

1960

A study of Eddy mass transport

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**A STUDY OF
EDDY MASS TRANSPORT**

By

FERDINAND C. CATANEO

A STUDY OF
EDDY MASS TRANSPORT

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Ferdinand C. Cataneo

A THESIS

presented to the Graduate Faculty
of Lehigh University
in Candidacy for the Degree of
MASTER OF SCIENCE

Lehigh University
Bethlehem, Pennsylvania
1960

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

October 6, 1960
(Date)

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Professor in Charge

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Head of the Department

ACKNOWLEDGMENTS

The author wishes to thank Professor C.W. Clump for his helpful suggestions and criticisms. The diverse aid given by Mr. Paul Tax is acknowledged.

The assistance given by Messrs. W. Szulborski and J. Spirer concerning the construction of the equipment is gratefully acknowledged.

Finally, the author thanks his wife, Mrs. Charlotte Cataneo, for typing and proofreading this manuscript.

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1. ABSTRACT

The fundamental importance of the study of turbulent mass transfer is demonstrated and the efforts of past workers examined. The necessary apparatus designed for this work is shown and discussed in detail and all major experimental procedures are presented. Theoretical considerations involving the derivation of the expression giving the numerical value of the "eddy mass diffusivity", the deduction of the general nature of the expected data, and the relationship of the latter with the former, are made.

EDDY MASS DIFFUSIVITY

2. INTRODUCTION

The marked and well-known influence of turbulence upon the transport of mass, momentum and heat in a flowing stream has been the object of much investigation.

Because of the extreme complexity of behavior of turbulent flow in the microscopic sense, workers in the field have turned to macroscopic methods of description, whose characteristics are more easily controlled and observed. It was reasoned by Karman (1) that the transport of any property in turbulent flow should be analogous to that in laminar flow (i.e.) by molecular transport. Thus the macroscopic concepts of eddy diffusivity of mass, momentum, and heat were evolved and defined respectively as follows:

$$\frac{Nm}{A} = - (D + \epsilon_m) \frac{dC_m}{dy} \dots\dots\dots (a)$$

$$\frac{N}{A} = \tau g_c = (\nu + \epsilon) \frac{d(u^p)}{dy} \dots\dots\dots (b)$$

$$\frac{N_Q}{A} = \frac{q}{A} = - (\alpha + \epsilon_H) \frac{d(C_p^p T)}{dy} \dots\dots\dots (c)$$

The general method used to determine the eddy diffusivity of a property has been to eliminate carefully the transfer of at least one of the remaining two transferable properties. In the case of momentum transfer studies it is possible to eliminate both of the interfering mechanisms. However, in the present work, while it is possible to prevent heat transport, the necessity for regarding the simultaneous effects of momentum transport is acknowledged. This fact has been surprisingly ignored by a number of previous investigators. The following review of the literature will serve to illustrate the difficulties which were encountered and the reasons why more and better data are needed.

T. K. Sherwood was among the first to investigate the role of turbulence in mass transfer. His first work, done in collaboration with B. B. Woertz (2) consisted of passing a turbulent stream of air through a rectangular duct (5.3 cm x 61 cm cross-section) furnished with one wall wetted with water and an opposing wall wetted with concentrated aqueous CaCl_2 solution. The concentration gradient of water vapor across the duct was measured by a bank of nickel sampling tubes traversing the duct at one arbitrary longitudinal position. The air stream Reynolds number range was given as 3600-102,000. Since this work was one of the first attempts in the field it is to be expected that some of the relevant variables were ignored or unknown at the time. For example,

a component material balance for a small volume element within the duct would show that ϵ_m is dependent upon the velocity profile and the longitudinal variation of concentration at a specified distance from the wall, as well as the transverse concentration gradient. In addition, the quantities which were measured are questionable for several reasons (i.e.) the wetted walls had an unknown effect on the velocity profile and on the general character of the flow; no adequate upstream calming length was provided so that the velocity profile in the test section was not fully developed; and the air velocity in the upper 3/4 of the N_{Re} range definitely caused rippling of the water film and probably even entrainment.

Also in 1939, Sherwood and Towle (3) described an alternate method which measured the turbulent diffusion of CO_2 or H_2 into an air stream flowing in a circular pipe. The CO_2 or H_2 was injected into the center of the air stream, 70 pipe diameters downstream of the air inlet, by a very small nozzle built into an aerofoil section which completely traversed the cross section of the pipe. Care was taken to inject the diffusing gas at a velocity equal to that of the air at the center of the duct (at v_{max}). Concentration traverses were made with a bank of sampling tubes similar to those of Woertz (2) at positions downstream of the aerofoil section of 3.6, 6.8, 9.8 and 11.4 pipe diameters for a pipe of 30.5 cm diameter, and 0.37, 0.52, 0.71, 0.89 and 1.0 diameters for a pipe of 215.24 cm diameter. The traverses were made over

the central third of the duct, with eddy diffusivities being calculated from center line concentrations only. The data showed, that ϵ_m increased asymptotically downstream from the injector tube, and, a lack of radial symmetry in the duct. In interpreting their data, the Wilson integration (4) for heat transport from a constant point source on the axis of a tube to a uniformly flowing fluid in that tube, was used. As was pointed out by Klinkenberg, Krajenbrink and Lauwerier (5) the conditions for the use of this equation require that the amount of solute gas injected at the source be so small so as not to upset the uniformity of the flow. Unfortunately, the uniformity of the flow was upset by a combination of the above mentioned factor and the physical interference of the aerofoil section as is readily seen from the data. It should also be pointed out that the use of the Wilson integration demands the flow field in question be isotropic and homogeneous. However, in turbulent flow in closed conduits the turbulence is not isotropic and/or homogeneous.

In 1953 Schlinger and Sage (6) published an account of their work which was described as "a part of an investigation of the combustion of natural gas and air". Natural gas was axially injected from a 1" copper tube into a stream of air flowing in a 4" I.D. copper tube and concentration gradients were measured at 11 downstream positions. No calming section preceded the point of injection so that the concen-

tration gradients determined were highly questionable. Velocity profiles were not measured. These workers were interested only in solving a problem specifically connected with the system used and not in determining the radial distribution of eddy diffusivity, which they assumed to be independent of radial position in their correlation with gross velocity.

Lynn (7) in 1953 completed work for a thesis which was similar to that of Scullinger and Sage (6) except that the solute gas was introduced as an annular stream at the wall of the air duct. A glance at the profiles he obtained for ϵ_m (8) show that the air stream could not have been in fully developed turbulence since the profiles vary in a disordered fashion with longitudinal position. It is felt that Lynn was probably unsuccessful in exactly matching the velocities of the two streams so that unpredictable secondary effects dominated his results.

The work of Lin, Moulton and Putnam (9) demonstrates the use of interferometric methods in measuring concentration profiles near solid walls. The flow path used was rectangular (1-1/4" x 3/4") and a calming length of 6 equivalent diameters $\left(\frac{2d_1 d_2}{d_1 + d_2}\right)$ was provided. Prandtl (10) and Nikuradse (11) have demonstrated the unpredictable nature of the flow in noncircular conduits. They observed flow toward the corners and away from the sides of the conduit. This secondary motion was superimposed on the longitudinal fluid motion.

Hence, the choice of a rectangular flow path was a poor one, and it explains the observations made by these authors concerning the presence of turbulence within the laminar sub-layer. In addition, the assumption was made that concentration gradients, measured at points downstream of the beginning of the test section greater than 6 equivalent diameters, were uniform. This seemed to allow the calculation of diffusion coefficients purely from concentration gradients, and, the photographs of the profiles presented may, at first glance, support the assumption. However, it should be noted that the longitudinal distance observed was so small (approximately one millimeter) as to make quantitative deductions concerning profile uniformity impossible. Further, material balance considerations point out that the only uniform (steady state) gradient possible in a closed system is the zero gradient.

In 1956 Schwarz and Hoelscher (12) described their experiments with a wetted-wall column in which the air flow was turbulent. A serious drawback in the use of wetted wall columns is the limitation on the range of N_{Re} possible, which is demonstrated by the fact that the maximum N_{Re} achieved without rippling of the detergent denatured water film was 25,000. This value of N_{Re} was the only one used. The authors arranged a flared entrance for the wetted-wall column into which was centered the end of the 8 ft. calming section. Although this procedure was necessary in order to allow water to be removed from the test section, it caused a deleterious

and unpredictable effect on the flow conditions, as would be expected, since part of the constraining boundary was removed.

In 1958, Dhanak (13) published a description of some work which was essentially a repetition of that of Sherwood and Woertz (2). He ingeniously replaced Woertz' wetted-wall with water-soaked green billiard felt glued to the duct walls in order to eliminate ripples. However, he states that at times parts of this felt "wall" were observed to be dry and that at other times water was entrained by the air stream (this was captured at the air outlet and appropriate corrections were made). Since his conditions, data, and theoretical analysis are the same as those used by Sherwood and Woertz (2), they are subject to the same criticisms.

More recently, Manratty et al., (14) completed an elegant study of point source turbulent diffusion in a pipe. The apparatus used, with the exception of some very definite refinements, was essentially that of Sherwood and Towle (3). The Wilson integration (4) was used in treating the data (as before) in conjunction with Taylor's (15) statistical description of homogeneous, isotropic turbulence. The non-isotropic, nonhomogeneous character of pipe flow is acknowledged by the authors.

3. DESCRIPTION OF APPARATUS

General: See Figure 1

A. The Annulus is composed of a 15 foot upstream calming section, a 5 foot test section and an 8 foot downstream calming section, thus ensuring fully developed, undisturbed turbulent flow at the test section. The core of the test section, while having the same diameter and being intimately joined to the cores of the two calming sections, will have been coated with a 1/16 inch layer of naphthalene by a procedure similar to the operation of an Oliver rotary filter (with vacuum section being replaced by slow crystallization of molten naphthalene).

B. The Sampling Apparatus has been arranged to obtain point velocity pressures for the determination of velocity distribution in the annulus. A standard impact tube fabricated from hypodermic tubing (0.042 in. O.D., 0.0075 in. wall) is used for this purpose. A micrometer feed mechanism will reproducibly position the impact tube in the duct to ± 0.001 in. Pressure readings will be taken from a precise micromenometer accurate to ± 0.0002 in. water for velocity pressures less than 0.2 in. water, and ± 0.001 in. water for the 0.2-24 in. range. (See 3.3).

