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400 Commonwealth Drive, Warrendale, PA 15096-0001

AEROSPACE RECOMMENDED PRACTICE

SAE ARP24 REV. C

Issued 1947-02
Reaffirmed 1991-11
Revised 2000-11

Supersedes ARP24B

Determination of Hydraulic Pressure Drop

FOREWORD

Changes in this revision are format/editorial only.

1. SCOPE:

This ARP is intended to be a guide for determining pressure drop in fluid systems such as hydraulic, fuel, oil, and coolant used in aerospace vehicles. Determining pressure drop by analytical and test methods will be discussed.

2. GENERAL:

A fluid flowing through a tube meets a certain amount of resistance due to kinetic and viscous effects. The pressure required to overcome this resistance and to maintain a certain flow rate is known as “pressure drop” or “back pressure.” Where the flow of hydraulic fluid is maintained at a certain rate through a horizontal length of tube, discharging to atmosphere, the pressure gage at the rear or upstream end of the tube would show the pressure required to overcome friction and maintain the rate of flow. This pressure is known as the “back pressure” or the drop in pressure due to friction for that length of tube at a certain flow rate. The flow rate is usually expressed in gallons per minute or gpm. The pressure drop is expressed in pounds per square inch or psi at a certain gpm flow; for example, the pressure drop is 50 psi at 3 gpm.

The approximate pressure drop can be determined by applying a fixed flow to a valve inlet port, with pressure gage attached, the outlet port open, and determining the time to fill a container of known capacity. The gage reading would then be the approximate pressure drop at that rate of flow. A piece of tubing, hose, or fitting could be tested for pressure drop in this manner.

2. (Continued):

All parts of a hydraulic system through which flow is maintained will have a certain pressure drop, including tubing, fittings, valves, etc. When using a hydraulic test stand, the pressure drop through a valve is measured by placing it in a line between the pump and the flow meter, with a pressure gage at each end of the valve. While reading the gages on the valve, the required flow must be stabilized through the valve and flow meter. The difference in readings of the two gages is the approximate pressure drop for the flow shown on the flow meter.

If more accurate results must be obtained, special pressure pick-ups must be used and they must be placed a sufficient distance from any flow disturbance.[1] See typical test set-up shown in Figures 1 and 2.

Example - The following example is for a 4-way pilot operated solenoid valve. The same set-up and procedure, with modifications, can be used to obtain the pressure drop of any unit.

Test Set-up - Make test set-up as shown in Figure 1. Use an accurately calibrated pressure gage with sufficient resolution to secure accurate readings. The use of a differential pressure gage (or transducer) eliminates accumulative error between several instruments and gives more accurate results. Use piezometers for pressure pick-up connections; a standard tee may give results considerably in error. Install piezometers at least 4 times the tube inside diameter upstream and at least 10 times tube inside diameter downstream from any other connection, using straight rigid lines.

Figure 2 shows the set-up to determine the “tare” pressure drop, which is the drop due to fittings and connecting tubing in the circuit. The gross pressure less the tare is the net pressure drop of the specimen or sample. The jumper line must be included in circuit during all pressure drop determinations.

3. EQUIPMENT:

The equipment for pressure drop testing should be so constructed that continuous controlled operation can be maintained throughout the test period.

3.1 Tank:

The tank should contain some means for controlling temperature variations. The fluid temperatures during pressure drop runs should be held such that the viscosity matches that of the intended service.

Baffles or other devices to remove turbulence and entrained air at the pump section should be provided. Evidence that there is no entrained air should be observed at a transparent tube section in the supply line downstream of both the low pressure tap and the test specimen, or in the transparent flow meter, if such is used.

[1] See “ASME Power Test Codes, 1959 Supplement on Instruments & Apparatus, Part 2 - Pressure Measurements” paragraph 20-31.

3.2 Pump:

The pump should be mounted as close to the tank as possible to minimize suction losses, and to preclude the possibility of sucking air into the line. The speed of the pump should not be exceptionally high. It is better to use industrial pumps of low rotational speed than aircraft pumps of much higher speeds. Flow variation may be obtained either by throttling the pump outlet and diverting excessive flow or by using a variable flow control directly on the pump.

