

Preventing molecular and particulate infiltration in a confined volume

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IN-35
045 898

ABSTRACT

Contaminants from an instrument's self-generated sources or from sources external to the instrument may degrade its critical surfaces and/or create an environment which limits the instrument's intended performance. Analyses have been carried out on a method to investigate the required purging flow of clean, dry gas to prevent the ingestion of external contaminants into the instrument container volume. The pressure to be maintained and the required flow are examined in terms of their effectiveness in preventing gaseous and particulate contaminant ingestion and abatement of self-generated contaminants in the volume. The required venting area or the existing volume venting area is correlated to the volume to be purged, the allowable pressure differential across the volume, the external contaminant partial pressure, and the sizes of the ambient particulates. The diffusion of external water vapor into the volume while it was being purged was experimentally obtained in terms of an infiltration time constant. That data and the acceptable fraction of the outside pressure into the volume indicate the required flow of purge gas expressed in terms of volume change per unit time. The exclusion of particulates is based on the incoming velocity of the particles and the exit flow speed and density of the purge gas. The purging flow pressures needed to maintain the required flows through the vent passages are indicated. The purge gas must prevent or limit the entrance of the external contaminants to the critical locations of the instrument. It should also prevent self-contamination from surfaces, reduce material outgassing, and sweep out the outgassed products. Systems and facilities that can benefit from purging may be optical equipment, clinical facilities, manufacturing facilities, clean rooms, and other systems requiring clean environments.

Key Words: Contamination Control, Gaseous Purging, Shipping Containers, Clean Rooms

1. INTRODUCTION

Systems that are critically dependent on cleanliness require protection at all times against molecular and particulate contaminants, which can deposit on surfaces and degrade the environment. Systems and facilities affected by those contaminants may be optical instruments, clinical facilities, manufacturing facilities, contamination sensitive devices, clean rooms or any other enclosed volume requiring clean ambient conditions. These need to be protected against particles of micron sizes; microbes and gases including water vapor and others identified as pollutants which reside in the environment.

In this paper, the flow of clean, dry nitrogen gas to purge the environment in a volume or to prevent the infiltration through openings of those contaminants in the volume is being investigated. The flow volume of the purging gas is predicated on the acceptable pressure in the location being purged and the vent area for the purging gas. The vent area is simultaneously the passage for the external contaminant to enter the system.

The purging parameters being investigated are the external environment conditions, the maximum purge flow that does not affect the elements in the system, and the size of the vent area. The vent area and the mass flow prevent and limit the infiltration of external molecules and particulate in the volume.

2. ANALYSIS

2.1. Molecular

A gas at temperature T with molecular mass M and partial pressure P_u will be employed to purge a volume V . The purging will prevent the infiltration of an external objectionable gas at partial pressure P_o to enter the volume via an opening of area A . A fraction P out of P_o may be maintained in the volume while purging is going on. From the conservation of mass applied to the mass of external contaminant flow $C(P_o - P)$ entering the volume and an exiting purging mass $Q(P - P_u)$, one can write this equation for the mass of contaminant in the volume,

$$V \frac{dP}{dt} = C(P_o - P) - Q(P - P_u) \quad (1)$$

where C (volume flow per unit time) is the conductance of the vent passage of area A for the gas at pressure P_o and Q (vol. per unit time) is the purging flow at pressure P_u . The general solution of this equation with constant k to be evaluated from the initial conditions is

$$P = k \cdot \exp\left(-\frac{C+Q}{V} \cdot t\right) + \frac{CP_o + QP_u}{C+Q} \quad (2)$$

For the steady state condition, $dP/dt = 0$, the contaminant pressure in the volume is

$$P = \frac{P_o + \frac{Q}{V} \cdot \frac{V}{C} P_u}{1 + \frac{Q}{V} \cdot \frac{V}{C}} = \frac{P_o + \frac{\tau_v}{\tau_c} P_u}{1 + \frac{\tau_v}{\tau_c}} \quad (3)$$

where $\tau_c = (V/Q)$ is time constant of the purging flow whose inverse $1/\tau_c$ represents the number of volume change Q/V and $\tau_v = (V/C)$ is the time constant for the infiltration flow. For a purging gas which is clean and does not contain any partial pressure of the objectionable external gas $P_u = 0$, the above reduces to

$$\frac{P}{P_o} = \frac{1}{1 + \frac{Q}{V} \cdot \frac{V}{C}} = \frac{1}{1 + \frac{\tau_v}{\tau_c}} \quad (4)$$

Since one is interested in the number of volume changes needed to prevent infiltration and maintain a low pressure of the infiltrate gas in the volume, we can write the above as

$$\frac{Q}{V} = \frac{1}{\tau_c} = \frac{C}{V} \cdot \left(1 - \frac{P}{P_o}\right) \quad (5)$$

This indicates that the purge flow depends directly on the conductance C of the entering gas and a desired P/P_o . The conductance C represents the ratio of the gas flow to its pressure differential across the passage through which the external molecules enter the volume. It is a function of the upstream P_o and downstream P partial pressures, the equivalent passage area A and the mean free path and the velocity of the entering molecules.

