AEROSPACE RECOMMENDED PRACTICE

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Determination of Hydraulic Pressure Drop

RATIONALE

This document has been determined to contain basic and stable technology which is not dynamic in nature.

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1. SCOPE:

This SAE Aerospace Recommended Practice (ARP) provides analytical and test methods for determining pressure drop in fluid systems such as hydraulic, fluid, oil, and coolant used in aerospace vehicles. Determining pressure drop by analytical and test results will be discussed.

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001; www.sae.org

ARP4386	Terminology and Definitions for Aerospace Fluid Power, Actuation and Control Technologies
AS4395	Fitting End, Flared Tube Connection, Design Standard

2.2 Related Publications:

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

2.2.1 National Fluid Power Association Publications: Available from National Fluid Power Association, Inc., 3333 N. Mayfair Road, Milwaukee, WI 53222-3219; www.nfpa.com

NFPA/T2.12.1 Hydraulic Fluid Power – Systems and Products – Method of Measuring Average Steady State Pressure

NFPA/T2.12.10 Recommended Practice - Hydraulic fluid power – Systems and products – Testing general measurement principles and techniques

2.3 Definitions:

Refer to ARP4386 for general hydraulic system terms that are used in this document.

PRESSURE DROP: 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.”

3. TEST METHODS:

3.1 Test Set-up:

All parts of a hydraulic system (including tubing fittings, valves, etc.) through which flow is maintained will have a certain pressure drop. 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 the flow meter. The difference in readings of the two gages is the approximate pressure drop for the flow shown on the flow meter.

If accurate results are to be obtained, special pressure pick-ups must be used and they must be placed at a sufficient distance from any flow disturbance, as shown in typical test set-ups shown in Figures 1 and 2. As a guideline, these should be installed at least 5 times the tube inside diameter upstream and at least 10 times the tube inside diameter downstream from any other connection using straight rigid lines.

3.1 (Continued):

The test set-up in Figure 1 is for testing a 4-way pilot operated solenoid valve. A similar set up and procedures, with modifications can be used to obtain the pressure drop of any hydraulic component. The pressure gauge in Figure 1 will actually measure the pressure drop in the component itself plus the “tare pressure drop”, which is the pressure drop due to fittings and connecting tubing in the circuit. The test set-up of Figure 2 (which is essentially Figure 1 minus the hydraulic component) can then be used to measure the “tare pressure drop”. Subtracting the “tare pressure drop” from the total pressure drop at the same flow and fluid temperature gives the component pressure drop at that flow and fluid temperature.

3.2 Test Equipment:

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

3.2.1 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.

3.2.2 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, these pressure ripples may need to be attenuated to a low value.

3.2.3 Flowmeter: Equipment for flow measurements 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. Empirical calibrations of turbine and float flow meters are not considered satisfactory when data accuracy better than 5% is required. Test temperatures should be that required to match the fluid property (density or viscosity), to which the meter is sensitive, to that at which the meter is calibrated. If this cannot be accomplished, appropriate corrections must be applied to reflect the different value of the fluid property.

3.2.4 Pressure Taps: Pressure tap fittings, Figure 3, or piezometer type tubes, Figure 4, 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 4, are preferred over the pressure tap fittings.

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

3.2.6 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 or availability considerations, 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 the pressure is measured. Viscosity should also be periodically checked to verify it.

4. THEORY:

4.1 Nomenclature:

V = Fluid velocity

Q = Volumetric flow

W = Weight flow

H = Pressure head loss

P = Pressure loss

L = Length of tubing

D = Tubing diameter, internal

A = Area of tubing or passage

ρ = Fluid mass density

4.1 (Continued):

s_g = Specific gravity [4] of fluid

μ = Absolute viscosity

ν = Kinematic viscosity

g = Gravitational constant

N_R = Reynolds number

ϕ = Energy loss coefficient

f = Friction factor

S = Dimensionless factor used to solve for Q

T = Dimensionless factor used to solve for D

4.2 Line Pressure Drop:

The pressures and flow rates at any two points in a liquid continuum are related by the Bernoulli's equation of flow for incompressible fluids:

$$P_s + \rho\, g\, h + \rho\, V^2/2 + P_f = \text{constant} \qquad \text{(Eq. 1)}$$

where:

P_s = Static pressure

ρ = Fluid density

g = Gravitational constant

h = Height above a datum

V = Fluid velocity

P_f = Pressure loss due to friction between the points being compared.