NOTE: Since low speed pumps give higher pressure ripple, the outlet must be filtered.

3.3 Flowmeter:

Equipment for flow measurement should give accurate and reproducible results; therefore, they must be calibrated periodically by weighing fluid that flows through the instrument in a specific time period or by some other means.[2]

3.4 Pressure Taps:

Pressure tap fittings, Figure 6, or piezometer type tubes, Figure 7, should be used to measure pressure drop. Tee fittings are considered undesirable. All drillings and flow passages should be smooth with clean intersections. Piezometer type tubes, Figure 7, are preferred over the pressure tap fittings, Figure 6.

3.5 Pressure Differential Measurement:

The means of measuring pressure differential between piezometer taps may vary with the pressure, fluid, and accuracy required. Accurate gages, strain gage transducers, mercury manometers, and air-test fluid manometers all have application. The best means for measuring pressure differentials is the use of a single gage, where the high and low pressure taps are such as to create a differential reading. This arrangement reduces gage errors to a minimum and also allows the use of a low range pressure gage having graduations which permit more accurate readings. Air fluid columns are usually the most accurate, but the columns become unmanageable at higher pressures. Valves and other means should be provided to allow thorough and positive venting of the manometer connections to eliminate trapped air.

3.6 Test Fluid:

Accessories should generally be tested on the fluid with which they will be used. In cases where this is not practical because of safety, facility, availability, etc., one should attempt to select a test fluid which matches the service fluid in viscosity and density (as applicable) as closely as possible to reduce the correction magnitude. Fluid temperature must be measured and recorded at the time pressure is recorded. Viscosity must be periodically checked to determine the datum point.

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[2] Empirical calibrations of turbine and float flow meters are not considered satisfactory when data accuracy better than 5% is required. Test temperature should be that required to match fluid property (density/viscosity), to which meter is sensitive, to that at which calibrated. Where this cannot be accomplished or is not desirable, corrections must be applied for changed fluid property (density/viscosity).

4. THEORY:

4.1 Nomenclature:

V	= Speed	ft/second
Q	= Volumetric flow	US gal/min
W	= Weight flow	lb/second
H	= Pressure head loss	ft
P	= Pressure loss	psi
L	= Length of pipe	ft
D	= Diameter of pipe or passage	inch
A	= Area of passage	$inch^2$
ρ	= Fluid density	Slugs/cu ft[3]
s	= Specific gravity[4] of fluid	(dimensionless)
μ	= Absolute viscosity	lb-second/ft^2
ν	= Kinematic viscosity	ft^2/second
g	= Gravitational constant	32.2 ft/$second^2$
N_R	= Reynolds number	(dimensionless)
ϕ	= Energy loss coefficient	
f	= Friction loss coefficient	Darcy (dimensionless)
S	= Dimensionless factor	
T	= Dimensionless factor	

4.2 Fundamental Information:

Several factors affect energy losses. Such factors are: type of flow, viscosity of fluid, surface roughness, sudden flow passage area and direction changes through fittings and tube bends, etc.

This energy loss is dissipated in the form of heat and, for a good first estimate, when the flow is turbulent, can be taken as being proportional to the fluid velocity squared.

It is convenient to express this in terms of velocity head:

$$H_{turb} = \phi \frac{V^2}{2g} \quad \text{(Eq. 1)}$$

where: ϕ is a coefficient of energy loss whose magnitude varies considerably for different types of flow impeders and, in general, is a function of the nature of flow.

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3 The slug is the gravitational unit of mass (lb-$second^2$/ft). It is defined as the mass which will receive an acceleration of 1 fps when acted upon by an unbalanced force of 1 pound.

4 Ratio of weight of volume of fluid at the temperature being flowed to that of an equal volume of water at 4 C. Use of data based on water at 60 F introduces an error of approximately 0.1%.

