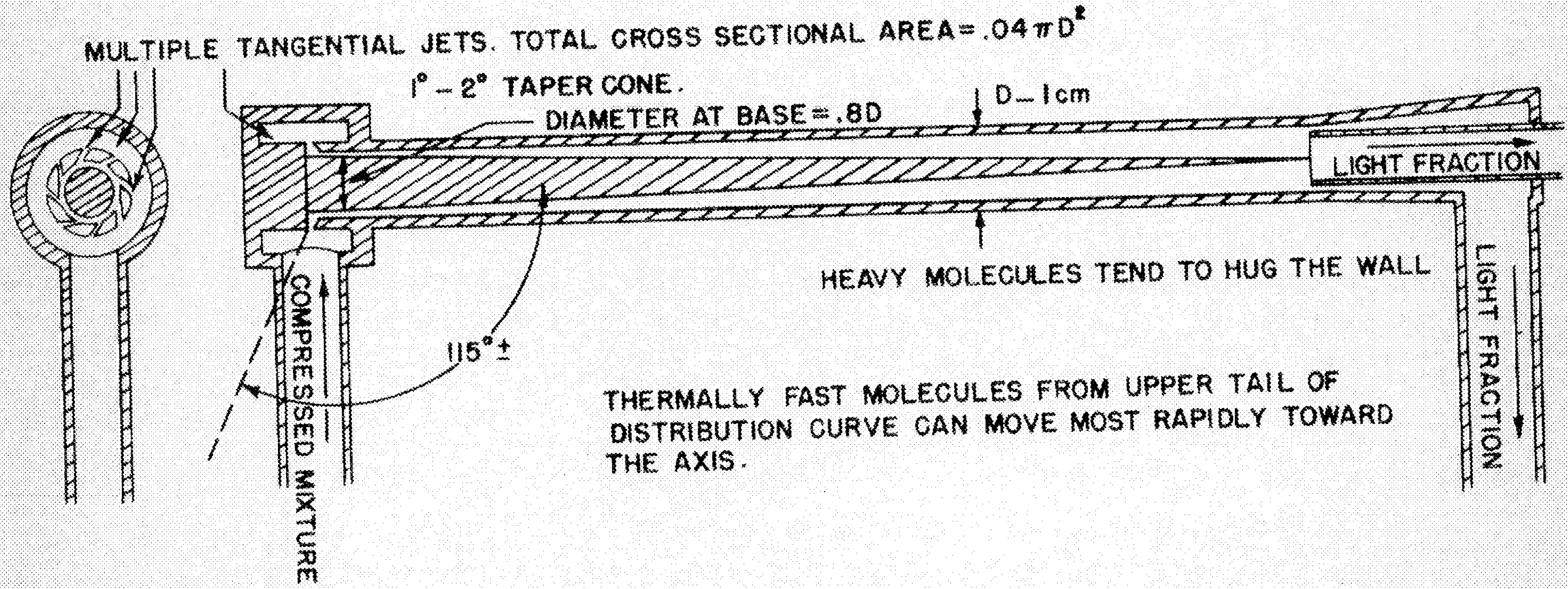


FIGURE 13. SEPARATOR SUGGESTED BY PROPOSED THEORY OF HILSCH TUBE

rate of flow. Other inconsistencies might be due to a difference in behavior of diatomic and monatomic gases in a Hilsch tube. This is conceivable, based upon occurrence in the tube of expansions and compressions with large temperature changes.