The author as shown in ref.1 carried out an experimental estimate of the conductance. A 0.651 m^3 vacuum space chamber was fitted with a variable exit port, a flow meter to measure the flow of the purging nitrogen, and a model 1000 hygrometer manufactured by Panametric Co, located at the center of the chamber. Figure

1 shows the set up. The ambient pressure in the laboratory was 760 torr, the temperature was 21 to 22°C and the RH was 50%, providing a 10 torr water vapor partial pressure. Measurements were carried out for the determination of V/C by measuring the partial pressure inside the chamber as a function of time when various orifice ports were used. The chamber was purged to about 10⁻² torr of water vapor pressure and then with no purging flow allowed to equilibrate with the ambient partial pressure. A plot of the vapor pressure versus time with the ratio of V/A as the parameter was obtained as shown in fig 2. From the solution of the mass balance equation for the initial conditions P=0 at t= 0, one gets

$$P = \frac{P_o + \frac{Q}{V} \cdot \frac{V}{C} \cdot P_u}{1 + \frac{Q}{V} \cdot \frac{V}{C}} \left[1 - \exp\left(-\frac{Q+C}{V} \cdot t\right) \right] \quad (6)$$

and for Q/V=0, i.e. no purging, $P = P_o (1 - \exp.-C t / V)$. The above tests provided the time constant, $\tau_o = V/C$ which corresponds to the time when $P = 0.63 P_o$ was obtained. Those times as shown in Fig.2 were obtained for the curves identified by the V/A (m) values. Fig.3 shows the V/A versus the time constants V/C (hr) obtained with the indicated diameters of orifices used in the tests. A 45 cm long pipe with an internal diameter of 1.27 cm was also tested. The data plotted with a slope of about ¼ indicating that C and A are related by the coefficient ¼. This may indicate that a molecular type of flow exists at the entrance passage.

With these experimental data on the infiltration time constant $\tau_v = (V/C)$ and the desired P/P₀ the volume changes of purge gas Q/V = (1/τ_v) can be evaluated using equation 5. Figure 4 shows graphically the required number of volume changes for several ratios of volume to orifice sizes and pressure ratios.

It is apparent that a comparison of the infiltration time constant (V/C) with that of the purge flow (V/Q) dictates the contaminant resulting partial pressure into the volume. If the infiltration passage is very small (V/C very long), the purge maintains the clean conditions in the volume. On the other case, a large passage (V/C very short), the purge time constant must be short (large flow) to keep the volume clean.

3. PARTICULATES

Particulates may be in the environment where the volume with the instrument is located. These may be moving in any random direction or may have a specific direction dictated by gaseous flows, as in clean rooms with a laminar flow. They may be entrained within a turbulent flow or originate from a nearby propulsive system. The velocities of the particles may vary from terminal to supersonic speeds. Terminal speeds of particles of about 10 μm in size with densities of about 2 g/cm³ may be less than 1cm/sec. Particles entrapped in the flow of horizontal clean room facilities may acquire velocities in the order of 1m/s. Particles produced by propulsive systems may have velocities of 2-3 km/s.

The effectiveness of the purging gas to prevent particles for entering the volume and the instrument within it via the vent area will depend on the purge gas efflux velocity compared to that of the incoming particle (Ref. 2, 3). We may exclude the ability to arrest or change the direction of a particle from a propulsive system. However, the terminal velocity of a particle results from the balance of its weight and the drag force it suffers while moving through the medium i.e. $mg = F_D$. The drag force F_D depends on the Reynold number, $R = Dv\rho/\mu$, where ρ (Kg/m³) is the density and μ (Pa·s) the viscosity of the medium, v is the particle velocity and D (m) its diameter. For $R > 10$ the drag force is given by Stokes law i.e. $F_D = 3\pi\mu Dv$. The terminal velocity is then $v = \rho g D^2 / 18\mu$. For $10^1 < R < 10^5$, the drag is $F_D = C_D(\pi D^2/4)\rho v^2$ and the particle velocity is $v = (2D\rho_p g / 3\rho)^{1/2}$ where ρ is the ambient density, ρ_p is the particle density, and C_D is the drag coefficient. The particle diameters in terms of the vent gas velocity are

$$D = \sqrt{\frac{18\mu v}{g\rho}} \quad \text{or} \quad D = \frac{3C_D\rho v^2}{2\rho_p g} \quad (7)$$

