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PRESSURE LOSS ASSOCIATED WITH AIR FLOW IN ELECTRICAL CONDUITS

by

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PREFACE

The Division of Building Research welcomed the opportunity to assist a Subcommittee of the Canadian Standards Association by undertaking to determine the friction coefficients for air flow in filled electrical conduits. This work, although immediately related to a very restricted interest in the broad field of building design and construction, has nevertheless paralleled very closely the interests of the Division in air flow in ducts for heating and air-conditioning systems. The flow measurement apparatus developed and the experience which has been obtained will be useful in future work of this kind. The effort made to obtain accurate data, although perhaps not justified by the immediate needs for electrical conduit application, has however resulted in good basic friction data for the particular cases tested which when published may find broader application.

Ottawa,
July 1956.

N. B. Hutcheon,
Assistant Director.

PRESSURE LOSS ASSOCIATED WITH AIR FLOW IN ELECTRICAL CONDUITS

by D. G. Stephenson

Recently the problem has arisen of how to design an electrical conduit system so that its internal static pressure will always exceed its ambient static pressure by a specified amount. This was needed to ensure that there would be no inflow where the conduit passed through a region of corrosive or explosive gases. Since some leakage is practically unavoidable with standard fittings there will have to be some flow through the conduit system; and associated with this flow there will be a pressure drop. It appears that there are no data in the engineering literature on the pressure drop for flow in partially filled conduits, so it was to provide these needed data that the present investigation was undertaken.

The pressure drop vs. mass flow has been obtained for each of the twenty seven combinations of the following variables:

(1)	Conduit size:	3/4 inch, 1 inch, 1 1/4 inch
(2)	Wire size:	10, 12, 14-gauge, with plastic insulation,
(3)	Arrangement:	One, two, and three conductors in each conduit - nontwisted.

In addition to the above listed tests the effects of the following variables were studied for some of the above combinations:

(1) Rubber insulation rather than plastic,

(2) Twisting the conductors, and

(3) A standard coupling and a 90° elbow in the conduit.

It has been possible to correlate the data from these tests so that they indicate a relationship between the geometry of the conduit and wire; the physical properties and mass flow rate of the gas flowing through the conduits; and the pressure loss associated with this flow.

DESCRIPTION OF APPARATUS

For all of the tests which required a flow of air through the conduit the apparatus was arranged as shown in Fig. 1. The air was obtained from the laboratory compressed air supply main and was reduced from 100 psi in the main to between 2 and 20 psi at the inlet side of the throttling valves. Immediately ahead of the pressure reducing valve the air passed through a Logan aridifier. This eliminated any droplets of water or oil as well as particles of pipe scale or rust which might be in the compressed air. No provisions were made for measuring or controlling the humidity of the air but when calculating the density of the air it was assumed to be saturated at 100 psig and 72°F (this corresponds to a dew point of 20°F at a pressure of 1 atmosphere). The quantity of air flowing through the system was controlled by the throttling valves on the low pressure side of the pressure reducing valve.

From the flow control panel the air passed through a 20-foot length of 1 1/4-inch galvanized iron pipe into a 1 1/4-inch header pipe and thence through any one of the three 40-foot runs of conduit to the orifice tank and through the flow metering orifice into the atmosphere. The orifice tank and orifice plates are essentially the same as those which were calibrated by Polson* and the orifice coefficients determined by Polson have been used for these tests.

Data were required for the pressure drop due to friction in a continuous run of conduit as well as in a conduit composed of 10-foot lengths of conduit jointed by a standard conduit coupling. Since conduit is usually supplied in 10-foot lengths, special couplings were needed to join the sections without causing any roughness or irregularity at the junction.

Because the conduit was supplied in 10-foot lengths it was convenient to measure the pressure drop along each 10-foot section of the continuous run. For this purpose six static pressure holes 1/16-inch in diameter were drilled at 60° intervals around the conduit approximately 4 inches from one end of each 10-foot section. These holes were covered by brass piezometer rings which were soldered to the outside of the conduit to make an airtight seal. Fig. 2 shows the details of both the coupling and the piezometer rings.

The inside of the conduit was reamed for approximately 6 inches at the end where the piezometer ring was fitted and 2 inches at the other end. This reaming ensured that the internal area of the flow passage was the same at each pressure tapping and also that the inside diameter of the two conduits which were brought together were the same. As shown in Fig. 1 all the differential pressure measurements were made with a Betz 400 mm water manometer and the gauge pressures through the system were measured by Merrian 100-inch vertical manometer using CCl_4 as the manometer fluid. To enable the manometers to be connected to any of the twelve piezometer rings as well as the static pressure taps on the orifice tank a simple pressure

*Polson, J.A. and J.G. Lowther. The flow of air through circular orifices in thin plates. Univ. of Ill., Engineering Experiment Station, Bull. No. 240, 1932.

switching panel was used. The schematic arrangement of this panel is shown in Fig. 3. With this arrangement the Betz manometer could be easily connected to read the differential pressure between any two piezometer rings or the pressure drop across the orifice plate.

Before the apparatus was assembled it was necessary to determine the internal cross-sectional area of each length of conduit. These measurements required an auxiliary apparatus which is shown schematically in Fig. 4. A 10-foot length of conduit was suspended vertically with its lower end about 2 inches below the surface of the water in a 4-liter beaker. This beaker was set on the pan of a Toledo 5-kg balance. The conduit was supported by a length of braided monel wire which passed over the two pulleys on the upper support bracket and then was attached to the upper end of the adjustment screw. By turning the large knurled nut on this screw it was possible to vary the vertical position of the conduit so that its lower end was always located the same distance below the surface of the water in the beaker. This adjustment was facilitated by attaching a hook gauge to the lower end of the conduit. The piezometer ring pressure fitting at the top end of the conduit was connected to the top of the 100-inch vertical manometer by plastic tubing. From a tee fitting at the top of the manometer both the manometer and the conduit were connected through a 1/8-inch needle valve to a low pressure tank. With this arrangement the pressure in the system could be progressively reduced causing water from the beaker to rise up the conduit as the carbon tetrachloride rose in the manometer tube.

DESCRIPTION OF TESTS AND REDUCTION OF DATA

1. Determination of the Friction Factor for the Empty Conduit

The friction factor for flow in a circular pipe is defined by:

$$f = \frac{\Delta P}{L} \cdot \bar{d} \cdot \frac{2}{\rho . V^2} ,$$

where ΔP = pressure drop due to friction in a piece of conduit of length L,

$\bar{d}$ = mean diameter of the flow passage,

ρ = mean density of the fluid,

V = mean velocity of the fluid.

Thus to determine the friction factor it is necessary to know the mean velocity as well as the pressure drop per unit length of pipe and the conduit diameter.

The mean velocity was obtained from the flow rate which was measured with a thin plate orifice. The mass flow through the orifice is given by:

$$M' = C'.A'.\rho'.V'.$$

Where C' = orifice discharge coefficient,

A' = orifice area,

ρ' = mass density of the fluid at the orifice

V' = the ideal velocity through the orifice,

The ' indicates conditions at the orifice.

The velocity V' is related to the differential pressure across the orifice (i') by:

$$(V')^2 = \frac{2\ i'}{\rho'}$$

Therefore, $M' = C'.A'.\ (2\ i'.\rho')^{\frac{1}{2}}$

The mass flow can also be expressed in terms of the velocity in the conduit:

$$M' = M = A.\rho.V,$$

Therefore, $\dfrac{\rho.V^2}{2} = \dfrac{(M')^2}{2\rho A^2}$.

Substituting for M' gives:

$$\frac{\rho V^2}{2} = (C')^2\ .\left(\frac{A'}{A}\right)^2\ .\ \frac{\rho'}{\rho}\ .i'.$$

But $\dfrac{\rho'}{\rho} = \dfrac{P'}{P}$ where the temperature is constant,

and $\dfrac{A'}{A} = \dfrac{D^2}{(\bar{d})^2}$

where D is the diameter of the orifice,

P is the absolute pressure in the conduit,

and P' is the absolute pressure at the orifice.

The expression for the friction factor becomes:

$$f = \frac{\Delta P}{L} \cdot \frac{(\bar{d})^5}{D^4} \cdot \frac{P}{P'} \cdot \frac{1}{(C')^2 . i'}$$

The units used in this expression need not all be of the same system but when mixed units are used it is necessary to check that f is dimensionless.

To obtain the pressure drop per unit length the drop in static pressure was measured between successive tappings located at 10-foot intervals along the conduit.

The procedure for these tests was as follows:

(1) The Betz manometer was connected to measure the differential pressure across the orifice plate and the flow was adjusted until a desired flow was established;

(2) The Betz manometer was switched to measure the pressure drop along one of the 10-foot sections of the conduit. The gauge pressure at the upstream end of the section under test was measured with the vertical 100-inch manometer;

(3) The Betz manometer was switched back to check the flow rate and if this was still at the desired value the pressure drop data for the pipe were recorded and the manometer switched to measure the loss along the next section of pipe.

This procedure was continued until each of the 10-foot test sections had been checked twice at the same rate, then the flow was increased and the same series of operations repeated. Four different flow rates were used for each orifice plate. These corresponded to differential pressures of 1 cm, 4 cm. 16 cm, and 39 cm of water. The 4 cm and 16 cm values were chosen since for these values the flow was approximately double its preceding value, hence when the data were plotted on a logarithmic scale the points were evenly spaced.

On the other hand, 1 cm and 39 cm values were used because they were close to the limits obtainable with the Betz manometer. The orifice plates used had nominal diameters of 1/2 inch, 3/4 inch and 1 1/4 inch which gave flow rates of approximately 2 to 13 cfm; 4 to 27 cfm and 12 to 90 cfm respectively when the differential pressures ranged between 1 and 39 cm of water.

The overlapping of the ranges of the orifice plates provided a check on the accuracy of the orifice coefficients. This point is discussed in the section dealing with the analysis of the test results.

The data obtained from this series of tests along with the calculated values of the friction factor and the Reynolds number are included in Table A-3 of Appendix A.

The methods of calculation are presented in Appendix B in the form of a sample calculation.

The friction factor equation shows that:

$$f \propto (\bar{d})^5.$$

Thus an error in the value of $\bar{d}$ causes fives times as great a percentage error in f. For this reason the mean diameters of the conduits were carefully measured.

2. Determination of the Root Mean Square value of the Conduit Diameter.

In principle the diameter of the conduit was obtained by measuring the internal volume of a length of the conduit. The volume ÷ length gave an average value of the cross-sectional area which equals $\pi/_4(\bar{d})^2$, where $\bar{d}$ is the r.m.s. value of the diameter.

With the apparatus arranged as shown in Fig. 4 the pressure inside the conduit could be reduced by opening the valve V_1. This caused the water to rise in the conduit and the carbon tetrachloride in the 100-inch manometer. In each case the rise in the fluid level above the level in the tank was related to the pressure difference between the inside of the conduit and the atmosphere by the expression:

$$12.\,\Delta p = (\rho.g.H)_m = (\rho.g.H)_c.$$

where,

Δp is the static pressure difference between the atmosphere and the inside of the conduit (lb/ft^2)

ρ is the mass density of the fluid ($slug/ft^3$)

g is the acceleration due to gravity (ft/sec^2)

H is the height of the fluid inside the conduit or manometer tube above the level of the tank (in.)

The subscripts m and c refer to the manometer and conduit respectively.

The tests were carried out in a room where the temperature was very nearly constant but any small changes in ρ_m or ρ_c were taken into account by a calibration which was performed immediately before each test on a length of conduit. For the calibration the plastic tubing was removed from the pressure connection on the upper end of the conduit and attached instead to the low pressure side of a Betz micromanometer. With the low pressure tank open to the atmosphere both the micromanometer and the 100-inch vertical manometer were adjusted to zero. Then the pressure in the system was reduced sufficiently to make H_m equal to 9 inches. The corresponding indication of the Betz manometer (H_w) was noted and also the temperature of the distilled water in the Betz manometer. Knowing this temperature the density of the distilled water (ρ_w) was obtained directly from a set of physical tables. Thus:

$$\rho_m = \frac{\rho_w . H_w .}{9}$$

To measure the internal cross-sectional area of a length of conduit the conduit was suspended as shown in Fig. 4, the mass of the beaker of water was measured first when $H_m = 0(M_0)$ and again when $H_m = 70$ inches (M_{70}). In each case the vertical position of the conduit had to be adjusted so that the hook gauge just touched the surface of the water in the beaker when the weight of the beaker was measured.

Then $\quad M_0 - M_{70} = \rho_c . H_c . \bar{A},$

where $\quad \bar{A} = \frac{\pi}{4} (\bar{d})^2 ,$

but $\quad H_c . \rho_c = 70 \rho_m = \frac{70}{9} . \rho_w H_w ,$

Therefore $\quad (\bar{d})^2 = \frac{4}{\pi} . \frac{9}{70} . \frac{M_0 - M_{70}}{\rho_w . H_w}$

Since the balance used to measure the mass of the beaker was calibrated in gm, and the manometer indicated H_w in cm it was convenient to calculate $\bar{d}$ in cm and ρ_w in gm/cm^3. Then to obtain $\bar{d}$ in feet it was only necessary to multiply by the conversion factor $\frac{1}{2.54 \times 12}$. A sample calculation is given in Appendix B.

The specific gravity of the manometer fluid (CCl_4) was approximately 1.6; thus the value of $\bar{d}$ calculated using M_0-M_{70} was an average for 112 inches of the 120-inch length of conduit. The 8 inches not included were the sections which had been reamed to a known diameter. The value of M was recorded for each value of H_m which was an integral multiple of five, i.e., for $H_m = 5, 10, 15,$ - - - - 70. The data were obtained only while the water level was rising in a dry piece of conduit because once the water had wetted the inside of the conduit, a thin film of water remained on the surface after the water level had fallen. These data showed the variations in diameter along each 10-foot piece of conduit. However, the variation was always so small that the difference between the rms(1) and rmf(1) values of $\bar{d}$ was negligible. Because of this, rms values were used to calculate the friction factor and only one complete set of data for a typical conduit is included in Table A-1(ii) of Appendix A. For all of the other lengths of conduit only the values of M_0 and M_{70} are included, along with H_w, ρ_w and the calculated r.m.s. value of $\bar{d}$.

3. The Calculation of the Reynolds Number for the Empty Conduit

The Reynolds number for flow in a circular pipe is defined as:

$$Re = \frac{V.\rho.\bar{d}}{\mu} ,$$

but $$\rho.V = \frac{M}{A} = C'.\frac{A'}{A}.(2i'\rho')^{1/2}$$

and $$\rho' = \frac{P'}{1715.5\ T} .$$

Therefore $$Re = \frac{C'D^2}{\bar{d}\mu}.\left(\frac{2\ i'\ P'}{1715.5\ T}\right)^{1/2}$$

For this quantity to be dimensionless a consistent system of units must be used. In this case the pressure is expressed in lb/ft^2; the temperature in °R; the diameters in ft.; and the visocsity in slug/ft/sec. However, since the pressures were measured by a manometer and a barometer it is more convenient to take i'_* in mm water and P'_* in mm mercury and include the appropriate conversion factor in the expression for Re. The subscript * is used to indicate that standard English units are not being used.

The Reynolds number is then given by:

$$Re = \frac{C'D^2}{\bar{d}\mu}\left(\frac{2 \times 0.20436}{1715.5\ T}\quad i'_* \times 2.7846\ P'_*\right)^{1/2}$$

$$= 0.025757\ \frac{C'D^2}{\bar{d}\mu}\left(\frac{i'_*\ P'_*}{T}\right)^{1/2} ,$$

---

1 The rms value of $\bar{d} = \sqrt[2]{(\overline{d^2})}$

and rmf value of $\bar{d} = \sqrt[5]{(\overline{d^5})}$

When calculating an average value of f the rmf value of $\bar{d}$ should be used because $f \propto d^5$.

where i'_* and P'_* are in mm of water at 72°F and mm mercury at 32°F respectively and the other quantities are in the usual English units.

A sample calculation is included in Appendix B.

4. Determination of the Equivalent Diameter for a Straight Conduit Partially Filled with Wire

For flow in an empty circular pipe in series with an orifice plate the relationship between the friction factor and the measured quantities is:

$$f = \frac{\Delta P}{i'} \cdot \frac{(\bar{d})^5}{L\ D^4} \cdot \frac{P}{P'} \cdot \frac{1}{(C')^2} .$$

By simply transposing, this becomes:

$$(\bar{d})^5 = f \cdot (C')^2 \cdot \frac{i'}{\Delta P} \cdot L\ D^4 \cdot \frac{P'}{P} .$$

When the conduit is partially filled by wire this equation can be used to calculate the diameter of an empty conduit which would have the same pressure drop vs. mass flow characteristic. This diameter is called the equivalent diameter d_e.

After the friction factors had been found for the empty conduits the various wire fills were pulled into the conduit. The wires were pulled in one at a time so that they could not become twisted. With each arrangement the pressure drop vs. mass flow relationship was determined in the same way as for the empty pipes.

The data obtained from these tests are presented in Tables A-4(i), A-4(ii), A-4(iii), and A-4(iv) of Appendix A. In Table A-5 data are included for a further series of tests in which the wire fills were twisted at the rate of three twists for each 10-foot length of conduit.

For the calculation of d_e it is assumed that f varies with Re in the same way as it did for the same piece of conduit without wire. Hence to calculate d_e it is necessary to assume a value of f, then use this to find a value of d_e and with this d_e calculate Re. From this value of Re and the curve relating f to Re for the empty pipe a second value of f is obtained and d_e recalculated. Since f changes only slowly with Re it is usually not necessary to make more than two calculations to obtain the accurate value of d_e. A sample of this calculation is included in Appendix B.

To avoid introducing an error into d_e due to an inaccurate value of the orifice discharge coefficient, the same values of C' were used when calculating the equivalent diameter as were used initially to determine the friction factor. In addition the value of f used for the accurate calculation of d_e was taken from the f vs. Re curve which was obtained from measurements made with the same orifice plate.

5. Determination of the Equivalent Length of a Threaded Coupling and a Long Radius 90° Elbow

When the tests on the continuous 40-foot runs of conduit were completed the conduits were cut at approximately 22 feet from the inlet end. A tapered pipe thread was cut on each of the pieces and the conduit re-assembled using a standard threaded coupling to join the two parts of each conduit.

Data were obtained on the pressure loss through the conduit for the same mass flow rates as were used for the original friction factor determinations. By comparing these data with those from the continuous runs of conduit it was possible to determine the equivalent length of the coupling.

The increase in pressure drop due to the presence of the coupling can be equated to the pressure drop in a length of pipe of the same diameter. This length of pipe is here called the equivalent length of the coupling. Then the pressure drop for 10 feet of conduit ΔP_*; and the pressure drop for 10 feet of conduit plus a coupling ΔP_c can be related to the equivalent length of the fitting by:

$$\left(\frac{\Delta P_c}{\Delta P_*}\right)_{iii} = \frac{10 + l_e}{10} \quad ,$$

$$\text{or} \quad l_e = 10\left\{\left(\frac{\Delta P_c}{\Delta P_*}\right)_{iii} - 1\right\}$$

The subscript iii indicates that the pressure drops were those measured for the third 10-foot length of conduit, i.e. between 20 and 30 feet from the conduit entry.

Since it was not possible to ensure that the conditions were exactly the same for the tests with the coupling as for the previous tests with continuous conduit, the ratio $(\Delta P_c/\Delta P_*)_{iii}$ was multiplied by a factor $(\Delta P_*/\Delta P_c)_{ii}$ which accounts for small changes in flow conditions between tests. Here the subscript ii indicates that the data are for the conduit between 10 and

20 feet from the entry. Thus the expression for l_e becomes:

$$l_e = 10 \left\{ \left(\frac{\Delta P_c}{\Delta P_*}\right)_{iii} \cdot \left(\frac{\Delta P_*}{\Delta P_c}\right)_{ii} - 1 \right\} \text{ ft.}$$

The ratio $l_e/\bar{d}$ for different pipe sizes and Reynolds numbers is given in Table A-6(i) of Appendix A along with the data on which the calculations are based.

Similarly a long radius 90° elbow was installed at the cut in each conduit. The elbow was joined to each piece of conduit by a standard threaded coupling and the equivalent length of the elbow plus couplings determined as described above for the coupling alone. These data and the calculated values of $l_e/\bar{d}$ are also given in Table A-6(i) of Appendix A. A sample calculation for $l_e/\bar{d}$ is given in Appendix B.

The equivalent lengths of the 90° elbows were also determined when the conduit and elbows contained one strand of 10-gauge rubber-insulated wire. In this case the data for the tests with the elbow were compared with the data for the same fill with the continuous conduit and the equivalent length calculated as before. The data are given in Table A-6(ii) of Appendix A along with the ratio l_e/d_e.