EQUIPMENT LAYOUT

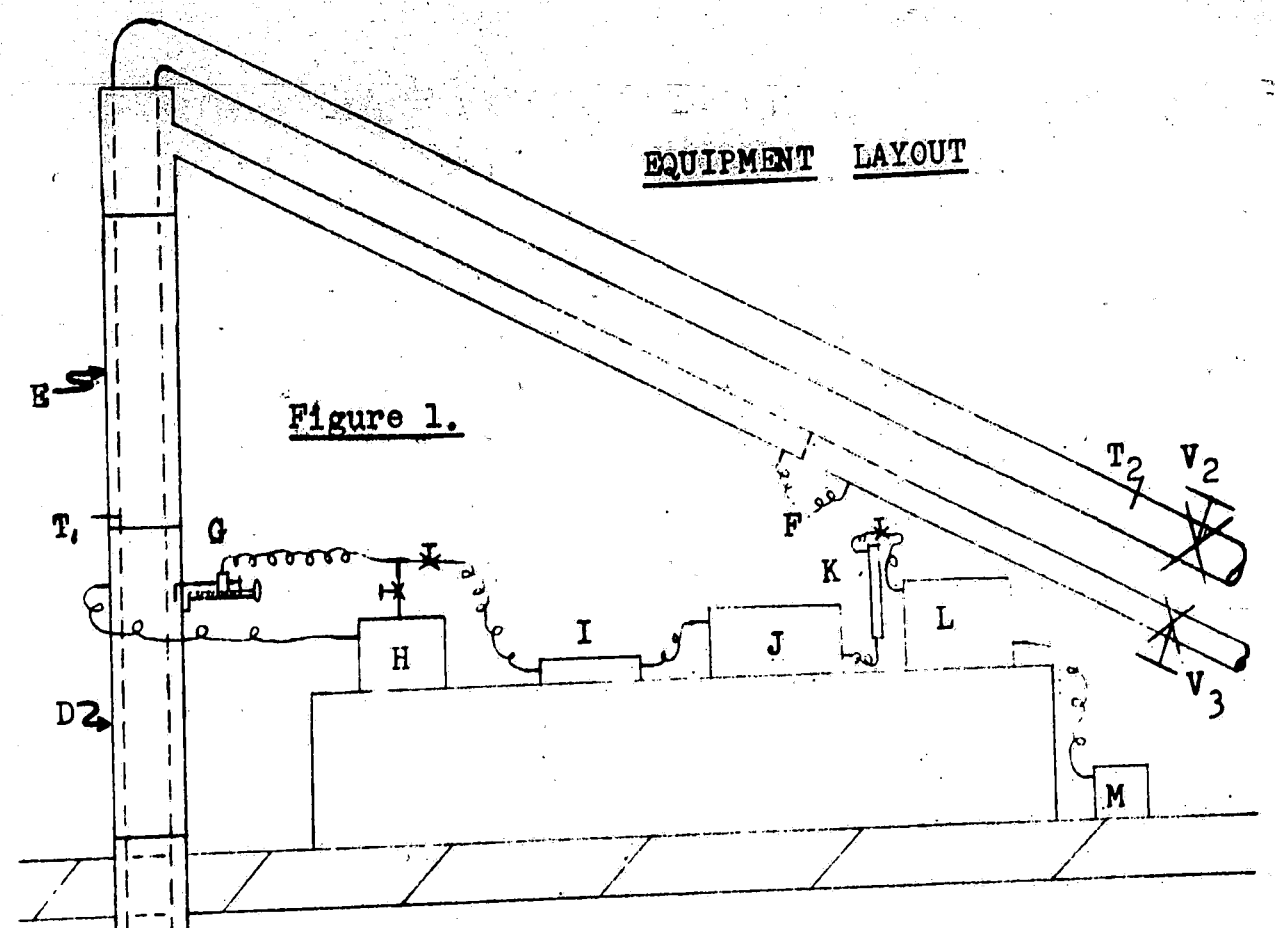
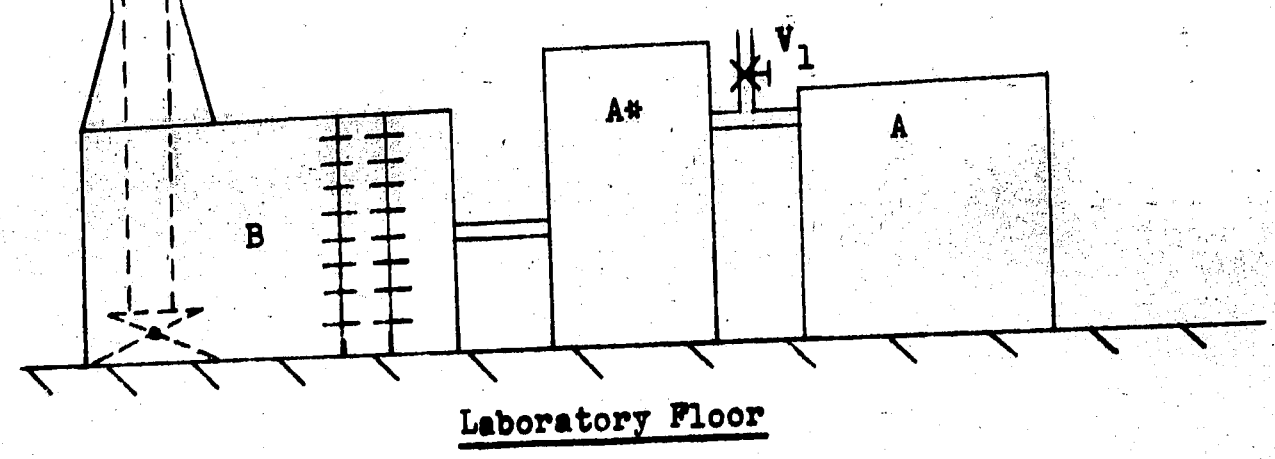


Figure 1.

- A Blower, 2000 cfm capacity; A* Entrainment remover
- B Surge Tank, 12 ft.³ with finned heaters.
- C Upstream Calming Section, 15 ft.
- D Test Section, 5 ft.
- E Downstream Calming Section, 8 ft.
- F Orifice Meter
- G Impact tube with micrometer feed mechanism.
- H Micromanometer
- I Catalytic Oxidation Furnace
- J Gow Mac Gas Analyzer
- K Rotameter
- L Vacuum Tank
- M Vacuum Pump
- T₁ Thermocouple to potentiometer.
- T₂ Thermometer
- V₁, V₂, V₃, Flow Control Valves.



Laboratory Floor

C. Continuous Stream Analysis will be performed in a previously calibrated thermal conductivity gas analyzer.

The sample gas mixture (air + naphthalene vapor) sucked through the impact tube probe, will be passed through a 20 inch long cylindrical tube packed with Al_2O_3 granules and heated to $900^{\circ}F$. The exit gas mixture (CO_2 , H_2O and air) will be desiccated and subsequently compared in the analyzer to a desiccated sample of reference air taken from the system. Stoichiometric considerations point out the great advantage of this method.

D. Air Supply from a high capacity blower (2,000 c.f.m.) will be brought to temperature via two banks of finned heaters, one steam heated and the other electrically heated, contained in a suitable tank immediately downstream of the blower. Temperature will be controlled by a rheostat connected to one of the electric heaters. The air mass rate will be controlled by the bleed valve (V_1) at the blower outlet, and V_3 . A portion of the heated air will be passed through the inner core in order to minimize thermal gradients in the system.

3.1 The Annulus

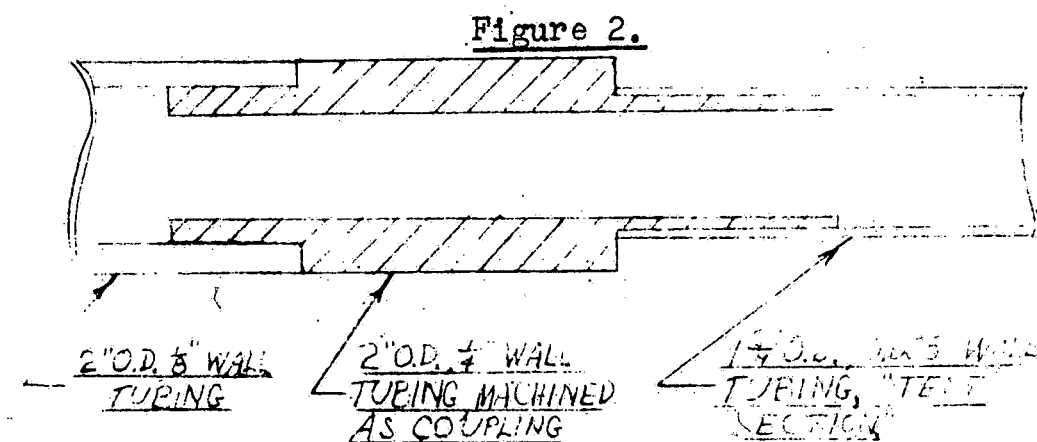
a. Materials and Fittings

Outer pipe 3" Standard extruded Aluminum pipe

Inner pipe 2" OD, 0.125" wall, round Aluminum tube

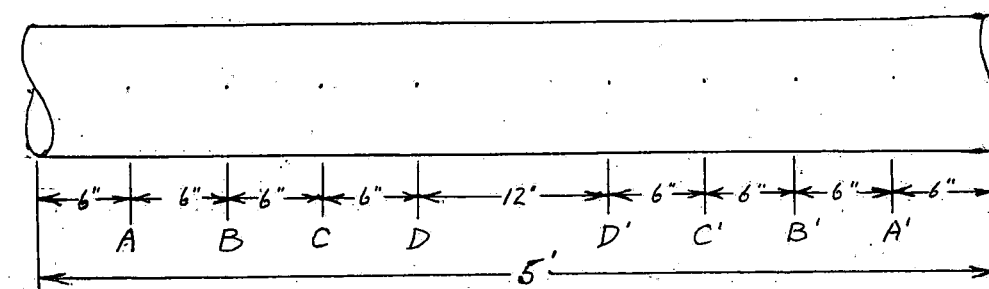
The core, as well as the outer shell, consists of three sections,

15 ft., 5 ft. and 8 ft. in length. The outer shell is joined by Victaulic "Roust-A-Bout" couplings so that constant annular cross section is assured. The mating faces are perfectly square with respect to the longitudinal axis of the pipe so that the flow conditions of a continuous annulus will be approached as closely as possible. The core sections are connected by simple precisely machined sleeve joints as shown in (Figure #2) which depicts the connection of the test section core with a calming section core.

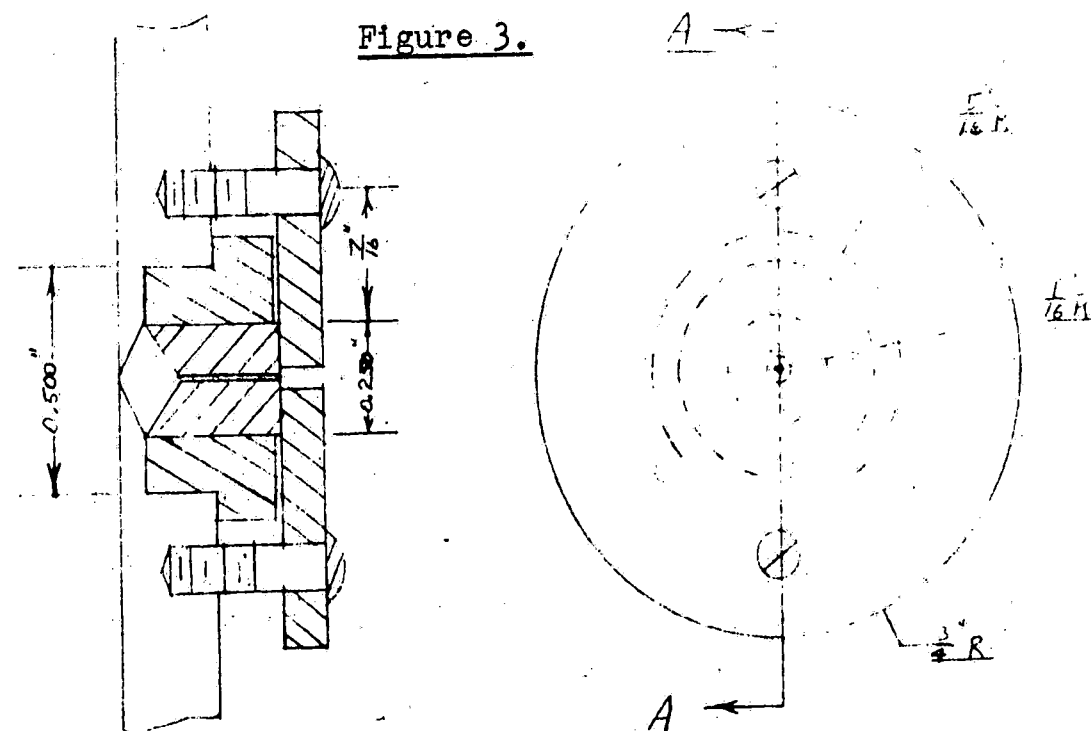


b. Outer Shell

Concentration profiles will be taken at eight different positions along the five foot test section. The spacing will be as shown below.