It would be expected that a velocity of the purge gas v , inserted in the above equations will indicate the diameter of the particle which could be stopped by the purge gas. An equal and opposite drag force can arrest the incoming particle. For higher R , the drag coefficient can be estimated based on the shape of the particle and the R number.

4. GAS FLOW

The nitrogen flow rate which has been indicated by the calculated number of volume changes, Q/V can be established based on the orifice area A (m^2), the outside ambient pressure, P_o the gas temperature T (K) and the gas internal pressure P . For small pressure differences $\Delta P = P - P_o$ and $P_o > 0.53 P$, which will exist for the ground evaluation of the flow, the equation for the flow obtained from the Torricelli equation is

$$Q = \gamma A V = \gamma A \cdot \sqrt{2gRT \frac{\Delta P}{P_o}} \quad (m^3/s) \quad (8)$$

where R (29.26 m/s) is the gas constant for air, g (9.81 m/s^2) the acceleration of gravity, and γ (0.64) accounts for the velocity coefficient and the vena contracta. The flow velocity is

$$V = \alpha \cdot \sqrt{2gRT \frac{\Delta P}{P_o}} = 24\alpha \cdot \sqrt{T \frac{\Delta P}{P_o}} \quad (m/s) \quad (9)$$

where α (0.98) is the velocity coefficient for the orifice.

5. APPLICATION

The purging flow provided by the number of volume changes per unit time can be obtained from Eq.5 or Fig. 3 when the volume to be purged V , the infiltration area A and the choice of P/P_o is given. The volume V is set by volumetric considerations while the infiltration area A may be dictated by other design needs. The area should be made as small as possible to avoid unwanted infiltrations. In many cases it may have to be estimated.

The other choice is the ratio P/P_o , which is the partial pressure of the unwanted contaminant external to the volume. As an example, for an external temperature of 20°C and relative humidity of 50%, the external water vapor pressure is $P_o = P_s \Phi = 8.75$ torr where $P_s = 17.5$ torr is the water saturated vapor pressure at 20°C and $\Phi = 50\%$ the relative humidity. The choice of P/P_o will depend on the temperature of devices within the volume. If one chooses $P/P_o = 1 \times 10^{-3}$, the water vapor pressure in the volume will be $P = 0.001 P_o$ or $P = 0.001 \times 8.75 = 8.75 \times 10^{-3}$ torr. At this pressure the water vapor in the volume will condense on surfaces at temperatures less than -60°C . The choice will depend on those considerations. It may be appropriate and conservative to choose $P/P_o = 1 \times 10^{-4}$.

The calculations of Q/V (hr) can be carried out using Eq.5 with the V/C obtained from Fig.2 in terms of V/A and with the chosen P/P_o . The required purging flow is then $Q = (Q/V)V$ (m^3/hr). The pressure differential ΔP to maintain the flow across the vent area A (m^2) can be obtained from Eq. 8 as $\Delta P/P_o = 1/(2gRT_o) (Q/\varphi A)^2 = 1/574.08 (Q/\varphi)^2$ where Q (m^3/s) and the other parameters are $g = 9.81 \text{ m/s}^2$, $R = 29.26 \text{ m/K}$ and $\varphi = 0.61$ for an orifice port. The pressures can be expressed in any convenient unit.

The exit velocity is given by Eq.9 as $v = \alpha (2gRT_o \Delta P/P_o)^{1/2} = 24 \alpha (T_o \Delta P/P_o)^{1/2} \text{ m/s}$ where $\alpha = 0.91$ for the orifice. The particle of diameter D which can be arrested by the flow velocity is obtained from Eq. 7 with the viscosity $\mu = 18 \times 10^{-3} \text{ (Pa}\cdot\text{s)}$ and the air density as $\rho = 1.27 \times 10^{-3} \text{ (Kg/m}^3\text{)}$.