ANALYSIS OF TEST DATA

1. Friction Factor Tests

In the tests to determine the relationship between the friction factor and the Reynolds number for the empty conduit it was possible to cover the same range of pipe Reynolds number with two or in some cases three different diameter orifice plates. When log f was plotted against log Re it was found that a smooth curve could be drawn through the data obtained with any one orifice plate; but there was a different curve for each orifice plate. This indicated that the values of the orifice discharge coefficient that were used were not accurate.

From the curves of log f vs. log Re it is possible to calculate the difference in the flow which would be indicated by the various orifice plates.

The pressure loss due to friction is:

$$\Delta P = f \cdot \frac{L}{\bar{d}} \cdot \frac{\rho V^2}{2} \quad ,$$

$$\text{and} \quad Re = \frac{V.\rho.\bar{d}}{\mu}$$

$$\text{Therefore} \quad \Delta P = f \cdot \frac{L\mu^2}{2\rho\bar{d}^3} \cdot (Re)^2 \; .$$

Thus for one particular piece of pipe with standard temperature and pressure conditions, a straight line of slope -2 on the log f vs. log Re graph corresponds to a constant value of ΔP or flow rate, since ΔP is dependent on flow rate. The values of Re for the points where this line intersects the various friction factor - Reynolds number curves correspond to the flow rates which the orifice plates would indicate if the same mass flow were passed through each.

Using this method and the curves for the third ten-foot section of the 1-inch conduit it was found that:

$$Q_{3/4} = 0.991\ Q_{1/2}$$

$$\text{and} \quad Q_{1\ 1/4} = 0.968\ Q_{1/2}$$

where $Q_{1/2}$, $Q_{3/4}$, and $Q_{1\ 1/4}$ are the rates of flow which would be indicated respectively by the 1/2-inch, 3/4-inch, and 1 1/4-inch orifice plates if each had the same flow rate passing through it. This indicates that some values of the orifice discharge coefficients may be in error by 3 per cent.

For pipes with an appreciable roughness $\left|\frac{df}{dRe}\right|$ is always less than for a smooth pipe at the same Reynolds number. When the calculated friction factors are plotted against Reynolds number as in Fig. 5 it can be seen that for each orifice plate the curve of f vs. Re is practically parallel to the accepted smooth pipe curve.* This indicates that the roughness is negligible and that the experimental results should agree with the smooth pipe curve if the data are accurate. By this reasoning the results obtained with the 1/2-inch diameter orifice are taken as correct and those for the other orifices as in error by the amounts calculated above.

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* The smooth pipe curve was taken from paper by Moody "Friction Factors for Pipe Flow" Trans. A.S.M.E. Vol. 66, p.671-684, 1948.

In Fig. 5(i) the relationship

$$f = \frac{0.340}{(Re)^{0.26}}$$

is shown to be an accurate representation of the data for Reynolds numbers between 5,000 and 50,000.

2. Correlation of Equivalent Diameter with Mass Flow and Conduit Geometry

The equivalent diameter was calculated from the formula:

$$d_e = f \cdot \frac{L}{\Delta P} \cdot \frac{\rho V^2}{2} \quad ,$$

$$\text{where} \quad f = \varphi \frac{(V \cdot \rho \cdot d_e)}{(\quad \mu \quad)} \ .$$

The function φ was determined by experiment on the conduit without wire and it was assumed that the same relation held when there was wire in the conduit.

For the purposes of correlation the equivalent diameter d_e was assumed to be a function of the conduit diameter $\bar{d}$, the wire diameter d_w, the number of strands of wire N and the Reynolds number for the flow $\frac{(V.\rho.d_e)}{\mu}$. These variables can be grouped to form one dependent and three independent dimensionless groups. Then $d_e/\bar{d} = \Theta(N, Re, d_w/\bar{d})$.

The data contained in Table A-4 were first plotted as in Fig. 6 to show the variation in $d_e/\bar{d}$ with Re. Values of $d_e/\bar{d}$ were obtained (from the curves) for Re = 10,000 and Fig. 7 shows them plotted against $d_w/\bar{d}$. All the data for each value of N fell on a straight line. Each of these lines passed through the point ($d_e/\bar{d}$ = 1.0; $d_w/\bar{d}$ = 0). The fact that all of the data obtained for the various sizes of wire and conduit, and with different insulations, could be correlated on the basis of the three independent variables indicated that only these variables had a significant effect on the dependent variable.

3. The Effect of Twisting the Wire Fill

For some tests the wire fill was given three twists for each 10-foot section of conduit. The data in Table A-5 show that for this condition the pressure losses were not significantly different from the comparable nontwisted cases.

4. Equivalent Length of 90° Elbow and Threaded Couplings

The equivalent lengths for elbows and couplings calculated from the data in Table A-6(i) are plotted against Reynolds number in Fig. 8. Since the fittings for different pipe sizes are not geometrically similar it is not surprising that there is a separate curve for each size of pipe. However, for a Reynolds number of 10,000, all of the elbows are equivalent to a conduit of approximately 23 diameters in length. For the usual design calculations this equivalent length can be used for all conduit sizes at all Reynolds numbers between 5,000 and 50,000 but if maximum accuracy is desired the equivalent length for elbows should be obtained from Fig. 8.

The results for the threaded couplings are much the same as for the elbows. An equivalent length of three diameters is the average for the three sizes tested at a Reynolds number of 10,000. The variation of the equivalent length with Reynolds number and conduit size is small and need only be considered in calculations of the highest accuracy. Here also the accurate value can be obtained from Fig. 8 when it is needed.

Table A-6(ii) contains the data for the tests on elbows and fittings when they were partially filled with wire. In this case the data have been used to calculate the equivalent length of a conduit whose diameter equals the equivalent diameter of the conduit containing wire. The results in Table A-6(ii) show that l_e/d_e for the conduit with wire is approximately 1.4 times $l_e/\bar{d}$ for the empty conduit.

APPLICATION OF RESULTS

The results of this series of tests can be incorporated into a set of design charts which facilitate the calculation of friction loss for air flow in pipes.

For flow in pipes at Reynolds numbers between 5,000 and 50,000 the friction factor has been found to be:

$$f = \frac{0.340}{(Re)^{0.26}} .$$

Since for these Reynolds numbers the flow is turbulent, the pressure drop due to friction is given by:

$$\Delta P = f \cdot \frac{L}{d_e} \cdot \rho \frac{V^2}{2}$$

$$= \frac{0.340}{(Re)^{0.26}} \cdot \frac{L}{d_e} \cdot \rho \frac{V^2}{2} .$$

Both the velocity and the Reynolds number can be related to the mass flow rate M.

$$V = \frac{4}{\pi} \quad \frac{M}{\rho d_e^2}$$

and $$Re = \frac{4}{\pi} \quad \frac{M}{\mu d_e} ,$$

Therefore, $$\Delta P = 0.340 \left\{\frac{\pi \mu d_e}{4\ M}\right\}^{0.26} \cdot \frac{L}{d_e} \cdot \frac{\rho}{2} \left\{\frac{4}{\pi} \cdot \frac{M}{\rho d_e^2}\right\}^2 .$$

but $$\rho = \frac{P}{1715T}$$

Therefore, $$\Delta P = K \ . \ M^{1.74}$$

where $$K = 444 \ \frac{T}{P} \ (\mu)^{0.26} \ . \ \frac{L}{d_e^{4.74}} .$$

Thus the relationship between ΔP and M for any particular run of pipe can be represented by a straight line of slope 1.74 on logarithmic graph paper. The intercept of the line with the ΔP axis depends on the value of K. Fig. 9 is a chart which gives ΔP directly when K and M are known. The nomograph, Fig. 10, does the same for a wider range of ΔP but the scale can only be read to approximately $\pm$ 5 per cent.

For added convenience when calculating K, Fig. 11 gives $(\mu)^{0.26}$ for dry air as a function of temperature and Fig. 12 gives $d_e^{4.74}$ as a function of d_e for the range of diameters commonly used.

The convenience of the charts can be demonstrated most easily by solving an example problem first by direct calculation and then by the use of the charts.

PROBLEM :

Find the pressure drop for air flowing through 100 feet of 1-inch conduit containing 2 strands of 10-gauge plastic insulated wire at a flow rate of 1 lb/min. The gauge pressure at the inlet to the conduit is 6 psi and the temperature is 72°F.

SOLUTION:

(1) Equivalent Diameter

The diameter of plastic insulated 10-gauge wire is

$$d_w = 0.165 \text{ in.}$$

The average internal diameter for 1-inch conduit is

$$\bar{d} = 1.045 \text{ in.}$$

Therefore, $\frac{d_w}{\bar{d}} = \frac{0.165}{1.045} = 0.158.$

From Fig. 7 for two wires the corresponding value of $\frac{d_e}{\bar{d}}$ is 0.880,

Therefore, $d_e = 0.880 \times 1.045 = 0.920 \text{ in.} = 7.66 \times 10^{-2} \text{ ft.}$

(2) Reynolds number

The Reynolds number for the flow is defined by:

$$Re = \frac{4}{\pi} \; \frac{M}{d_e \cdot \mu}$$

where M is the mass flow rate, and

μ is the absolute viscosity.

For this case:

$$M = \frac{1.0}{32.2 \times 60} \text{ slug/sec.}$$

$$\mu_{72°F} = 3.82 \times 10^{-7} \text{ slug/ft./sec.} \quad \text{and,}$$

Therefore, $Re = \frac{4}{\pi} \times \frac{1.0}{32.2 \times 60} \times \frac{10^2}{7.66} \times \frac{10^7}{3.82} = 2.26 \times 10^4,$

(3) Friction Factor

$$f = \frac{0.340}{(Re)^{0.26}}$$

Thus for $Re = 2.26 \times 10^4$

$$f = \frac{0.340}{(2.26)^{0.26}\,(10)^{1.04}} = 2.50 \times 10^{-2}.$$

(4) Density

$$\rho = \frac{P}{1715\ T} \quad \text{slug/ft}^3$$

where P is absolute pressure lb/ft^2

T is absolute temperature °R

Therefore, $\rho = \frac{(14.7 + 6) \times 144}{1715 \times (460 + 72)} = 3.27 \times 10^{-3}$ ($slug/ft^3$).

(5) Velocity

$$V = \frac{4}{\pi} \cdot \frac{M}{\rho d_e^{\,2}}$$

Therefore, $V = \frac{4}{\pi} \cdot \frac{1.0}{32.2 \times 60} \times \frac{10^3}{3.27} \times \frac{10^4}{(7.66)^2} = 34.4$ ft/sec

(6) Pressure drop due to Friction

$$\Delta P = f \cdot \frac{L}{d_e} \cdot \frac{\rho V^2}{2} \ .$$

Therefore, $\Delta P = 2.50 \times 10^{-2} \times \frac{10^2}{7.66 \times 10^{-2}} \cdot \frac{3.27 \times 10^{-3}}{2} \cdot (34.4)^2$

$= 63.1\ lb/ft^2$

$= \frac{63.1}{144} = 0.44$ psi

To obtain the greatest accuracy the density should be recalculated using a mean value for the gauge pressure; in this case, 5.78 psi rather than 6.00. However, the change would be only 1 per cent so this last step has been omitted.

Solution of Sample Problem using Charts

$$\frac{d_w}{\bar{d}} = \frac{0.165}{1.045} = 0.158$$

From Fig. 7 for two wires $\frac{d_e}{\bar{d}} = 0.880$

Therefore, $d_e = 0.880 \times \frac{1.045}{12} = 7.66 \times 10^{-2}$ ft.

$L = 100$ ft.

$T = 460 + 72 = 532$ °R

$P = (14.7 + 6.0) \times 144 = 2980$ lb/ft^2

$(\mu)^{0.26} = 2.144 \times 10^{-2}$

$M = \frac{1.0}{32.2 \times 60} = 5.18 \times 10^{-4}$ slug/sec

Therefore, $K = 444 \times \frac{532}{2980} \times 2.144 \times 10^{-2} \times \frac{10^2}{5.1 \times 10^{-6}} = 3.34 \times 10^7$

From Fig. 9:

For $K = 3.34 \times 10^7$ and $M = 5.18 \times 10^{-4}$

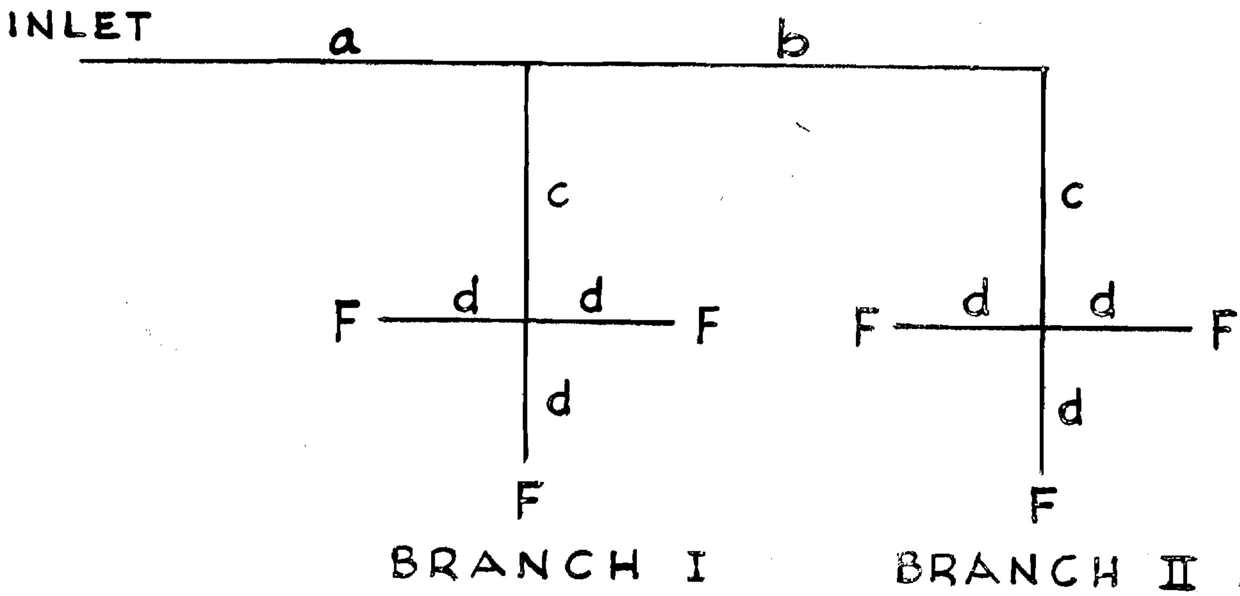
$\Delta P = 63$ lb/ft^2.

The advantages of using the design charts increase as the problems become more complex. The following design problem further illustrates the use of the charts.

Example Design Problem

PROBLEM

Determine the mass flow and static pressure required at the inlet of the conduit system shown which will ensure that every point in the system has a gauge pressure greater than 1 inch water. Assume that there is negligible friction loss and leakage at the tee and cross fittings and that the fixture at the end of each branch has a mass flow vs. pressure characteristic similar to a 1/4-inch diameter orifice. The temperature everywhere is 72°F and the ambient pressure 15 psia.



a	1 1/4-inch conduit 60 ft. 3 strands 10 g plastic covered wire.
b	1 1/4-inch conduit 60 ft. 2 strands 10 g plastic covered wire.
c	1-inch conduit 20 ft. 2 strands 12 g plastic covered wire.
d	3/4-inch conduit 20 ft. 2 strands 12 g plastic covered wire.
F	Fixtures which have some mass flow vs. pressure as 1/4-inch diameter orifice.

SOLUTION

A. Calculation of Equivalent Diameters

(a) $$\frac{d_w}{\bar{d}} = \frac{0.165}{1.384} = 0.119 .$$

From Fig. 7 $\frac{d_e}{\bar{d}} = 0.875$,

Therefore, $(d_e)_a = 0.875 \times \frac{1.384}{12} = 0.1009$ ft.

(b) $\frac{d_w}{\bar{d}} = 0.119.$

From Fig. 7 $\frac{d_e}{\bar{d}} = 0.909,$

Therefore, $(d_e)_b = 0.909 \times \frac{1.384}{12} = 0.1049$ ft.

(c) $\frac{d_w}{\bar{d}} = \frac{0.165}{1.045} = 0.158.$

From Fig. 7 $\frac{d_e}{\bar{d}} = 0.880,$

Therefore, $(d_e)_c = 0.880 \times \frac{1.045}{12} = 0.0766$ ft.

(d) $\frac{d_w}{\bar{d}} = \frac{0.151}{0.825} = 0.183.$

From Fig. 7 $\frac{d_e}{\bar{d}} = 0.860,$

Therefore, $(d_e)_d = 0.860 \times \frac{0.825}{12} = 0.0591$ ft.

B. <u>Calculation of K</u>

$$K = 444 \frac{T}{P} (\mu)^{0.26} \cdot \frac{L}{d_e^{4.74}}$$

$$P = 15 \times 144 = 2160 \text{ lb/ft}^2$$

$$T = 460 + 72 = 532 \text{ °R}$$

$$(\mu)_{72}{}^{0.26} = 2.144 \times 10^{-2} \text{ (slug/ft./sec)}^{0.26}$$

Thus $K = \frac{2.35\ L}{d_e{}^{4.74}}$

Therefore, $K_a = \frac{2.35 \times 60}{(0.1009)^{4.74}} = \frac{2.35 \times 60}{1.88 \times 10^{-5}} = \underline{7.50} \times 10^6,$

$K_b = \frac{2.35 \times 60}{(0.1049)^{4.74}} = \frac{2.35 \times 60}{2.27 \times 10^{-5}} = \underline{6.20} \times 10^6,$

$$K_c = \frac{2.35 \times 20}{(0.0766)^{4.74}} = \frac{2.35 \times 20}{5.10 \times 10^{-6}} = \underline{9.21} \times 10^6,$$

$$K_d = \frac{2.35 \times 20}{(0.0591)^{4.74}} = \frac{2.35 \times 20}{1.54 \times 10^{-6}} = \underline{3.05} \times 10^7.$$

C. Calculation of Pressure Losses

(1) Branch II

Figure 13 gives the mass flow as a function of the differential pressure which exists across the fixture. For this example the fixture is assumed equivalent to a 1/4-inch diameter orifice. For a gauge pressure at the fixture of 1 inch H_2O the flow rate is:

$$M_d = 3.22 \times 10^{-5} \text{ slug/sec.}$$

Figure 14 gives the pressure drop vs. mass flow for each of the four different types of conduit.

Thus for $M_d = 3.22 \times 10^{-5}$ slug/sec.,

$$(\Delta P)_d = 0.465 \text{ lb/ft}^2$$

$$M_c = 3 \times 3.22 \times 10^{-5} = 9.66 \times 10^{-5} \text{ slug/sec.}$$

and $(\Delta P)_c = 0.94 \text{ lb/ft}^2$.

Hence the gauge pressure at the entry to Branch II is

$$5.20 + 0.46 + 0.94 = 6.60 \text{ lb/ft}^2$$

for a mass flow of $\underline{9.66} \times 10^{-5}$ slug/sec.

The pressure drop in the supply pipe b is:

$$(\Delta P)_b = 0.63 \text{ lb/ft}^2.$$

Thus the pressure at the inlet to Branch I is

$$6.60 + 0.63 = \underline{7.23} \text{ lb/ft}^2.$$

(2) Branch I

It is now necessary to determine what the flow will be into Branch I when the pressure at the branch inlet is 7.23 lb/ft^2. To do this it is necessary to find the relation between the supply pressure and mass flow for the branch.

Since Branches I and II are identical one point on the characteristic is 6.60 lb/ft^2 at 9.66×10^{-5} slug/sec. To obtain a second point assume that the fixture pressure is 6.00 lb/ft^2. Then from Fig. 13 the mass flow through each fixture is 3.47×10^{-5} slug/sec. and the corresponding pressure drop in the d conduits is 0.53 lb/ft. The mass flow in the c conduit is $3 \times 3.47 \times 10^{-5} = 10.41 \times 10^{-5}$ slug/sec. and the pressure drop is $(\Delta P)_c = 1.08$ lb/ft^2.

This gives a supply pressure of $6.00 + 0.53 + 1.08 = 7.61$ lb/ft^2 and a flow of 10.41×10^{-5} slug/sec. Similarly a third point has been found to be 7.12 lb/ft^2 with a flow of 10.19×10^{-5} slug/sec. These three sets of values were used to draw the curve in Fig. 15. From this curve the flow rate corresponding to 7.23 lb/ft^2 is 10.19×10^{-5} slug/sec.

(3) <u>Supply Line</u>

The mass flow through the main supply conduit is $10.19 + 9.66 = 19.85 \times 10^{-5}$ slug/sec. and the corresponding pressure drop in the supply pipe is 2.66 lb/ft^2.

