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Technical Memorandum

SCTM 29-60-81

LEAKAGE FROM PRESSURIZED CONTAINERS
DURING LONG TERM STORAGE

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LEAKAGE FROM PRESSURIZED CONTAINERS
DURING LONG TERM STORAGE

A. N. Blackwell - 8116-1

ABSTRACT

Concern for the protection of water-sensitive components by storage in pressurized containers has prompted this study. This report summarizes work carried out to determine leakage rates which will ensure a positive pressure within the container for a specified storage period. These analyses consider molecular flow and two cases of viscous flow through physical gaps or holes in the container.

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LEAKAGE FROM PRESSURIZED CONTAINERS DURING LONG-TERM STORAGE

Introduction

Concern over the protection of water-sensitive container-stored components from the detrimental effects associated with the presence of water and water vapor has prompted a series of studies. Considerable effort has been concentrated on internal pressurization to prevent moisture migration into the container, because pressurization affords a barrier to wet air at physical gaps in the sealed container and prevents the container from inhaling wet air during temperature cycling. It also affords a means for checking the condition of the container seal during its storage life, because the magnitude of pressure decay over a known storage period is an indication of the effectiveness of the seal.

This is the report of a study undertaken to determine the acceptable initial leakage rates through the physical gaps between mating parts which will assure a positive pressure within the container over given storage periods. Because the number of gaps and their geometries relative to the mean free path of the gas will vary in every instance, two flow phenomena have been investigated in three analyses:

1. Viscous isothermal flow
 - a. With constant friction factor
 - b. With variable friction factor
2. Free molecule flow

Very likely, the flow from a container is a combination of viscous and free molecular flow, because of the presence of many gaps through which leakage occurs. Gap geometry has a definite effect on the nature of the flow, especially in determining whether the flow is viscous or molecular. The dividing line between those two flow mechanisms is related to the ratio of the mean free path of the gas, λ , to the characteristic dimension, D , of the gaps through which flow occurs. When the ratio is much less than unity,

$$\frac{\lambda}{D} \ll 1,$$

the gas molecules collide with each other much more often than with the walls of the gap; the gas then acts as a continuum and exhibits viscous behavior.

When the ratio is larger than unity,

$$\frac{\lambda}{D} \gg 1,$$

the gas molecules collide with the walls more often than with each other, giving a rise to a deviation from continuum behavior (the gas cannot support viscous stresses); the flow is then molecular in nature.

The viscous isothermal flow analysis with constant friction factor yields the most conservative leakage rate for a specific pressure requirement. Therefore, until the flow mechanism can be established through experiment, this is the recommended analysis for specifying leakage rates.

For convenience, the acceptable leakage rate has been incorporated into a dimensionless parameter involving the container volume and the storage period. Then this leakage rate parameter, as shown in Figure 2, can be used to find the acceptable rate for any storage life and container volume for the pressure requirements specified in the figure.

Analysis and Results

The weight rate of leakage from the container is equal to the weight rate of depletion of gas within the container; and the weight of gas within the container, at any given time, is given by the perfect gas equation in terms of the pressure and temperature of the gas and of the volume of the container:

$$pV = WRT$$

$$W = \frac{pV}{RT} \quad (1)$$

The rate of depletion is given by the time derivative of this weight, which is

$$w = \frac{-dW}{d\theta} = \frac{-V}{R} \frac{d(p/T)}{d\theta} \quad (2)$$

for a rigid container. (The negative sign indicates that mass is leaving the container.)

The leakage rate must now be related to the pressures inside and outside the container. Because this relationship will depend upon the nature of the flow, the following analyses consider both viscous and molecular flow. In both cases the leakage is considered to occur through gaps between mating parts of the container rather than through the metal parts of the container; the diffusion of gases through metal parts is considered to be negligible compared with the leakage through gaps.

Viscous Flow

Constant Friction Factor

Assuming that the dimensions of the gap(s) are large compared with the mean free path of the gas, the gas acts essentially as a continuum, exhibiting viscous shear stresses at the walls of the gap. Again, assuming the existence of an isothermal compressible flow of a gas through a gap of uniform hydraulic radius, the leakage rate can be related to the internal and external pressures by the well-established Poiseuille Equation:

$$\frac{p^2 - p_e^2}{RT} = \frac{w^2}{gA^2} \frac{fl}{D}$$

This equation neglects the change in the velocity head of the gas in comparison with the frictional head loss.