Considering the results shown in Fig. 10 it is seen that, if the gas coming from the cold end is assumed to have come all of the way from the hot-end barrier back past the jet, it starts the return with 20.79% oxygen and leaves with 20.91% oxygen. Looking at the action this way it is seen that the enhancement obtained is given by

$$\frac{\dfrac{100 - 20.79}{20.79}}{\dfrac{100 - 20.91}{20.91}} = 1.0073 .$$

Presumably, useful enhancements of this order of magnitude might be obtained by merely supplying the counter-flowing gas from an external source somewhat as done in Fig. 7. Even without modifications, greater enhancements than any shown should be possible by proper adjustment of jet angle, valve location and size of barriers and, possibly, higher pressure. The marked difference between the results obtained in Figs. 9 and 12 may indicate that the enhancements shown constitute merely a small difference between two or more large competing effects. To make a device in which the centrifuging effect and the diffusion effect cooperate for the entire length of the device, it is necessary to eliminate the counterflow of the inner and outer stream and to lose the regenerative effect due to this counterflow. This is probably not an important loss as the high concentration of the light fraction which may exist at the "hot spot" in the inner stream is inaccessible.

The device illustrated in Fig. 13 combines the separation effect of the centrifugal force with the separation effect of the diffusion of the fastest moving particles from the jet stream. If the proposed theory of the Hilsch tube is valid, enhancements much larger than any shown in these four tests may be obtained.

In addition to persons already mentioned, the authors are indebted to Martin Kuna, René Bolomey, A. T. Grefig and E. C. Johnson for their assistance in gas analyses. We wish to thank C. K. Beck for enabling us to have analyses done at K-25.

Bibliography

1. U. S. Patent No. 1952281, March 27, 1943. "Method and Apparatus for Obtaining from Fluid Under Pressure Two Currents of Fluids at Different Temperatures", by G. J. Ranque. (This is apparently the first description by the original inventor. Ranque was concerned only with the thermal effects.)

2. Journal Applied Physics, Vol. 16, page 285, 1945, "A Novel Form of Refrigerator", by J. R. Roebuck.

3. Industrial and Engineering Chemistry, Industrial Edition, Vol. 38, No. 5, page 5, May 1946 (unbound edition). "Maxwellian Demon at Work". (Pictures and brief description of Hilsch tube.)

4. Fortune, Vol. 34, No. 6, page 180, July 1946. (Simple description of Hilsch tube.)

5. Industrial and Engineering Chemistry, Industrial Edition, Vol. 38, No. 12, page 5, December 1946 (unbound edition). "The Demon Again". (Working drawing and various analyses of how the demon works.)

6. Review of Scientific Instruments, Vol 18, No. 2, page 108, February 1947. "The Use of the Expansion of Gases in a Centrifugal Field as Cooling Process", by R. Hilsch. (Submitted by R. M. Milton, Department of Chemistry, Johns Hopkins University)

7. Science News Letter for April 26, 1947, page 263. "Whirling in Simple Tube Separates Hot and Cold Air". (Brief nontechnical description of Westinghouse experimental model.)

8. Popular Science, page 144, May 1947. "Maxwell's Demon Come to Life". (Popular nontechnical description of original tube.)

9. Science Illustrated, page 32, July 1947. "Mystery Pipe". (Brief nontechnical description of Westinghouse experimental model.)

10. Science Digest, page 32, August 1947. "Mysterious Hot-Cold Pipe". (Simple description of large hot-cold tube.)

11. Canadian Journal of Research, Vol. 25, No. 5, page 299, September 1947. "Quantitative Study of Hilsch Heat Separator" , by A. L. Johnson. (Technical analysis and quantitative data of Hilsch tube. Analysis of thermal efficiencies.)

12. Popular Science, page 190, November 1947. "Home-Made Maxwell Demon Gives Hot and Cold". (Instructions for constructing a simple tube.)

13. Zeitschrift fur Naturforschung, Band 3A, Heft 1, January 1948, page 46. "Von Gerd Burkhardt". (Mathematical analysis of Hilsch Tube per Hilsch's theory of operation.)

14. Science in Progress, Second Series, page 232, Yale Press. "Ultra-centrifuge", J. W. Beams. (The separation of gases by centrifuging.)

15. Atomic Energy, by Henry DeWolf Smyth, Princeton University Press, page 160. (Separations of isotopes by centrifuging.)