4.2 (Continued):

The flow velocity is usually of little practical interest and is most conveniently interpreted in terms of flow rate, using either volumetric or weight measure. Also measuring pressure in psi, and for a circular passageway of diameter D, equation (1) can be written:

For volumetric measure:

$$P_{turb} = \phi \frac{0.00112\ sQ^2}{D^4} \qquad \text{(Eq. 2)}$$

For weight measure:

$$P_{turb} = \phi \frac{0.05809\ W^2}{sD^4} \qquad \text{(Eq. 2A)}$$

Equations (2) and (2A) can be used for non-circular passageways, provided D is an equivalent diameter computed from the equation:

$$D = 1.128\sqrt{A} \qquad \text{(Eq. 3)}$$

where: A is the area of the passageway.

The nature of flow is dependent upon the ratio of inertial to viscous forces in the stream of fluid. This ratio is known as Reynolds number, N_R, and is a dimensionless factor given by:

$$N_R = \frac{\rho\ VD}{\mu} \qquad \text{(Eq. 4)}$$

or

$$N_R = \frac{VD}{\nu} \qquad \text{(Eq. 5)}$$

For laminar flow, where the viscous forces are predominant, the ratio N_R is small. In a turbulent flow the inertial forces predominate and therefore the value of N_R is large.

4.2 (Continued):

Substituting rate of flow in place of V in equation (4):

For volumetric measure:

$$N_R = \frac{0.0660\ sQ}{\mu D} \quad \text{(Eq. 6)}$$

For weight measure:

$$N_R = \frac{0.4750\ W}{\mu D} \quad \text{(Eq. 6A)}$$

Most of the flow encountered in aircraft installations is turbulent. In general, for straight tubing, laminar flow is predominant for values of N_R below about 1400, and becomes fully turbulent above about 3600 (see Figure 3). When the flow is disturbed by the presence of bends and fittings a turbulent condition is found to prevail down to N_R = 1000 or less.

The value of ϕ, equations (2) and (2A), must be determined experimentally for hydraulic fittings and tube bends, etc., over a range of Reynolds numbers relevant to system requirements.

For the special case of straight smooth tubing, much classical work has been done. Pressure head loss may be computed from the following equation, derived from the Darcy - Weisbach law:

$$H = f\frac{LV^2}{2Dg} \quad \text{(Eq. 7)}$$

in which the energy loss coefficient ϕ, equation (1), is replaced by a coefficient of friction “f”.

i.e.,

$$\phi = f\frac{L}{D} \quad \text{(Eq. 8)}$$

From the theory of laminar flow it can be shown that:

$$f_{lam} = \frac{64}{N_R} \quad \text{(Eq. 9)}$$

4.2 (Continued):

The coefficient "f" for turbulent flow, from experimental work by Blasius, can be expressed by:

$$f_{turb} = \frac{0.316}{N_R^{0.25}} \quad \text{(Eq. 10)}$$

By substituting flow rate and pressure in place of V and H in equation (7), then combining with equations (9) and (10), the following expressions can be found:

For laminar-flow, and using volumetric measure (gpm):

$$p_{lam} = \frac{13.07\ \mu LQ}{D^4} \quad \text{(Eq. 11)}$$

For laminar-flow, and using weight measure (lb/second):

$$p_{lam} = \frac{94.04\ \mu LW}{sD^4} \quad \text{(Eq. 11A)}$$

For turbulent flow, and using volumetric measure (gpm):

$$p_{turb} = \frac{0.008422\ \mu^{0.25} s^{0.75} Q^{1.75} L}{D^{4.75}} \quad \text{(Eq. 12)}$$

For turbulent flow, and using weight measure (lb/second):

$$p_{turb} = \frac{0.2662\ \mu^{0.25} W^{1.75} L}{sD^{4.75}} \quad \text{(Eq. 12A)}$$

It will be noted that English units of measure are specified in the above equations. If metric units or a combination of metric and English units are used (metric units are commonly used for fluid viscosity), then care should be taken to properly compensate for these changes. See Table 1 for table of systems of units and Table 2 for viscosity conversion factors. Since viscosities and density varies with applied pressure, pressure drops should be measured at hydraulic pressure levels encountered in the design environment. Caution should be exercised in use of the equations contained in this document to assure that the parameters are in the correct units. For example, in equation (4), D must be converted from inches to feet to make the equation dimensionless.