Solving for the leakage rate:

$$w = \left[\frac{gA^2 D}{fl} \right]^{1/2} \left[\frac{p^2 - p_e^2}{RT} \right]^{1/2} \quad (3)$$

This is of the form:

$$w = \frac{A_v}{RT_s^{1/2}} \left[\frac{p^2 - p_e^2}{T} \right]^{1/2} \quad (4)$$

where A_v is some undetermined constant which describes the geometry of the gap(s) and properties of the gas. A_v has the units of volume/unit time.

Note that although we are continuing with the assumption of a gap of uniform hydraulic radius, this assumption is not considered an important restriction. Since we do not know the geometry of the gap(s), we must resort to the use of the constant, A_v . A_v will be determined later in satisfying the residual pressure requirement after a certain storage period.

Equating the leakage rate, (4), and the depletion rate, (2),

$$-\frac{V}{R} \frac{d(p/T)}{d\theta} = \frac{A_v}{RT_s^{1/2}} \left[\frac{p^2 - p_e^2}{T} \right]^{1/2}$$

Expanding the left side and simplifying:

$$\frac{dp}{d\theta} - \frac{1}{T} \frac{dT}{d\theta} p = -\frac{A_v}{V} \left[\frac{T}{T_s} \right]^{1/2} \left[p^2 - p_e^2 \right]^{1/2} \quad (5)$$

This equation is nonlinear and has no known closed-form solution, even for relatively simple temperature functions. However, for the special case of constant

temperature, the equation can be integrated directly, since the time derivative of temperature is zero.

The constant temperature assumption is justified on the basis that the absolute temperature of the container would vary only a small percentage of its magnitude.

In this case (4) reduces to:

$$\frac{dp}{d\theta} = -\frac{A_v}{V} \left[\frac{T}{T_s} \right]^{1/2} \left[p^2 - p_e^2 \right]^{1/2} \quad (6)$$

Separating variables and integrating:

$$\int_{p_o}^p \frac{dp}{\left[p^2 - p_e^2 \right]^{1/2}} = -\frac{A_v}{V} \left[\frac{T}{T_s} \right]^{1/2} \int_0^\theta d\theta$$

$$\ln \left[\frac{p + \sqrt{p^2 - p_e^2}}{p_o + \sqrt{p_o^2 - p_e^2}} \right] = -\frac{A_v}{V} \left[\frac{T}{T_s} \right]^{1/2} \theta$$

Now A_v can be determined by specifying a pressure at the end of some period of storage; at $\theta = \theta_f$ specify $p = p_f$. Substituting and solving:

$$A_v = -\frac{V}{\theta_f} \left[\frac{T_s}{T} \right]^{1/2} \ln \left[\frac{p_f + \sqrt{p_f^2 - p_e^2}}{p_o + \sqrt{p_o^2 - p_e^2}} \right]$$

Therefore, the solution to (6) is:

$$p + \sqrt{p^2 - p_e^2} = \left[p_o + \sqrt{p_o^2 - p_e^2} \right] \left[\frac{p_f + \sqrt{p_f^2 - p_e^2}}{p_o + \sqrt{p_o^2 - p_e^2}} \right]^{\theta/\theta_f} \quad (7)$$

where the pressure, p , is implicitly expressed as a function of time, θ . For convenience in visualizing the pressure history in a container for a specific set of initial and final pressures Figure 1 has been prepared for:

Initial container pressure = $p_o = 30$ psia

Final container pressure = $p_f = 16.7$ psia

External (ambient) pressure = $p_e = 14.7$ psia

Pressure-Time Histories Computed
from Equations 7, 16, and 23 with:

$$p_o = 30 \text{ psia}$$

$$p_f = 16.7 \text{ psia}$$

$$p_e = 14.7 \text{ psia}$$

Figure 1. Pressure-time histories

Now the leak rate must be determined which will meet these pressure requirements. Normally, these leak rates are measured as a standard volumetric flow rate, so: $Q = v_s w$

$$\begin{aligned} &= \frac{RT_s}{p_s} \cdot w \\ &= - \frac{RT_s}{p_s} \frac{V}{R} \frac{d(p/T)}{d\theta} \end{aligned}$$

