potential leakage paths such as valve stem or packing that may have a connection to the applied pressure. Such other potential leakage paths are of course absent in valve designs in which the stem and packing have a connection only to the downstream side of the valve.

Reference 1, which is ASME Code, Section XI, paragraph IWV-3423 (e), states the following rule for tests at less than function differential pressure:

> "Leakage tests involving pressure differentials lower than function pressure differentials are permitted in those types of valves in which service pressure will tend to diminish the overall leakage channel opening, as by pressing the disk into or onto the seat with greater force. Gate valves, check valves, and globe-type valves having function pressure differential applied over the seat, are examples of valve applications satisfying this requirement. When leakage tests are made in such cases using pressures lower than function maximum pressure differential, the observed leakage shall be adjusted to function maximum pressure differential value. This adjustment shall be made by calculation appropriate to the test media and the ratio between test and function pressure differential, assuming leakage to be directly proportional to the pressure differential to the one-half power."

In the discussion below, it is shown that if (a) the test medium is air, (b) Pa is appreciable compared to one atmosphere, and (c) the leakage path is such as to produce laminar viscous flow (i.e., capillary-like rather than orifice-like), the calculation appropriate to this test medium yields a substantially higher calculated value of Pa than would be obtained by assuming leakage to be directly proportional to the pressure differential to the one-half power.

For air flow through an orifice, assuming uniform flow velocity over the orifice area, the mass flow rate per unit orifice area is ρv, where ρ is the density of air in the orifice and v is velocity in the orifice. Assuming that the discharge pressure is Pat = 1 atmosphere and the source pressure is Po, where Po and Pat are both absolute pressures, ρv is given by

$$(\rho v)^2 = \frac{2\gamma g}{\gamma - 1} \frac{Pat^2}{R_o T} \left(\frac{Po}{Pat} - 1 \right) G \qquad \text{(A-1)}$$

where $\gamma = 1.4$ is the specific heat ratio for air, $g = 32.2$ ft/sec^2 is the acceleration of gravity, T is source (upstream, at Po) temperature (°R), P is absolute pressure (psf), $R_o = 53.26$ ft-lb/lb°F is the gas constant for air and G is given by

$$G = \left(\frac{Pe}{Pat}\right)^2 \frac{x^{\frac{\gamma-1}{\gamma}}\left(x^{\frac{\gamma-1}{\gamma}} - 1\right)}{\left(\frac{Po}{Pat} - 1\right)} \qquad \text{(A-2)}$$

$$x = \frac{Po}{Pe}$$

Pe = Pat for subsonic flow

Pe = 0.5283 Po for choked flow

Choked flow occurs when

$$\frac{Pat}{Po} \leq \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma}{\gamma-1}} = 0.5283$$

$\sqrt{G}$ is proportional to $\rho v/\sqrt{Po-Pat}$. Values of $\sqrt{G}$ are listed in Table A-1. $\sqrt{G_o}$, the limiting value of $\sqrt{G}$ for small (Po-Pat), is $\sqrt{(\gamma-1)/\gamma} = 0.5345$.

In Table A-1, inspection of $\sqrt{G}/\sqrt{G_o}$ shows the accuracy of the assumption that for an orifice-like leakage flow resistance, leakage mass flow rate is proportional to pressure difference to the one-half power. For example, if Po ≙ 60 psig (Po-Pat = 60 in Table A-1), $\sqrt{G}/\sqrt{G_o} = 1.210$. Extrapolation of mass flow rate measured with Pt = 15 psig to mass flow rate predicted for Pa = 60 psig will underestimate the mass flow rate by the factor 0.968/1.210 = 0.80, or 20%.

The foregoing argument tacitly assumes that the orifice coefficient is = 1.0. However, the same conclusion concerning extrapolation from low values of Pt to high values of Po can be drawn if the orifice coefficient is assumed to be constant, i.e., independent of Po. Consequently,

Table A-1. $\sqrt{G}$ for Various Values of Po - Pat for Orifice. (Pat taken = 15 psia.)