5. CHART METHOD OF SOLUTION FOR STRAIGHT SMOOTH PIPES:

In order to simplify calculations, particularly in the turbulent flow region, the classical equations for flow in straight tubes can be written in terms of dimensionless factors S and T:

$$S = \frac{1}{\mu}\left(\frac{\Delta P}{L} \cdot D^3 \rho\right)^{1/2} = N_R\left(\frac{f}{2}\right)^{1/2} \qquad \text{(Eq. 13)}$$

$$T = \frac{1}{\mu}\left(\frac{\Delta P}{L} \cdot Q^3 \cdot \rho^4\right)^{1/5} = \frac{N_R}{4}(8\pi^3 f)^{1/5} \qquad \text{(Eq. 14)}$$

From the right hand sides of equations (13) and (14), S and T are plotted against “f” in Figures 4 and 5.

The left hand sides of equation (13) and (14) are expressed in terms of five convenient elements of flow relationship:

$$(1)\ \mu;\ (2)\ \rho;\ (3)\ D;\ (4)\ \frac{\Delta P}{L};\ (5)\ Q$$

Also Figure 3 shows N_R plotted against “f”, as derived from classical work.

By using the left hand sides of equations (13) and (14) in conjunction with Figures 3, 4 and 5, either S, T, N_R or “f” can be found (depending which is most convenient for a given problem) in terms of the four known elements. Having computed the values of this factor, the factor containing the 5th, or unknown, element can be read from the relevant curve. From this, the unknown element of flow or pressure drop, etc., is then calculated.

PREPARED BY THE FLUIDS PANEL OF SUBCOMMITTEE A-6C,
FLUID POWER DISTRIBUTION ELEMENTS, OF COMMITTEE A-6,
AEROSPACE FLUID POWER & CONTROL TECHNOLOGIES

TABLE 1 - SYSTEMS OF UNITS

QUANTITY	SYMBOL	SYSTEM	
		ABSOLUTE	GRAVITATIONAL (Engineering)
Mass	M	M (lb)	FTi^2/L [slug (lb sec^2 ft)]
Force	F	ML/Ti^2 [Poundal (lb ft/sec^2)]	F (lb)
Density	ρ	M/L^3 (lb/ft^3)	FTi^2/L^4 [$slug/ft^3$ (lb sec^2/ft^4)]
Absolute Viscosity	ρ	M/LTi (lb/ft sec)	FTi/L^2 (lb sec/ft^2)
Kinematic Viscosity	$\nu = \mu/\rho$	L^2/Ti (ft^2/sec)	L^2/Ti (ft^2 sec)