Since $T = \text{constant}$:

$$Q = - \frac{V}{p_s} \frac{T_s}{T} \frac{dp}{d\theta} \quad (8)$$

Differentiating (7):

$$\frac{dp}{d\theta} = \frac{\sqrt{p^2 - p_e^2}}{\theta_f} \left[\frac{p_o + \sqrt{p_o^2 - p_e^2}}{p + \sqrt{p^2 - p_e^2}} \right] \left[\frac{p_f + \sqrt{p_f^2 - p_e^2}}{p_o + \sqrt{p_o^2 - p_e^2}} \right]^{\theta/\theta_f} \ln \left[\frac{p_f + \sqrt{p_f^2 - p_e^2}}{p_o + \sqrt{p_o^2 - p_e^2}} \right] \quad (9)$$

$$\text{Hence: } Q = - \frac{V}{\theta_f} \frac{T_s}{T} \frac{\sqrt{p^2 - p_e^2}}{p_s} \left[\frac{p_o + \sqrt{p_o^2 - p_e^2}}{p + \sqrt{p^2 - p_e^2}} \right] \left[\frac{p_f + \sqrt{p_f^2 - p_e^2}}{p_o + \sqrt{p_o^2 - p_e^2}} \right]^{\theta/\theta_f} \ln \left[\frac{p_f + \sqrt{p_f^2 - p_e^2}}{p_o + \sqrt{p_o^2 - p_e^2}} \right] \quad (10)$$

where Q has the units of V/θ_f .

The initial leak rate is obtained by setting $Q = Q_0$ and $p = p_o$ in (10). The dimensionless leak-rate parameter, $Q_0 \theta_f T / VT_s$, computed from (10) is plotted in Figure 2 for a range of initial pressures using $p_s = p_e = 14.7$ psia and $p_f = 16.7$ psia. Thus, the acceptable initial leak rate from a container of volume V with an initial pressure of p_o and final pressure of 16.7 psia after a storage period of θ_f at a mean storage temperature of T can be readily determined from this graph. A final pressure of 16.7 psia was chosen to assure a positive pressure differential at temperatures above 0°F . The leak rate in cc/sec can be determined by multiplying ft^3/year by 8.98×10^{-4} .

Variable Friction Factor

The variable friction factor form of (3) is:

$$\begin{aligned} \frac{p^2 - p_e^2}{RT} &= \frac{256 \mu l}{g \pi D^4} w \\ \text{when } f &= \frac{64}{\text{Re}} \end{aligned} \quad (11)$$

Initial Leakage-Rate Parameter as a
Function of Initial Pressure Using
Final Pressure = 16.7 psia
Ambient Pressure = 14.7 psia

Figure 2. Initial leakage-rate parameter as a function of initial pressure

Thus, for isothermal viscous laminar flow with variable friction factor:

$$w = \frac{g\pi}{256l\mu} \frac{D^4}{RT} (p^2 - p_e^2) \quad (12)$$

Which is of the form:

$$w = \frac{A_{vf}}{p_s} \frac{[p^2 - p_e^2]}{RT} \quad (13)$$

Where A_{vf} is, again, an undetermined constant. Combining (13) with (2) and simplifying:

$$\frac{dp}{d\theta} - \frac{1}{T} \frac{dT}{d\theta} p = \frac{-A_{vf}}{V} \frac{p^2 - p_e^2}{p_s} \quad (14)$$

Solving (14) for the constant temperature case, $T = \text{constant}$, and evaluating A_{vf} by specifying $p = p_f$ at $\theta = \theta_f$, we have:

$$A_{vf} = \frac{-Vp_s}{2p_e\theta_f} \ln \left[\frac{(p_f - p_e)(p_o + p_e)}{(p_f + p_e)(p_o - p_e)} \right] \quad (15)$$

and,
$$\frac{p - p_e}{p + p_e} = \left[\frac{p_o - p_e}{p_o + p_e} \right] \left[\frac{(p_f - p_e)(p_o + p_e)}{(p_f + p_e)(p_o - p_e)} \right]^{\theta/\theta_f} \quad (16)$$

The pressure history given by (16) is also plotted in Figure 1.