It is well known that the existence of an aperture in the conduit wall will significantly affect established flow patterns. To avoid this, it will be necessary to use four individual outer walls, each having an aperture at one of the four positions A, B, C or D. Positions A', B', C' and D' may then be obtained by rotating the pipe about its longitudinal center. In order to minimize leakage through the apertures, a packing gland will be used to accommodate the impact tube (see Figure #3 below)



Static pressure taps were made diametrically opposite the pitot tube openings in the annulus. The holes were made according to the rigid specifications stated by Folsom (16), "A true square-edged hole without edge burrs, flush with the inside pipe wall, and with a depth of constant cross section for at least two diameters, provides an accurate piezometer when there are no fluid swirls or crossflow. A slight rounding does not change the reading of the piezo-

meter and is easier to produce than a sharp edge without burrs." To comply with the foregoing, a 1/16" D hole was drilled perpendicular to the pipe wall and all burrs carefully removed with steel wool. Interruption of the cross section of the hole was avoided by making no direct tap connection to the pipe itself. Instead, a gasketed connection formed from a 3" length of 3.5" I.D. pipe (so as to fit snugly over the 3.5" O.D. test section pipe) cut along its longitudinal axis, was used. The necessary compression fitting was attached only to the cover pipe, which was subsequently used to sandwich a piece of soft rubber, 1/16" thick equipped with a 1/8" D hole, against the test section pipe. The assembly was then held together with worm-gear type hose clamps.

To facilitate replacement of test section cores and outer shells, a 5 ft. length of the outer shell immediately downstream of the test section was replaced with a suitable length of heavy duty rubber hose of 3.5" I.D. having a smooth inner wall. This rubber shell, secured with worm-gear hose clamps, may be moved vertically (after loosening the hose clamps), thus exposing the annulus core. The core support jack may then be lowered, freeing the core length associated with the rubber shell and allowing the necessary replacements to be made.

3.2 The Sampling Apparatus

A pitot tube fabricated from standard hypodermic tubing will remove air-naphthalene samples from the annular

stream. The rate of removal will be controlled by vacuum (See Fig. 1) and will correspond closely to the velocity of the stream at the point of measurement. The tube will be positioned in the duct with the aid of the micrometer feed mechanism (Figures 4, 5, and 6). The "sampling apparatus" will also be used to establish complete and precise velocity profiles. Calibration of the impact tube to determine the magnitude of the coefficient C_1 of the impact tube equation $V_{\infty} = C_1 \sqrt{2g_c (P_1 - P_{\infty})}$ was unnecessary, according to Folsom (16).

Intimately related to the sampling apparatus are the high precision Micromanometer and the Stream Analysis System, described below.

3.3 The Micromanometer (Figures 7 and 8)

This instrument is a null-reading hydrostatic device with an accuracy of ± 0.0002 in. H_2O . Its design is similar in principle to the general description given in (17) of Prandtl's instrument (reputed to have an accuracy of 0.001 " H_2O) with a number of refinements. The accuracy is increased in the low range of pressure differentials via the use of a dial gage which reads to the nearest 0.0001 in. and a 100 power microscope with crosshair eye piece to aid in locating the meniscus.

The device is essentially a U-tube manometer with one movable leg. The reservoir (A) is attached via a screw (10-32) mechanism to a cantilever beam brazed to a collar

IMPACT TUBE FEED MECHANISM ASSEMBLY

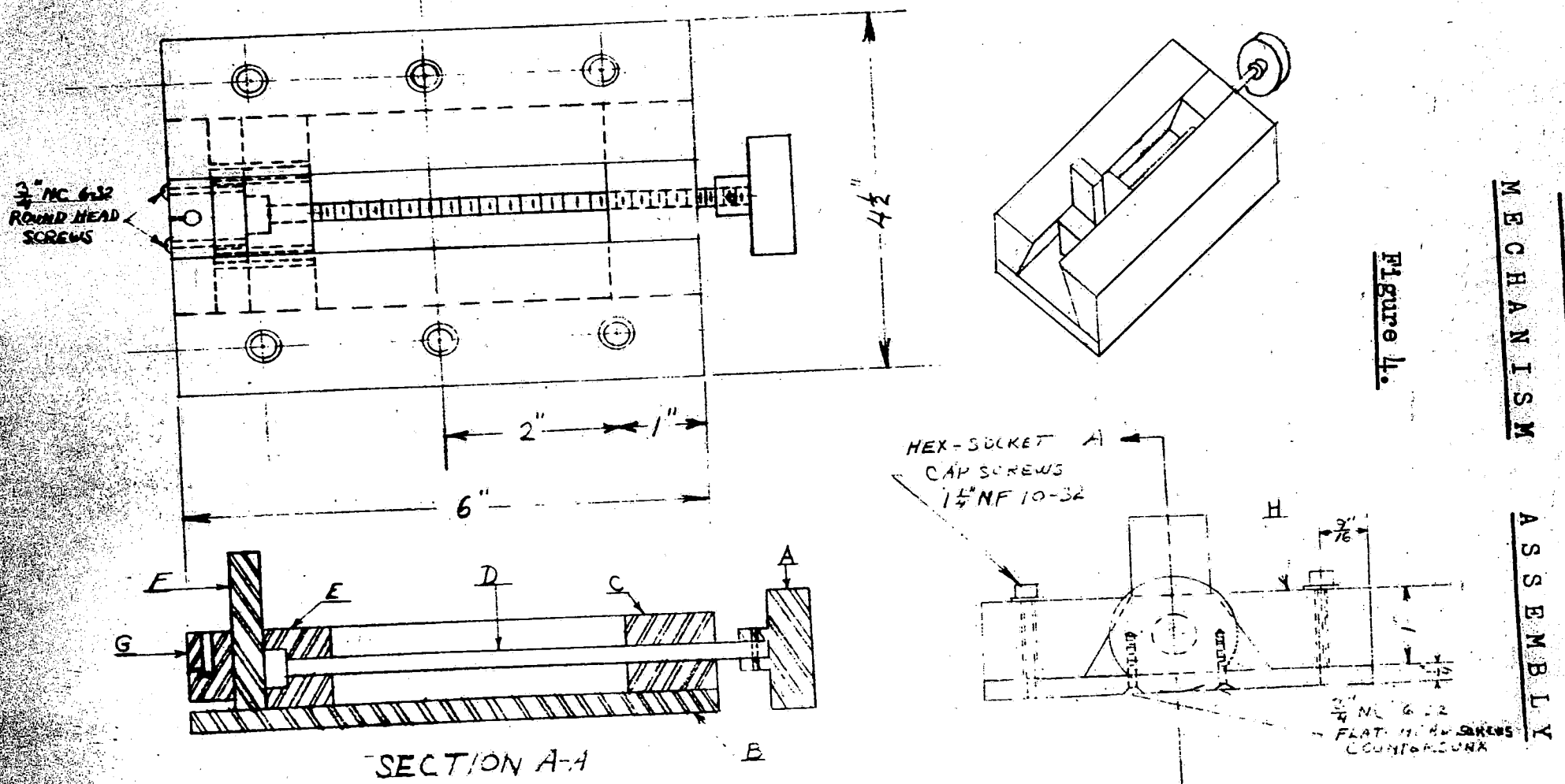
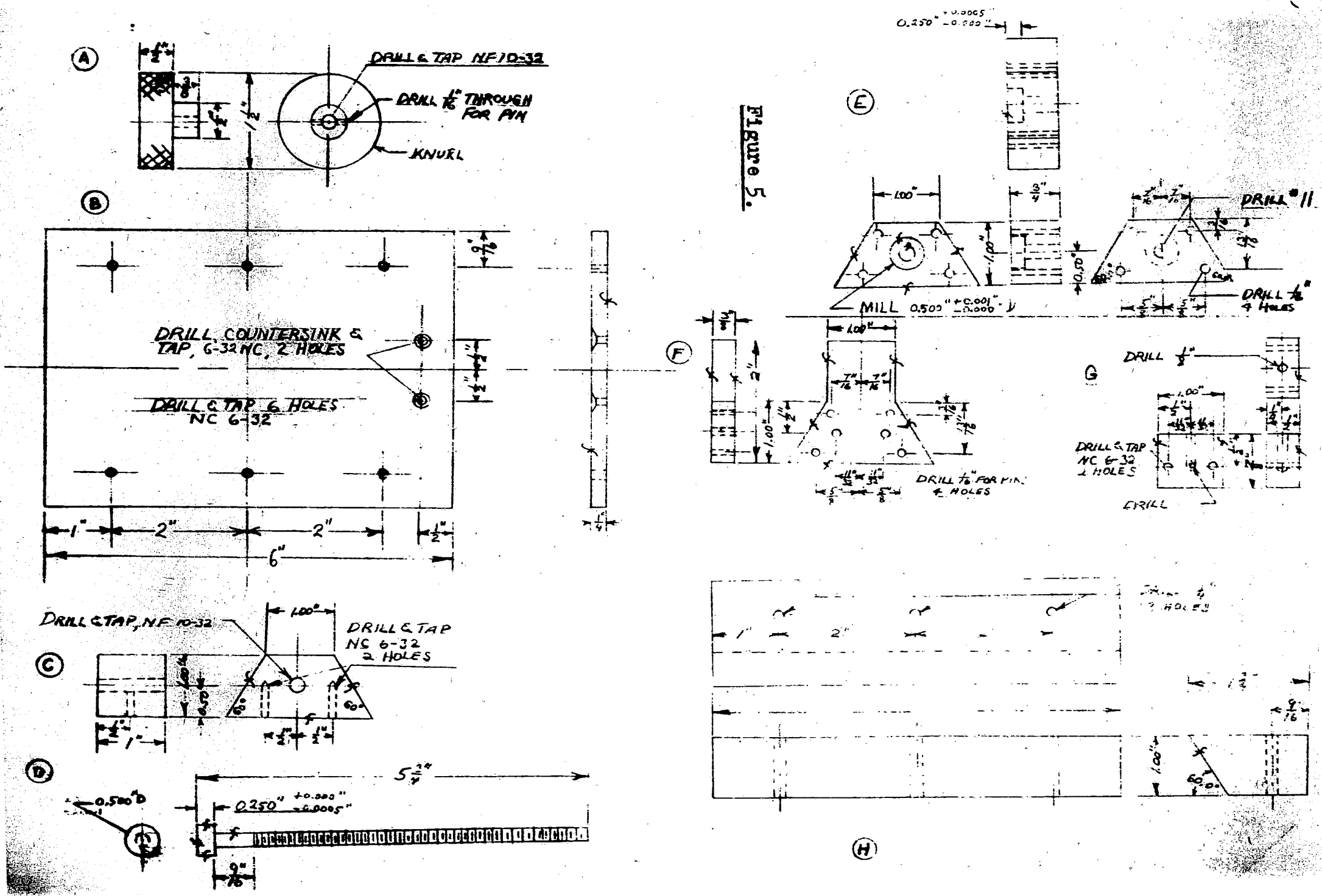


Figure 4.