Hence at the entrance to the conduit system the gauge pressure must be $7.23 + 2.66 = 9.89$ lb/ft^2 = <u>1.90</u> inches water and the mass flow is:

$$19.85 \times 10^{-5} \text{ slug/sec} = \underline{19.85 \times 10^{-5} \times 60} \times \frac{1715 \times 532}{2160}$$

$$= 5.03 \text{ cfm}$$

CONCLUSIONS

The sample design calculation in the section on Application of Results shows that with the data included in this report it is possible to calculate approximately the pressure distribution throughout a conduit system that contains wire. This neglects the losses in the various cross, tee, elbow, and reducing fittings. If there are so many of these fittings that they cannot be safely allowed for by a design safety factor, further tests will be required to provide data for these fittings. From the limited data obtained with long radius elbows it appeared that the equivalent length of fittings with wire are of the order of 40 per cent more than when the conduit is empty. This should only be used as a guide until better design data for fittings are available.

ACKNOWLEDGMENTS

The author wishes to express his thanks to J. E. Berndt who assembled most of the apparatus and carried out all of the tests, to P. Janecek who made many of the calculations, and to R. G. Evans for his assistance in building the apparatus that was used to measure the conduit diameter.

APPENDIX A

DATA TABLES

TABLE A-1 (i)

DETERMINATION OF CONDUIT DIAMETER

Conduit Number		M_0 gm	M_{70} gm	H_w cm H_2O	ρ_w gm/cm^3	$\log_{10} \bar{d}$	$\bar{d}$ ft.
	I	4210	3230	36.29	0.9970	$\bar{2}.839\ 384$	6.908×10^{-2}
	II	4808	3839	36.30	0.9970	$\bar{2}.836\ 874$	6.869×10^{-2}
$\frac{3}{4}$"	III	4799	3816	36.29	0.9970	$\bar{2}.840\ 048$	6.919×10^{-2}
	IV	4692	3734	36.30	0.9974	$\bar{2}.834\ 308$	6.828×10^{-2}
	I	4988	3417	36.30	0.9975	$\bar{2}.941\ 690$	8.744×10^{-2}
	II	4709	3164	36.30	0.9975	$\bar{2}.938\ 066$	8.671×10^{-2}
1"	III	4748	3185	36.28	0.9966	$\bar{2}.940\ 898$	8.728×10^{-2}
	IV	4758	3201	36.27	0.9967	$\bar{2}.940\ 112$	8.712×10^{-2}
	I	4979	2217	36.40	0.9980	$\bar{1}.063\ 508$	11.575×10^{-2}
	II	4849	2164	36.40	0.9978	$\bar{1}.057\ 412$	11.413×10^{-2}
$1\frac{1}{4}$"	III	4963	2195	36.41	0.9979	$\bar{1}.063\ 942$	11.586×10^{-2}
	IV	4880	2117	36.40	0.9978	$\bar{1}.063\ 622$	11.578×10^{-2}

TABLE A-1 (ii)

COMPLETE DATA FOR A TYPICAL SECTION

Man. Height in. CCl_4	Mass gm	ΔM gm	Notes
0	4799		
5	4729	70	9" Man. Scale
10	4658	71	= 36.29 cm H_2O
15	4588	70	at 25.25 °C
20	4517	71	
25	4448	69	$\therefore \rho_w = 0.9970.$
30	4378	70	
35	4308	70	
40	4237	71	
45	4166	71	
50	4096	70	
55	4025	71	
60	3955	70	
65	3886	69	
70	3816	70	

TABLE A-2

ORIFICE PLATE DATA

Nominal Diam.	½ in.		3/4 in.		1¼ in.	
Actual Diam.	4.1850×10^{-2} ft.		6.2817×10^{-2} ft.		10.397×10^{-2} ft.	
Differential Pressure	C'	Log_{10} C'	C'	Log_{10} C'	C'	Log_{10} C'
10 mm H_2O	0.6045	$\bar{1}.781400$	0.6026	$\bar{1}.780040$	0.5935	$\bar{1}.773405$
40 mm H_2O	0.6049	$\bar{1}.781700$	0.6029	$\bar{1}.780240$	0.5940	$\bar{1}.773785$
160 mm H_2O	0.6066	$\bar{1}.782910$	0.6040	$\bar{1}.781070$	0.5961	$\bar{1}.775310$
390 mm H_2O	0.6099	$\bar{1}.785230$	0.6063	$\bar{1}.782660$	0.6001	$\bar{1}.778235$

TABLE A-3

FRICTION FACTORS FOR EMPTY CONDUIT

Conduit	1¼" Conduit - Section # 3											
Orifice	½"				3/4"				1¼"			
i'_* mm H_2O	10.0	40.0	160.0	390.0	10.0	40.0	160.0	390.0	10.0	40.0	160.0	390.0
T °C	21.6	21.6	20.8	20.7	21.5	21.5	21.0	21.0	21.7	21.7	21.4	21.4
$B_{corr.}$ mm Hg.	750.8	750.8	749.3	749.3	753.3	753.3	753.4	753.4	752.0	752.0	750.8	750.8
$\bar{\Delta}$ in. CCl_4	0.28	1.06	4.16	10.08	0.32	1.24	4.80	11.42	0.68	2.49	8.93	20.30
$\Delta P_*/L$ $\frac{\text{mm } H_2O}{\text{ft.}}$	0.019	0.080	0.270	0.573	0.099	0.331	1.101	2.370	0.581	1.939	6.445	14.060
f x 10^2	3.5	3.7	3.15	2.76	3.66	3.06	2.56	2.27	2.95	2.47	2.08	1.90
Re x 10^{-3}	2.32	4.65	9.38	14.80	5.23	10.46	21.08	33.22	14.08	28.20	56.79	89.76

Conduit	1" Conduit - Section # 3										
Orifice	½"				3/4"				1¼"		
i'_* mm H_2O	10.0	40.0	160.0	390.0	10.0	40.0	160.0	390.0	10.0	40.0	160.0
T °C	21.7	21.7	21.1	21.1	21.4	21.4	20.9	20.9	21.5	21.5	21.5
$B_{corr.}$ mm Hg.	758.4	758.4	758.2	758.2	754.1	754.1	754.1	754.1	752.6	752.6	761.5
$\bar{\Delta}$ in. CCl_4	0.31	1.20	4.60	11.00	0.50	1.81	6.62	15.12	1.66	5.59	18.80
$\Delta P_*/L$ $\frac{\text{mm } H_2O}{\text{ft.}}$	0.090	0.311	1.032	2.208	0.389	1.282	4.231	9.058	2.240	7.375	24.35
f x 10^2	4.07	3.52	2.92	2.57	3.49	2.88	2.40	2.14	2.77	2.31	1.98
Re x 10^{-3}	3.10	6.20	12.51	19.76	6.95	13.91	28.01	44.13	18.71	37.48	75.88

Conduit	3/4" Conduit - Section # 3							
Orifice	½"				3/4"			
i'_* mm H_2O	10.0	40.0	160.0	390.0	10.0	40.0	160.0	390.0
T °C	21.8	21.8	21.0	21.0	21.6	21.6	21.0	21.0
$B_{corr.}$ mm Hg.	756.3	756.3	754.9	754.9	753.1	753.1	748.5	748.5
$\bar{\Delta}$ in. CCl_4	0.43	1.56	5.80	13.58	0.94	3.28	11.53	25.85
$\Delta P_*/L$ $\frac{\text{mm } H_2O}{\text{ft.}}$	0.282	0.941	3.090	6.578	1.170	3.830	12.495	26.45
f x 10^2	3.99	3.34	2.75	2.42	3.29	2.72	2.26	2.03
Re x 10^{-3}	3.90	7.81	15.75	24.86	8.75	17.50	35.19	55.24

TABLE A-4 (i)

PRESSURE DROP FOR PARTIALLY FILLED CONDUIT

$1\frac{1}{4}$" Conduit Section # 3 Plastic Covered Wire

Fill	1 Strand 10 gauge				2 Strands 10 gauge				3 Strands 10 gauge			
Orifice	$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"	
i'_* mm H_2O	40.0	390.0	40.0	390.0	40.0	390.0	40.0	390.0	40.0	390.0	40.0	390.0
T °C	21.5	21.1	21.6	21.7	21.6	20.9	21.5	22.2	21.6	20.8	21.1	21.5
$B_{corr.}$ mm Hg.	757.5	757.4	758.1	758.1	757.7	757.5	759.9	756.8	759.4	757.6	764.0	764.0
$\bar{\Delta}$ in. CCl_4	1.07	10.15	2.80	22.06	1.09	10.22	2.99	23.40	1.09	10.28	3.10	24.44
$\Delta P_*/L$ $\frac{mm\ H_2O}{ft.}$	0.105	0.710	2.345	16.97	0.132	0.872	2.865	20.50	0.172	1.064	3.419	23.90
$d_e/\bar{d}$	0.949	0.959	0.960	0.963	0.904	0.917	0.920	0.926	0.854	0.879	0.884	0.893
Re x 10^{-3}	4.93	15.38	29.58	93.55	5.17	16.22	30.85	97.04	5.48	16.93	32.92	101.30

Fill	1 Strand 12 gauge				2 Strands 12 gauge				3 Strands 12 gauge			
Orifice	$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"	
i'_* mm H_2O		390.0	40.0	390.0	40.0	390.0	40.0	390.0	40.0	390.0	40.0	390.0
T °C		21.5	22.2	22.0	21.6	20.9	21.5	21.7	22.3	20.8	21.5	21.6
$B_{corr.}$ mm Hg.		752.5	752.2	751.8	752.2	752.3	752.2	752.2	745.3	744.9	743.7	743.9
$\bar{\Delta}$ in. CCl_4		10.11	2.65	21.25	1.08	10.19	2.81	22.32	1.09	10.24	3.05	24.12
$\Delta P_*/L$ $\frac{mm\ H_2O}{ft.}$		0.700	2.330	16.72	0.131	0.834	2.725	19.58	0.162	1.017	3.276	22.84
$d_e/\bar{d}$		0.961	0.961	0.964	0.905	0.926	0.930	0.932	0.870	0.888	0.894	0.902
Re x 10^{-3}		15.38	29.27	92.93	5.14	16.01	30.34	96.28	5.31	16.62	31.38	99.02

Fill	1 Strand 14 gauge				2 Strands 14 gauge				3 Strands 14 gauge			
Orifice	$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"	
i'_* mm H_2O	40.0	390.0	40.0	390.0	40.0	390.0	40.0	390.0	40.0	390.0	40.0	390.0
T °C	21.4	20.7	21.2	21.1	21.5	20.7	21.4	21.7	21.6	21.1	21.4	21.6
$B_{corr.}$ mm Hg.	745.6	746.3	746.7	746.9	752.1	752.2	752.3	752.2	752.3	752.3	755.8	755.9
$\bar{\Delta}$ in. CCl_4	1.06	10.13	2.69	21.45	1.08	10.16	2.82	22.32	1.08	10.22	2.94	23.18
$\Delta P_*/L$ $\frac{mm\ H_2O}{ft.}$	0.101	0.690	2.298	16.58	0.122	0.801	2.635	18.76	0.146	0.918	2.958	20.80
$d_e/\bar{d}$	0.957	0.964	0.964	0.965	0.919	0.934	0.937	0.940	0.885	0.908	0.914	0.921
Re x 10^{-3}	4.85	15.33	29.20	92.87	5.07	15.89	30.15	95.70	5.26	16.32	30.98	95.50

TABLE A-4 (ii)

PRESSURE DROP FOR PARTIALLY FILLED CONDUIT

1" Conduit Section # 3 Plastic Covered Wire

Fill	1 Strand 10 gauge				2 Strands 10 gauge				3 Strands 10 gauge			
Orifice	1/2"		1 1/4"		1/2"		1 1/4"		1/2"		1 1/4"	
i_*' mm H_2O	10.0	160.0	40.0	160.0	10.0	160.0		150.0	10.0	160.0		100.0
T °C	21.6	20.7	21.5	21.7	21.7	21.3		22.1	21.8	21.2		22.2
B corr. mm Hg.	750.0	750.7	751.0	757.0	752.3	752.1		751.1	750.8	751.3		753.6
$\bar{\Delta}$ in. CCl_4	0.34	4.76	6.55	22.20	0.36	4.84		23.1	0.38	5.10		19.08
$\Delta P_*/L$ $\frac{mm\ H_2O}{ft.}$	0.140	1.392	9.649	31.49	0.200	1.835		38.92	0.271	2.365		34.22
$d_e/\bar{d}$	0.921	0.938	0.944	0.946	0.856	0.885		0.900	0.801	0.839		0.852
Re x 10^{-3}	3.34	13.29	39.66	79.91	3.58	14.00		80.8	3.85	14.84		69.58

Fill	1 Strand 12 gauge				2 Strands 12 gauge				3 Strands 12 gauge			
Orifice	1/2"		1 1/4"		1/2"		1 1/4"		1/2"		1 1/4"	
i_*' mm H_2O	10.0	160.0	40.0	160.0	10.0	160.0	40.0		10.0	160.0	40.0	
T °C	21.3	20.7	21.4	21.4	21.7	21.0	21.4		21.7	21.0	21.4	
B corr. mm Hg.	748.3	748.6	749.3	749.5	750.9	754.7	755.2		755.4	755.4	755.4	
$\bar{\Delta}$ in. CCl_4	0.32	4.70	6.19	21.05	0.34	4.81	6.94		0.38	4.98	7.99	
$\Delta P_*/L$ $\frac{mm\ H_2O}{ft.}$	0.129	1.360	9.460	30.86	0.185	1.740	11.86		0.240	2.141	14.42	
$d_e/\bar{d}$	0.937	0.943	0.948	0.950	0.871	0.896	0.905		0.821	0.856	0.867	
Re x 10^{-3}	3.29	13.21	39.45	79.25	3.54	14.10	41.50		3.76	14.59	43.33	

Fill	1 Strand 14 gauge				2 Strands 14 gauge				3 Strands 14 gauge			
Orifice	1/2"		1 1/4"		1/2"		1 1/4"		1/2"		1 1/4"	
i_*' mm H_2O	10.0	160.0	40.0	160.0	10.0	160.0	40.0	160.0	10.0	160.0	40.0	130.0
T °C	21.6	21.0	21.5	21.5	21.5	20.6	21.4	21.3	21.5	20.6	21.4	21.7
B corr. mm Hg.	752.1	751.8	750.7	750.7	745.6	745.1	743.7	741.3	738.4	744.4	745.1	745.3
$\bar{\Delta}$ in. CCl_4	0.31	4.66	6.08	20.50	0.34	4.80	6.72	22.60	0.37	4.94	7.70	21.75
$\Delta P_*/L$ $\frac{mm\ H_2O}{ft.}$	0.125	1.290	9.010	29.40	0.169	1.579	10.77	34.82	0.220	1.961	13.14	35.40
$d_e/\bar{d}$	0.943	0.954	0.958	0.961	0.886	0.913	0.922	0.926	0.838	0.873	0.884	0.888
Re x 10^{-3}	3.27	13.07	39.05	78.40	3.47	13.62	40.41	80.92	3.65	14.23	42.20	76.01

TABLE A-4 (iii)

PRESSURE DROP FOR PARTIALLY FILLED CONDUIT

3/4" Conduit Section # 3 Plastic Covered Wire

Fill	1 Strand 10 gauge				2 Strands 10 gauge				3 Strands 10 gauge			
Orifice	½"			3/4"	½"				½"			3/4"
i'_* mm H_2O	10.0	40.0	160.0	160.0	10.0	40.0	160.0	390.0	10.0	40.0	160.0	160.0
T °C	21.4	21.4	21.7	21.2	21.4	21.3	20.7	20.7	21.8	21.8	21.4	21.5
$B_{corr.}$ mm Hg.	760.0	760.0	769.3	759.3	749.7	749.7	749.9	749.9	754.8	754.8	753.7	750.6
$\bar{\Delta}$ in. CCl_4	0.50	1.74	6.34	13.50	0.60	2.04	7.28	16.60	0.69	2.30	8.05	20.15
$\Delta P_*/L$ $\frac{\text{mm } H_2O}{\text{ft.}}$	0.440	1.369	4.353	17.36	0.715	2.120	6.570	13.67	0.960	2.798	8.517	32.66
$d_e/\bar{d}$	0.915	0.922	0.932	0.940	0.826	0.841	0.854	0.860	0.772	0.792	0.806	0.812
Re x 10^{-3}	4.28	8.46	16.88	37.75	4.70	9.22	18.40	28.85	5.040	9.850	19.500	43.300

Fill	1 Strand 12 gauge				2 Strands 12 gauge				3 Strands 12 gauge			
Orifice	½"				½"				½"			
i'_* mm H_2O	10.0	40.0	160.0	390.0	10.0	40.0	160.0	390.0	10.0	40.0	160.0	390.0
T °C	21.8	21.8	20.8	20.8	21.7	21.7	21.2	21.2	21.8	21.8	21.0	21.0
$B_{corr.}$ mm Hg.	758.6	758.6	758.0	758.0	755.5	755.5	755.3	755.3	754.3	754.3	751.3	751.3
$\bar{\Delta}$ in. CCl_4	0.50	1.74	6.30	14.62	0.57	1.94	6.92	15.88	0.66	2.19	7.66	17.38
$\Delta P_*/L$ $\frac{\text{mm } H_2O}{\text{ft.}}$	0.428	1.345	4.282	9.000	0.621	1.894	5.880	12.22	0.862	2.536	7.705	15.90
$d_e/\bar{d}$	0.916	0.925	0.932	0.937	0.847	0.860	0.871	0.878	0.790	0.809	0.821	0.830
Re x 10^{-3}	4.260	8.450	16.900	26.62	4.600	9.060	17.950	28.30	4.930	9.640	19.170	29.85

Fill	1 Strand 14 gauge				2 Strands 14 gauge				3 Strands 14 gauge			
Orifice	½"				½"				½"			
i'_* mm H_2O	10.0	40.0	160.0	390.0	10.0	40.0	160.0	390.0	10.0	40.0	160.0	390.0
T °C	21.8	21.8	21.0	21.0	21.6	21.6	22.6	22.6	21.7	21.7	20.8	20.8
$B_{corr.}$ mm Hg.	752.0	752.0	751.4	751.4	750.7	750.7	749.9	749.9	748.7	748.7	749.7	749.7
$\bar{\Delta}$ in. CCl_4	0.46	1.70	6.22	14.44	0.56	1.86	6.72	15.45	0.60	2.07	7.30	16.60
$\Delta P_*/L$ $\frac{\text{mm } H_2O}{\text{ft.}}$	0.410	1.296	4.121	8.682	0.546	1.678	5.290	11.01	0.730	2.171	6.670	13.78
$d_e/\bar{d}$	0.925	0.933	0.940	0.944	0.871	0.884	0.891	0.898	0.819	0.836	0.848	0.855
Re x 10^{-3}	4.200	8.350	16.720	26.280	4.470	8.80	17.570	27.45	4.740	9.300	18.460	28.900

TABLE A-4 (iv)

PRESSURE DROP FOR PARTIALLY FILLED CONDUIT

$1\frac{1}{4}$" Conduit Section # 3 Rubber Covered Wire

Fill	1 Strand 14 gauge				2 Strands 14 gauge				3 Strands 14 gauge			
Orifice	$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"	
i'_* mm H_2O	40	160	40	160	40	160	40	160	40	160	40	160
T C	21.7	21.0	21.5	22.1	21.9	20.8	21.6	21.5	21.4	20.8	21.5	21.6
$B_{corr.}$ mm Hg.	763.4	763.4	759.6	758.7	757.6	756.0	755.3	754.2	752.5	753.0	753.7	753.5
$\bar{\Delta}$ in. CCl_4	1.07	4.20	2.71	9.55	1.08	4.21	2.83	9.98	1.08	4.23	2.93	10.30
$\Delta P_*/L$ $\frac{mm\ H_2O}{ft.}$	0.106	0.340	2.358	7.872	0.128	0.394	2.662	8.798	0.150	0.468	3.100	10.12
$d_e/\bar{d}$	0.943	0.948	0.958	0.960	0.905	0.918	0.934	0.936	0.876	0.883	0.905	0.910
Re x 10^{-3}	4.98	10.00	29.70	59.55	5.16	10.29	30.30	60.85	5.33	10.54	31.30	62.50