4.2 (Continued):

The pressure loss due to friction, P_f, in a straight run of tubing can be calculated by the Darcy-Weisbach formula:

$$P_f = f\, L\, \rho\, V^2 \;/\; (2\, D) \qquad \text{(Eq.2)}$$

where:

f = Friction factor

D = Tubing diameter, internal

The value of the friction factor f depends upon whether the flow in the tube is laminar or turbulent. The existence of laminar or turbulent flow is strongly dependent the corresponding Reynolds number, N_R, which is given by the equation:

$$N_R = V\, D \,/\, \nu \qquad \text{(Eq. 3)}$$

where:

ν = Kinematic viscosity of fluid at the fluid temperature and pressure

The flow tends to be laminar for low values of Reynolds number (less than about 1400), is turbulent for high values of Reynolds number (higher than about 3600), and may be laminar or turbulent for values of Reynolds number between 1400 and 3600. When the flow is disturbed by the presence of bends and fittings a turbulent condition is found to prevail down to the lower end of this transition range.

The value of the friction factor f during turbulent flow also depends upon the internal smoothness or roughness of the tubing.

The relationship between the Reynolds number and the friction factor f for a smooth tube is shown in Figure 5. The value of f can also be calculated from N_R by the equations:

$$f = 64 \,/\, N_R \text{ for laminar flow} \qquad \text{(Eq. 4)}$$

and

$$f = 0.316 \,/\, N_R^{0.25} \text{ for turbulent flow in smooth tubes (Blasius Law)} \qquad \text{(Eq. 5)}$$

4.2 (Continued):

Combining Equations 2 and 3 with Equations 4 and 5, one gets:

$$P_f = 32\,\nu\,L\,\rho\,V\;/\;D^2 \text{ for laminar flow} \qquad \text{(Eq. 6)}$$

and

$$P_f = 0.158\,\nu^{0.25}\,L\,\rho\,V^{1.75}\;/\;D^{1.25} \text{ for turbulent flow in smooth tubes} \qquad \text{(Eq. 7)}$$

The above equations can be used for any set of consistent units, whether English or SI units (see Table 1 for sets of consistent units). See Table 2 for viscosity conversion factors to help achieve consistent set of units.

If non-consistent units are used, then the equations will have an additional constant dependent upon the selected units. For example, if pressure drop P_f^* is in psi, kinematic viscosity ν^* is in centistokes, line length L^* is in ft, mass density ρ is expressed in terms of specific gravity s_g, flow Q^* is in gpm, and line diameter D^* is in inches, then Equations 3 and 2 are replaced by Equations 8 and 9 for use with Equations 4 and 5:

$$N_R = 3162.6\,Q^*\,/\,(D^*\,\nu^*) \qquad \text{(Eq. 8)}$$

and

$$P_f^* = 0.013479\,f\,L^*\,s_g\,(Q^*)^2\;/\;(D^*)^5 \qquad \text{(Eq. 9)}$$

Sometimes the pressure drop in a line is specified and the corresponding diameter needs to be calculated. A different set of equations, equivalent to Equations 3, 4, and 5, is then used as below:

$$T = (1\,/\,\nu)\,(P_f\;Q^3)^{0.2}\,/\,(L\,\rho)^{0.2} \qquad \text{(Eq. 10)}$$

$$f = 127.0\,/\,T^{\,1.25} \text{ for laminar flow} \qquad \text{(Eq. 11)}$$

and

$$f = 0.276\,/\,T^{\,0.26316} \text{ for turbulent flow in smooth tubes} \qquad \text{(Eq. 12)}$$

The relationship between T and f, given by Equations 11 and 12, is also shown graphically in Figure 6. Once f is known, Equation 2 is then used to calculate the line diameter D.