PART	NAME	# REQD	MATL	PART	NAME	# REQD	MATL	PART	NAME	# REQD	MATL
A	HANDLE	1	CRS	E	CRS HEAD BLOCK	1	CRS	6	1/4" 10-32 NF HEX LOCK CAP SCREW	6	CRS
B	BASE PLATE	1	CRS	F	MICROMETER PLATE	1	CRS	2	3/8" 6-32 NC FLAT-HEAD SCREW	2	CRS
C	THREADED BLOCK	1	CRS	G	IMPACT TUBE BLOCK	1	CRS	2	3/8" 6-32 NC ROUND HEAD SCREW	2	CRS
D	LEAD SCREW	1	CRS	H	BEARING GUIDE BLOCK	2	CRS	4	1/8" DIAM. PINE	4	CRS

Figure 5.



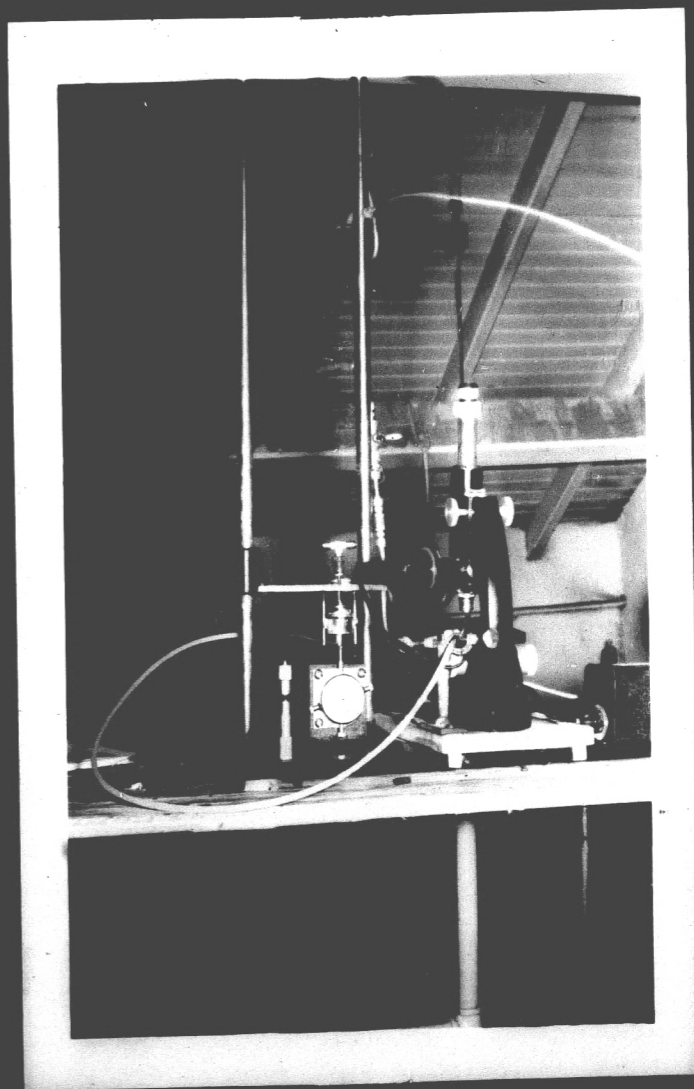
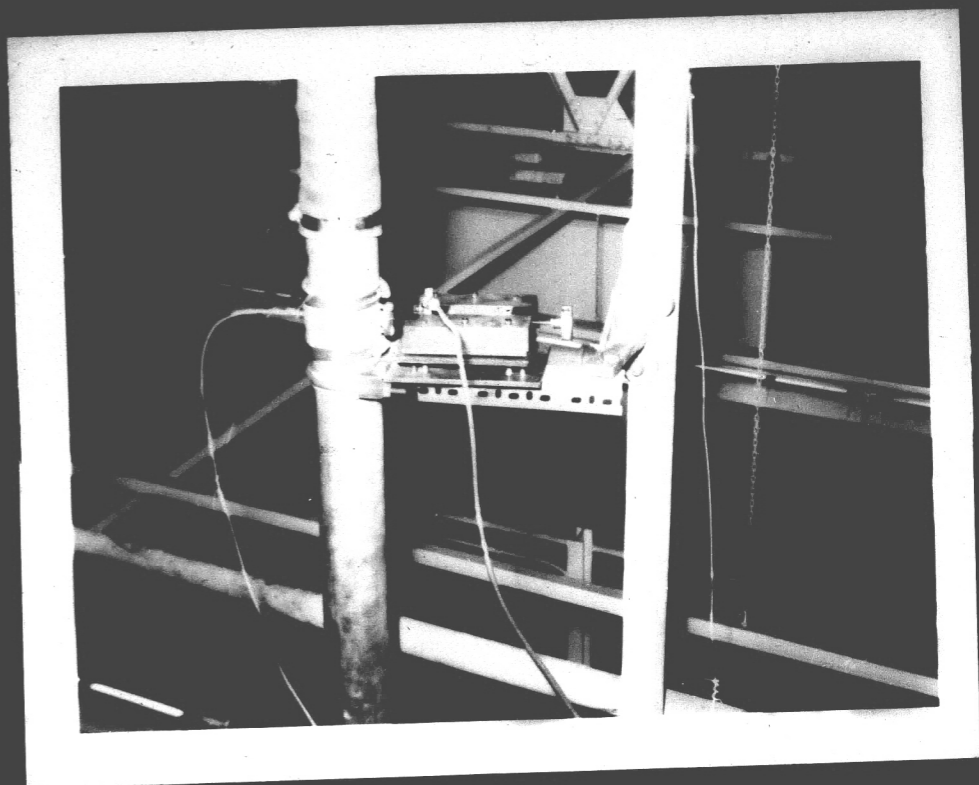
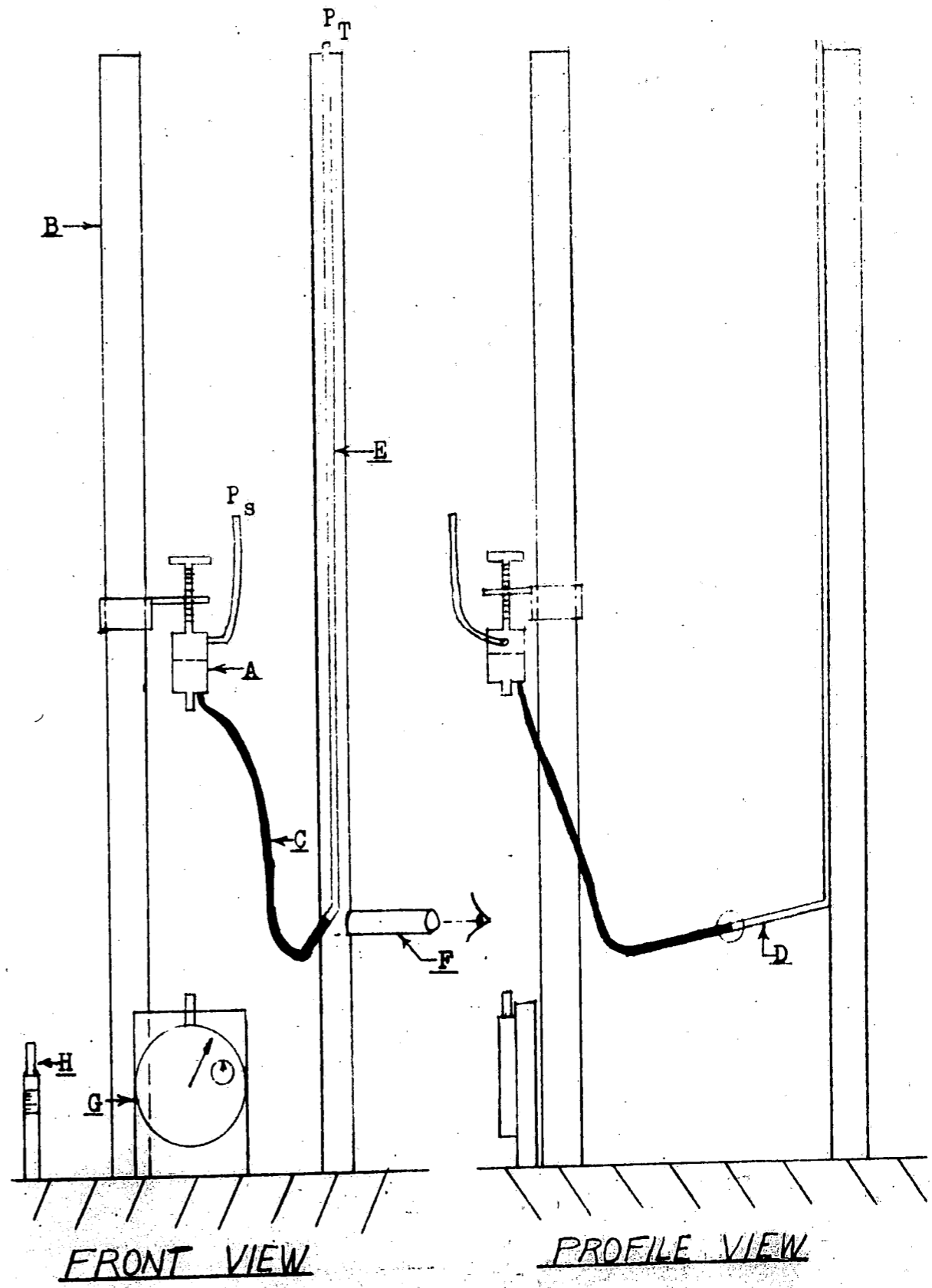


Figure 8.

MICROMANOMETER



which in turn slides vertically on the steel shaft (B). Connected to the reservoir is a piece of plastic tubing (C), providing the linkage to the inclined (20:1) glass capillary tubing (D) which is part of the rigid leg of the U-tube (E). The inclined glass capillary tube will contain the meniscus of the manometer fluid (G.E., SF-81(50) Silicone oil) whose position is determined with the aid of the microscope (F) to 0.0001 in. of vertical height by (G) the dial gage, for distances up to 0.2000 in., and to 0.001 in. of vertical height by (H), the inside micrometer head, for distances up to 24 in.

Prior to operation, both pressure connections (P_S and P_T) are vented; the reservoir lowered to its minimum; the position of the meniscus in the inclined tube noted and recorded by the position of the microscope crosshair; and the corresponding zero readings noted on both the dial gage and micrometer head. When a pressure differential is applied (total head at the rigid leg opening and static head at the reservoir), the reservoir is raised until the meniscus returns to its original position. Hence we have a null reading system which is unaffected by capillary and meniscus errors or by any possible inconsistencies of the inclined tube.

3.4 Stream Analysis System

1. The naphthalene-air mixtures removed with the sampling probe will be passed through a catalytic oxidation furnace (Figure 9).