TABLE 2 - VISCOSITY CONVERSION FACTORS*

Multiply by appropriate entry to obtain ↓	Centipoise	Poise	g_F sec cm^{-2}	lb_F sec in^{-2}	lb_F sec ft^{-2}	lb_F hr in^{-2}
Centipoise	1	$1x10^{-2}$	$1.0197x10^{-5}$	$1.4504x10^{-7}$	$2.0886x10^{-5}$	$4.0289x10^{-11}$
Poise	$1.x10^{2}$	1	$1.0197x10^{-3}$	$1.4504x10^{-5}$	$2.0886x10^{-3}$	$4.0289x10^{-9}$
g_F sec cm^{-2}	$9.8067x10^{4}$	$9.8067x10^{2}$	1	$1.4224x10^{-2}$	2.0482	$3.9510x10^{-6}$
lb_F sec in^{-2}	$6.8947x10^{6}$	$6.8947x10^{4}$	$7.0505x10^{1}$	1	$1.4400x10^{2}$	$2.7778x10^{-4}$
lb_F sec ft^{-2}	$4.7880x10^{4}$	$4.7880x10^{2}$	$4.8823x10^{-1}$	$6.9445x10^{-3}$	1	$1.9290x10^{-6}$
lb_F hr in^{-2}	$2.4821x10^{10}$	$2.4821x10^{8}$	$2.5310x10^{5}$	$3.6000x10^{3}$	$5.1841x10^{5}$	1
lb_F hr ft^{-2}	$1.7237x10^{8}$	$1.7237x10^{6}$	$1.7577x10^{3}$	$2.5001x10^{1}$	$3.6001x10^{3}$	$6.9446x10^{-3}$
g_M sec^{-1} cm^{-1}	$1x10^{2}$	1	$1.0197x10^{-3}$	$1.4504x10^{-5}$	$2.0886x10^{-3}$	$4.0289x10^{-9}$
lb_M sec^{-1} in^{-1}	$1.7858x10^{4}$	$1.7858x10^{2}$	$1.8210x10^{-1}$	$2.5901x10^{-3}$	$3.7298x10^{-1}$	$7.1948x10^{-7}$
lb_M sec^{-1} ft^{-1}	$1.4882x10^{3}$	$1.4882x10^{1}$	$1.5175x10^{-2}$	$2.1585x10^{-4}$	$3.1083x10^{-2}$	$5.9958x10^{-8}$
lb_M hr^{-1} in^{-1}	4.9605	$4.9605x10^{-2}$	$5.0582x10^{-5}$	$7.1947x10^{-7}$	$1.0361x10^{-4}$	$1.9985x10^{-10}$
lb_M hr^{-1} ft^{-1}	$4.1338x10^{-1}$	$4.1338x10^{-3}$	$4.2152x10^{-6}$	$5.9957x10^{-8}$	$8.6339x10^{-6}$	$1.6655x10^{-11}$

Multiply by appropriate entry to obtain ↓	lb_F hr ft^{-2}	lb_M sec^{-1} in^{-1}	lb_M hr^{-1} ft^{-1}	slug sec^{-1} in^{-1}	slug hr^{-1} ft^{-1}	g_M sec^{-1} cm^{-1}
Centipoise	$5.8016x10^{-9}$	$5.5998x10^{-5}$	2.4191	$1.7405x10^{-6}$	$7.5188x10^{-2}$	$1x10^{-2}$
Poise	$5.8016x10^{-7}$	$5.5998x10^{-3}$	$2.4191x10^{2}$	$1.7405x10^{-4}$	7.5188	1
g_F sec cm^{-2}	$5.6895x10^{-4}$	5.4916	$2.3723x10^{5}$	$1.7068x10^{-1}$	$7.3733x10^{3}$	$9.8067x10^{2}$
lb_F sec in^{-2}	$4.0000x10^{-2}$	$3.8609x10^{2}$	$1.6679x10^{7}$	$1.2000x10^{1}$	$5.1840x10^{5}$	$6.8947x10^{4}$
lb_F sec ft^{-2}	$2.7778x10^{-4}$	2.6812	$1.1583x10^{5}$	$8.3335x10^{-2}$	$3.6000x10^{3}$	$4.7880x10^{2}$
lb_F hr in^{-2}	$1.4400x10^{2}$	$1.3899x10^{6}$	$6.0044x10^{10}$	$4.3199x10^{4}$	$1.8662x10^{9}$	$2.4821x10^{8}$
lb_F hr ft^{-2}	1	$9.6524x10^{3}$	$4.1698x10^{8}$	$3.0000x10^{2}$	$1.2960x10^{7}$	$1.7237x10^{6}$
g_M sec^{-1} cm^{-1}	$5.8016x10^{-7}$	$5.5998x10^{-3}$	$2.4191x10^{2}$	$1.7405x10^{-4}$	7.5188	1
lb_M sec^{-1} in^{-1}	$1.0360x10^{-4}$	1	$4.3200x10^{4}$	$3.1081x10^{-2}$	$1.3427x10^{3}$	$1.7858x10^{2}$
lb_M sec^{-1} ft^{-1}	$8.6339x10^{-6}$	$8.3333x10^{-2}$	$3.6000x10^{3}$	$2.5902x10^{-3}$	$1.1189x10^{2}$	$1.4882x10^{1}$
lb_M hr^{-1} in^{-1}	$2.8779x10^{-8}$	$2.7778x10^{-4}$	$1.2000x10^{1}$	$8.6337x10^{-6}$	$3.7297x10^{-1}$	$4.9605x10^{-2}$
lb_M hr^{-1} ft^{-1}	$2.3983x10^{-9}$	$2.3148x10^{-5}$	1	$7.1946x10^{-7}$	$3.1081x10^{-2}$	$4.1336x10^{-3}$