6. CONCLUSION

A method to estimate the quantity of purging gas necessary to prevent infiltration of unwanted gas and particulates into a volume containing systems to be protected against those gases and particulates has been provided. The infiltration occurs via intentional openings in the volume. Examples of such openings include open doors, gaps between doors and walls, or through intentionally opened areas needed to permit the volume venting. The purging flow rate expressed in terms of volume changes per unit time is based on limiting the unwanted external contaminant to an acceptable partial pressure and on the time constant of the infiltrating contaminant flow into the volume via the venting passage. The pressure gradient required to maintain the purging flow through the vent area and its efflux velocity to arrest an incoming particle have also been suggested. Indications on the approach to evaluate the volume change rates and related data have been shown.

ACKNOWLEDGEMENTS

The author wishes to thank and acknowledge the help in the preparation of the manuscript by his coworker, Peggy Isaac.

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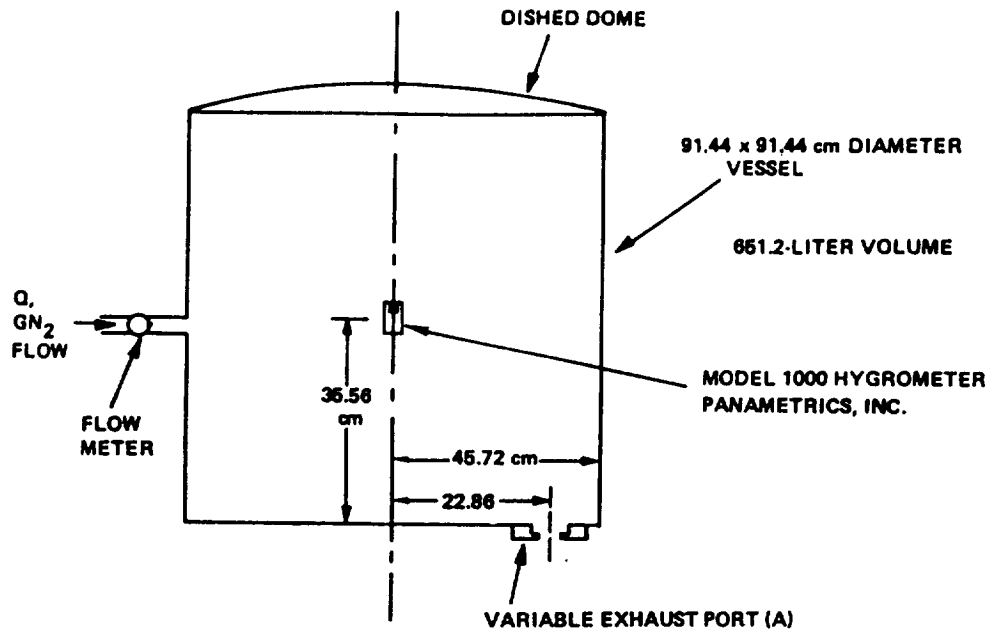


Figure 1. Test setup.