3/4" Conduit Section # 3 Rubber Covered Wire

Fill	1 Strand 10 gauge				2 Strands 10 gauge				3 Strands 14 gauge			
Orifice	$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"		$\frac{1}{2}$"		$1\frac{1}{4}$"	
i'_* mm H_2O	10	40	160	30	10	40	160	20	10	40	160	25
T °C	21.8	21.8	21.1	21.7	21.6	21.6	20.9	21.5	21.8	21.8	21.0	21.7
$B_{corr.}$ mm Hg.	761.2	761.2	761.1	759.2	754.2	754.2	754.3	754.3	764.4	764.4	764.5	764.0
$\bar{\Delta}$ in. CCl_4	0.54	1.89	6.84	16.80	0.76	2.47	8.51	18.18	0.68	2.25	7.87	18.75
$\Delta P_*/L$ $\frac{mm\ H_2O}{ft.}$	0.568	1.740	5.532	29.86	1.050	3.100	9.552	35.96	0.910	2.681	8.210	36.84
$d_e/\bar{d}$	0.867	0.881	0.886	0.892	0.761	0.779	0.785	0.795	0.784	0.802	0.815	0.824
Re x 10^{-3}	4.51	8.69	17.80	46.00	5.11	9.99	20.08	41.90	5.02	9.80	19.53	45.40

TABLE A-5

DATA FOR TWISTED COMPARED WITH NONTWISTED WIRES

Orifice	3/4" Conduit 3 Strands 14 gauge Plastic covered							
	½"							
i'_*	10.0		40.0		160.0		390.0	
	ΔP_*							
	NT	T	NT	T	NT	T	NT	T
Sect # II	0.780	0.772	2.281	2.270	6.915	6.893	14.16	14.10
Sect # III	0.730	0.738	2.171	2.193	6.670	6.748	13.78	13.93
Sect # IV	0.650	0.772	2.298	2.293	7.090	7.096	14.76	14.78
Twist	3 Twists per 10 ft. length of conduit							

Orifice	1" Conduit 3 Strands 14 gauge Plastic covered											
	½"								1¼"			
i'_*	10.0		40.0		160.0		390.0		10.0		40.0	
	ΔP_*		ΔP_*		ΔP_*		ΔP_*		ΔP_*		ΔP_*	
	NT	T	NT	T	NT	T	NT	T	NT	T	NT	T
Sect # II	0.268	0.258	0.756	0.755	2.311	2.307	4.798	4.781	4.859	4.850	15.38	15.36
Sect # III	0.240	0.239	0.700	0.705	2.141	2.166	4.457	4.517	4.516	4.594	14.42	14.64
Sect # IV	0.241	0.231	0.699	0.694	2.125	2.141	4.409	4.470	4.472	4.540	14.38	14.58
Twist	3 Twists per 10 ft. length of conduit											

T = Twisted

NT = Nontwisted

TABLE A-6 (i)

EQUIVALENT LENGTH OF LONG RADIUS 90° ELBOWS AND THREADED COUPLINGS WITHOUT WIRE

$1\frac{1}{4}$" Conduit

Orifice	$\frac{1}{2}$"											
i_*' mm H_2O	10.0			40.0			160.0			390.0		
	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c
Sect # II	0.20	0.20	0.20	0.88	0.84	0.88	2.89	2.80	2.90	6.14	6.09	6.19
Sect # III	0.19	0.28	0.19	0.80	1.00	0.82	2.70	3.29	2.78	5.73	7.13	5.95
Sect # IV	0.19	0.19	0.19	0.81	0.79	0.80	2.69	2.64	2.70	5.71	5.68	5.76
$L_e/\bar{d}$		41.0	0.0		27.0	2.2		22.4	2.4		22.0	2.6
Re x 10^{-3}	2.32			4.65			9.38			14.80		

Orifice	$1\frac{1}{4}$"											
i_*' mm H_2O	10.0			40.0			160.0			390.0		
	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c
Sect # II	6.23	6.21	6.22	20.77	20.61	20.60	68.50	68.15	68.44	148.0	147.0	147.4
Sect # III	5.81	7.28	6.00	19.39	24.64	19.85	64.45	83.15	66.45	140.6	182.1	144.8
Sect # IV	5.80	5.79	5.80	19.20	19.02	19.12	63.54	63.65	63.69	138.5	138.0	138.0
$L_e/\bar{d}$		21.9	2.9		23.7	2.8		25.2	2.8		25.7	2.8
Re x 10^{-3}	14.08			28.20			56.79			89.76		

1" Conduit

Orifice	$\frac{1}{2}$"											
i_*' mm H_2O	10.0			40.0			160.0			390.0		
	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c
Sect # II	0.92	0.94	0.97	3.21	3.22	3.25	10.64	10.66	10.68	22.72	22.72	22.80
Sect # III	0.90	1.10	0.92	3.11	3.72	3.20	10.32	12.44	10.60	22.08	26.80	22.72
Sect # IV	0.90	0.91	0.93	3.16	3.19	3.19	10.49	10.50	10.51	22.48	22.50	22.56
$L_e/\bar{d}$		25.4	-3		22.6	2.0		23.7	2.5		24.6	2.8
Re x 10^{-3}	3.10			6.20			12.51			19.76		

Orifice	$1\frac{1}{4}$"											
i_*' mm H_2O	10.0			40.0			160.0					
	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c			
Sect # II	23.08	22.99	23.20	75.62	75.42	75.49	245.9	244.7	246.1			
Sect # III	22.40	27.02	23.11	73.75	90.82	75.85	243.5	302.8	251.2			
Sect # IV	22.80	22.71	22.93	75.68	75.70	75.64	245.9	255.8	256.0			
$L_e/\bar{d}$		24.0	3.1		26.6	3.4		28.1	3.4			
Re x 10^{-3}	18.71			37.48			75.88					

3/4" Conduit

Orifice	$\frac{1}{2}$"											
i_*' mm H_2O	10.0			40.0			160.0			390.0		
	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c
Sect # II	2.94	2.94	2.94	9.80	9.82	9.80	32.01	32.00	32.02	67.93	67.73	67.86
Sect # III	2.82	3.29	2.88	9.41	10.90	9.62	30.90	36.22	31.82	65.78	78.16	67.84
Sect # IV	3.01	3.00	3.00	10.04	10.02	10.01	32.91	32.92	32.97	70.40	70.28	70.30
$L_e/\bar{d}$		24.3	3.0		22.8	3.2		24.8	4.3		27.5	4.5
Re x 10^{-3}	3.90			7.81			15.75			24.86		

Orifice	3/4"											
i_*' mm H_2O	10.0			40.0			160.0			390.0		
	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c	ΔP_*	ΔP_e	ΔP_c
Sect # II	12.18	12.16	12.18	39.72	39.66	39.70	128.5	127.8	128.2	268.4	266.4	268.0
Sect # III	11.70	13.56	11.99	38.30	45.15	39.45	124.9	149.1	128.7	264.5	319.6	272.7
Sect # IV	12.47	12.44	12.48	40.91	40.90	40.90	134.6	133.8	134.6	289.1	289.1	288.9
$L_e/\bar{d}$		23.1	3.5		26.0	4.3		28.1	4.5		30.1	4.6
Re x 10^{-3}	8.75			17.50			35.19			55.24		

ΔP_* Pressure drop mm H_2O for 10 ft. of straight conduit

ΔP_e Pressure drop mm H_2O for 10 ft. of conduit when # III Section includes 90° elbow in addition to 10 ft. of pipe

ΔP_c Pressure drop mm H_2O for 10 ft. of conduit when # III Section includes 1 screwed coupling.

TABLE A-6 (ii)

EQUIVALENT LENGTH OF LONG RADIUS 90° ELBOW (WITH WIRE)

(1 Strand 10 gauge Rubber covered)

3/4" Conduit												
Orifice	½"								1¼"			
i'_*	10		40		160		390		10		30	
	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'
Sect # II	5.99	5.88	18.39	18.33	58.01	58.01	121.6	121.1	122.5	123.3	306.4	304.8
Sect # III	5.68	6.96	17.40	21.40	55.32	67.89	116.9	143.5	117.5	146.1	298.6	369.8
Sect # IV	5.89	6.19	18.43	19.28	58.94	61.85	125.4	131.3	126.5	133.8	327.2	346.5
Re x 10^{-3}	4.5		8.7		17.8		28.2		26.5		46.0	
$L_{e/de}$	40.8		38.2		37.4		38.0		38.3		40.3	

1" Conduit												
Orifice	½"								1¼"			
i'_*	10.0		40.0		160.0		390.0		10.0		40.0	
	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'
Sect # II	1.70	1.80	5.30	5.51	17.00	17.30	35.91	36.34	36.15	37.05	117.5	121.1
Sect # III	1.62	2.29	5.14	6.80	16.33	21.44	34.51	45.45	34.98	46.32	114.1	153.3
Sect # IV	1.62	1.79	5.08	5.43	16.38	17.25	34.69	36.44	35.01	37.28	115.5	124.5
Re x 10^{-3}	3.4		6.8		13.8		21.8		20.6		41.2	
$L_{e/de}$	42.7		34.4		36.6		38.0		36.8		38.0	

1¼" Conduit																
Orifice	½"								1¼"							
i'_*	10.0		40.0		160.0		390.0		10.0		40.0		160.0		390.0	
	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'	ΔP	ΔP'
Sect # II	0.41	0.40	1.30	1.28	4.11	4.11	8.64	8.64	8.77	8.89	28.60	28.74	95.01	94.90	204.8	202.7
Sect # III	0.38	0.51	1.20	1.61	3.80	5.21	7.99	11.08	8.09	11.39	26.24	37.58	87.20	127.4	189.8	274.7
Sect # IV	0.36	0.34	1.17	1.19	3.67	3.85	7.63	8.18	7.84	8.40	25.08	27.55	83.18	93.60	181.2	204.6
Re x 10^{-3}	2.5		5.0		10.1		15.9		15.2		30.4		61.1		96.6	
$L_{e/de}$	35.0		33.8		34.5		36.0		36.2		39.5		43.2		43.5	

ΔP Pressure drop mm H_2O for 10 ft. of straight conduit with wire

ΔP' Pressure drop mm H_2O for 10 ft. of conduit + 90° elbow with wire

APPENDIX B

SAMPLE CALCULATIONS

1. <u>Calculation of Conduit Diameters</u>

$$(\bar{d})^2 = \frac{4}{\pi} \cdot \frac{9}{70} \cdot \frac{M_0 - M_{70}}{\rho_w \cdot H_w}$$

$M_0 \quad = 4692$ gm

$M_{70} \quad = 3734$ gm

Therefore $\quad M_0 - M_{70} = 958$ gm

$H_w \quad = 36.30$ cm water at 23.6°C

Therefore $\quad \rho_w \quad = 0.9974$ gm/cm^3

$$2 \log \bar{d} = \log(M_0 - M_{70}) - \log \rho_w - \log H_w - 3.753975.$$

This last number is:

$$\log \left\{\frac{\pi}{4} \times \frac{70}{9}\right\} + 2 \left(\log 2.54 + \log 12\right)$$

$$\begin{aligned} \log 0.9974 &= \bar{1}.998\ 869 \\ \log 36.30 &= 1.559\ 907 \\ &+ \underline{3.753\ 975} \\ & \quad\ 5.312\ 751 \end{aligned}$$

$$\begin{aligned} \log 958 &= 2.981\ 366 \\ &- \underline{5.312\ 751} \\ 2 \log \bar{d} &= \bar{3}.668\ 615 \\ \log \bar{d} &= \bar{2}.834\ 308 \\ \bar{d} &= 6.828 \times 10^{-2} \text{ ft.} \end{aligned}$$

2. <u>The Density of Air</u>

The mass density of dry air is given by:

$$\rho = \frac{P}{1715.5\ T}$$

ρ is in slug/ft^3

P is in lb/ft^2 absolute

T is in $^\circ$R

or $$\rho = 1.6232 \times 10^{-3} \frac{B}{T} .$$

B barometric pressure mm mercury

For moist air the expression for density is:

$$\rho = 1.6232 \times 10^{-3} \frac{(B - 0.375\ e)}{T} ,$$

where e is the partial pressure of the water vapour in the air vapour mixture. Thus the effect of moisture on the density can be accounted for by using the dry air formula with the barometer reduced by 0.375 e.

The air flowing through the conduit was assumed to be saturated at 100 psig and 72°F. Hence at atmospheric pressure this air had a vapour pressure of:

$$20.0 \times \frac{14.6}{114.6} = 2.55 \text{ mm mercury.}$$

Thus the barometric correction to take account of the moisture in the air is:

$$- 0.375 \times 2.55 = -0.956 \text{ mm mercury}$$

Since the barometric pressures are measured only to the nearest 0.1 mm this correction is -1.0 mm mercury.

3. Sample Calculation of Friction Factor and Reynolds number

The expression relating the friction factor to measurable quantities was shown to be:

$$f = \frac{\Delta P_{*}}{L} \cdot \frac{(\bar{d})^5}{D^4} \cdot \frac{P_{*}}{P_{*}^{!}} \cdot \frac{1}{(C')^2\ i_{*}^{!}}$$

The following data are typical:

3/4-inch conduit - third section
3/4-inch orifice plate
Temperature 21.6°C
Barometer 756.8 mm mercury at 21.8°C

The barometer correction for temperature is -2.7 and as discussed in the previous section a further correction of -1.0 takes account of the moisture content of the air.

$$B_{corr} = 756.8 - 2.7 - 1.0 = 753.1 \text{ mm mercury at } 0°C,$$

$$P_* = B_{corr} + 2.99\ \bar{\Delta}\ ,$$

where $\bar{\Delta}$ is the mean gauge pressure for the length of conduit, in inches of carbon tetrachloride. For this case $\bar{\Delta} = 0.94$.

Therefore $$P_* = 753.1 + 2.99 \times 0.94 = 755.9 \text{ mm mercury,}$$

$$P'_* = B_{corr} + \frac{i'_*}{27.2}\ ,$$

where i'_* is the differential pressure across the orifice in mm of water.

Thus for $i'_* = 10.0$ mm water

$$P'_* = 753.1 + \frac{10.0}{27.2} = 753.5 \text{ mm mercury.}$$

The values of log T and log μ used for the following calculation were obtained from graphs of these variables vs. temperature in °C. Similarly values of log C' were taken directly from Table A-2.

Quantity	Value	Log_{10}
P'_*	753.5	2.877 199
D^4		$\bar{5}.192\ 300$
i'_*	10.0	1.000 000
C'		$\bar{1}.780\ 040$
C'		$\bar{1}.780\ 040$
N		$\bar{2}.629\ 579$
P_*	755.9	2.878 464
$(\bar{d})^5$		$\bar{6}.200\ 240$
$\Delta P_*/L$	1.170	0.068 186
		$\bar{3}.146\ 890$

	N		$- \bar{2}.629\ 579$
Therefore	f	0.03291	$\bar{2}.517\ 311$

The expression for the Reynolds number was shown to be:

$$Re = 0.025757 \frac{C' D^2}{\bar{d}\mu} \left\{ \frac{i'_* P'_*}{T} \right\}^{1/2}$$

The quantities here are the same as discussed above.

	Quantity	Value	Log_{10}
	i'_*	10.0	1.000 000
	P'_*	755.9	2.877 199
			3.877 199
	T		- 2.724 780
	÷ 2		1.152 419
			0.576 209
	C'		$\bar{1}.780\ 040$
	D^2		$\bar{3}.596\ 150$
	Factor	0.025757	$\bar{2}.410\ 897$
	X		$\bar{4}.363\ 296$
	$\bar{d}$		$\bar{2}.840\ 048$
	μ		$\bar{7}.581\ 310$
	Y		$\bar{8}.421\ 358$
	X		$\bar{4}.363\ 296$
	Y		$- \bar{8}.421\ 358$
Therefore	Re	8.749×10^3	3.941 938

4. <u>Sample Calculation Equivalent Diameter</u>.

The equivalent diameter d_e is related to the measurable quantities by the relation:

$$(d_e)^5 = f. \ (C')^2 \ . \ \frac{(i_*')}{(\Delta P_*)} \ L \ \ D^4 \ \ \frac{P_*'}{P_*}$$

where the quantities have the same meaning as in the expression for f.

As an example the following data were obtained for the third section of the 3/4-inch conduit containing 1 strand of 10-gauge plastic covered wire.

1/2-inch orifice plate

$i_*' \quad = 10.0$ mm water

$\Delta P_{*/L} \quad = 0.440$ mm water

$\bar{\Delta} \quad = \frac{0.55 + 0.95}{2} = 0.50$ in carbon tetrachloride

Temperature 21.4°C

Barometer 763.7 mm mercury at 22.8°C

$\text{Barometer}_{\text{corr.}} = 763.7 - 2.8 - 1.0 = 759.9$ mm mercury at 0°C

$$P_* = B_{corr.} + 2.99\bar{\Delta} = 759.9 + 2.99 \times 0.50 = 761.4$$

$$P_*' = B_{corr.} + \frac{1}{13.6} \cdot \frac{(i_*')}{(\ 2)} = 759.9 + \frac{10}{27.2} = 760.3$$

Quantity	Value	First Trial Log	Correction
P_*	761.4	2.881 613	
$\Delta P_*/L$	0.440	$\bar{1}$.643 453	
		2.525 066	
f		$\bar{2}$.605 000	$\bar{2}$.6000
C'	0.6045	$\bar{1}$.781 400	
C'		$\bar{1}$.781 400	
D^4		$\bar{6}$.486 784	
P'_*	760.3	2.880 985	
i'_*	10.0	1.000 000	
		$\bar{4}$.535 569	
		- 2.525 066	
$(d_e)^5$		$\bar{6}$.010 503	
d_e		$\bar{2}$.802 101	2.8011
μ		$\bar{7}$.581 070	
		$\bar{8}$.383 171	
i'_*	10.0	1.000 000	
P'_*	760.3	2.880 985	
		3.880 985	
T		- 2.724 480	
÷2		1.156 505	
		0.578 252	
D^2		$\bar{3}$.243 392	
C'	0.6045	$\bar{1}$.781 400	
Factor	0.025757	$\bar{2}$.410 897	
		4.013 941	
		- $\bar{8}$.383 171	
Re		3.630 770	

5. Sample Calculation of $l_e/\bar{d}$ for 90° elbow.

Data:

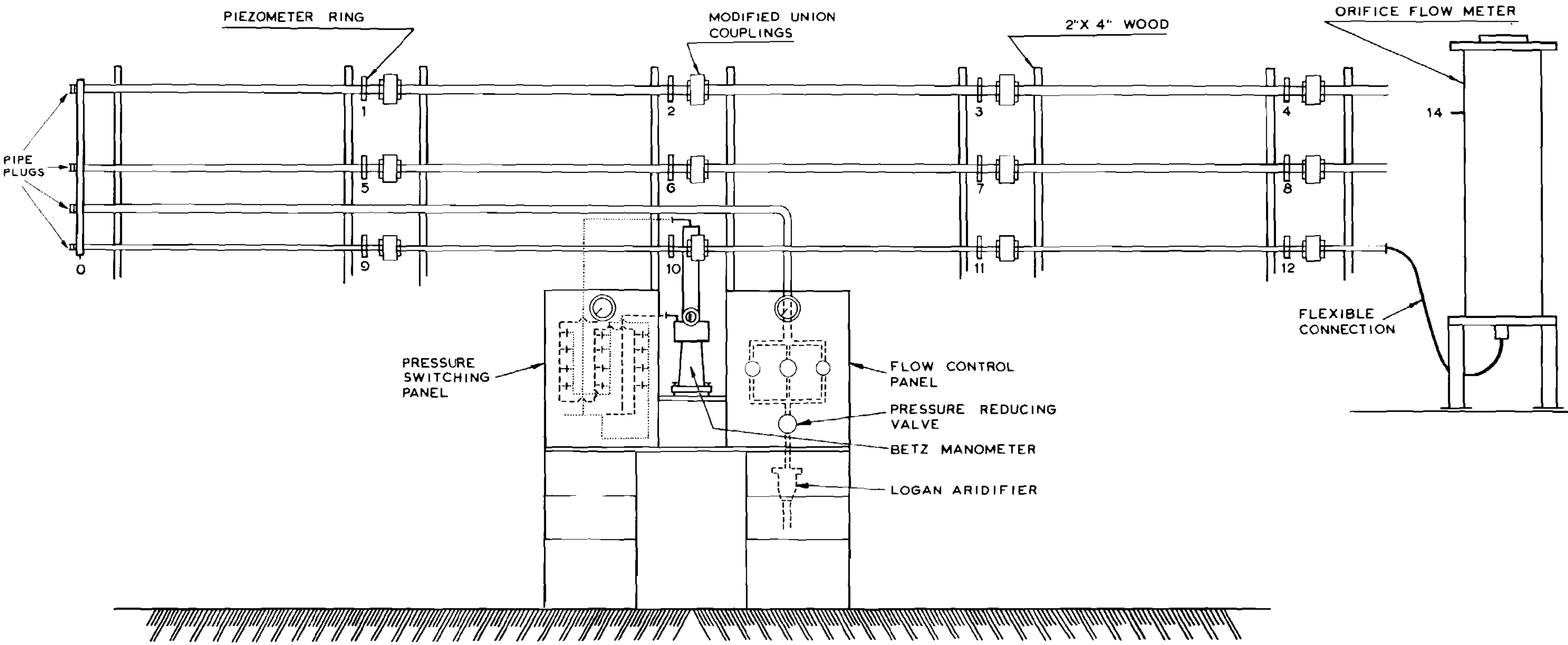
3/4-inch conduit empty $\bar{d} = 6.919 \times 10^{-2}$ ft.

