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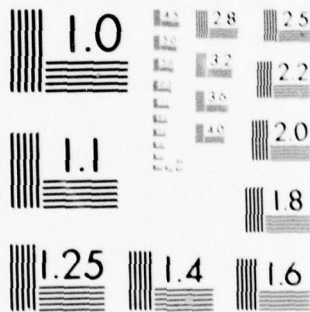
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**PREDICTED LONG-TERM STORAGE EFFECTS  
ON THE MODEL 4841 LANCE ACCELEROMETER**

Vernon A. Nieberlein  
Advanced Systems Development  
and Manufacturing Technology Directorate  
Engineering Laboratory

21 November 1977

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The Model 4841 Lance accelerometer has experienced numerous cases where, after extended storage, gas ingestion through leaks in the oil seal caused the voltage output to drift. A solution to this problem has been to backfill the outer dust cover with xenon. The present work describes in detail several engineering analyses undertaken to evaluate the anticipated performance of such a solution.

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ABSTRACT (Continued)

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ABSTRACT (Continued)

First, the relative effectiveness of the O-ring seal versus the Loctite seal is investigated. Then, detailed calculations are made which lead to predictions of storage lifetimes as a function of the leak size in the outer dust cover. Finally, an analysis is made which shows the effect of a leaky float box and predicts the internal pressure in the float as a function of time.

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## I. INTRODUCTION

The model 4841 accelerometer produced by the Systron-Donner Corporation has been prone to a low-temperature drift problem over a period of several years. This problem was first experienced during a prefire checkout at White Sands Missile Range in 1973. At that time, the root cause was identified as gas ingestion in the damping oil. Tests disclosed that after thermal cycling and storage, gas encased in the dust cover which surrounded the accelerometer leaked into the damping oil and dissolved. This gas was released from the solution as a bubble in cold weather when the ambient pressure on the accelerometer dropped. The bubble attached itself, in many cases, to the moving system, causing the voltage output to drift.

Several approaches were tried, but the final solution settled upon was to augment the O-ring seal with Loctite 290. This is an anerobic-type low-viscosity liquid which may be applied around the edges of all interfaces and allowed to wick in. The cured Loctite gave an improved seal which performed well in the simulated long-term storage tests and in the complete Qualification Test Program, so Loctite sealing was accepted as a solution to the low-temperature drift problem. A complete review of the drift problem and illustrations of the accelerometer assembly are given by Hunter [1] and Gedeon [2].

## II. CURRENT PROBLEM

In 1976 a number of malfunctioning accelerometers was discovered in the field. That is, these accelerometers exhibited a drifting voltage output at low temperatures even though they had been sealed with Loctite 290. The root cause was determined to be identical to the cause of the problem in 1973, namely ingestion of gas in the damping oil.

Investigations by Draper Laboratories [3] showed that the helium leak rates, after one hour at test conditions, increased drastically as a result of thermal shocking of the accelerometers. These leak rate increases varied from 2-fold to 14-fold over the leak rates of unshocked accelerometers on a total of three instruments. The conclusion drawn from these tests was that gas was entering the oil through microcracks in the Loctite or through debonded areas at the steel-Loctite interface as a result of the mismatch of thermal expansion rates between these two materials.

A variety of solutions to this problem was proposed and a few of these were explored in some depth. The solution which ultimately prevailed, and which is dealt with here, involves backfilling the dust cover with a gas different from the original mixture of 90% nitrogen and 10% helium. The purpose of this was to allow the dissolved gas to diffuse out of the oil, while the new backfill gas was simultaneously

diffusing in. The new backfill gas had to be chosen in such a way that its solution equilibrium pressure in the damping oil would build up slowly compared to the decline in equilibrium pressure resulting from the outward diffusion of the old gas already dissolved in the oil.

A variety of candidate gases was examined for potential backfilling, but xenon was chosen because of the following considerations:

- a) Electronically compatible with the system.
- b) Had a large atomic weight which favored a slow leak rate.
- c) Completely inert to all materials used in the system.
- d) Had a high solubility in DC-510 damping oil.