Po - Pat (psi)	$\sqrt{G}$	$\sqrt{G}/\sqrt{G_o}$
0.01	0.5345	1.000
1	0.5332	0.998
5	0.5282	0.988
13.3	0.5185	0.970
13.4*	0.5184	0.970
15 *	0.5176	0.968
20 *	0.5230	0.978
25 *	0.5346	1.000
30 *	0.5490	1.027
35 *	0.5648	1.057
40 *	0.5811	1.087
45 *	0.5977	1.118
50 *	0.6143	1.149
55 *	0.6307	1.180
60 *	0.6470	1.210

*Choked flow

for leakage paths that are known to be entirely orifice-like, the assumption that leakage mass flow rate is proportional to pressure difference to the one-half power gives a reasonably accurate correlation, underestimating the leakage mass flow rate by at most 20% for Pa $\leq$ 60 psig. To correct the underestimate, the factor $(\sqrt{G}/\sqrt{G_o})_a/(\sqrt{G}/\sqrt{G_o})_t$ has to be applied, where a and t mean Po = Pa and Pt, respectively. References 2, 3, and 4 discuss the conversion formulas to be applied for various fluids (e.g., air and water) for various types of leakage path. For viscous flow of a gas, the mass flow rate from a source at absolute inlet pressure P_1 to absolute outlet pressure P_2 is proportional to $(P_1^2 - P_2^2)$. The proportionality factor is $C/\mu T$, where C is a function of geometry, T is absolute temperature, and μ is viscosity (which is a function only of temperature).

Assuming that test pressure Pt psig is applied at the same temperature as that at which function pressure Pa psig is applied, and assuming

further that the downstream pressure is one atmosphere, Pat psia, then the ratio of the mass flow rates is

$$\frac{\dot{m}a}{\dot{m}t} = \frac{(Pa + Pat)^2 - (Pat)^2}{(Pt + Pat)^2 - (Pat)^2} \qquad \text{(A-3)}$$

If the temperatures are not the same, the right side of Equation (A-3) has to be multiplied by

$$\frac{\mu(Tt) \cdot Tt}{\mu(Ta) \cdot Ta} \qquad \text{(A-4)}$$

Assuming that Tt = Ta, Table A-2 shows the ratio $\dot{m}a/\dot{m}t$ for various values of Pa and Pt, along with values of $(Pa\ psig/Pt\ psig)^{1/2}$. Pat is taken to be 15 psia in calculating $\dot{m}a/\dot{m}t$.

Table A-2. $\dot{m}a/\dot{m}t$ for Various Values of Pa and Pt.

Pt (psig)	$\dot{m}a/\dot{m}t$ Pa=50	55 (psig)	60	$(Pa/Pt)^{1/2}$ 50	55	60	$\frac{(\dot{m}a/\dot{m}t)}{(Pa/Pt)^{1/2}}$ 50	55	60
5	22.86	26.71	30.86	3.16	3.32	3.46	7.2	8.1	8.9
15	5.93	6.93	8.00	1.83	1.91	2.00	3.2	3.6	4.0
25	2.91	3.40	3.93	1.41	1.48	1.55	2.1	2.3	2.5
35	1.76	2.05	2.37	1.20	1.25	1.31	1.5	1.6	1.8
45	1.19	1.39	1.60	1.05	1.11	1.15	1.1	1.3	1.4

In all cases, the assumption that mass flow rate is proportional to pressure differential to the one-half power is unconservative for purely viscous flow. For Pa = 60 psig and Pt = 5 psig, it is unconservative by a factor of 8.9.

RECOMMENDED PROCEDURE

Any one of the following procedures, A, B, or C should be adopted.

A. Test Program

An extensive test program, covering several components of each type for which a correlation from Pt to Pa is sought, should be performed, in which sufficient experimental data showing the relation between Pt and leakage mass flow rate are obtained to permit a conservative empirical correlation to be established. Care must be taken to ensure that experimental orifice-like leaks are not used to represent actual, potentially capillary-like or viscous leaks.

B. Conservative Theoretical Correlation

Use Equation (A-3) as the correlation formula, including the factor (A-4) if necessary.

C. Measure Leakage Characteristic

For a given penetration, several values of Pt may be applied, so that an empirical correlation can be established. A statistical analysis of the data would be required to ensure at a 95% confidence level, that the predicted value of $\dot{m}a$ is not exceeded by the actual value of $\dot{m}a$.

REFERENCES

1. ASME Code, Section XI, paragraph IWV-3423(e).

2. Amesz, J., "Conversion of Leak Flow-Rates for Various Fluids and Different Pressure Conditions," 1966, EUR 2982.e, ORGEL Program, Ispra Establishment, Italy.

3. Maccary, R.R., DiNunno, J.J., Holt, A.E., and Arlotto, G.A., "Leakage Characteristics of Steel Containment Vessels and the Analysis of Leakage Rate Determinations," May, 1964, Division of Safety Standards, AEC, TID-20583.

4. Cottrell, Wm. B., and Savolainen, A.W., editors, "U.S. Reactor Containment Technology," ORNL-NSIC-5, Aug. 1965. Chapter 10, "Performance Tests," R.F. Griffin and G.H. Dyer. Sections 10.4.5 and 10.4.6 adapted from Reference 3.