1/2-inch orifice plate $i_*^! = 40.0$ mm water

Section #	ΔP_*	ΔP_e
2	9.80 mm water	9.82 mm water
3	9.41 mm water	10.90 mm water
4	10.04 mm water	10.02 mm water

Calculation:

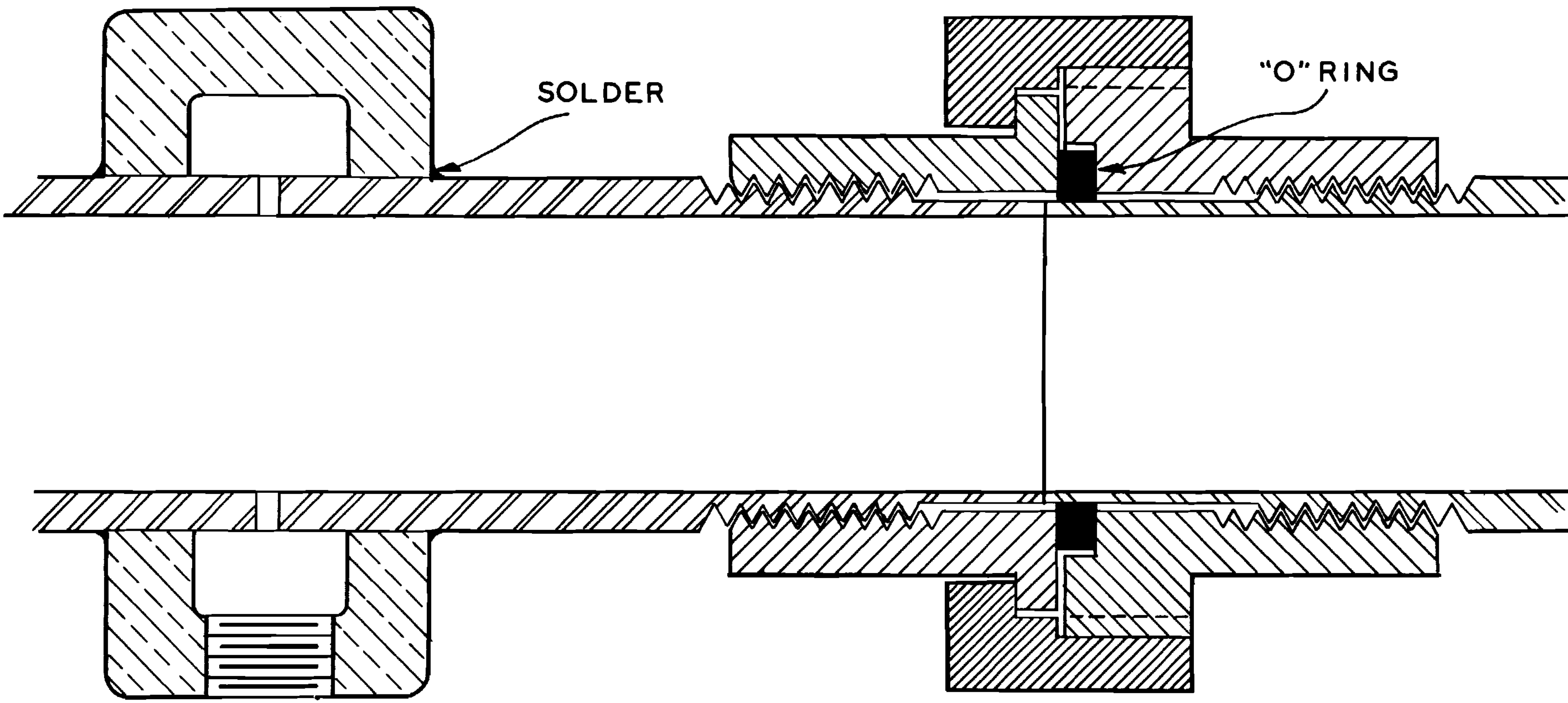
$$l_e/\bar{d} = \frac{10}{6.919 \times 10^{-2}} \left\{ \frac{10.90}{9.41} \times \frac{9.80}{9.82} - 1 \right\} = 22.8$$



PIEZOMETER RINGS AND PRESSURE TAPS ARE CONNECTED TO THE CORRESPONDINGLY NUMBERED PRESSURE SWITCH ON THE SWITCHING PANEL.

FIGURE 1

LAYOUT OF APPARATUS



SCALE = 2 X FULL SIZE

FIGURE 2

SECTION THROUGH CONDUIT COUPLING AND PIEZOMETER RING.

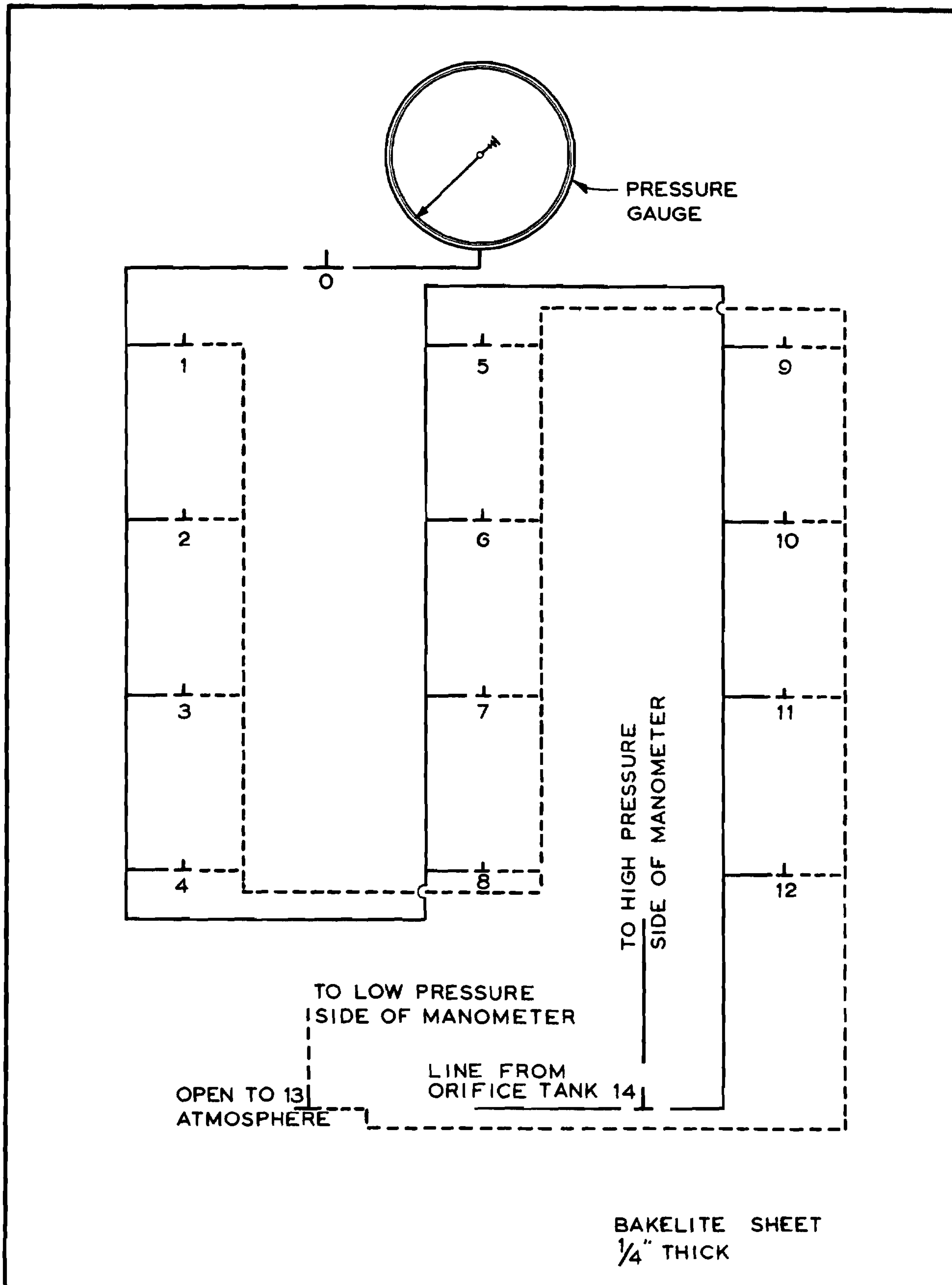


FIGURE 3

PRESSURE SWITCHING PANEL

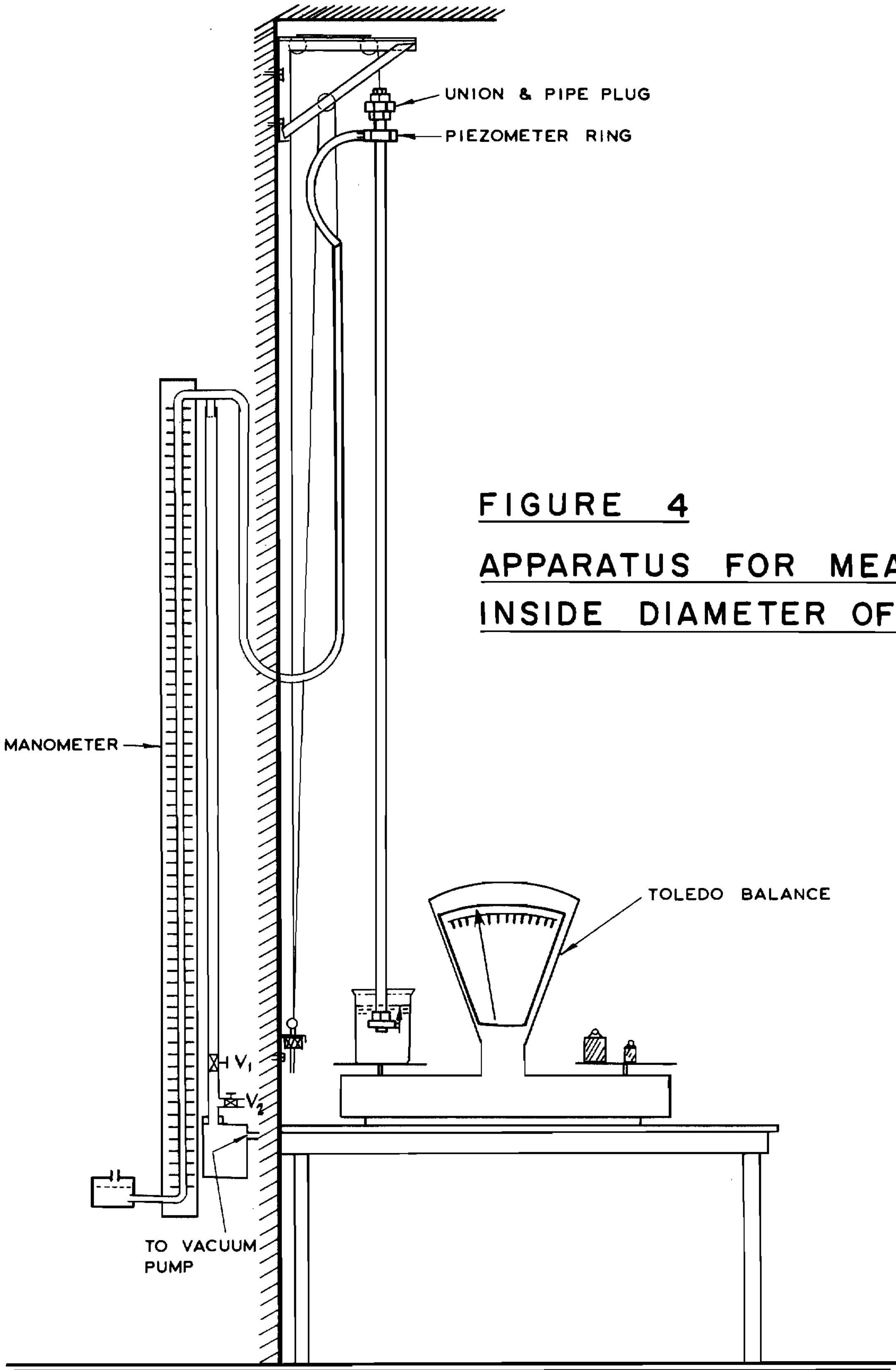


FIGURE 4

APPARATUS FOR MEASURING INSIDE DIAMETER OF CONDUIT

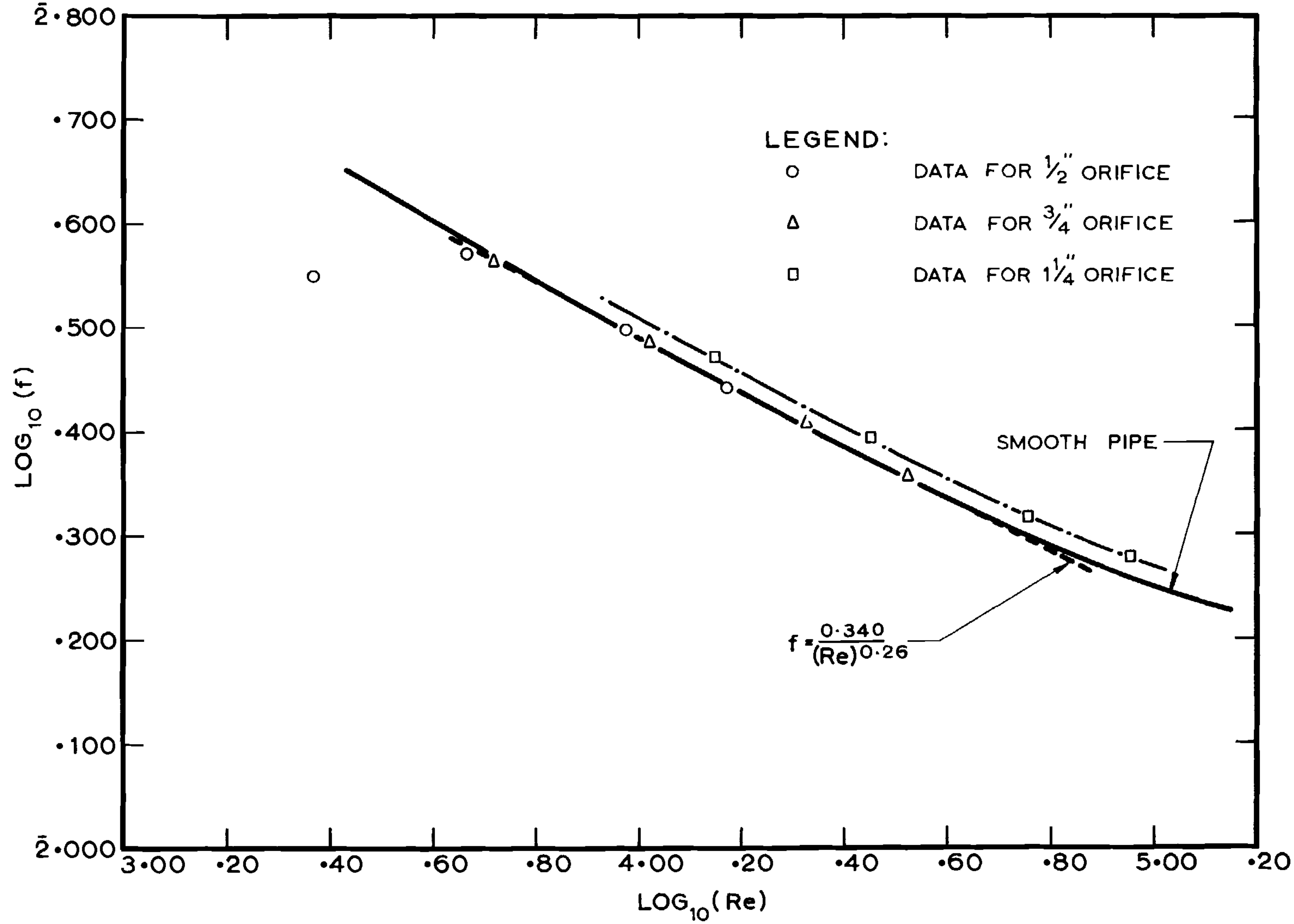


FIGURE 5 (i)

FRICTION FACTOR VS REYNOLDS NUMBER

1 1/4" CONDUIT SECTION NO. 3

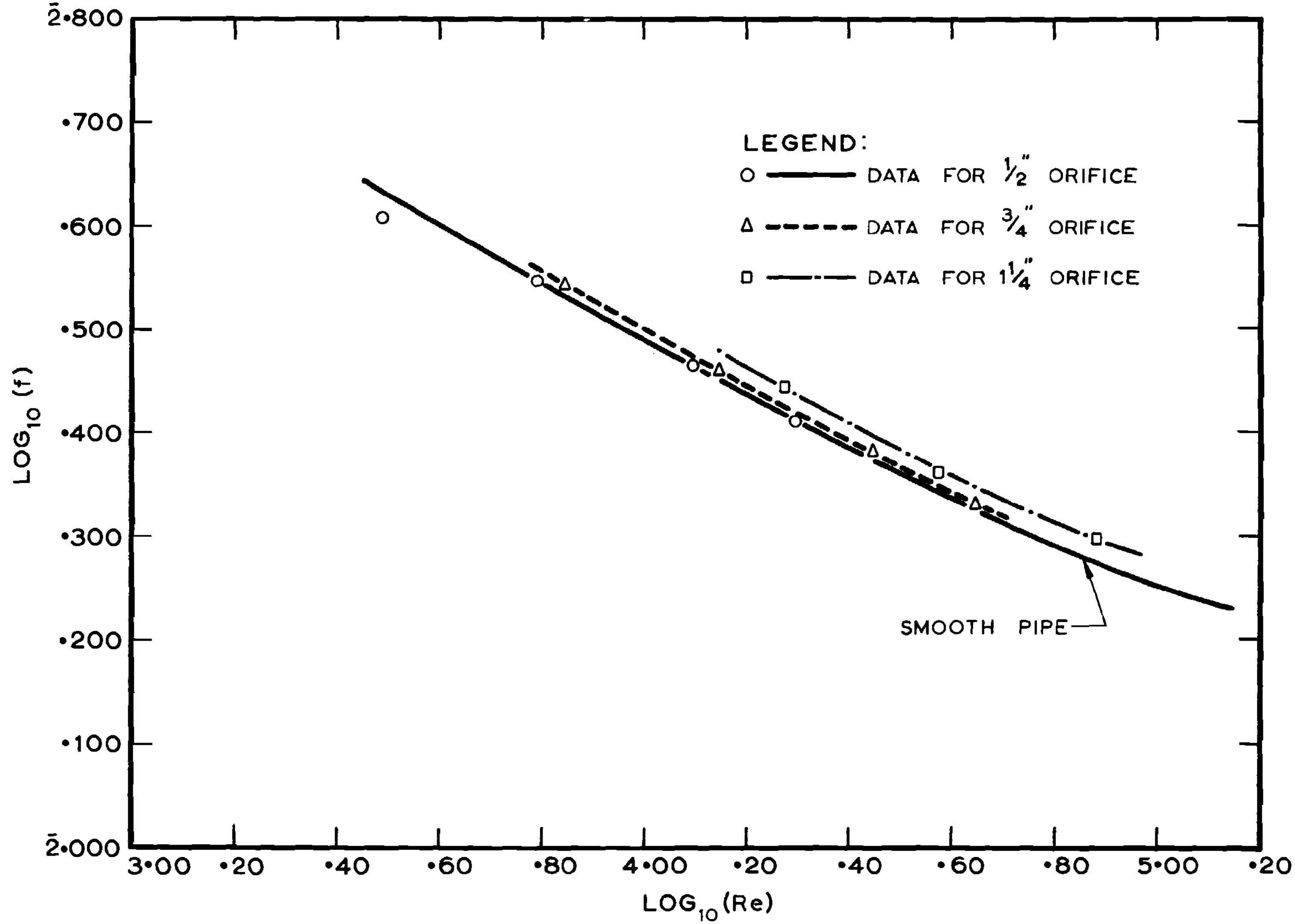


FIGURE 5(ii)