The solubility of xenon in DC-510 was determined by the US Army Missile Research and Development Command (MIRADCOM) Engineering Laboratory to be  $2.705 \text{ cm}^3$  per  $\text{cm}^3$  of oil at one atmosphere pressure and  $25^\circ\text{C}$ . This compares to 0.233 for argon, 0.138 for nitrogen, and 0.045 for helium expressed in the same units.

Some questions arose which needed to be addressed: (a) Is the seal on the accelerometer primarily furnished by the O-ring or the Loctite or, perhaps, is the seal furnished about equally by each? This is important to know because it could play an important part in the leak mechanism around which any mathematical model is built. If the elastomeric O-ring furnishes most of the seal, then the solubility of xenon in fluorosilicones, and the diffusivity of xenon through fluorosilicones would play a major part in determining the equilibrium gas pressure as a function of time. As a corollary, this O-ring seal would determine the useful life of the accelerometer after a xenon backfill. (b) After a xenon backfill, how many useful years may be expected from the accelerometer? (c) What effect does a leaky float box have on the instrument life expectancy and on the pressures that may be generated on the float box walls? These questions will be discussed in the following paragraphs.

#### A. Sealing Merits of the O-Ring Versus That of the Loctite

The O-ring and Loctite seals are in series around the perimeter of the cavity which holds the damping oil; thus, gas which enters the oil must necessarily penetrate both seals. The total resistance to penetration offered by both seals is therefore the sum of the resistances of the individual seals. By treating the reciprocals of the penetration rates as resistances, one may add them. Thus,

$$\frac{1}{P_{T1}} = \frac{1}{P_{L1}} + \frac{1}{P_{O1}} \quad (1)$$

where

$P_{T1}$  = the total gas penetration rate with both barriers in series.

$P_{L1}$  = the penetration rate through Loctite only.

$P_{O1}$  = the penetration rate through the O-ring only.

Subscript 1 = the respective rates before thermal cycling of the accelerometer.

Solving Equation (1) for the total penetration rate,

$$P_{T1} = \frac{P_{L1} P_{O1}}{P_{L1} + P_{O1}} \quad (2)$$

Letting the subscript 2 designate the respective penetration rates after thermal cycling, a similar equation results:

$$P_{T2} = \frac{P_{L2} P_{O2}}{P_{L2} + P_{O2}} \quad (3)$$

The ratio of the total penetration rates after thermal cycling to that before thermal cycling is

$$\frac{P_{T2}}{P_{T1}} = \frac{P_{L2} P_{O2}}{P_{L1} P_{O1}} \left( \frac{P_{L1} + P_{O1}}{P_{L2} + P_{O2}} \right) \quad (4)$$

A reasonable assumption is that the thermal cycling does not degrade the O-ring seal because of the elasticity of the fluorocarbon elastomer; therefore,  $P_{O2}$  is equated to  $P_{O1}$  and designated as simply  $P_O$ . Equation (4) becomes

$$\frac{P_{T2}}{P_{T1}} = \frac{P_{L2}}{P_{L1}} \left( \frac{P_{L1} + P_O}{P_{L2} + P_O} \right) \quad (5)$$

In Figure 1 the effect of thermal cycling on the total penetration rate is plotted against the effect of thermal cycling on the Loctite penetration rate using Equation (5). If the penetration through Loctite before and after thermal cycling is much less than that through the O-ring seal, the term inside the parentheses approaches unity. As a result, the effect of thermal cycling on the total seal is simply the effect of thermal cycling on the Loctite. (This is represented by the sloping straight line in Figure 1.) However, if the penetration through