4.2 (Continued):

If pressure drop P_f and diameter D are known and the flow Q needs to be calculated, then the following set of equations, equivalent to Equations 3, 4, and 5, is used:

$$S = (1 / \nu) (P_f\ D^3)^{0.5} / (L\ \rho)^{0.5} \quad \text{(Eq. 13)}$$

$$f = 2048 / S^{2.0} \text{ for laminar flow} \quad \text{(Eq. 14)}$$

and

$$f = 0.2428 / S^{0.2857} \text{ for turbulent flow in smooth tubes} \quad \text{(Eq. 15)}$$

The relationship between S and f, given by Equations 14 and 15, is also shown graphically in Figure 7. Once f is known, Equation 2 is then used to calculate the flow Q.

TABLE 1 - Sets of Consistent Units

Variable	Common English Units	Consistent English Units	Consistent SI Units
Speed	ft/sec	ft/sec	m/s
Volumetric flow	gpm	ft^3/sec	m^3/s
Pressure head loss	psi	lbf/ft^2	Pa or N/m^2
Length of pipe	ft	ft	m
Diameter of pipe or passage	in	ft	m
Area of pipe or passage	In^2	ft^2	m^2
Fluid mass density	lbm/in^3	lbf-sec^2/ ft^4	kg/m^3
Absolute viscosity	lbf-sec/in^2	lbf-sec/ft^2	Pa/s
Kinematic viscosity	centistokes	ft^2/sec	m^2/s

5. NOTES:

5.1 The change bar (I) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document.

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	1×10^{-2}	1.0197×10^{-5}	1.4504×10^{-7}	2.0886×10^{-5}	4.0289×10^{-11}
Poise	$1. \times 10^{2}$	1	1.0197×10^{-3}	1.4504×10^{-5}	2.0886×10^{-3}	4.0289×10^{-9}
g_F sec cm^{-2}	9.8067×10^{4}	9.8067×10^{2}	1	1.4224×10^{-2}	2.0482	3.9510×10^{-6}
lb_F sec in^{-2}	6.8947×10^{6}	6.8947×10^{4}	7.0505×10^{1}	1	1.4400×10^{2}	2.7778×10^{-4}
lb_F sec ft^{-2}	4.7880×10^{4}	4.7880×10^{2}	4.8823×10^{-1}	6.9445×10^{-3}	1	1.9290×10^{-6}
lb_F hr in^{-2}	2.4821×10^{10}	2.4821×10^{8}	2.5310×10^{5}	3.6000×10^{3}	5.1841×10^{5}	1
lb_F hr ft^{-2}	1.7237×10^{8}	1.7237×10^{6}	1.7577×10^{3}	2.5001×10^{1}	3.6001×10^{3}	6.9446×10^{-3}
g_M sec^{-1} cm^{-1}	1×10^{2}	1	1.0197×10^{-3}	1.4504×10^{-5}	2.0886×10^{-3}	4.0289×10^{-9}
lb_M sec^{-1} in^{-1}	1.7858×10^{4}	1.7858×10^{2}	1.8210×10^{-1}	2.5901×10^{-3}	3.7298×10^{-1}	7.1948×10^{-7}
lb_M sec^{-1} ft^{-1}	1.4882×10^{3}	1.4882×10^{1}	1.5175×10^{-2}	2.1585×10^{-4}	3.1083×10^{-2}	5.9958×10^{-8}
lb_M hr^{-1} in^{-1}	4.9605	4.9605×10^{-2}	5.0582×10^{-5}	7.1947×10^{-7}	1.0361×10^{-4}	1.9985×10^{-10}
lb_M hr^{-1} ft^{-1}	4.1338×10^{-1}	4.1338×10^{-3}	4.2152×10^{-6}	5.9957×10^{-8}	8.6339×10^{-6}	1.6655×10^{-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	5.8016×10^{-9}	5.5998×10^{-5}	2.4191	1.7405×10^{-6}	7.5188×10^{-2}	1×10^{-2}
Poise	5.8016×10^{-7}	5.5998×10^{-3}	2.4191×10^{2}	1.7405×10^{-4}	7.5188	1
g_F sec cm^{-2}	5.6895×10^{-4}	5.4916	2.3723×10^{5}	1.7068×10^{-1}	7.3733×10^{3}	9.8067×10^{2}
lb_F sec in^{-2}	4.0000×10^{-2}	3.8609×10^{2}	1.6679×10^{7}	1.2000×10^{1}	5.1840×10^{5}	6.8947×10^{4}
lb_F sec ft^{-2}	2.7778×10^{-4}	2.6812	1.1583×10^{5}	8.3335×10^{-2}	3.6000×10^{3}	4.7880×10^{2}
lb_F hr in^{-2}	1.4400×10^{2}	1.3899×10^{6}	6.0044×10^{10}	4.3199×10^{4}	1.8662×10^{9}	2.4821×10^{8}
lb_F hr ft^{-2}	1	9.6524×10^{3}	4.1698×10^{8}	3.0000×10^{2}	1.2960×10^{7}	1.7237×10^{6}
g_M sec^{-1} cm^{-1}	5.8016×10^{-7}	5.5998×10^{-3}	2.4191×10^{2}	1.7405×10^{-4}	7.5188	1
lb_M sec^{-1} in^{-1}	1.0360×10^{-4}	1	4.3200×10^{4}	3.1081×10^{-2}	1.3427×10^{3}	1.7858×10^{2}
lb_M sec^{-1} ft^{-1}	8.6339×10^{-6}	8.3333×10^{-2}	3.6000×10^{3}	2.5902×10^{-3}	1.1189×10^{2}	1.4882×10^{1}
lb_M hr^{-1} in^{-1}	2.8779×10^{-8}	2.7778×10^{-4}	1.2000×10^{1}	8.6337×10^{-6}	3.7297×10^{-1}	4.9605×10^{-2}
lb_M hr^{-1} ft^{-1}	2.3983×10^{-9}	2.3148×10^{-5}	1	7.1946×10^{-7}	3.1081×10^{-2}	4.1336×10^{-3}