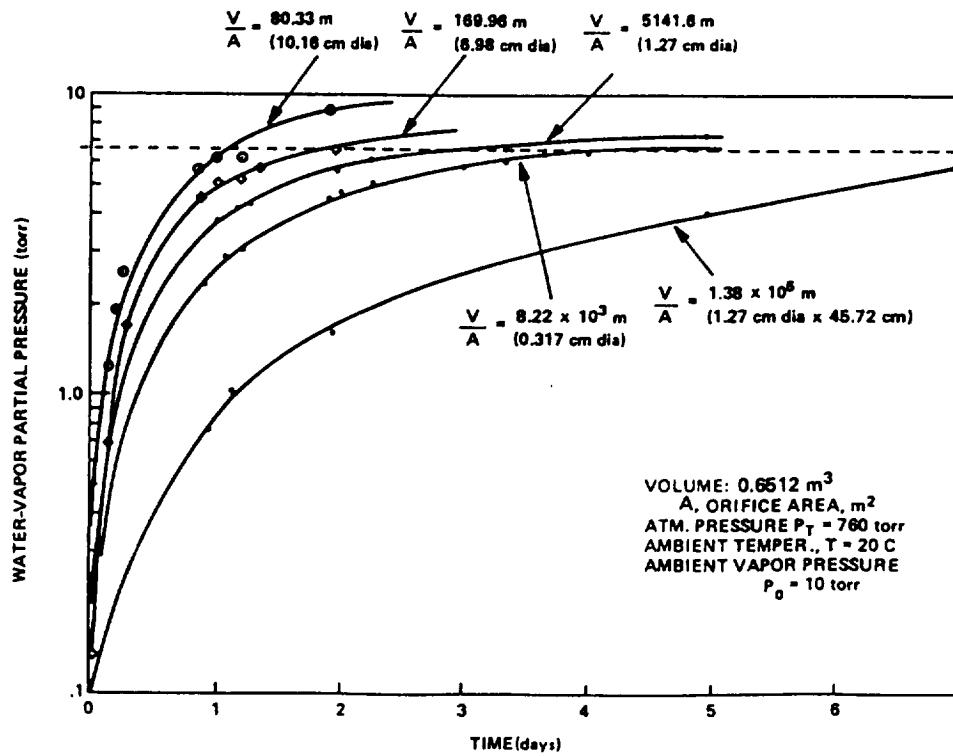


Figure 2. Water-vapor pressure versus time in an initially dry vessel.

**Volume Orifice Time Constant vs.
Volume Orifice Area Ratio for Vapor Diffusion**

$$\tau_v = (0.42)(24) \left(\frac{V}{A} \right)$$

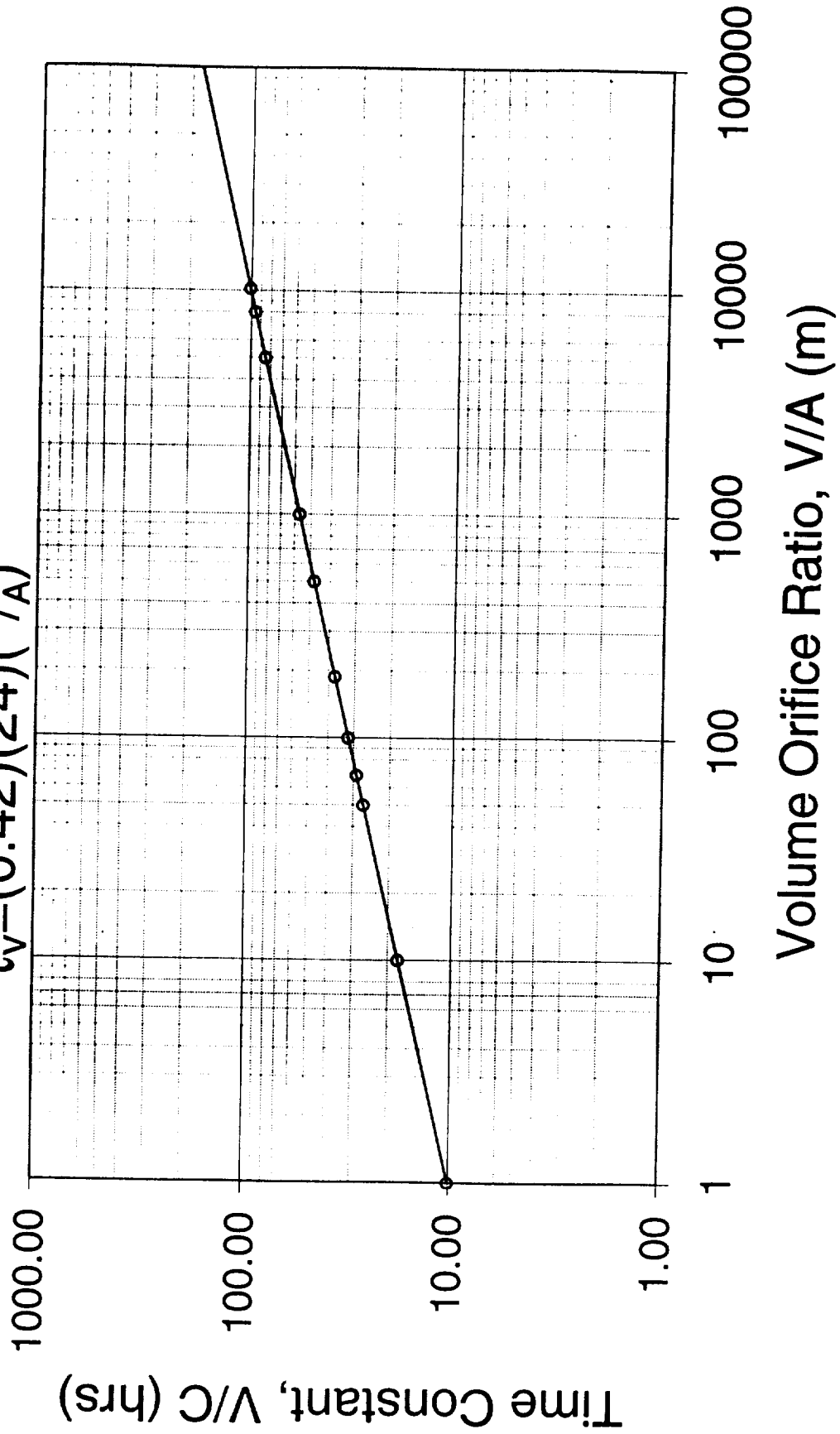


FIG. 3

Volume Internal Vapor Pressure Versus Dry Air Changes as a Function of Volume to Vent Area Ratio