FRICTION FACTOR VS REYNOLDS NUMBER

1" CONDUIT SECTION NO. 3

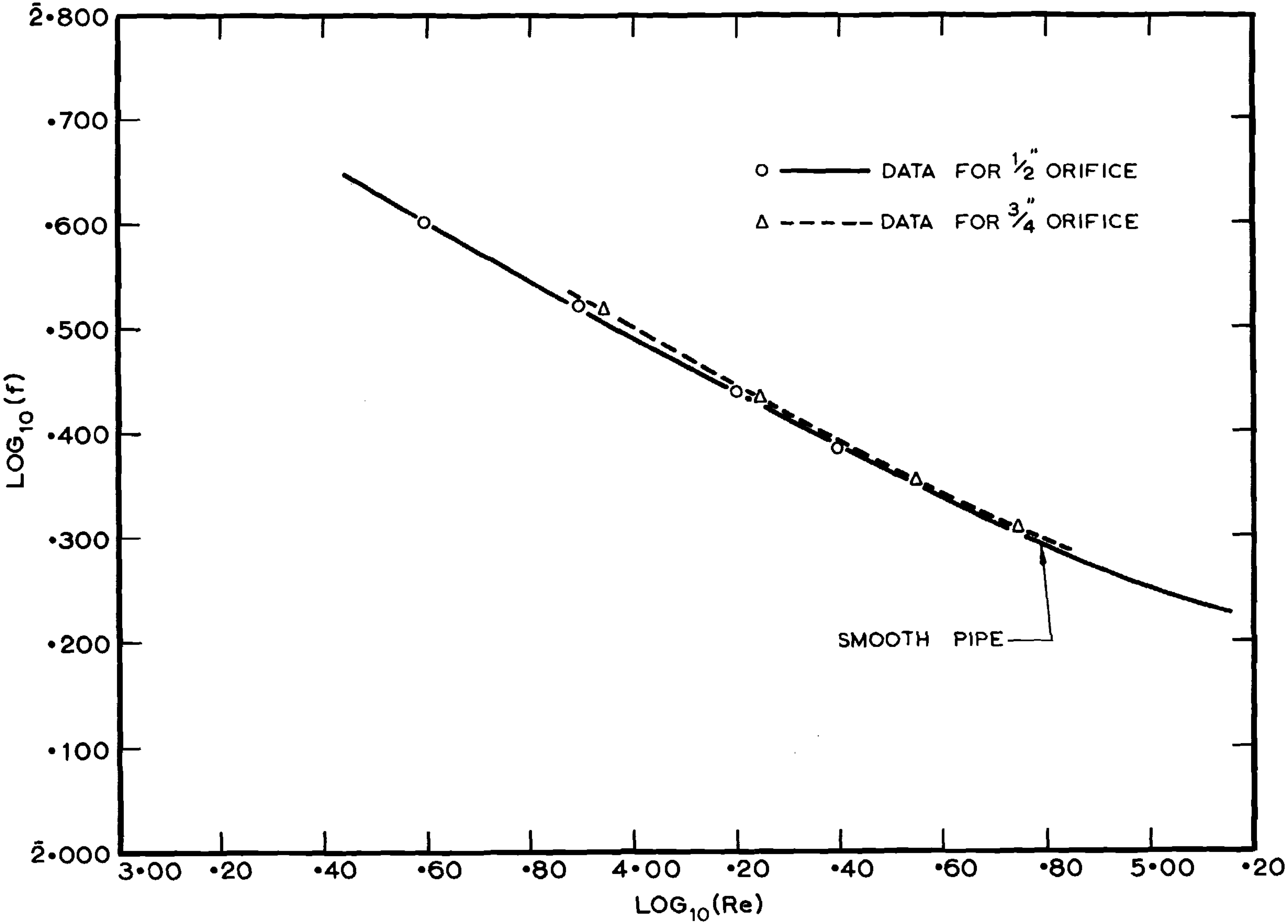


FIGURE 5(iii)

FRICTION FACTOR VS REYNOLDS NUMBER

3/4" CONDUIT SECTION NO. 3

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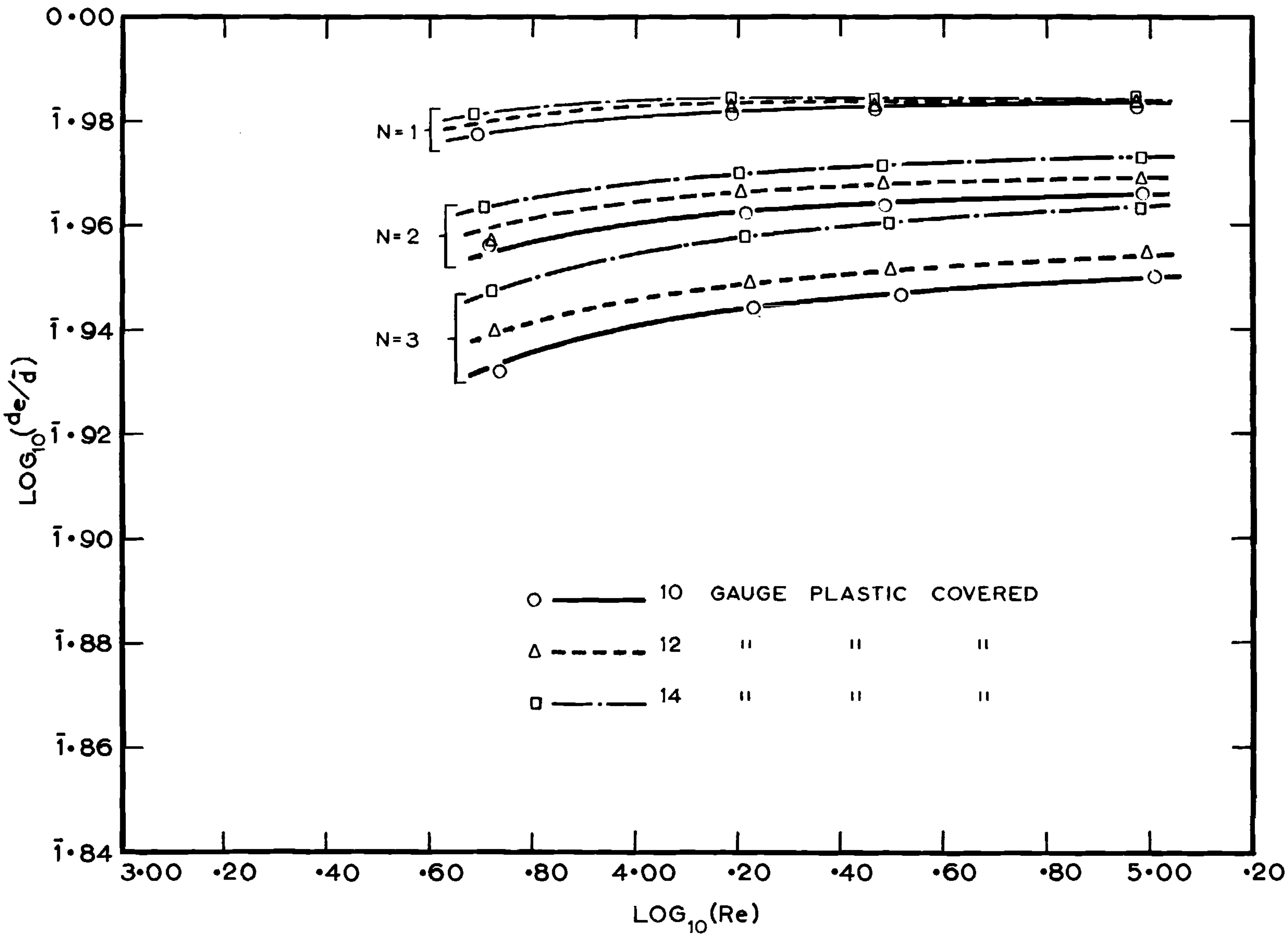

FIGURE 6 (i)

VARIATION OF $d_e/\bar{d}$ WITH REYNOLDS NUMBER

1¼" CONDUIT SECTION NO. 3

DBR. REPORT 99

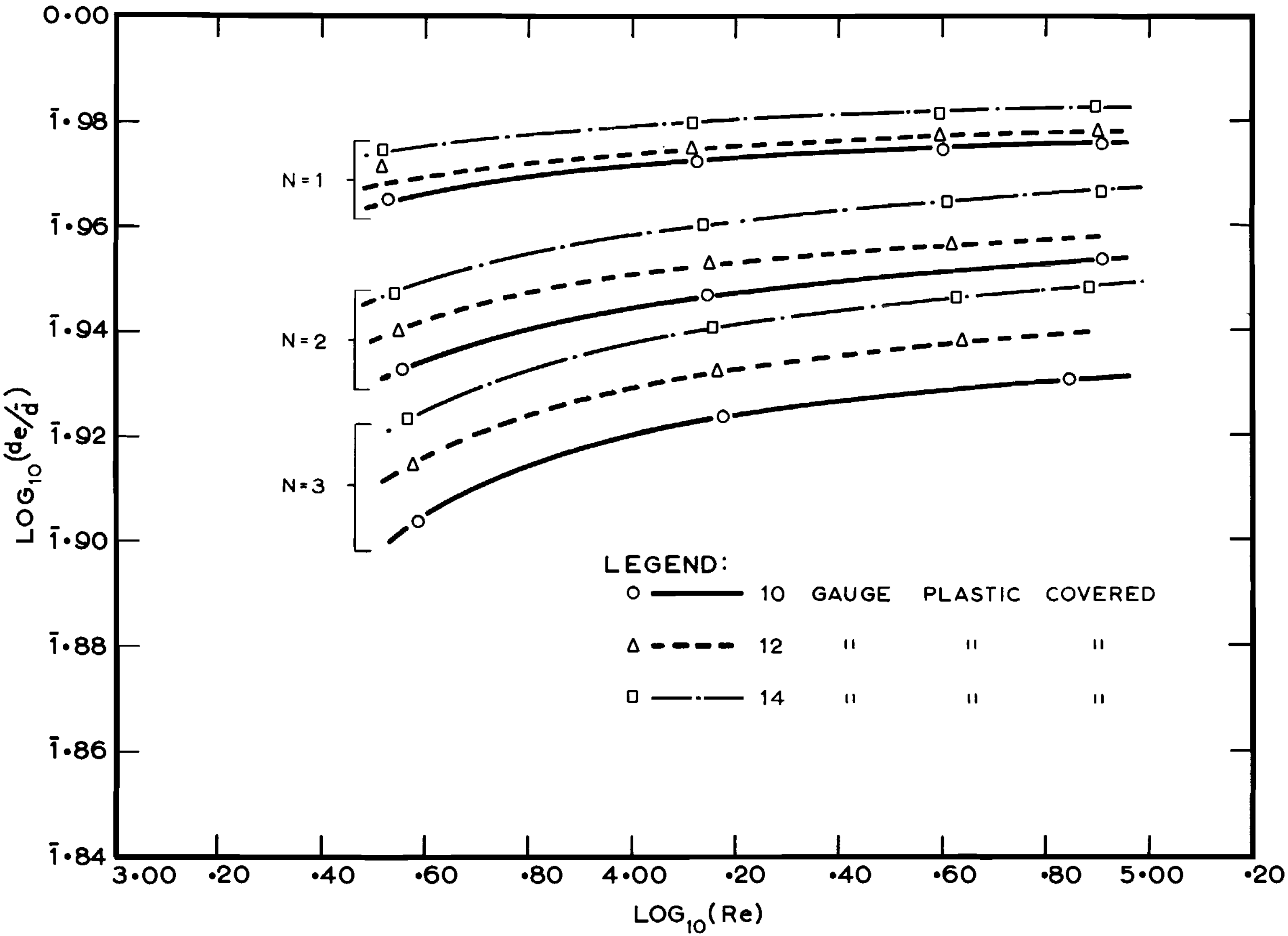

FIGURE 6(ii)

VARIATION OF $d_e/\bar{d}$ WITH REYNOLDS NUMBER

1 CONDUIT SECTION NO. 3

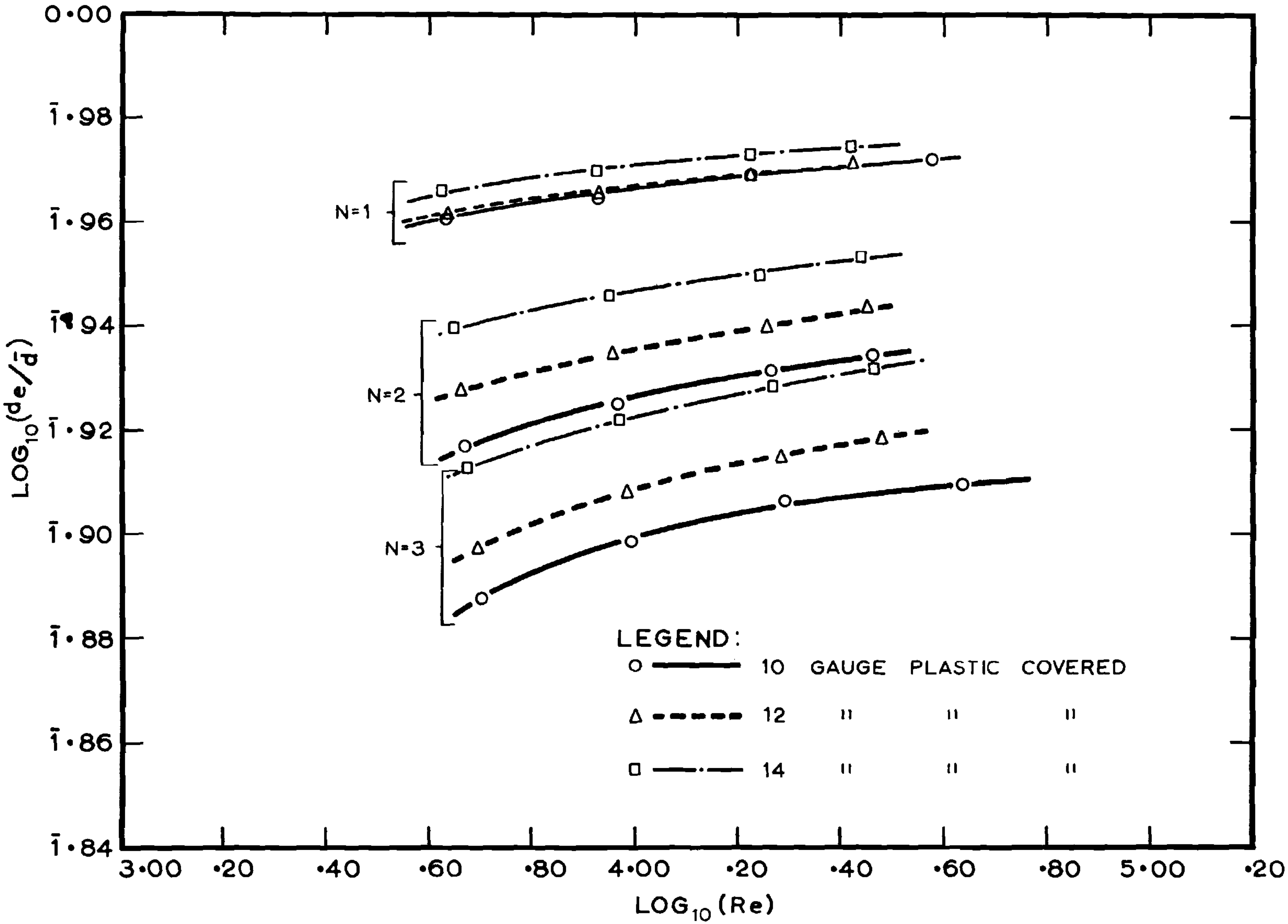

FIGURE 6 (iii)

VARIATION OF $^{d}e/\bar{d}$ WITH REYNOLDS NUMBER

3/4" CONDUIT - SECTION NO. 3 - PLASTIC COVERED WIRE

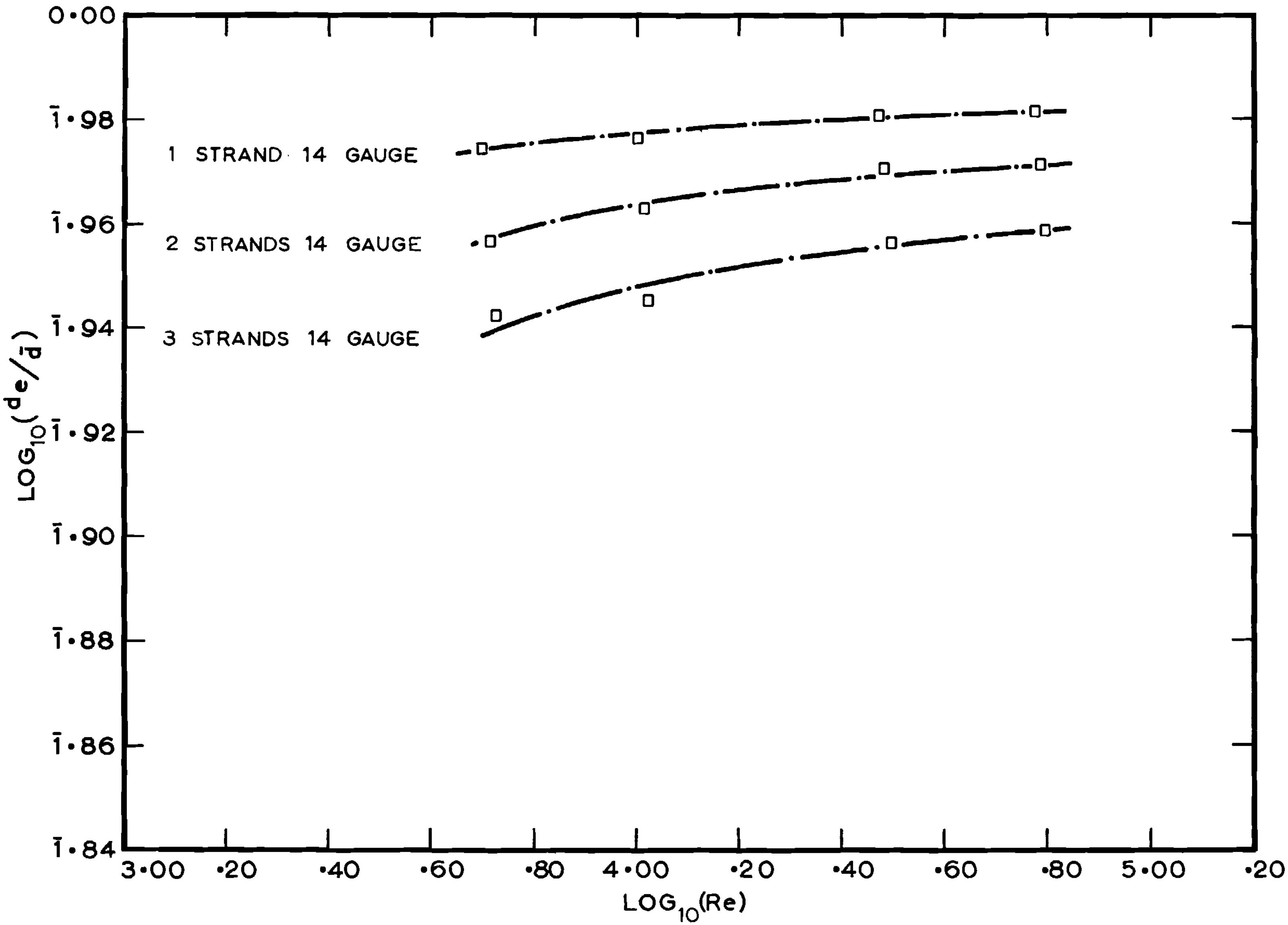

FIGURE 6 (iv)