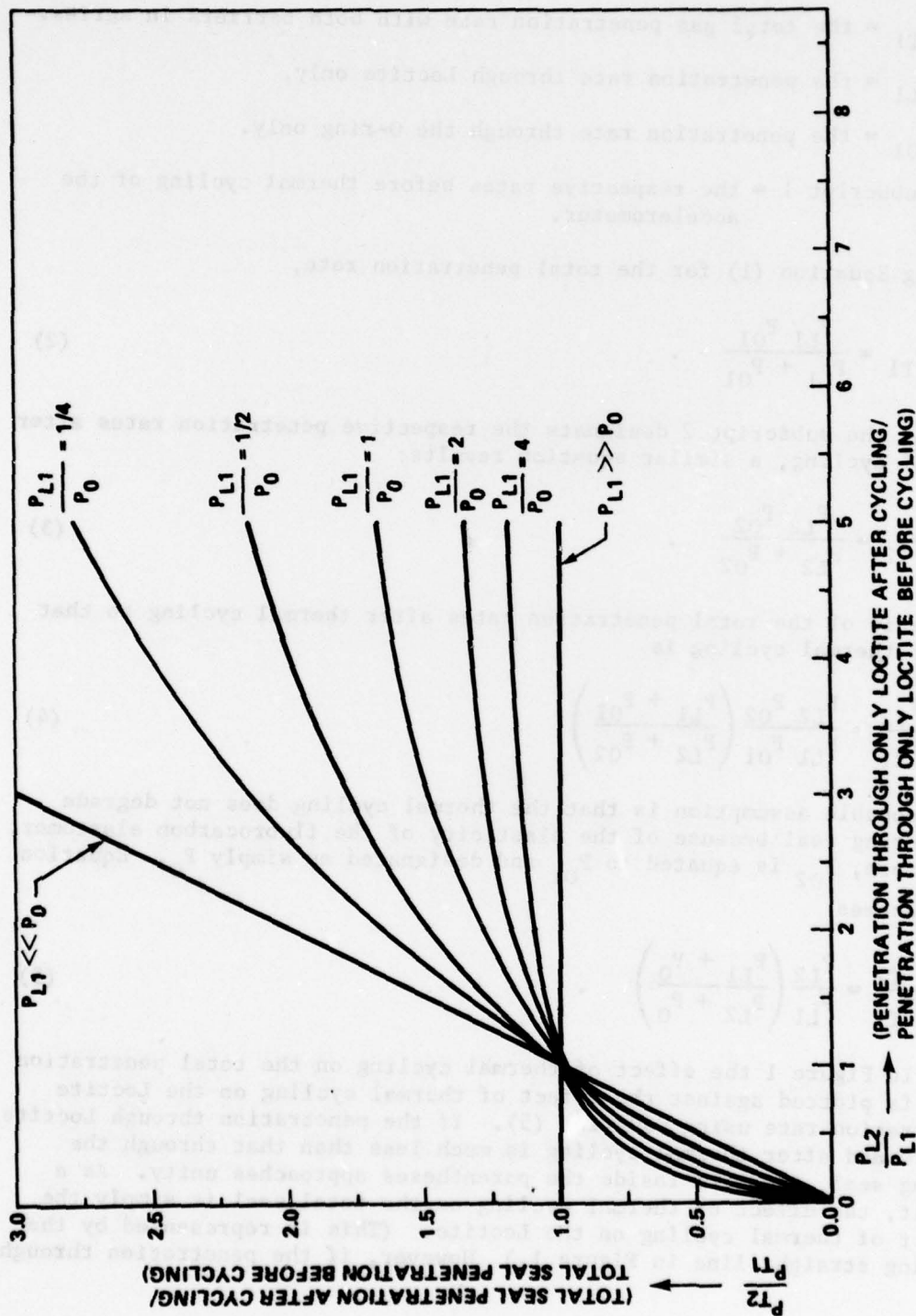


Figure 1. Gas penetration through accelerometer seals before thermal cycling.



the Loctite before and after thermal cycling is much greater than that of the O-ring, the entire right side of Equation (5) approaches unity. (This is represented by the horizontal straight line in Figure 1.) In the latter case, thermal cycling would have no effect. If the penetration through either Loctite or the O-ring is significant with respect to the other, one obtains the system of curves on the graph.

The graphs in Figure 1 are limited in the information they can provide because the ratio of Loctite penetration to O-ring penetration ( $P_{L1}/P_O$ ) is unknown. However, if this graph is used in conjunction with the Draper Report [3] certain conclusions may be drawn. The leak rates in the Draper report varied from 2-fold to 14-fold as a result of thermal shock; thus, one knows that  $P_{T2}/P_{T1}$  can vary experimentally from 2 to 14. If, in Figure 1, one follows the middle curve, i.e., the curve for the case where Loctite penetration equals O-ring penetration ( $P_{L1}/P_O = 1$ ), it may be seen that it would be very difficult to reach a value like  $P_{T2}/P_{T1} = 2$  and almost impossible to reach a value of  $P_{T2}/P_{T1} = 14$ . This points to the conclusion that the penetration through Loctite must be much less than that through the O-ring ( $P_{L1}/P_O \ll 1$ ). This can be stated differently; i.e., Loctite furnishes most of the seal before thermal cycling.