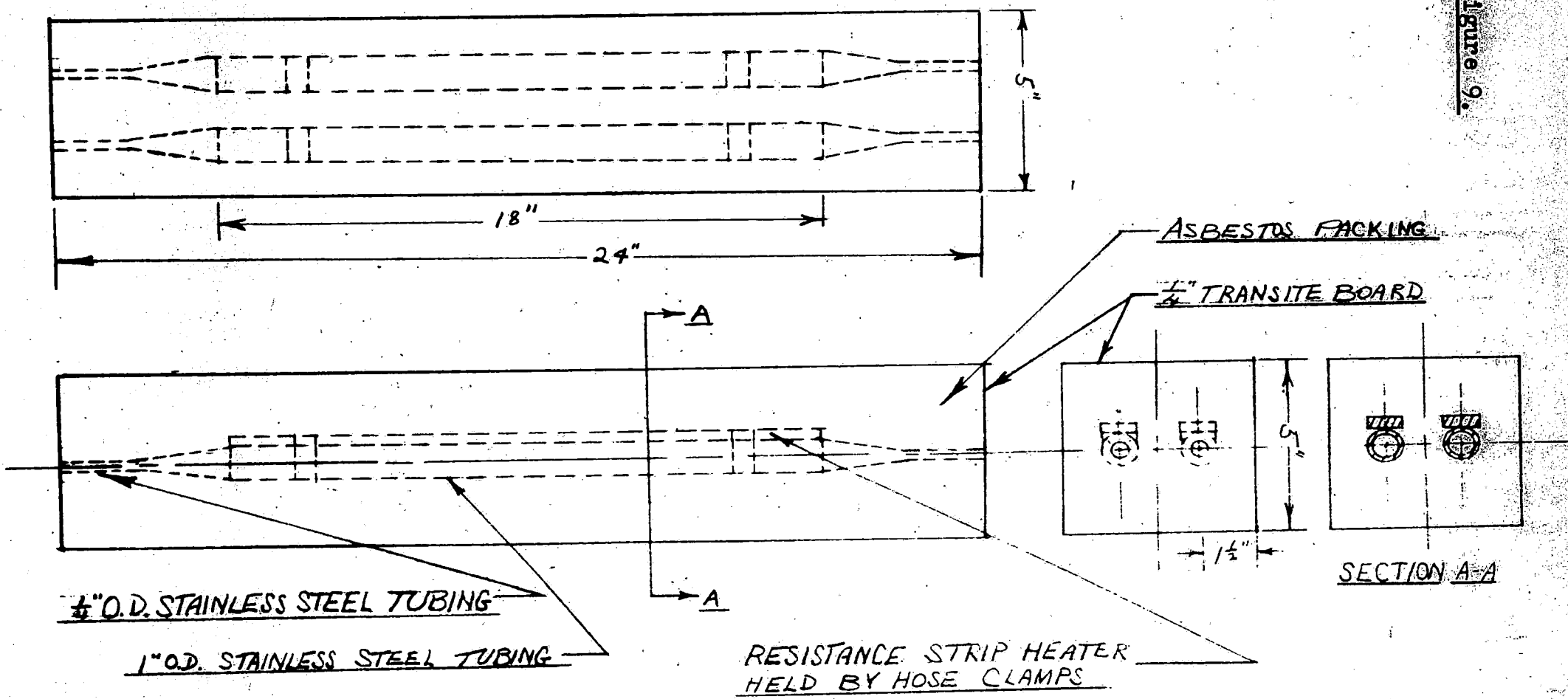
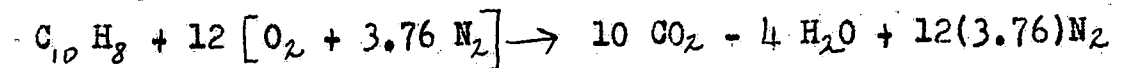


Figure 9.

The stoichiometry is as follows:



Suppose the concentration of naphthalene in air entering the furnace is 9210 ppm; then:

Basis = 1 lb. mole entering gas mixture

<u>compound</u>	<u>in</u>	<u>formed or consumed</u>	<u>out</u>
$C_{10}H_8$	0.00921 # mole	0.009210	0.0000
$O_2 + 3.76 N_2$	0.99079	0.110526	0.880264
CO_2	0.0000	0.092105	0.092105
H_2O	0.0000	0.036842	0.036842
			<u>1.009211</u>

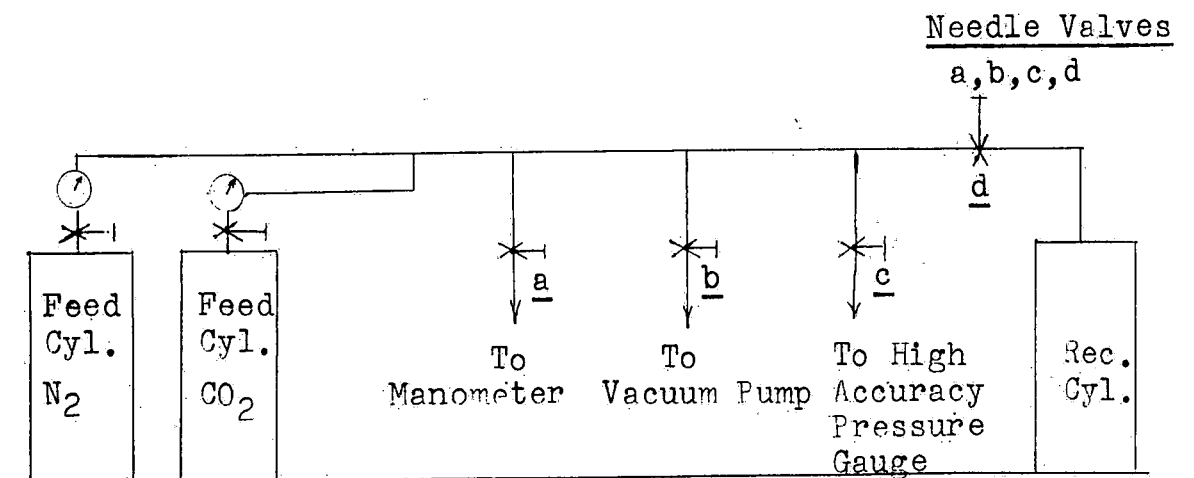
$$CO_2 = \frac{0.092105}{1.009211} \times 10^6 = 91,264 \text{ ppm}$$

2. The advantages of analyzing for CO_2 in lieu of naphthalene are as follows:

- (a) Any error in analysis for CO_2 is reduced by a factor of $\frac{9210}{91264} = 0.10091$ in terms of naphthalene.
- (b) A thermal conductivity gas analyzer may be used to give results to within ± 2 ppm CO_2 or ± 0.2 ppm naphthalene.
- (c) Calibration of any instrument is far easier for CO_2 - air mixtures than for naphthalene - air mixtures.
- (d) The instrument necessary for direct naphthalene detection, a U.V. analyzer, was highly priced at \$3,500.00.

3. Calibration of the analyzer for CO₂ - air mixture at 1 atm. total pressure.

Gas mixtures of CO₂ in air will be made and fed to the thermal conductivity analyzer equipped with a recorder. The following system will be used to make the gas mixtures.



Since O₂ and N₂ cause virtually the same reaction in the thermal conductivity analyzer, CO₂ - N₂ mixtures will suffice for the calibration.

PROCEDURE:

1. The receiving cylinder and lines are evacuated.
2. N₂ is fed to the receiving cylinder to a pressure of one atmosphere.
3. CO₂ is fed to the receiving cylinder at a pressure such that at the final pressure (total) of the mixture, the CO₂ concentration is

10% or 100,000 ppm. N_2 is fed to the cylinder until the final total pressure is attained.

4. Subject the receiving cylinder to a large temperature gradient across its longitudinal axis with a dry ice - acetone bath or heating blanket for approximately six hours.
5. Mixtures of lower concentration are produced from this first high pressure mixture by dilution with N_2 (steps 1 to 4)

Calibration will be spot-checked before each run.

3.5 The Surge Tank - (Figures 10 and 11)

The surge tank houses two banks of finned heaters, one heated by steam and the other heated electrically. The steam bank is composed of three independent finned tubes each having a finned length of 22 inches. The electrical bank has two 500 watt heaters, and three 250 watt heaters, each being independently controlled. One of the 250 watt heaters is connected to a Variac to allow fine temperature regulation. The reader may consult Appendix A for the design considerations involved.

The obvious function of the surge tank is aided by the presence of the converging section. The outer shell is partially supported from above by standard pipe supports, while the core is supported by an adjustable jack. When the test section core is to be changed, the jack is lowered to permit removal and then readjusted for the new core. Immediately downstream of the converging section, 4 symmetrically

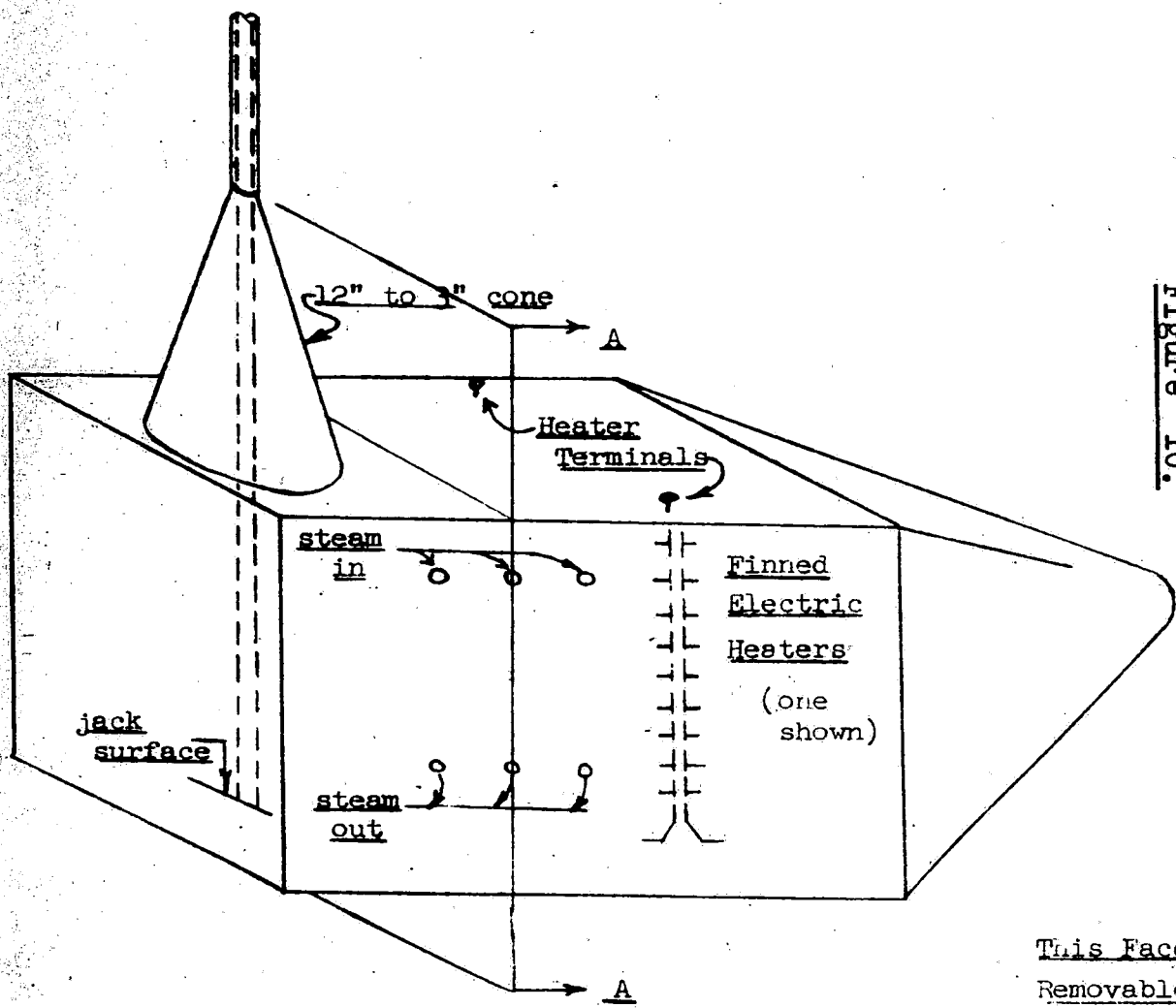
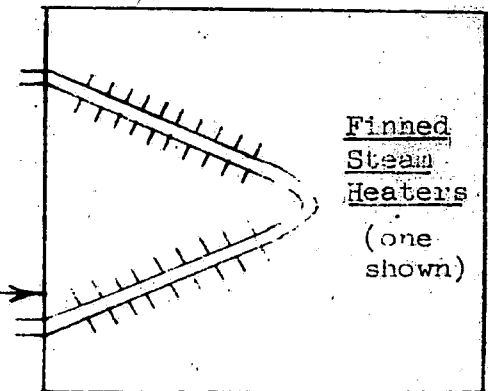


Figure 10.