*From WADC TR 58-638 Vol I Part I

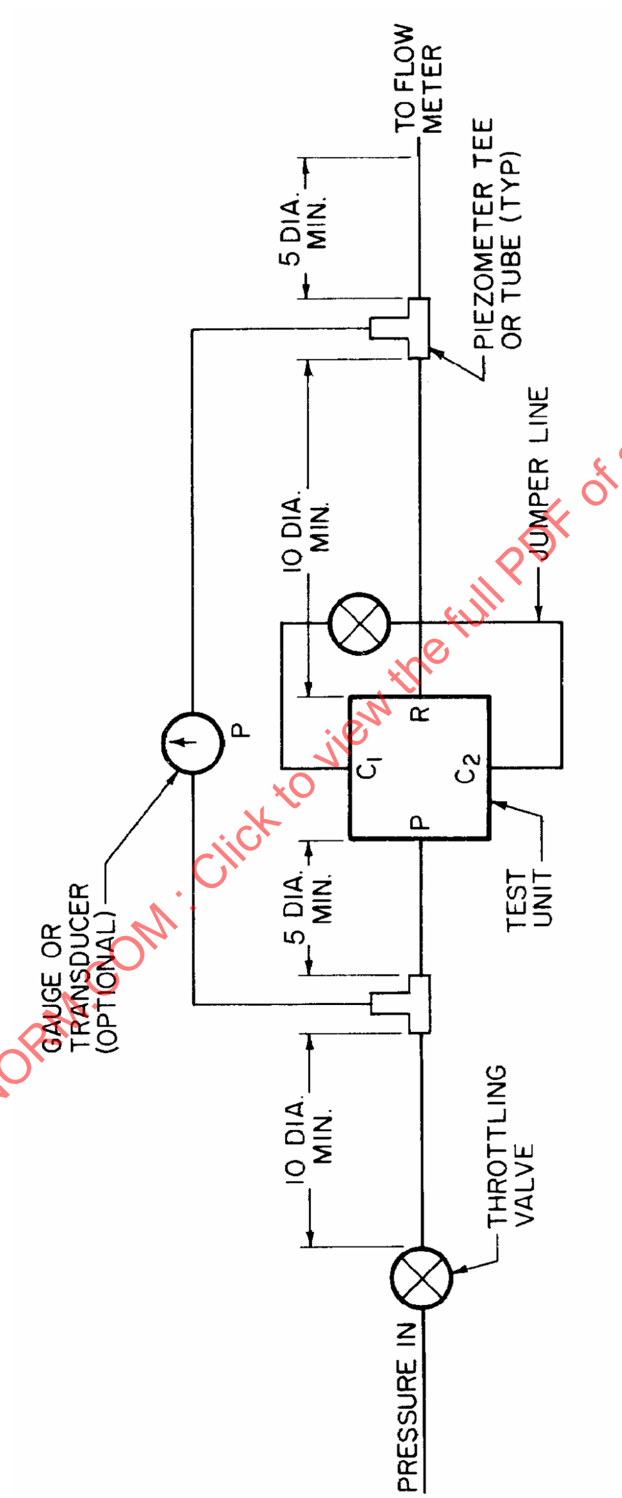


FIGURE 1 - Test Loop Schematic