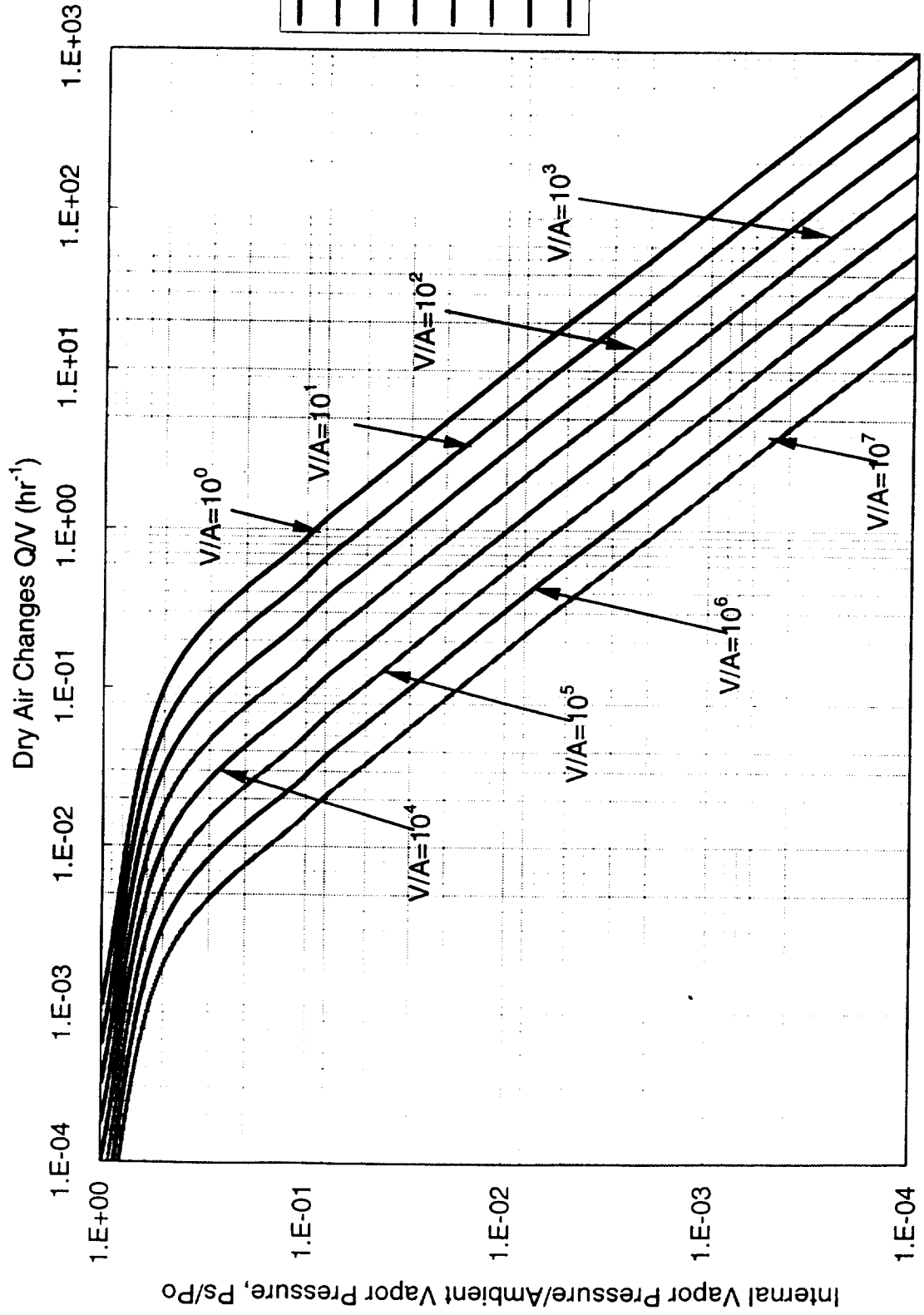


FIG 4.