This Face
Removable



Section AA



placed straightening vanes (fashioned from sheet aluminum) serve also to position the core of the annulus. These vanes 12" x 7/16" are rectangular in shape and are held rigidly by the milled slots provided on the inner core. A piece of 28 mesh stainless steel gauze placed in the flow path at the base of the converging section effectively reduces still further the turbulent fluctuations caused by the blower. The explanation of this action is that large-scale eddies are replaced by a larger number of much smaller eddies, which are known to decay much more rapidly. The design and location of the gauze are according to material presented by Rank-hurst (18).

3.6 Casting Apparatus

Two techniques were considered by the author:

- (1) Casting in a pre-cast, hard, smooth plaster mold.
- (2) Casting via the operating method of the Oliver filter (with vacuum action replaced by slow crystallization of molten naphthalene).

The reasons which led to the selection of method (2) are now summarized.

A thickness of 1/16" of naphthalene must be cast on the core before every run. The cast coating should be as dense as possible and the absence of air pockets must be assured. Method number (1) would consume too much time and would not guarantee reproducibility. Since the mold

must of necessity be made in two halves, great pains would have to be taken to remove parting line flash while maintaining a perfect circular cross section. Method (2) is described below. (See Figure #12).

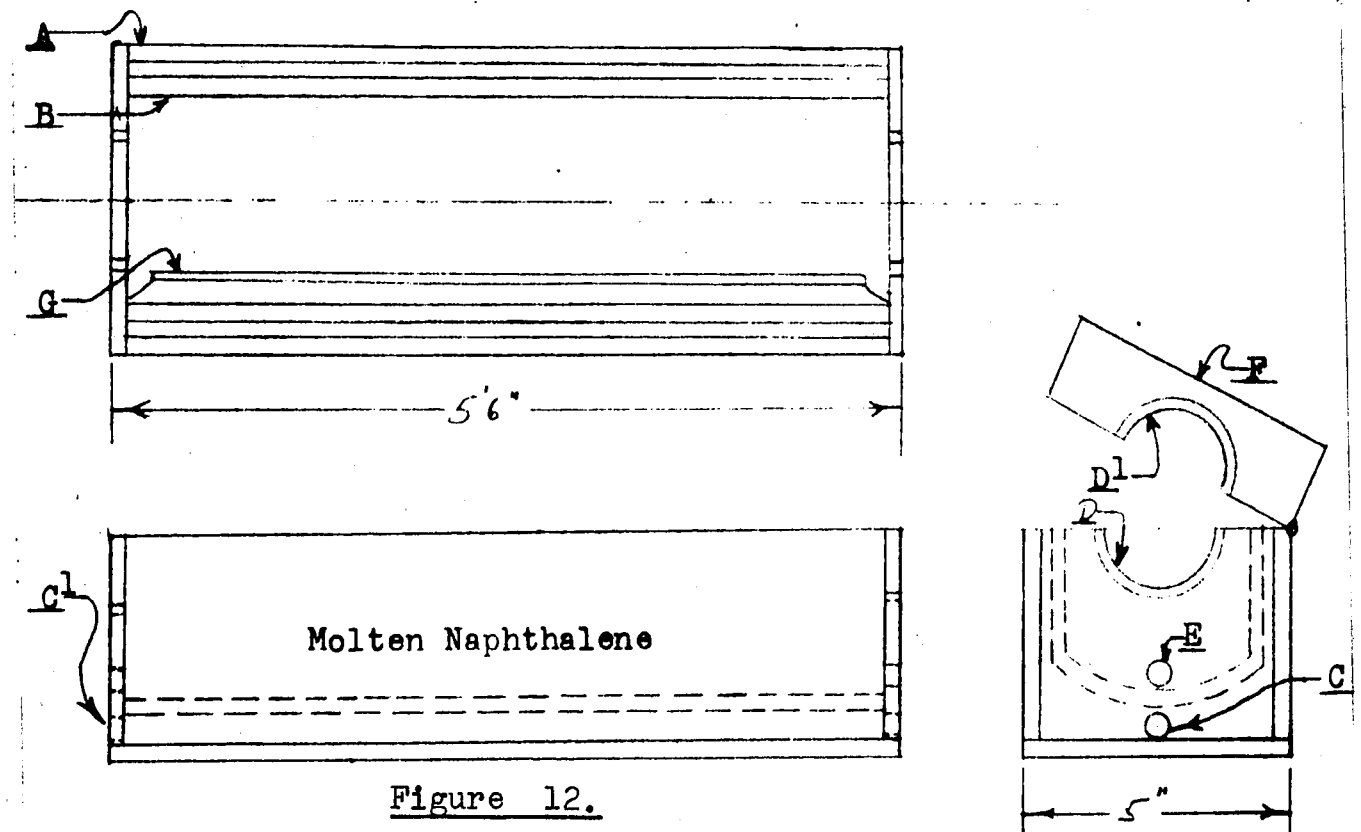


Figure 12.

All connections welded:

- A. Rectangular body, $\frac{1}{4}$ " steel.
- B. Naphthalene chamber, $\frac{1}{8}$ " steel sheet.
- C. Steam inlet hole.
- C' Steam outlet.
- D. Teflon Bushing (self lubrication, won't scratch).
- D' Mate to D.
- E. Drain for molten naphthalene.
- F. Hinged clamp, 2 required.
- G. Knife Blade, equipped with electrical strip heater.

PROCEDURE:

1. Melt naphthalene; clamp core into place and pass steam through it.
2. Set knife edge. Activate strip heaters on knife to a temperature of 82°C.
3. Begin rotation and cut off steam to core while continuing to pass steam to the chamber to keep the naphthalene molten. Pass cooling water through core.
4. When the coating has reached full thickness, allow molten Naphthalene to run out while maintaining rotation.

4. PROCEDURE AND THEORETICAL ANALYSIS

4.1 Procedure:

The forthcoming data will consist of velocity and concentration profiles of the annular stream at eight distinct longitudinal positions within the test section.

Before taking actual data, it will be necessary to determine empirically the rate of change of core diameter with time at some arbitrary turbulent Reynold's number (say 72,000) and at an air temperature of 70°C. The exposure-time periods will evolve from experience and the diameter measurements made to the nearest 0.001" using a micrometer caliper. The resulting change in diameter versus time data will aid in determining the maximum number of points on a particular concentration profile which may be taken during any one run. Preliminary calculations (See Appendix B) show a radial loss of $\sim 0.008 \frac{\text{in.}}{\text{min.}}$, calculated for the worst possible conditions. The following is a description of a typical point concentration run:

With valve V_3 (Figure #1) closed, V_1 and V_2 open, the blower is turned on along with the predetermined number of surge tank heaters required to heat the air to approximately 70°C, measured at temperature point T_2 . Air at 70°C will thus flow through the core only (for at least 0.25 hr.).
Turn on vacuum pump M.

With the naphthalene bed at temperature, the impact tube and feed mechanism are installed. It will be necessary to preheat the test section outer wall and the impact tube with electrical heating tape and a heating lamp to prevent undesirable crystallization of naphthalene. In order to prevent contamination of the analysis system with naphthalene, N_2 from a commercial cylinder will be back flushed slowly from the Gas Analyzer exit port through to the impact tube until ready to take data. It is understood that the long-needle control valve at the vacuum tank will have been set previously.

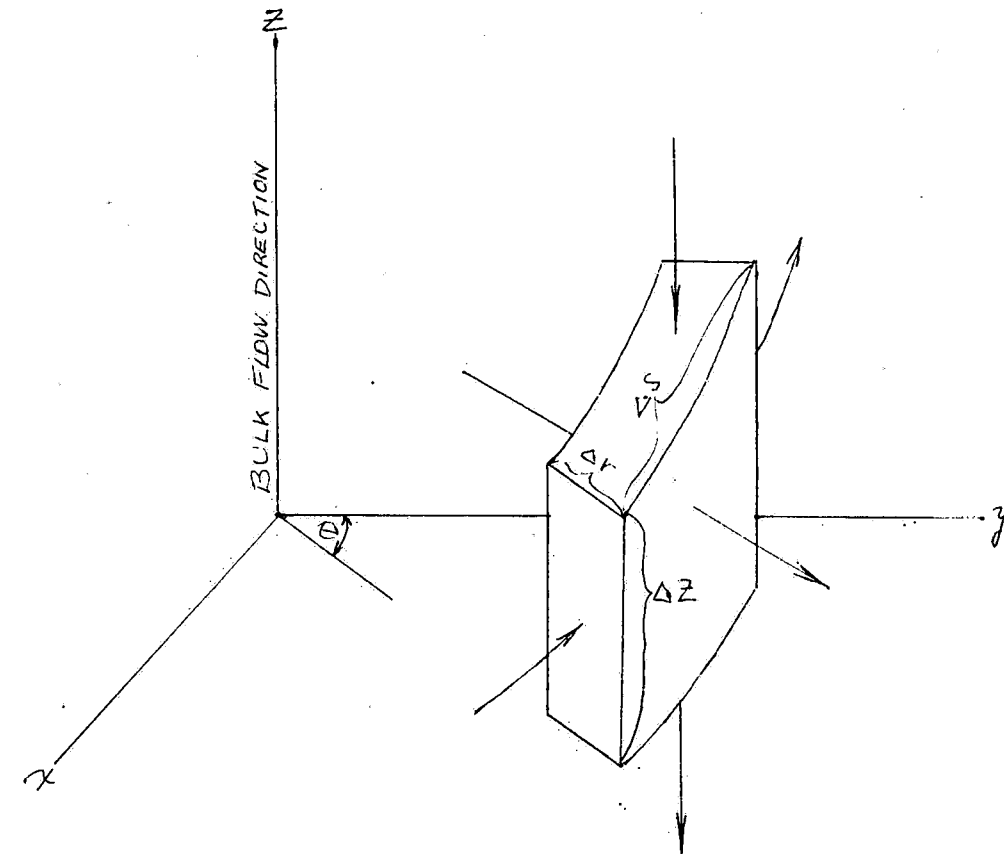
At this point, Valve V_3 is opened wide and V_2 is closed. The two valves are now manipulated as quickly as possible (for about one minute) to obtain the desired orifice meter reading at point F. Final air temperature adjustments (temperature point T_1) are made via the surge tank rheostat prior to stopping the N_2 backflush in the analysis system and cutting in the pre-set suction head from the vacuum tank.

The number of readings taken for a particular profile at any one time will of course depend upon the approximate rate of change of core diameter with time and the maximum allowable error tolerance, which will be governed by the reproducibility of the data. The author will not

attempt to make an error analysis at this time because there exist a myriad variables in the system as a whole, whose approximate range of variation is unknown.

4.2 Theoretical Analysis

The derivation and solution of the differential equation describing the physical situation within the test section will now be shown.



The Equation of material balance for the element shown.....
for Naphthalene, Input - Output = Accumulation

Assumptions

1. Ficks first law ($N_A = -D_{AB} \nabla C_A \frac{\text{mass of A}}{\text{area x time}}$) holds and molecular diffusion in the radial direction only need be considered.