*From WADC TR 58-638 Vol I Part I

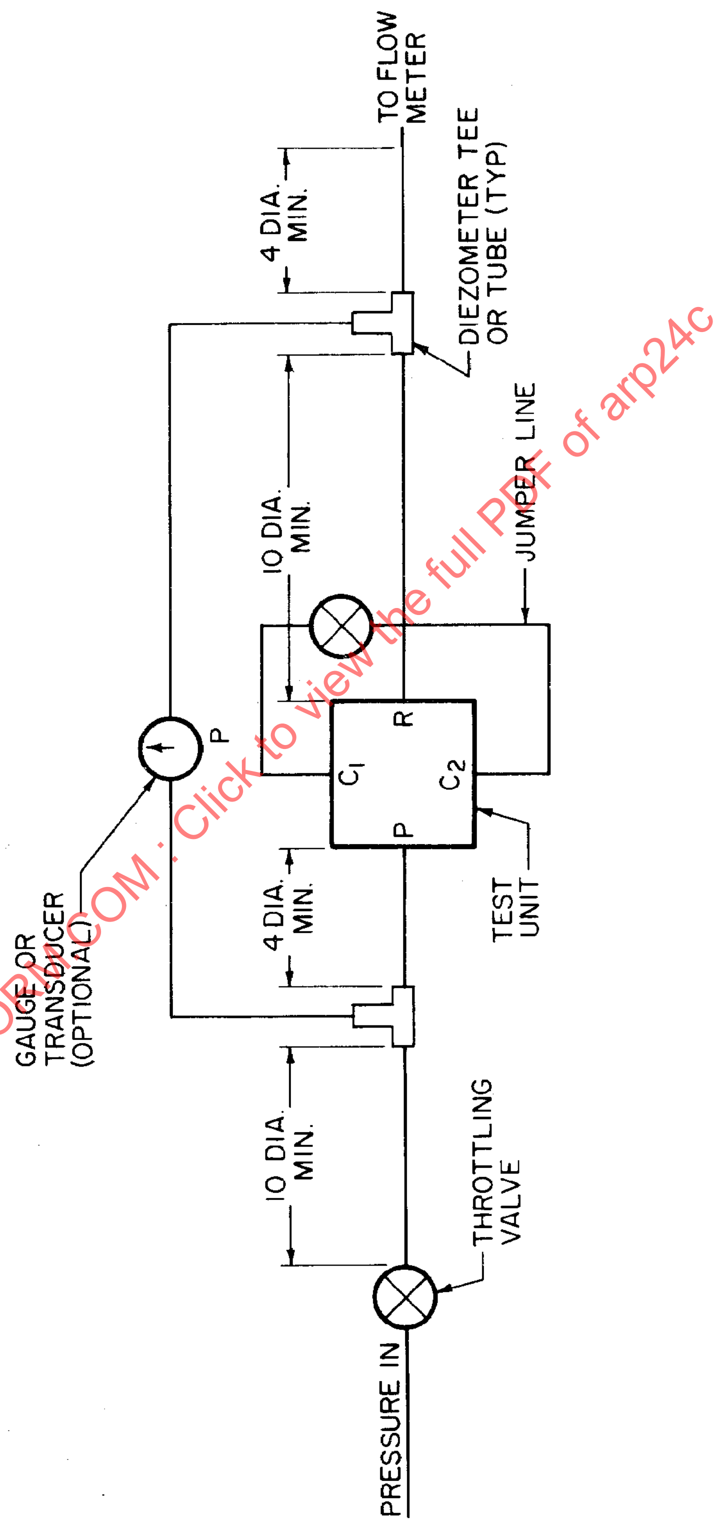

FIGURE 1 - TEST LOOP SCHEMATIC

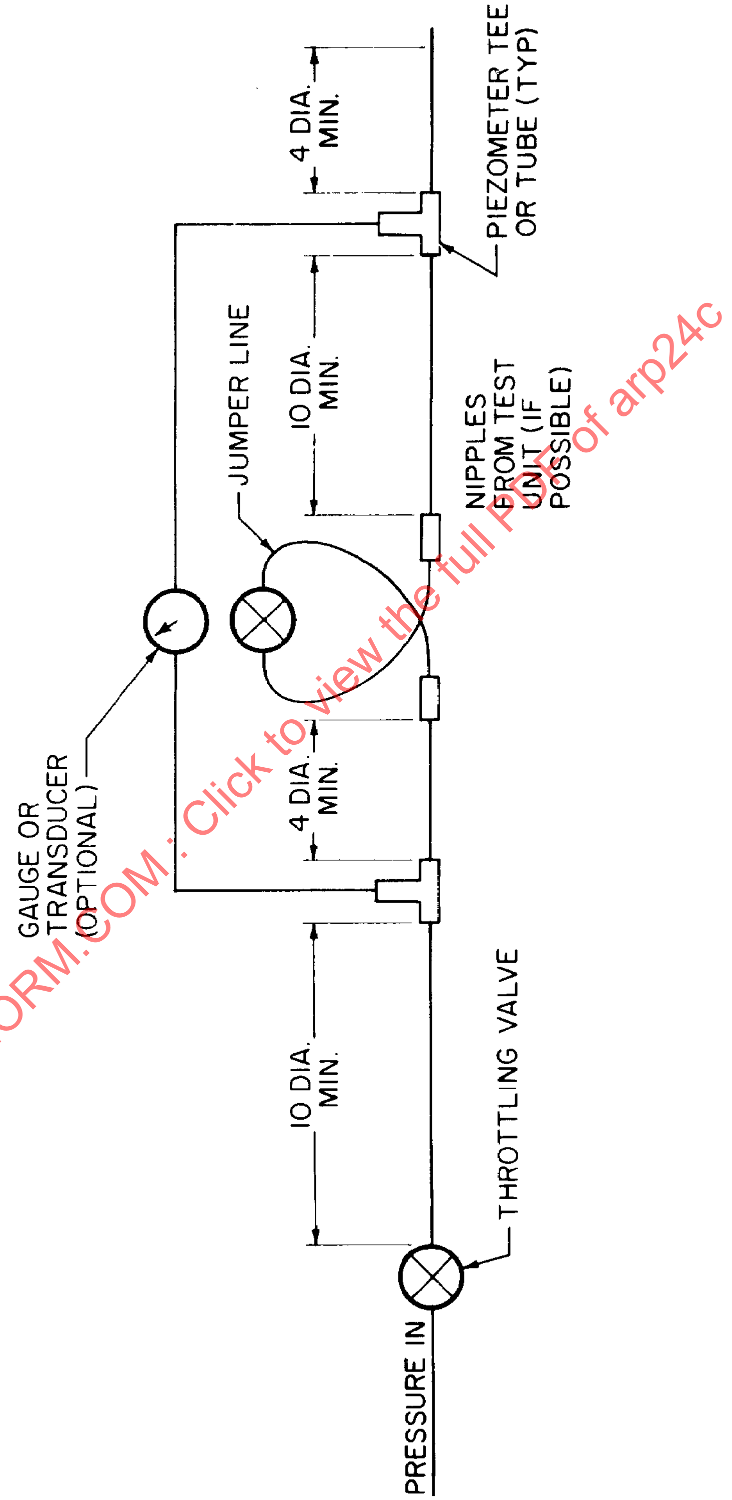