Taking the derivative of (16) and using (8), the leakage rate at any time is given by:

$$Q = \frac{-V}{f} \frac{T_s}{T} \frac{p^2 + p_e^2}{2p_e p_s} \left[\frac{p_o - p_e}{p_o + p_e} \right] \left[\frac{(p_f - p_e)(p_o + p_e)}{(p_f + p_e)(p_o - p_e)} \right]^{\theta/\theta_f} \ln \left[\frac{(p_f - p_e)(p_o + p_e)}{(p_f + p_e)(p_o - p_e)} \right] \quad (17)$$

Then, at $\theta = 0$, $p = p_o$, and the acceptable initial leak rate is given by:

$$Q_o = -\frac{V}{\theta_f} \frac{T_s}{T} \frac{p_o^2 - p_e^2}{2p_e p_s} \ln \left[\frac{(p_f - p_e)(p_o + p_e)}{(p_f + p_e)(p_o - p_e)} \right] \quad (18)$$

The dimensionless leak-rate parameter $Q_o \theta_f T / VT_s$ is plotted in Figure 2 for a range of initial pressures.

Free Molecule Flow

Flow through gaps having a hydraulic diameter less than the mean free path of the gas causes a departure from the continuum behavior discussed above, and the flow is of a free molecular nature.

Knudsen's equation from the kinetic theory of gases predicts the following relationship for free molecular flow through a long tube:

$$Q = \frac{1}{6} (2\pi RT_s)^{1/2} \frac{D^3}{l} (p - p_e) \quad (19)$$

This is of the form:

$$Q = \frac{A_m}{p_s} (p - p_e) \quad (20)$$

where A_m is, as before, an undetermined constant which defines the geometry of the gap and:

$$\begin{aligned} w &= \frac{Q}{v_s} = \frac{p_s}{RT_s} Q \\ &= \frac{p_s}{RT_s} A_m (p - p_e) \end{aligned}$$

Equating this to (2):

$$-\frac{V}{R} \frac{d(p/T)}{d\theta} = \frac{A_m}{RT_s} (p - p_e)$$

Expanding the left side and simplifying:

$$\frac{dp}{d\theta} - \frac{1}{T} \frac{dT}{d\theta} = \frac{-A_m}{V} \frac{T}{T_s} (p - p_e) \quad (21)$$

Although this equation is linear and is amenable to solution for analytic forms of the temperature history, the constant-temperature approach will be employed here. Therefore, with $T = \text{constant}$:

$$\frac{dp}{d\theta} = -\frac{A_m}{V} \frac{T}{T_s} (p - p_e) \quad (22)$$

Integrating (22) and evaluating A_m using $p = p_f$ at $\theta = \theta_f$:

$$A_m = -\frac{V}{\theta_f} \frac{T_s}{T} \ln \left[\frac{p_f - p_e}{p_o - p_e} \right]$$

the solution to (22) is:

$$p = p_e + (p_o - p_e) \left[\frac{p_f - p_e}{p_o - p_e} \right]^{\theta/\theta_f} \quad (23)$$

This pressure history is plotted in Figure 1 for comparison.

The leakage rate is given by (7) and the derivative of (15):

$$Q = - \frac{V}{\theta_f} \frac{T_s}{T} \frac{p_o - p_e}{p_s} \left[\frac{p_f - p_e}{p_o - p_e} \right]^{\theta/\theta_f} \ln \left[\frac{p_f - p_e}{p_o - p_e} \right] \quad (24)$$

Again, Q has the units of V/θ_f .

The acceptable initial leak-rate parameter, $Q_o VT/\theta_f T_s$, from equation (24) is also plotted in Figure 2 as a function of initial pressure for a final pressure of 16.7 psia and ambient pressure of 14.7 psia.

Discussion

Nature of the Flow

The allowable leakage rate has been computed for viscous flow with constant and variable friction factors and for free molecule flow to meet specific pressure-time requirements. The results of these analyses, shown in Figure 2, indicate a range of leakage rates using the indicated theories of leakage. The theory which best describes the behavior of the leakage from a particular container can only be determined from experimental results.