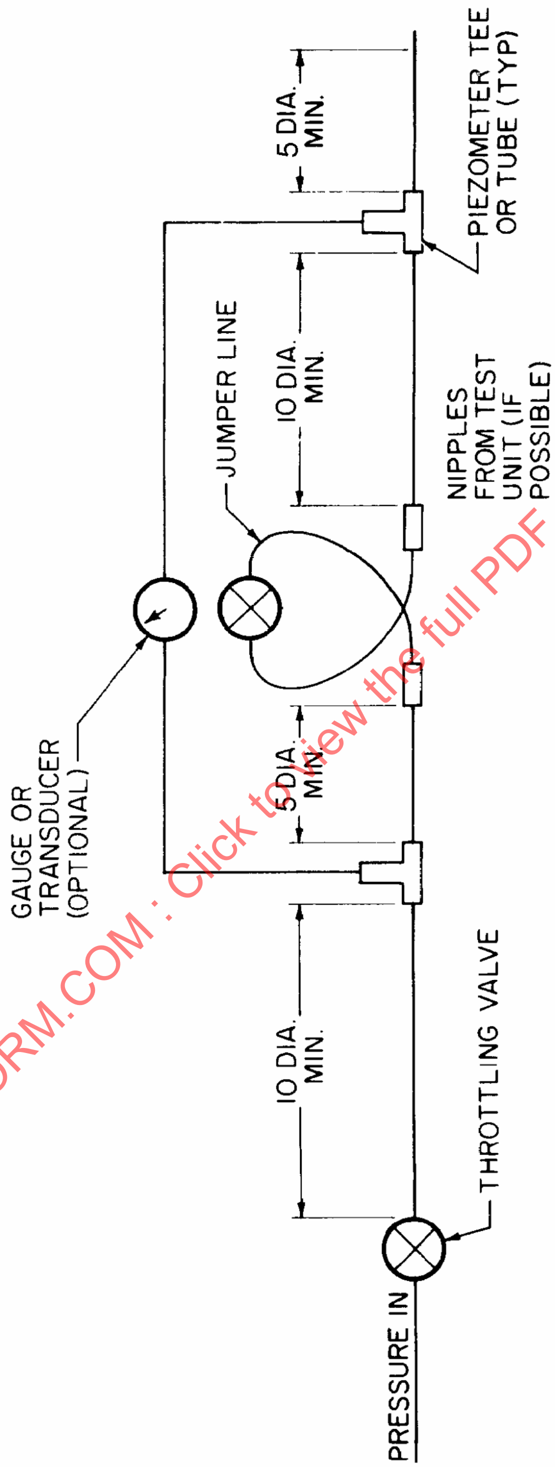
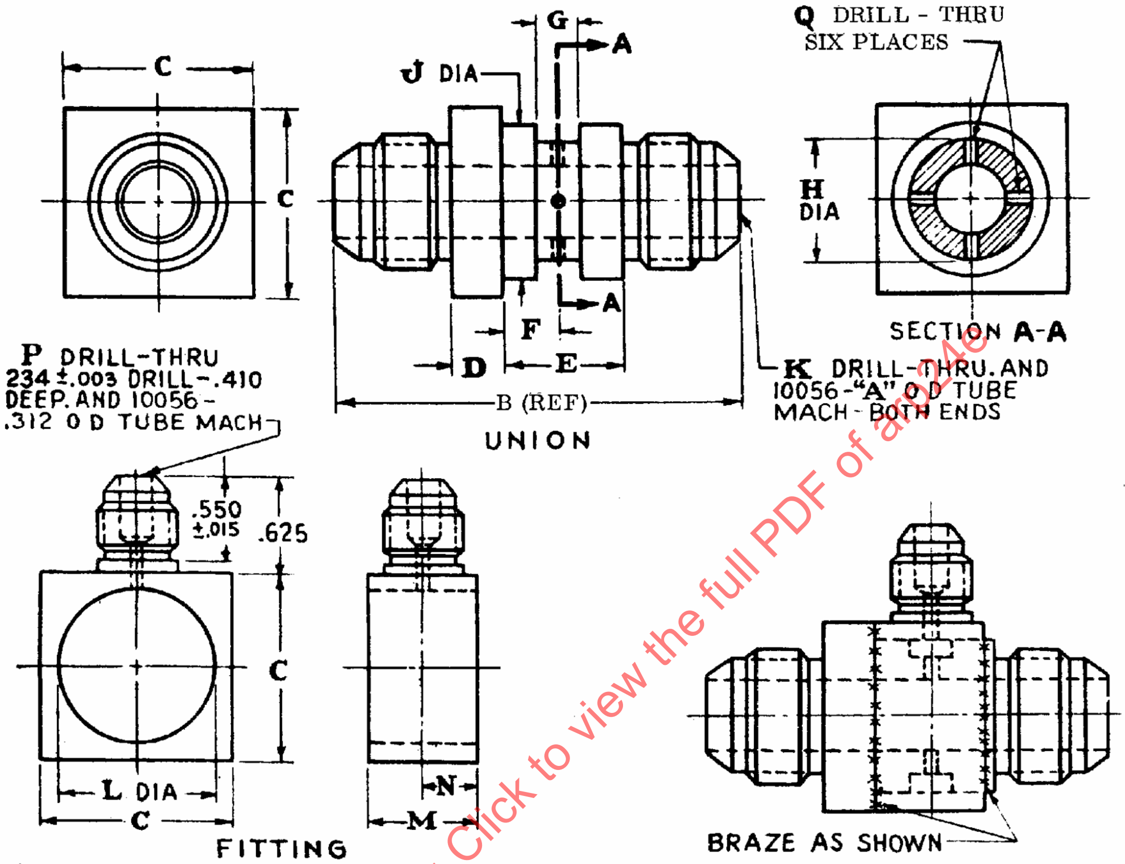