FIGURE 2 - TARE SCHEMATIC

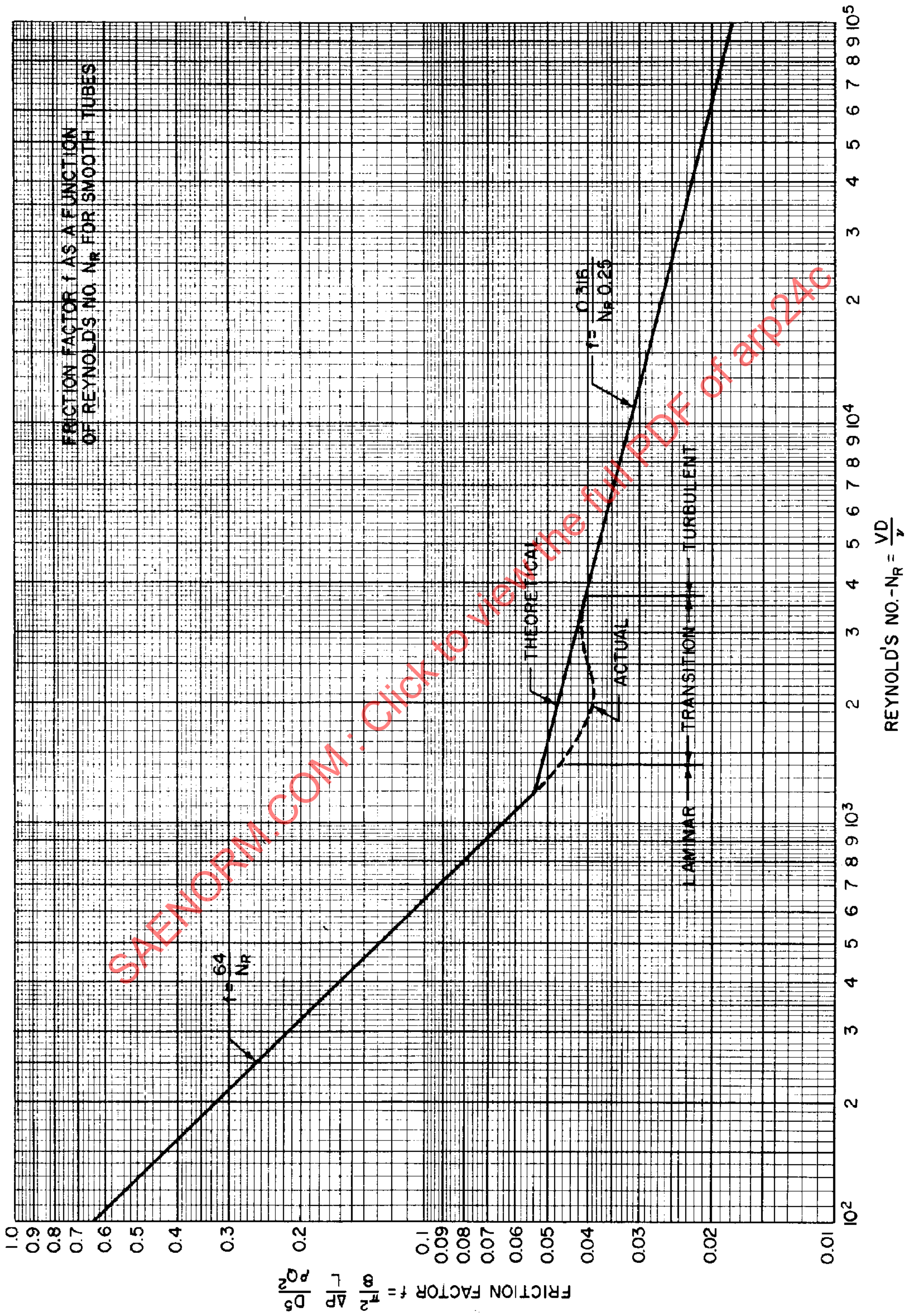
FRICTION FACTOR f AS A FUNCTION OF REYNOLD'S NO. N_R FOR SMOOTH TUBES
f = 64/N_R
f = 0.316/N_R^0.25
THEORETICAL
ACTUAL
LAMINAR
TRANSITION
TURBULENT
REYNOLD'S NO.-N_R = VD/ν
FRICTION FACTOR f = π²/8 ΔP/L D⁵/ρQ²

FIGURE 3