As noted in the Introduction, the actual flow mechanism is probably a combination of both the molecular and viscous phenomena, since there are likely to be a number of gaps of varying sizes through which leakage occurs. To establish the magnitudes of λ and D for discussion purposes, the diameter of a single capillary 0.2 inch long has been computed for an air-leakage rate of 8×10^{-4} cc/sec.* The pressures p_o and p_e were taken to be 30 and 14.7 psia, respectively. This diameter was computed by re-arranging (12) to be:

$$D = \left[\frac{256}{\pi g} \frac{RTl}{(p^2 - p_e^2)} \right]^{1/4}$$

$$\approx 1.53 \times 10^{-3} \text{ inches}$$

The mean free path of air at one atmosphere and room temperature is about:

$$\lambda \approx 3.6 \times 10^{-6} \text{ inches}$$

* The magnitudes of parameters of interest in this study affecting the leakage rate in this study are container volumes of the order of a cubic foot, initial pressures of less than 40 psia, and storage periods of several years. Thus, the acceptable initial leakage rates are of the order of 10^{-5} to 10^{-3} cc/sec.

Then, for this case:

$$\frac{\lambda}{D} \approx 0.00235 \ll 1$$

Therefore, if the flow takes place principally from one, or even from several gaps, it is very likely to be viscous in nature for flow rates in this range. Note that the computed gap diameter is relatively insensitive (varies as the one-fourth power) to variations in the gap length and the leak rate.

Both instances of viscous flow have been assumed to be isothermal; that is, the change in temperature of the gas as it passes through the gap is negligible. This assumption seems quite reasonable for small rates of leakage at moderate pressures, especially since temperature changes should be negated by heat transfer through the metal walls of the gap.

Figure 2 clearly shows wide differences between the two viscous predictions of allowable leakage rate. In the absence of any experimental verification of the nature of the leakage, the constant friction factor result must be used for specification of allowable initial leakage rates, since this result requires the smallest of the predicted leakage rates. However, the experimental data should support the variable friction factor results. This analysis considers the effects of the flow rates (and indirectly, the pressures) on the friction factor; thus, the actual flow conditions from the container should be more accurately represented. Clearly, the leakage rate itself will be an important factor in determining the flow mechanism, since at higher leakage rates through a particular gap the flow will be viscous; while at very low rates, it will likely approach molecular flow.

Uncertainties which will cloud the issue until good experimental data becomes available include the geometries of the gaps and the effects of the pressures and age on these geometries. The above analyses have all used modifications of the uniform-tube hydraulic diameter results. The modifications used have all been linear, in the sense that the pressure-flow rate relationships have not been altered. This modification cannot be refined by analysis, since the gap geometry as a function of distance along the flow path is unknown. However, the net effect of deviations from uniform gap geometry should cancel out if leakage occurs from several gaps.

The effect of pressure on gap geometry will, in general, be to enlarge the gaps as it tends to separate mating parts of the container, the effect being most severe when the pressure difference is greatest. However, since the greatest pressure difference occurs at the time that the container is pressurized, and since the measurement for leakage rate is made at this same time, the measurement is probably made at the time of maximum leakage rate. Then, if the gaps close up to some extent as the pressure decreases, the leakage rate will drop below the predicted rate at that instantaneous pressure, adding conservatism to the predicted acceptable leakage rate. This effect is not likely to be detected in experiment. If a unit is tested under different pressures for leakage rate determination, any deviations of the A_v , A_{vf} , or A_m from constant values will appear as a pressure effect. Thus, care must be exercised in experiment to establish the correct flow mechanism.

Effect of Variable Storage Temperature

The above analyses have assumed constant temperature storage. To establish the effect of this assumption on the pressure history, a numerical solution of the constant friction factor viscous case, represented by (5), was run on an ELECOM 125 Digital Computer by F. L. Whitworth, 8142-2, using a variable temperature. The temperature history was composed of the mean storage temperature plus a triangular-wave diurnal variation with a 15°F amplitude, and a cosine wave with a 20°F amplitude to simulate the annual variation. The temperature function was, essentially:

$$T(\theta) = T_{\text{mean}} \pm 15 + 20 \cos w \theta$$

where w has a period of 1 year.

The constant A_v in (5) was determined on the basis of:

$$p_o = 30 \text{ psia}$$

$$p_e = 14.7 \text{ psia}$$

$$\theta_f = 4 \text{ years}$$

$$V = 2.4 \text{ ft}^3$$

$$Q_o \doteq 8 \times 10^{-4} \text{ cc/sec}$$

The pressure resulting after four years of this cycling was well within one percent of the constant temperature solution. Therefore, it is evident that variable storage temperature has little effect on the leakage in these ranges of pressures and leakage rates. This effect will, however, become more pronounced in cases where the pressure fluctuation is a significant percentage of the absolute pressure in the container.