2. The physical properties of the flowing stream are constant.
3. Steady State
4. Bulk Flow in the azimuthal (θ) and radial direction does not occur.

$$(\rho_A v_r | r \Delta r \Delta z - \rho_A v_r | r + \Delta r \Delta r \Delta z) - (D_{AB} \frac{\partial C_A}{\partial r} | r - D_{AB} \frac{\partial C_A}{\partial r} | r + \Delta r) \Delta r \Delta z + (\rho_A v_z | z \Delta r \Delta z - \rho_A v_z | z + \Delta z \Delta r \Delta z) = 0$$

now, since $\Delta s = r \Delta \theta$

$$(\rho_A v_r | r \Delta r \Delta z - \rho_A v_r | r + \Delta r \Delta r \Delta z) - (D_{AB} \frac{\partial C_A}{\partial r} | r \Delta r \Delta z - D_{AB} \frac{\partial C_A}{\partial r} | r + \Delta r \Delta r \Delta z) + (\rho_A v_z | z \Delta r \Delta z - \rho_A v_z | z + \Delta z \Delta r \Delta z) = 0$$

divide by $r \Delta \theta \Delta r \Delta z$

$$\left(\frac{\rho_A v_r | r}{\Delta r} - \frac{\rho_A v_r | r + \Delta r}{\Delta r} - \frac{\rho_A v_r | r + \Delta r}{r} \right) - \left(\frac{D_{AB} \frac{\partial C_A}{\partial r} | r}{\Delta r} - \frac{D_{AB} \frac{\partial C_A}{\partial r} | r + \Delta r}{\Delta r} - \frac{D_{AB} \frac{\partial C_A}{\partial r} | r + \Delta r}{r} \right) + \left(\frac{\rho_A v_z | z}{\Delta z} - \frac{\rho_A v_z | z + \Delta z}{\Delta z} \right) = 0$$

Let Δr and $\Delta z \rightarrow 0$

$$-\frac{\partial}{\partial r} \rho_A v_r - \frac{\rho_A v_r}{r} + \frac{\partial}{\partial r} D_{AB} \frac{\partial C_A}{\partial r} + \frac{D_{AB} \frac{\partial C_A}{\partial r}}{r} - \frac{\partial}{\partial z} \rho_A v_z = 0$$

This may be written as

$$\text{Eq. I} \quad -\frac{1}{r} \frac{\partial}{\partial r} (\rho_A v_r) + \frac{1}{r} \frac{\partial}{\partial r} (r D_{AB} \frac{\partial C_A}{\partial r}) - \frac{\partial}{\partial z} \rho_A v_z = 0$$

Now $\rho_A v_r$ and $\rho_A v_z$ are mass fluxes: $\rho_A v_r$ is the flux due to radial eddy diffusion (see assumption 4) while $\rho_A v_z$ is the axial flux due to bulk flow.

Re-writing Eq. I

$$\text{Eq. II } \frac{\partial}{\partial z} \rho_A v_z = \frac{1}{r} \frac{\partial}{\partial r} r [-\rho_A v_r + \rho_{AB} \frac{\partial C_A}{\partial r}]$$

By definition

$$N_A = -\epsilon \frac{\partial C_A}{\partial r} = \text{eddy mass flux; } \rho_A = C_A M_A$$

\therefore we may write

$$\text{Eq. III } \frac{\partial}{\partial z} C_A M_A v_z = \frac{1}{r} \frac{\partial}{\partial r} r [\epsilon + \rho_{AB}] \frac{\partial C_A}{\partial r}$$

Unfortunately, there exists no analytical solution to Equation III. Therefore, an approximate method will be used.

The left hand member of Equation III may be found experimentally - call it "Q"; expanding the right hand member:

$$\frac{1}{r} \left[(\epsilon + \rho_{AB}) \frac{\partial C_A}{\partial r} + \frac{\partial (\epsilon + \rho_{AB})}{\partial r} r \frac{\partial C_A}{\partial r} + \frac{\partial^2 C_A}{\partial r^2} r (\epsilon + \rho_{AB}) \right] = Q$$

or

$$\frac{\partial C_A}{\partial r} \left[\frac{(\epsilon + \rho_{AB})}{r} + \frac{\partial (\epsilon + \rho_{AB})}{\partial r} \right] + (\epsilon + \rho_{AB}) \frac{\partial^2 C_A}{\partial r^2} = Q$$

Since, at any given r , $\frac{\partial C_A}{\partial r}$ and $\frac{\partial^2 C_A}{\partial r^2}$ may be calculated, we have an equation of the following form:

$$B \left[C \frac{d(\epsilon + \rho_{AB})}{dr} + D(\epsilon + \rho_{AB}) \right] = Q$$

or

$$BC(\epsilon + \rho_{AB}) + B \frac{d(\epsilon + \rho_{AB})}{dr} + D(\epsilon + \rho_{AB}) = Q$$

or

$$\text{Eq. IV } \frac{d(\epsilon + \rho_{AB})}{dr} + \frac{(\epsilon + \rho_{AB})(BC + D)}{B} = \frac{Q}{B}$$

An integrating factor for this linear first order equation is $e^{\int \frac{BC+D}{B} dr} = e^{\frac{BC+D}{B} r}$. Multiplying Equation IV by this

factor gives

$$e^{\frac{BC+D}{B} r} \left[\frac{d(\epsilon + D_{AB})}{dr} + \frac{BC+D}{B} (\epsilon + D_{AB}) \right] = \frac{Q}{B} e^{\frac{BC+D}{B} r}$$

or

$$\frac{d}{dr} \left[(\epsilon + D_{AB}) e^{\frac{BC+D}{B} r} \right] = \frac{Q}{B} e^{\frac{BC+D}{B} r}$$

integrating

$$(\epsilon + D_{AB}) e^{\frac{BC+D}{B} r} = \frac{\frac{Q}{B} e^{\frac{BC+D}{B} r}}{\frac{BC+D}{B}} + k$$

or

$$(\epsilon + D_{AB}) e^{\frac{BC+D}{B} r} = \frac{Q}{BC+D} e^{\frac{BC+D}{B} r} + k$$

or

$$(\epsilon + D_{AB}) = \frac{Q}{BC+D} + k e^{-\frac{BC+D}{B} r}$$

If it is assumed that ϵ tends to zero at the naphthalene - air interface, we may find "k"

$$\text{at } r = \frac{1}{c} = r_1, \epsilon \rightarrow 0$$

$$\text{then } D_{AB} = \frac{Q}{BC+D} + k e^{-\frac{BC+D}{B} r_1}$$

$$k = \left[D_{AB} - \frac{Q}{BC+D} \right] e^{\frac{BC+D}{B} r_1}$$

$$(\epsilon + D_{AB}) = \frac{Q}{BC+D} + \left[D_{AB} - \frac{Q}{BC+D} \right] \exp\left[\frac{BC+D}{B} r_1\right] \exp\left[-\frac{BC+D}{B} r\right]$$

$$\epsilon = \frac{Q}{BC+D} - D_{AB} + \left[D_{AB} - \frac{Q}{BC+D} \right] \exp\left[\frac{BC+D}{B} r_1 - \frac{BC+D}{B} r\right]$$

finally,

$$\text{Eq. V } \epsilon = \frac{Q}{Bc + D} - D_{AB} + \left[D_{AB} - \frac{Q}{B + D} \right] \exp \left[-\frac{D}{B} \left(\frac{1}{c} - r_i \right) \right]$$

$$\text{where: } B = \frac{\partial C_A}{\partial r} \text{ at } r$$

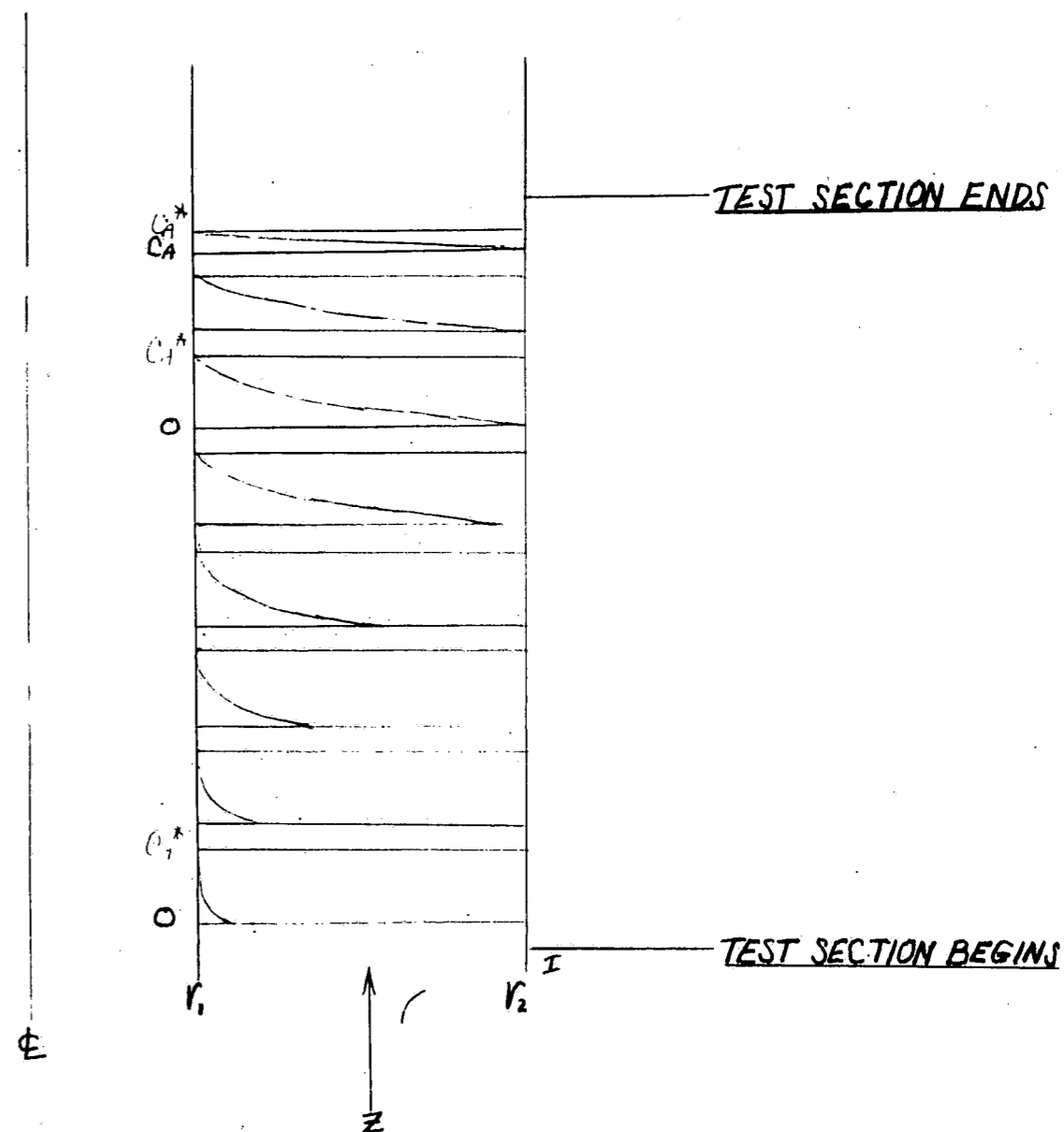
$$C = \frac{1}{r}$$

$$D = \frac{\partial^2 C_A}{\partial r^2} \text{ at } r$$

$$Q = \frac{\partial}{\partial z} C_A M_A \bar{v}_z \text{ at } r$$

Quantities "B", "D" and "Q" are all easily calculated from the data, via difference formulae. In particular $\frac{\partial C_A}{\partial r}$ and $\frac{\partial^2 C_A}{\partial r^2}$ are calculated from the radial concentration profiles and $\sqrt{z} M_A \frac{\partial C_A}{\partial z}$ from the longitudinal concentration profiles. Fortunately, the calculations are such that they may be programmed for a digital computer.