VARIATION OF $^{d}e/\bar{d}$ WITH REYNOLDS NUMBER

1¼" CONDUIT - SECTION NO. 3 - RUBBER COVERED WIRE

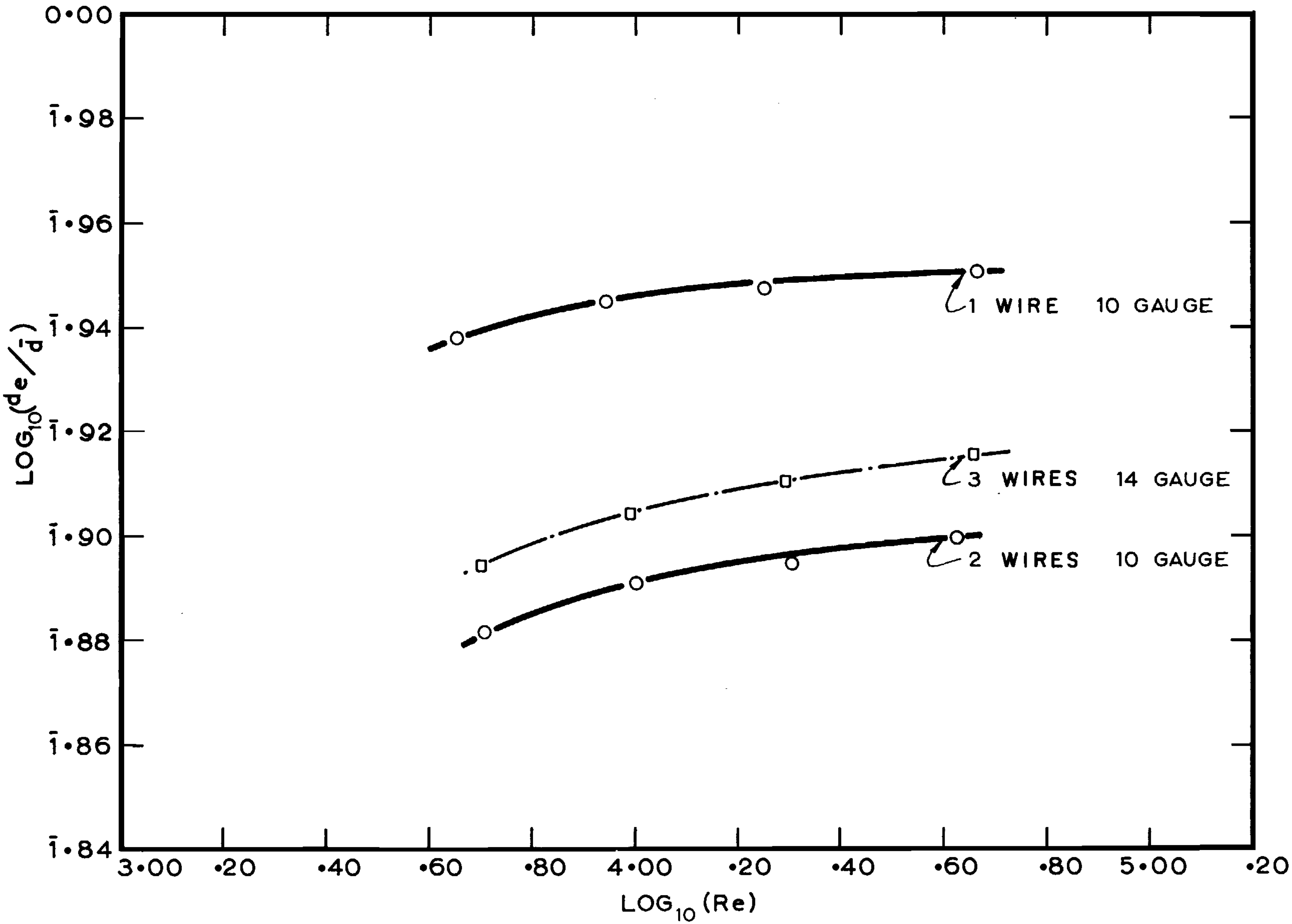

FIGURE 6 (v)

VARIATION OF $d_e/\bar{d}$ WITH REYNOLDS NUMBER

3/4" CONDUIT - SECTION NO. 3 - RUBBER COVERED WIRE

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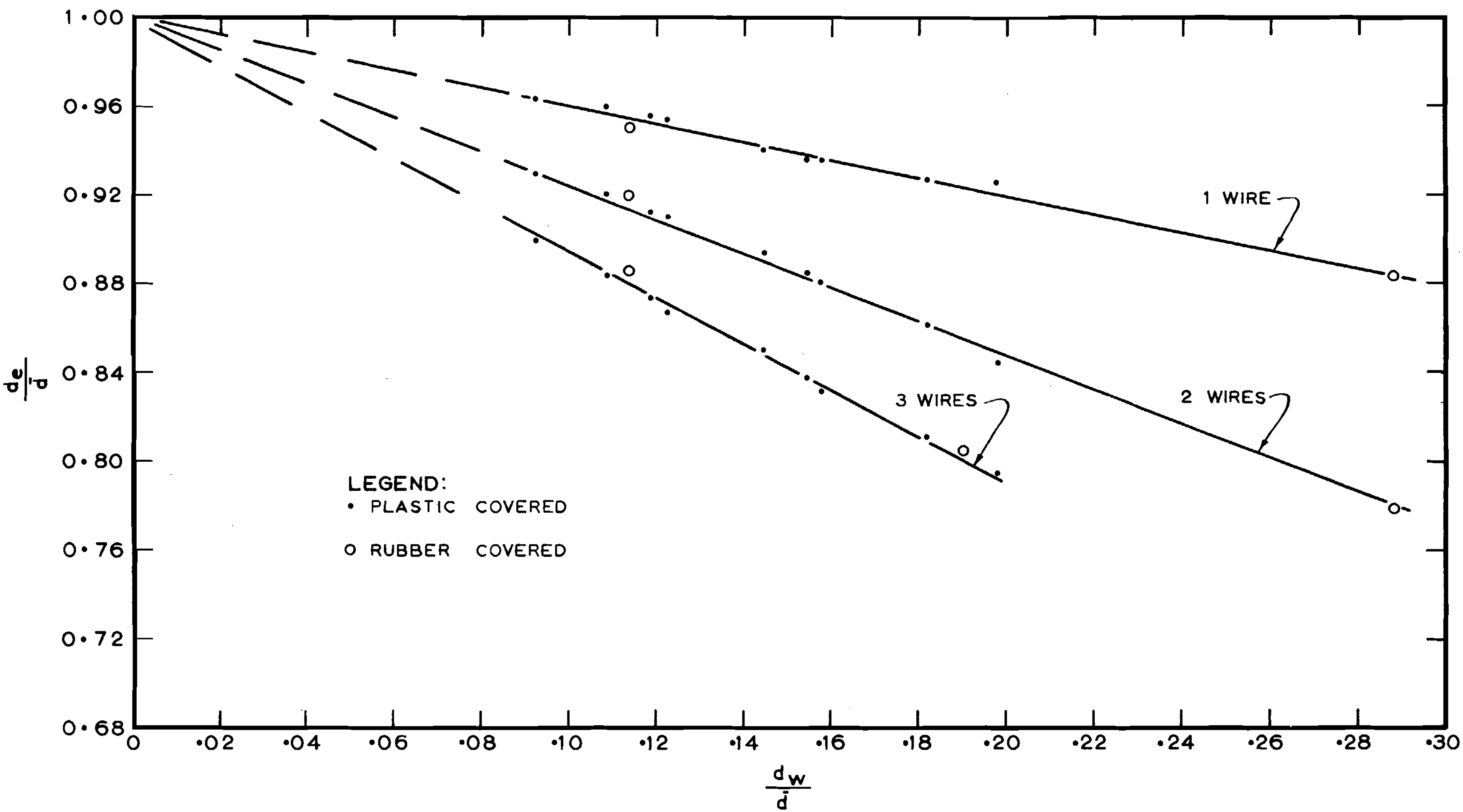

FIGURE 7

VARIATION OF EQUIVALENT DIAMETER WITH WIRE DIAMETER

FOR REYNOLDS NUMBER OF 10,000

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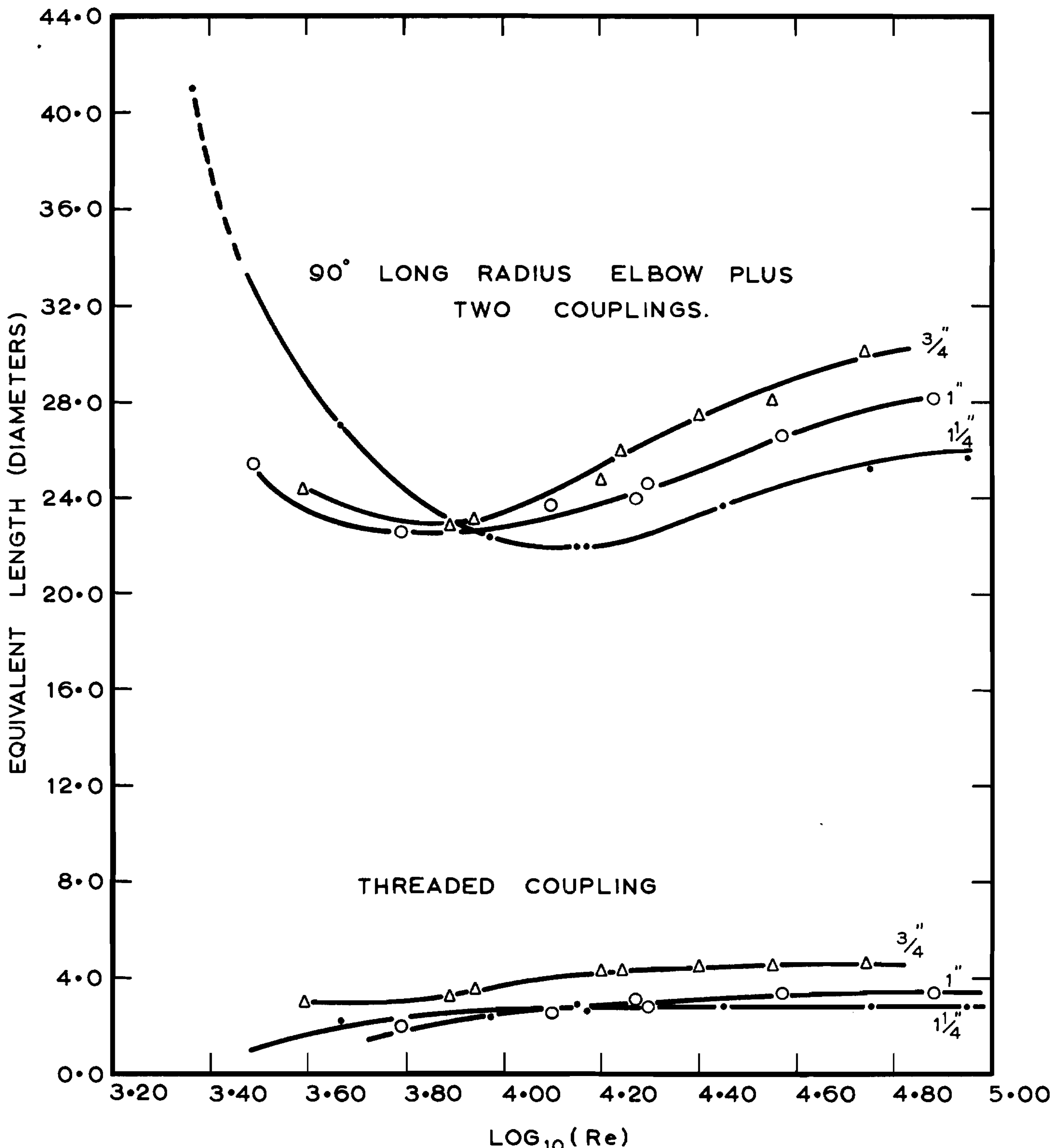

FIGURE 8

EQUIVALENT LENGTHS FOR ELBOWS AND COUPLINGS WHEN EMPTY.

$$K = 444\,(\mu)^{0\cdot 26} \cdot \frac{L}{d^{4\cdot 74}} \cdot \frac{T}{P}$$

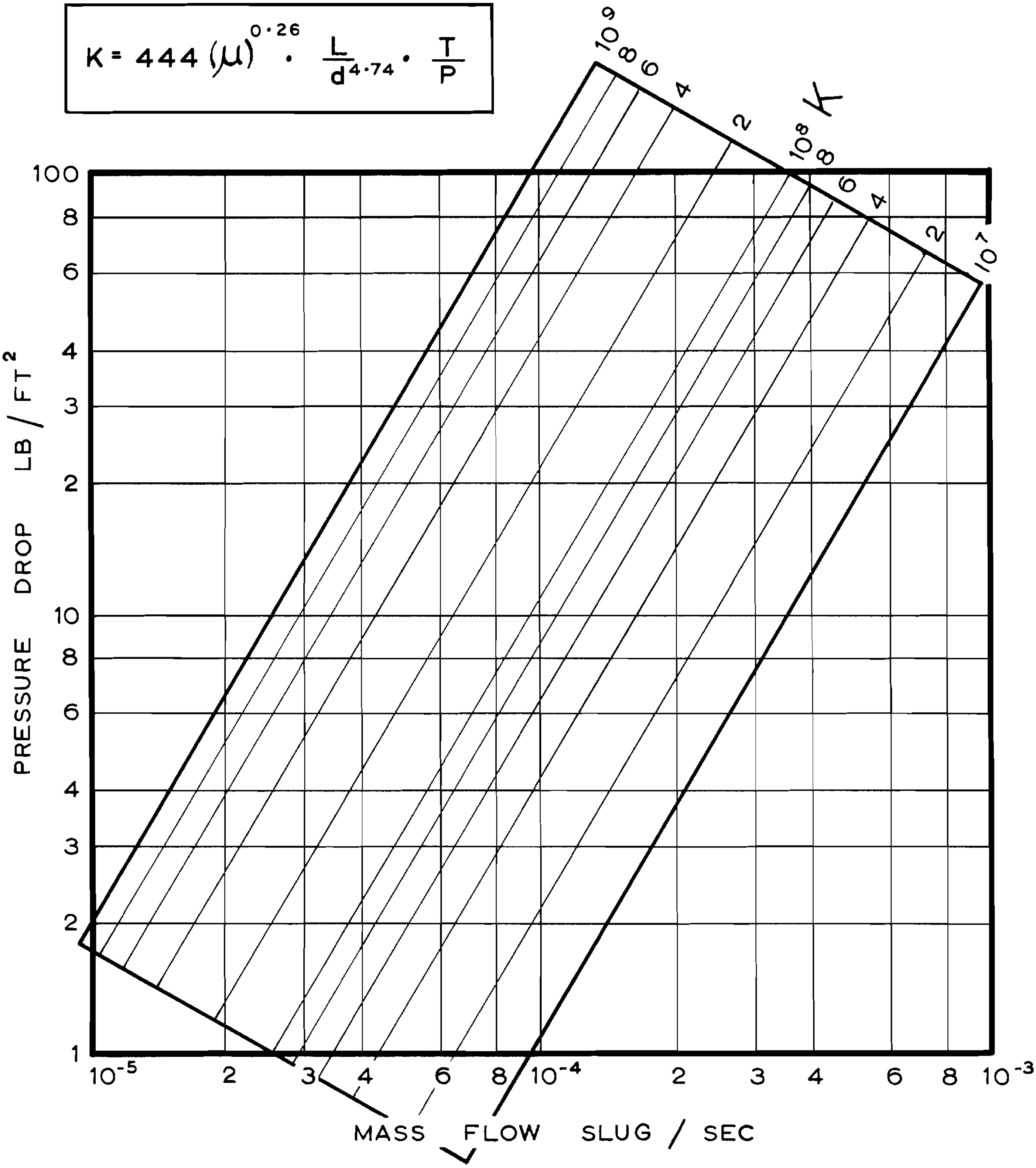

FIGURE 9

PRESSURE LOSS FOR TURBULENT FLOW IN A SMOOTH PIPE.

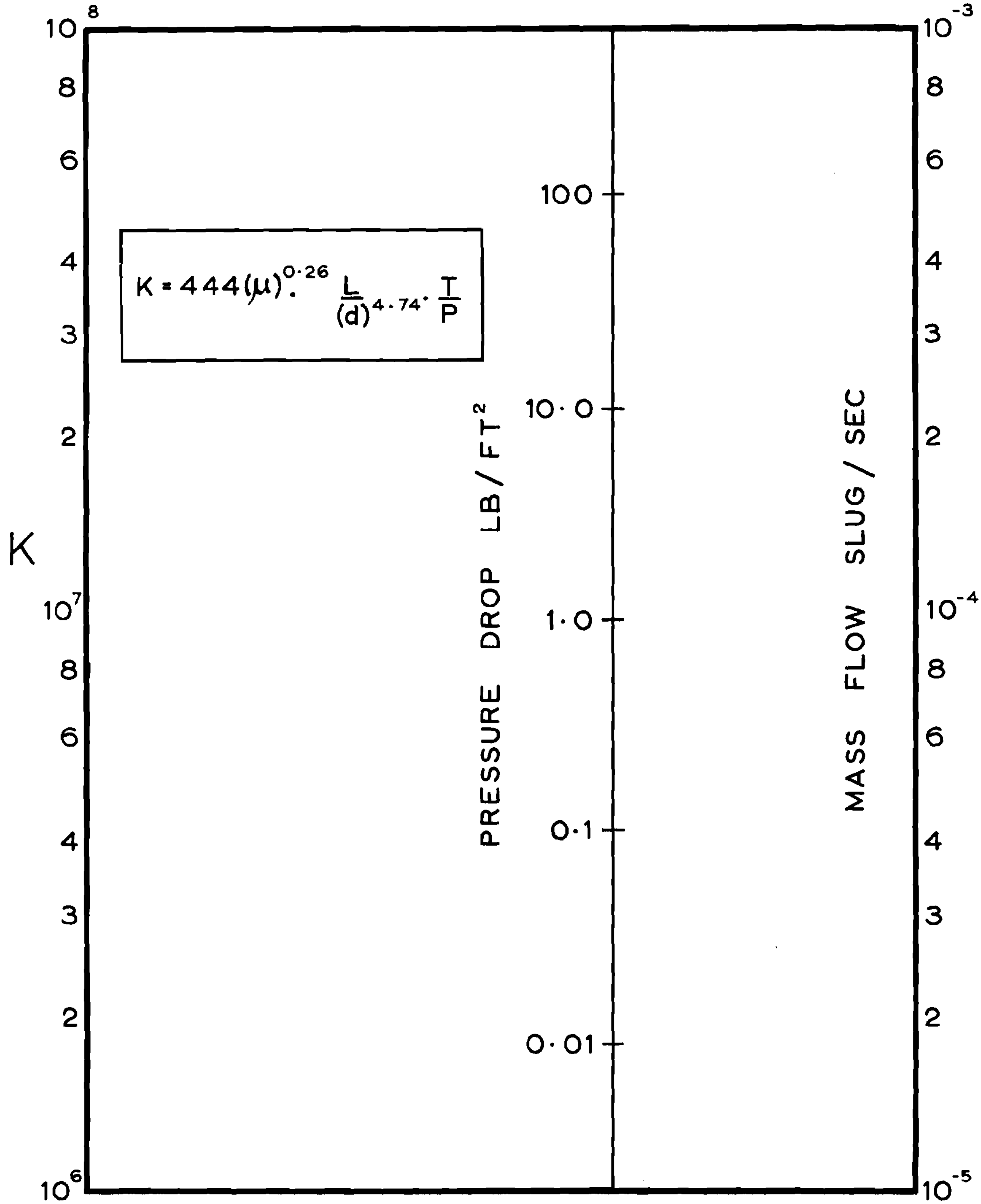

FIGURE 10

PRESSURE LOSS FOR TURBULENT FLOW IN A SMOOTH PIPE.