Comments on Flow Measurement in a Vacuum

The leakage rates of interest here are of the magnitude which requires measurement by very sensitive methods. One method currently being used employs a vacuum chamber and a mass-spectrometer. The chamber, enclosing the container to be checked, is evacuated and the gas escaping from the container is drawn through the mass-spectrometer. The low rate of gas coming from the container is then measured by comparison with a known calibrated leak. The increased pressure differential imposed on the container by this evacuation process will increase the leakage rate by some amount which will be determined by the nature of the flow. These increased flow rates must then be related to the allowable flow rates specified for storage. The corrections are outlined below.

Viscous Isothermal Flow

Constant Friction Factor

Equation (4) gives the flow rate/pressure relationship:

$$w = \frac{A_v}{RT_s^{1/2}} \left[\frac{p^2 - p_e^2}{T} \right]^{1/2}$$

where A_v is a constant by definition.

Then, during a measurement in a vacuum, where $p_e \doteq 0$, the correction for the pressure difference is (neglecting temperature effects):

$$\frac{Q_{p_e = 14.7}}{Q_{p_e = 0}} = \frac{w_{p_e = 14.7}}{w_{p_e = 0}} = \left[\frac{p^2 - 14.7^2}{p^2} \right]^{1/2}$$

Variable Friction Factor

Using (13) the corresponding correction for the variable friction factor case is:

$$\frac{Q_{p_e = 14.7}}{Q_{p_e = 0}} = \frac{p^2 - 14.7^2}{p^2}$$

Free Molecule Flow

The correction for free molecule flow is derived from (20)

$$\frac{Q_{p_e = 14.7}}{Q_{p_e = 0}} = \frac{p - 14.7}{p}$$

These corrections are plotted in Figure 3 for comparison.

In the consideration of an experimental technique for determining the flow mechanism from a container, it is worthwhile to consider the effects of making measurements in a vacuum with $p_e = 0$. The three flow equations used in the analyses then reduce to:

1. Viscous Isothermal Flow

a. Constant Friction Factor:

$$Q \propto p$$

b. Variable Friction Factor:

$$Q \propto p^2$$

2. Molecular Flow:

$$Q \propto p$$

Thus, it is clear that constant friction factor viscous flow and free molecule flow will appear as the same mechanism when measured in a vacuum, since they will each vary directly with pressure. However, the flow mechanism can be easily established if it should follow the variable friction factor equation, since it varies as the square of pressure. The difference between constant friction factor and molecular flows can only be detected with $p_e \neq 0$.

Figure 3. Ratio of flow rate with 14.7 psia ambient pressure to flow rate with zero ambient pressure as a function of internal pressure

Conclusion

The acceptable leakage rates from pressurized containers have been determined for viscous isothermal flow with constant and variable friction factors and free molecule flow. These leakage rates are specified in terms of the pressure-time requirements and of the volume of the container. The actual flow mechanism defining the leakage rate-pressure relationship must be established through experiment. Until this relationship can be confirmed experimentally, the constant friction factor viscous flow result should be used for specification of the leakage rate, a result that is more conservative than other two predicted leakage rates.

Nomenclature

A	Area - ft^2
A_v, A_{vf}, A_m	Dimensional constants which describe the geometry and gas properties in the path of the leak(s) - $\text{ft}^3/\text{unit time}$
D	Hole or tube hydraulic diameter - ft
f	Friction factor
g	Gravitational constant - ft/sec^2
l	Length of tube - ft
p	Pressure inside container - psia
p_e	External (ambient) pressure - psia
p_f	Final pressure in container after a period of time, θ_f - psia
p_o	Initial pressure in container - psia
p_s	Standard pressure = 14.7 psia
Q	Standard Volumetric Leakage rate - $\text{ft}^3/\text{unit time}$
R	Gas constant - $\text{ft}\cdot\text{lb}/\text{lb} \cdot ^\circ\text{R}$
Re	Reynolds number
T	Absolute temperature of gas inside container - $^\circ\text{R}$
T_s	Standard temperature = 520°R
v	Specific volume - ft^3/lb
V	Volume of container - ft^3
w	Weight rate of leakage - $\text{lb}/\text{unit time}$
W	Weight of gas in container - lb
ρ	Density = $1/v = \text{lb}/\text{ft}^3$
μ	Absolute viscosity - $\text{lb}/\text{hr ft}$
θ	Time - any consistent time unit

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