A similar analysis was performed to determine whether Loctite or the O-ring furnished most of the seal after thermal cycling. The graph is shown in Figure 2. This graph, however, is completely inconclusive because almost any ratio of penetration values through the Loctite and O-ring ( $P_{L2}/P_O$ ) appears reasonable as far as permitting a 2-fold or 14-fold penetration increase from thermal cycling ( $P_{T2}/P_{T1} = 2$  to 14).

Question a) of the previous section has been answered by the preceding work for a sensor which has never been thermally shocked. A further conclusion is that the solubility of xenon in the fluorosilicone O-ring and the diffusivity of xenon through the same material is not a major factor since the O-ring furnishes only a minor part of the seal before thermal cycling. Question (a) is not answered by the preceding analysis for the case after thermal cycling. However, such a case is answered by the experimental data of Springer [4] who found that the leak rate of a sensor was inversely proportional to the square root of the molecular weight of the leaking gas. This relationship serves as a method for leak rate prediction, based on the kinetic energy of dissimilar gas molecules. It would hold for flow through cracks but would not be likely to have any correspondence to permeation rates through solid fluorosilicone elastomers (the material of the O-ring). Therefore, since the sensors leaked in accordance with the inverse square root law, it can be concluded that the O-ring plays a minor role in sealing before and after thermal cycling, and the leak mechanism is that of viscous flow of the gas through tiny open channels.