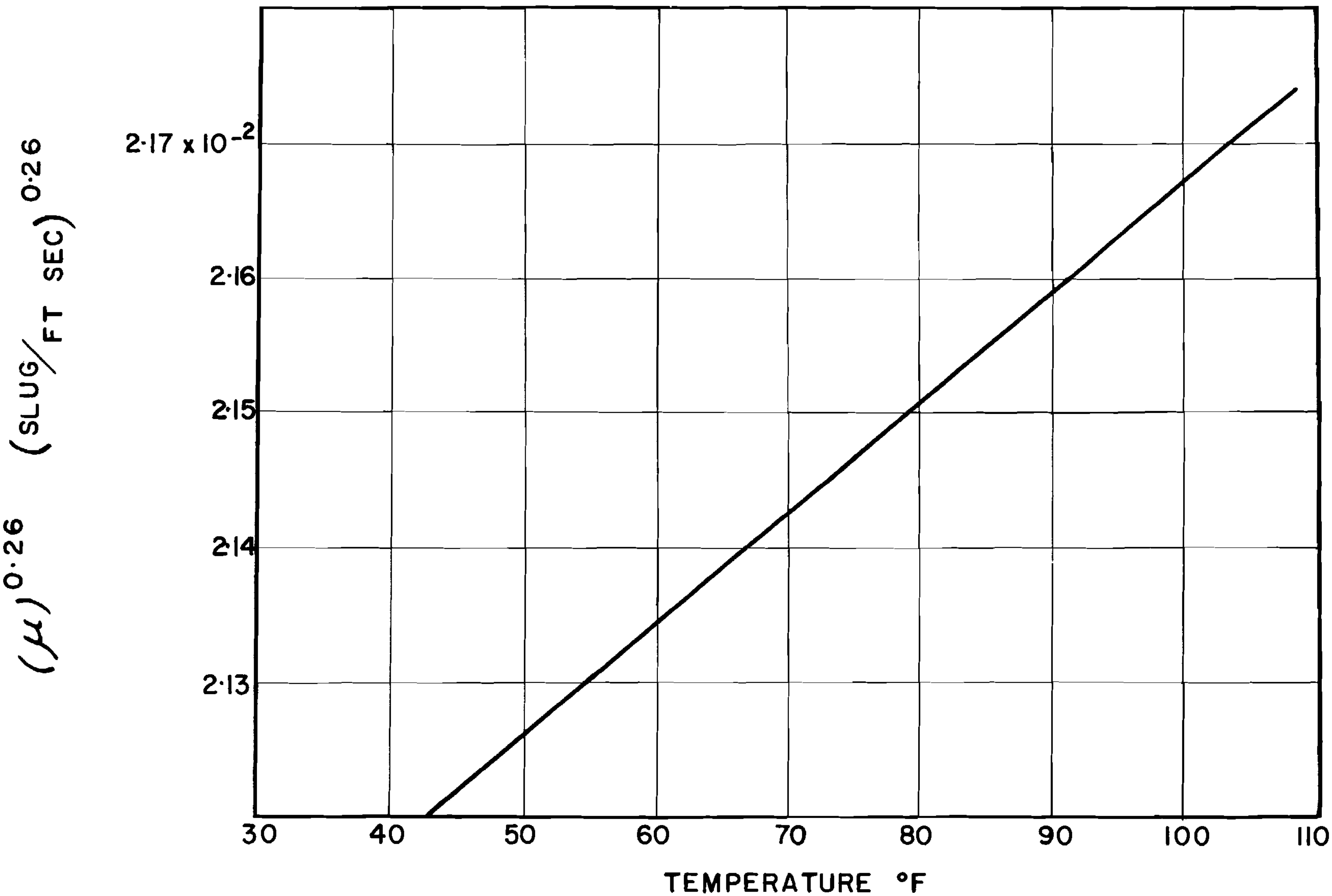

FIGURE 11 $(\mu)^{0.26}$ vs. T FOR DRY AIR

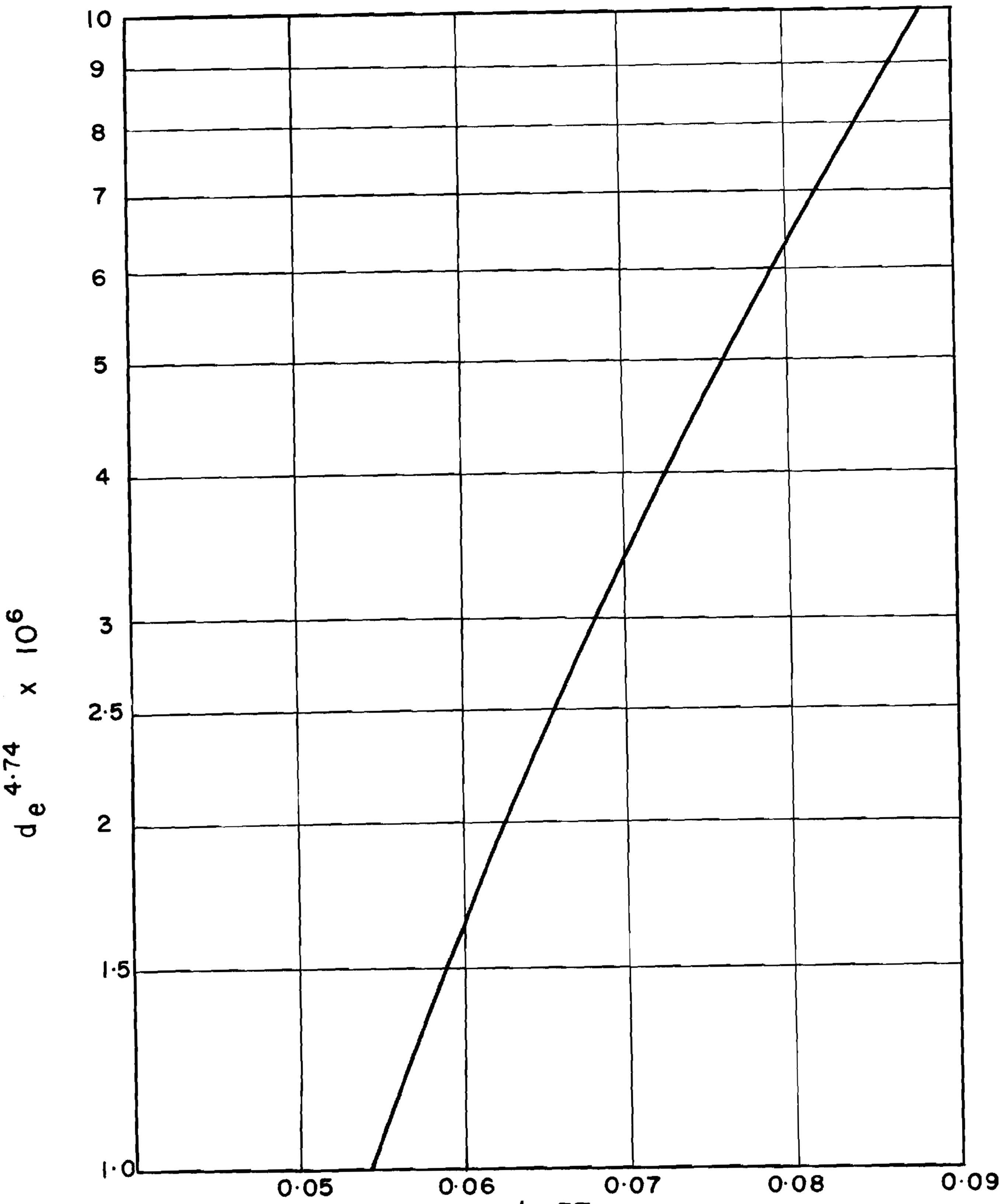

FIGURE 12 (i)

$d_e^{4.74}$ vs. d_e

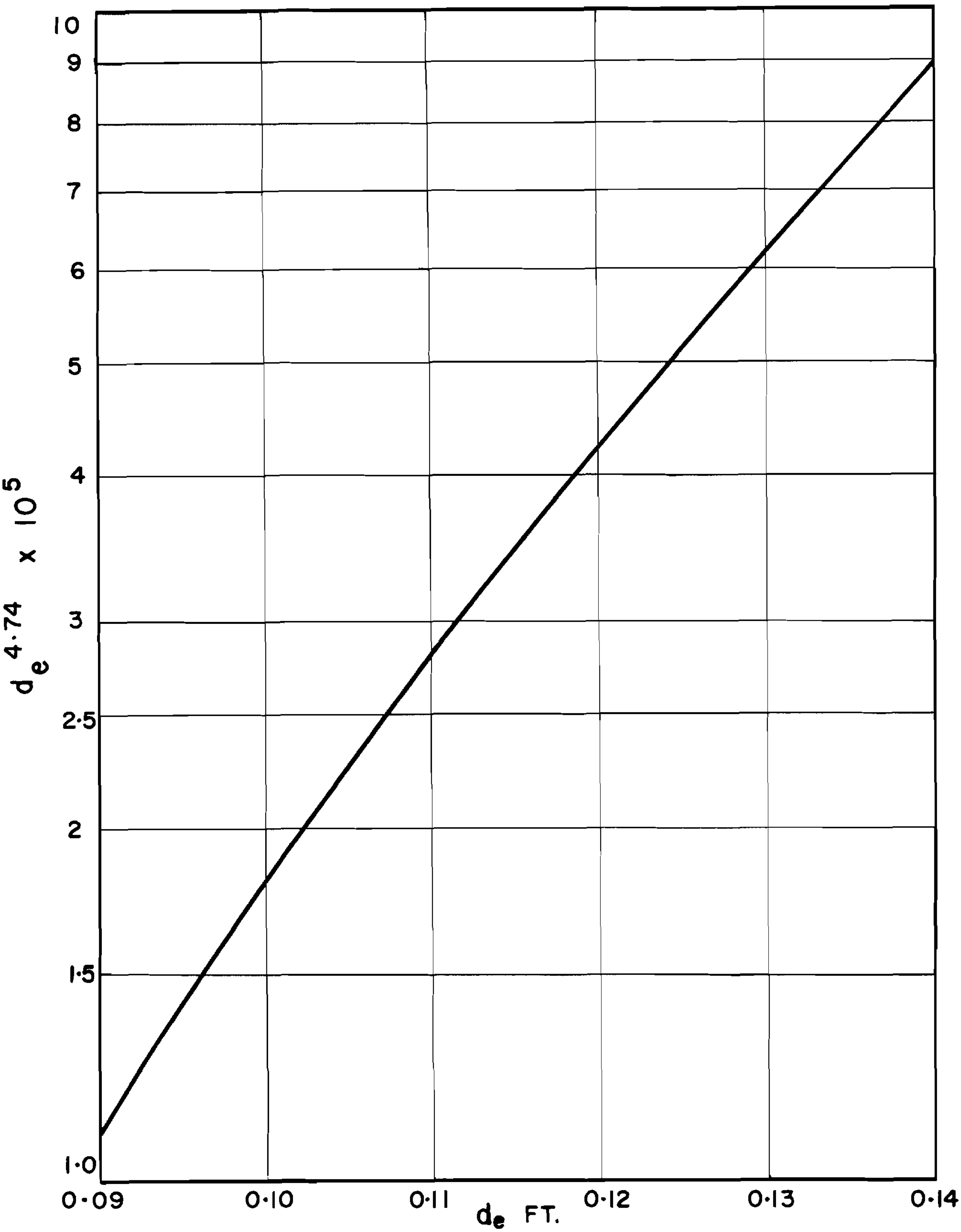

FIGURE 12 (ii)

$d_e^{4·74}$ vs. d_e

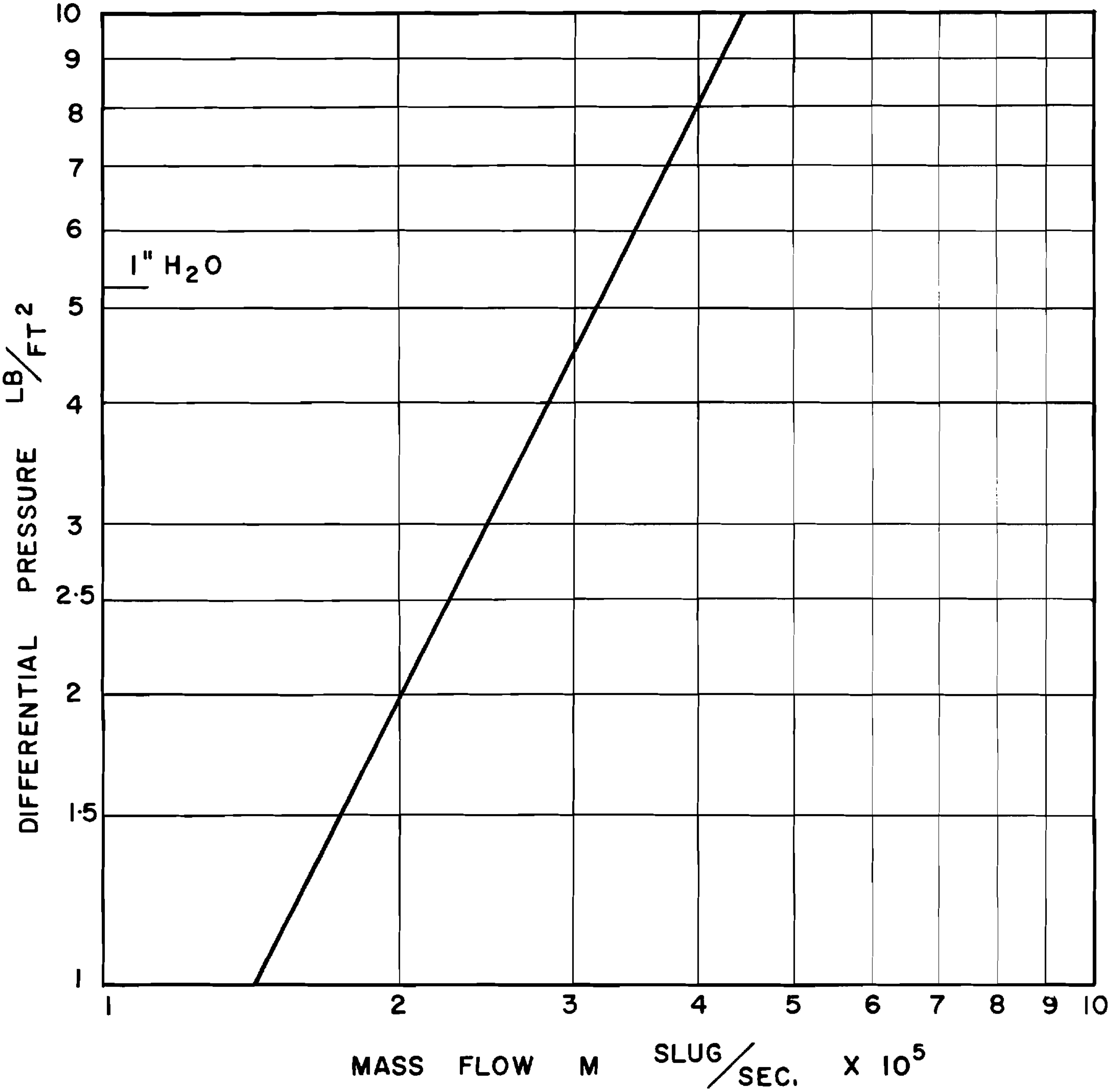

FIGURE 13

MASS FLOW FOR 1/4" DIA. ORIFICE

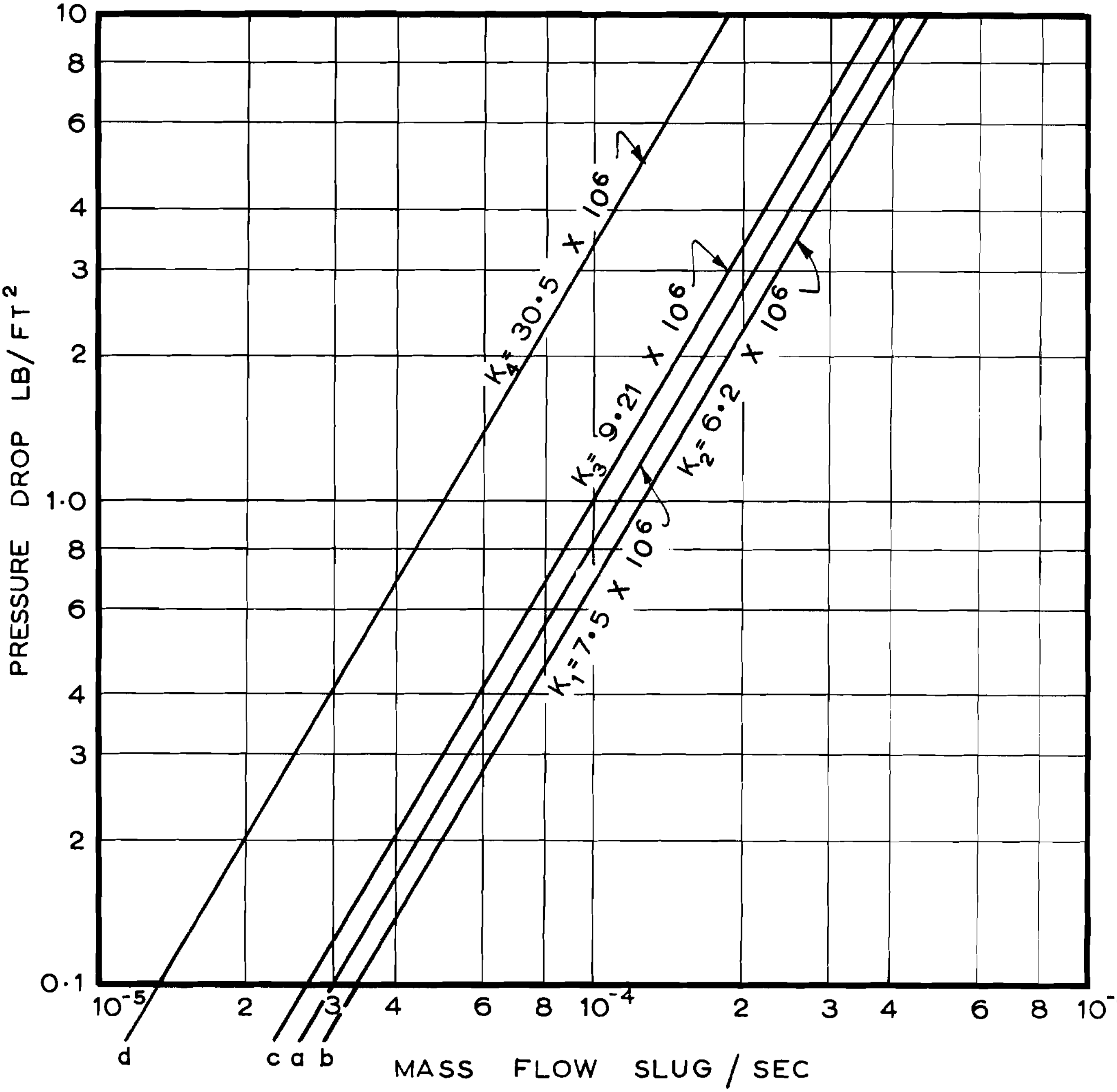

FIGURE 14

PRESSURE LOSS FOR TURBULENT PIPE FLOW.

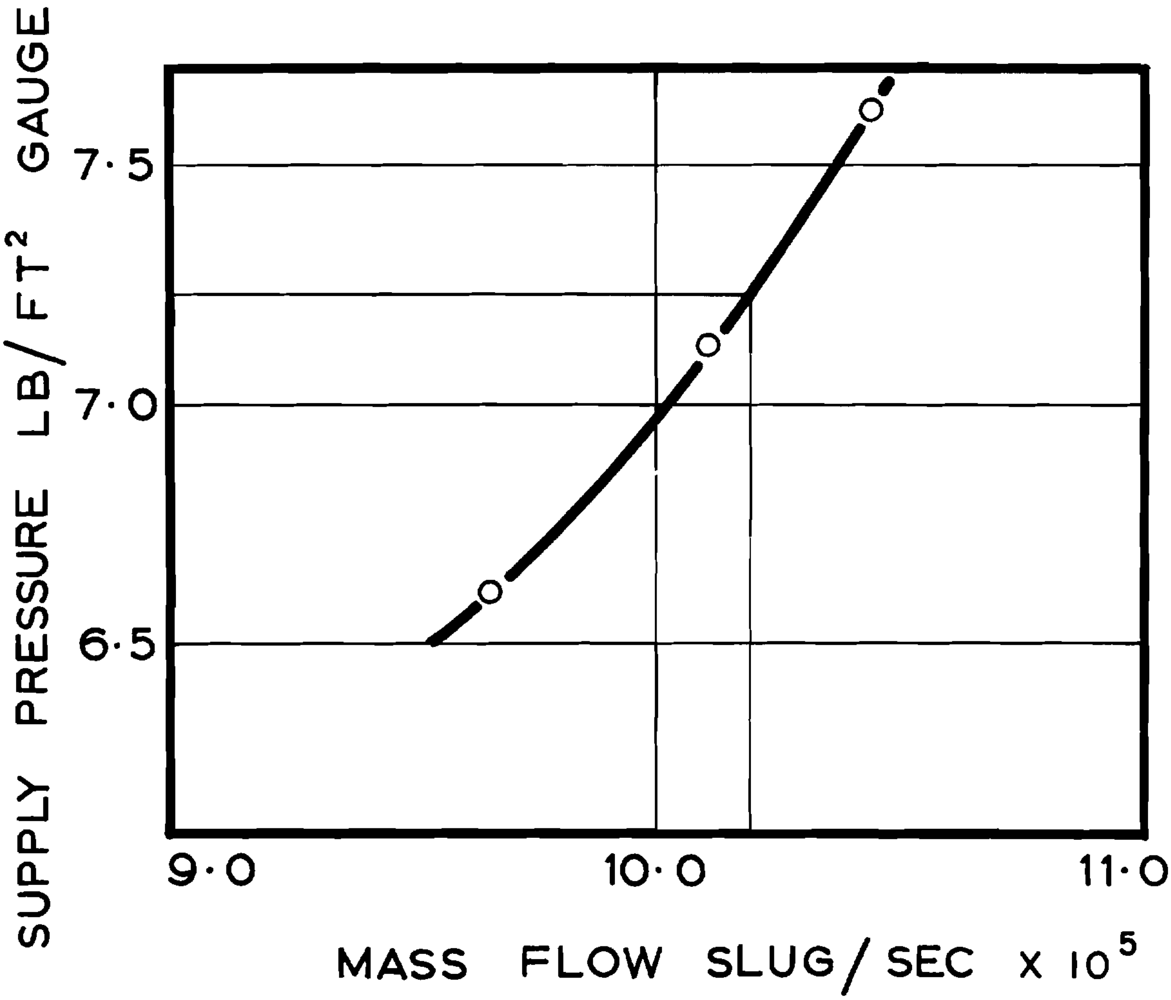

FIGURE 15

MASS FLOW vs SUPPLY PRESSURE FOR BRANCH II.