As an aid to the further discussion of Equation V, I now show the expected general shape of the concentration profiles for an arbitrary turbulent Reynolds number.



The concentration of naphthalene in the air at the core wall will reach a constant equilibrium value C_A^* (i.e.) molecular diffusion controls close to the interface since it is generally accepted that the flow in this region approaches the laminar regime. As one proceeds down the test section, the obvious occurs and the highly ordered situation at longi-

tudinal position I gives way to the increasing randomness of the downstream positions. It should be noted that the slope of the profile at the outer wall, anywhere in the test section, is zero - this must be true because there can be no transfer of mass through the boundary.

We now return to a further look at equation V-- does the expression conform with presently accepted facts? First, substitution of $r = r_1$, results in $\zeta = 0$, an assumption forced upon the equation as a boundary condition. Second, it was shown above that as r_2 is approached, $\frac{\partial C_A}{\partial r} \rightarrow 0$. As expected therefore, equation V results in an indeterminate value for ζ as $r \rightarrow r_2$ (i.e.) this result is also obtainable from the defining expression for ζ , namely,

$$N_A = - \zeta \frac{\partial C_A}{\partial r} .$$

5. NOMENCLATURE

- A area of flow path
- B $\frac{\partial C_A}{\partial r}$ at r
- C $\frac{1}{r}$
- C_A concentration of naphthalene at r, moles per unit volume
- C_A^* concentration of naphthalene at the air-naphthalene interface.
- D $\frac{\partial^2 C_A}{\partial r^2}$ at r.
- D_{AB} molecular diffusivity of naphthalene in air
- M_A molecular weight of naphthalene.
- N transfer of property per unit time.
- Q $\frac{\partial}{\partial z} C_A M_A \mathcal{V}_z$ at r.
- r radial distance from longitudinal axis.
- r_1 radial distance from longitudinal axis to outer surface of core.
- r_2 radial distance from longitudinal axis to inner surface of outer shell.
- \mathcal{V}_z bulk point velocity at r.
- α molecular diffusivity of heat -
- ∇ del operator
- ϵ eddy momentum diffusivity
- ϵ_H eddy diffusivity of heat
- ϵ_m eddy mass diffusivity
- ν kinematic viscosity

ρ_A Concentration of naphthalene = C_{AA}^M , mass per unit
volume.

τ shear force per unit area.

APPENDIX A

A I R H E A T I N G R E Q U I R E M E N T S

The following table was constructed as an aid; sample calculations appear below the table:

<u>N_{Re}</u>	<u>Inlet Rate To Tank, ft³/min.</u>	<u>Heat Required BTU/min.</u>		<u>Wattage Required K W</u>	
		<u>Air in at 90°F</u>	<u>Air in at 80°F</u>	<u>Air in at 90°F</u>	<u>Air in at 80°F</u>
10,000	35.8	42.9	49.3	0.755	0.860
20,000	71.6	85.6	98.5	1.51	1.73
30,000	107.8	129	148	2.27	2.61
40,000	143.5	172	197	3.03	3.46
50,000	179	214	247	3.77	4.35
60,000	214	256	294	4.51	5.18
72,500	260 (max)	311	358	5.46	6.30

Air out at
158°F

Sample Calculations:

Properties of air at 158°F

$$\mu = \frac{0.0000134 \text{ lb.m}}{\text{ft sec}}$$

$$\rho = \frac{1/\text{M.Wt.}}{V} = \frac{P}{R_T}$$

$$\rho = \frac{P(\text{M.Wt.})}{R(t^{\circ}\text{F} + 459.7)} = \frac{1.327P}{t + 459.7} = \frac{1.327(29.92)}{617.7}$$

$$\rho = 0.0641 \text{ lb/ft}^3$$

$$\nu = \frac{\mu}{\rho} = \frac{0.0000134}{0.0641} = 0.000209 \frac{\text{ft}^2}{\text{sec.}}$$

$$\text{For } N_{Re}(\text{max}) = \frac{D \text{ eq } U}{\nu} \quad D \text{ eq} = D_2 - D_1 = 3 - 2 = 1 \text{ in. or } \frac{1}{12} \text{ ft}$$

$$U = \frac{Q}{A} = \frac{260 (617.6)}{\frac{\pi}{4} (3^2 - 2^2)/144} = 181.5 \frac{\text{ft.}}{\text{sec}}$$

$$N_{Re}(\text{max}) = \frac{(\frac{1}{12}) (181.5)}{0.000209} = 72,500$$

For Heat Required at N_{Re} (max)

$$\text{at } 80^{\circ}\text{F}, \rho = \frac{1.327(29.92)}{540} = 0.0735 \text{ lb/ft}^3$$

$$260 \frac{\text{ft}^3}{\text{min}} \times 0.0735 \frac{\text{lb.}}{\text{ft}^3} \times 0.24 \frac{\text{BTU}}{\text{lb}^{\circ}\text{F}} (158-80)^{\circ}\text{F} = 358 \frac{\text{BTU}}{\text{min.}}$$

For Wattage Required at N_{Re} (max)

$$\frac{358 \text{ BTU/min.}}{56.92 \frac{\text{BTU/min.}}{\text{K W}}} = 6.3 \text{ K W}$$

The power rating at the Graduate Laboratory (30 amps, 120 V) is too low to handle a 5 - 6 KW load. Consequently heating will be accomplished mostly by steam heated finned tubes.

A quantity of old refrigeration finned tubing was found in storage and the finned area per lineal inch was measured as 29.2 in²/inch. The heat transfer coefficient was found very approximately using Fig. 17-26, p. 519 of "Fluid Dynamics and Heat Transfer" by Knudsen and Katz. The value was found to be $\sim 10 \frac{\text{BTU}}{\text{hr ft}^2\text{ }^{\circ}\text{F}}$.

A number of mental trials with the aid of the heating table resulted in the following arrangement:

3 independent steam tubes of 100 $\frac{\text{BTU}}{\text{min.}}$ capacity and

A group of electrical finned heaters whose combined capacity equals one steam tube.

For length of steam heaters required

$$\text{Area in in}^2 = \frac{100 \text{ BTU/min.}}{10 \frac{\text{BTU}}{\text{hr ft}^2\text{ }^{\circ}\text{F}} \times \frac{1 \text{ hr}}{60 \text{ min.}} \times \frac{1 \text{ ft}^2}{144 \text{ in}^2} \times (212-80)^{\circ}\text{F}}$$

$$\text{Area} = 655 \text{ in}^2$$

$$\text{Length req'd.} = \frac{655 \text{ in}^2}{29.2 \text{ in}^2/\text{in}} = 22.4 \text{ in.}$$

For Electrical Heaters (Chromalox brand)

One steam finned tube has a capacity of 100 $\frac{\text{BTU}}{\text{min.}}$
or $\sim 1.75 \text{ KW.}$ The charts found in the Chromalox Catalog
were used to size the heaters as follows:

500 W } S-F - 21, IRON SHEATH, 120 V
500 W }

250 W } S-F - 12, IRON SHEATH, 120 V
250 W }
250 W }

1750 Watts

APPENDIX B

CALCULATION FOR EXPECTED RATE OF LOSS OF
NAPHTHALENE FROM CORE SURFACE

The laminar sublayer on the naphthalene core provides the greatest resistance to mass transfer so that the relation describing rate of loss of solid is

$$\frac{N}{A} = -\mathcal{D} \frac{dC}{dy}$$

Units

N, $\frac{\text{lb}}{\text{hr}}$ A, ft^2 \mathcal{D} , $\text{ft}^2/\text{hr.}$ C, lb/ft^3

y, - ft.

For \mathcal{D}

Gilliland's equation for diffusion coefficients becomes

$$\mathcal{D} = \frac{20.25(T)^{3/2}}{P} \times 10^{-6}$$

T = temp, °R

P = pressure, atm.

At the conditions chosen for this work, T = 15°R.
and P = 1 atmosphere, $\mathcal{D} = 0.306 \text{ ft}^2/\text{hr.}$

For $\frac{dC}{dy}$

The concentration gradient in the laminar sublayer will necessarily change along the test section, being greatest at the beginning of the test section. The gradient at this point will be used for the calculation since it constitutes the worst possible case.

The thickness of the laminar sublayer, δ , decreases with increasing Reynolds number, as shown in (19). It is seen that at $N_{Re} \approx 85,000$, the highest for this work, $\delta \approx 0.003"$.

The concentration at the solid naphthalene surface is assumed to be given by the vapor pressure of the solid at the chosen conditions. (20) gives a value of 4.88 in in Hg. Hence the surface concentration is $\frac{4.88}{760} = 6.41 \times 10^{-3}$ mole naphthalene / mole air + naphthalene.

At the beginning of the test section, the concentration of naphthalene at the outer edge of the laminar sublayer is zero.

Since δ is so small, $C = f(y)$ may be considered linear

$$\text{and } \frac{dC}{dy} = \frac{\Delta c}{\Delta y} = \frac{6.41 \times 10^{-3} - 0}{0.003/12} \left(\frac{\text{mole Naphthalene}}{\text{mole mixture}} \right) \times \frac{128 \text{ lb. Nap}}{\text{lb mole Nap}} \times \frac{1 \text{ lb mole air}}{451 \text{ ft}^3}$$

$$\frac{dC}{dy} = 7.26 \frac{\text{lb naphthalene/ft}^3 \text{ mixture}}{\text{ft.}}$$

$$\text{Hence } \frac{N}{A} = (-0.306 \frac{\text{ft}^2}{\text{hr}}) (7.26 \frac{\text{lb naphthalene/ft}^3}{\text{ft.}}) = -2.22 \frac{\text{lb. Nap}}{\text{hr ft}^2}$$

In terms of volume, since $\rho_{\text{Naphthalene}} \approx 70 \frac{\text{lb}}{\text{ft}^3}$

$$\frac{N}{A} = -2.22 \left(\frac{1 \text{ ft}^3}{70 \text{ lb}} \right) = -0.0318 \frac{\text{ft}^3 \text{ naphthalene}}{\text{hr ft}^2}$$

The exposed surface area will shrink with time, but the initial area will be considered as the sublimation area so that the calculation will give a high result.

$$\text{Surface Area} = 2\pi r^2 = 2\pi \left(\frac{1}{12} \right)^2 (5) = 2.62 \text{ ft}^2$$

$$\text{and } N = (-0.0318)(2.62) = -0.0832 \frac{\text{ft}^3 \text{ naphthalene}}{\text{hr.}}$$

In terms of radial loss,

$$\pi \left[\left(\frac{1}{12} \right)^2 - r_{\text{final}}^2 \right] 5 = 0.0832 \frac{\text{ft}^3}{\text{hr}}$$

$$\frac{1}{144} - r_f^2 = \frac{0.0832}{5\pi} = 0.00530$$

$$r_f^2 = 0.00695 - 0.0053 = 0.00165$$

$$r_f = 0.0410$$

$$r_{\text{initial}} - r_{\text{final}} = \frac{0.0833}{0.0410} = 0.0423 \text{ ft/hr}$$

$$\quad \quad \quad \times \frac{12 \text{ in}}{\text{ft}}$$

$$r_{\text{initial}} - r_{\text{final}} = 0.518 \text{ in./hr}$$

or 0.0084"/minute

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V I T A

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