FIGURE 2 - Tare Schematic



DASH NO.	TUBE SIZE A	B (REF)	C	D	E	F	G	H	J +.000 -.003	K ±.003	L +.003 -.000	M	N	P ±.005	Q ±.003
3	.188	1.843	.750	.218	.671	.304	.187	.343	.530	.125	.531	.609	.304	.076	.062
4	.250	2.021	.812	.250	.671	.304	.187	.406	.592	.172	.593	.609	.304	.076	.076
5	.312	2.052	.875	.281	.671	.304	.187	.468	.655	.234	.656	.609	.304	.076	.076
6	.375	2.064	.938	.281	.671	.304	.187	.531	.717	.297	.718	.609	.304	.076	.076
8	.500	2.344	1.125	.312	.718	.328	.234	.718	.905	.391	.906	.656	.328	.0935	.093
10	.625	2.640	1.250	.343	.781	.359	.281	.781	1.030	.484	1.031	.718	.359	.125	.125
12	.750	2.978	1.375	.375	.875	.398	.359	.843	1.155	.609	1.156	.796	.398	.154	.154
16	1.000	3.321	1.750	.406	1.093	.500	.578	1.156	1.530	.844	1.531	1.000	.500	–	.213
20	1.250	3.571	2.062	.437	1.218	.562	.687	1.468	1.842	1.078	1.843	1.125	.562	–	.234
24	1.500	3.852	2.250	.468	1.218	.562	.687	1.656	2.030	1.312	2.031	1.125	.562	–	.234

NOTES: Tolerance ±0.010 unless noted.
"C" dimension may be increased as necessary to allow use of AS4395 boss for the pressure pick-off.

FIGURE 3 - Pressure Tap Fitting