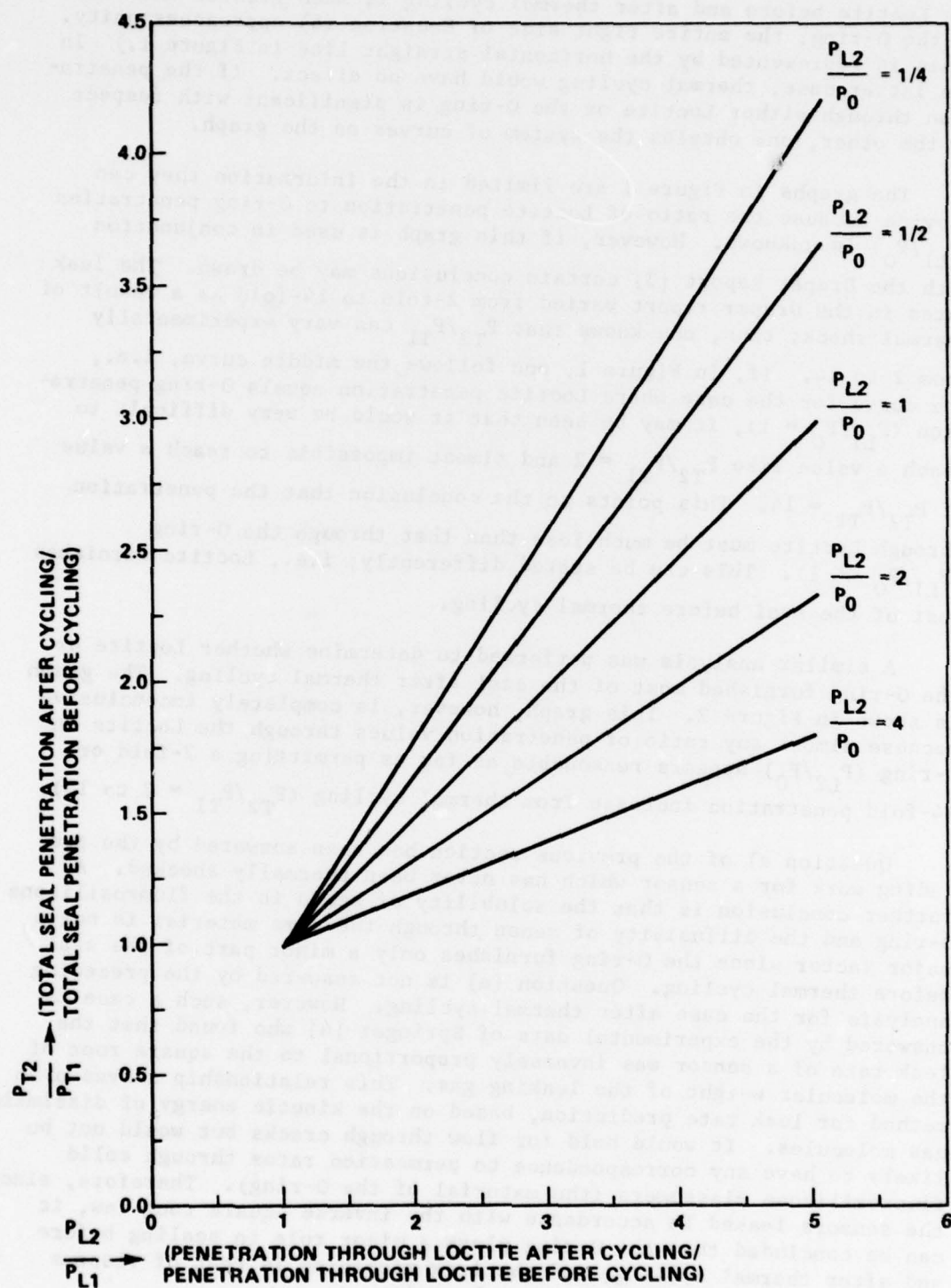


Figure 2. Gas penetration through accelerometer seals after thermal cycling.

### B. Useful Life After a Xenon Backfill

To perform a useful life analysis, a model is proposed in Figure 3.

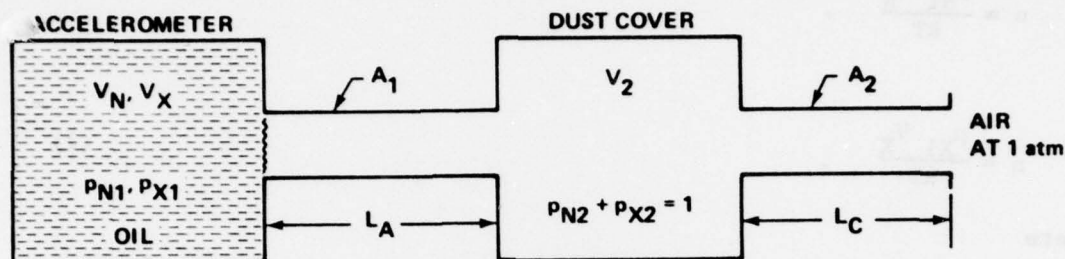


Figure 3. Model of the accelerometer dust cover system.

The model shows the accelerometer connected to the dust cover by a crack of cross-sectional area  $A_1 \text{ cm}^2$  and length  $L_A \text{ cm}$ . In turn, the dust cover is connected to the open air by a crack of cross-sectional area  $A_2 \text{ cm}^2$  and length  $L_C \text{ cm}$ .  $V_N$  and  $V_X$  are volumes available to nitrogen and xenon, respectively, in the oil by way of solubility, and  $V_2$  is the volume of the dust cover. The dust cover is backfilled with pure xenon to a pressure of 1 atmosphere.

Assumption: Nitrogen entering the dust cover from the accelerometer is ignored since  $V_N \ll V_2$ .

Assumption: Air = 100% nitrogen. This does not appear unreasonable since the diffusional properties of oxygen are very similar to those of nitrogen.

A nitrogen balance is first performed on the dust cover,

$$\begin{array}{rclcl} \text{Rate in} & - & \text{Rate out} & = & \text{Rate of accumulation} \\ A_2 N_{N2} & - & 0 & = & \frac{dn}{dt} \end{array} \quad , \quad (6)$$

where  $N_{N2}$  is the flux of nitrogen through crack  $A_2$  expressed in  $\text{moles cm}^{-2} \text{ sec}^{-1}$ , and  $n$  is moles of nitrogen inside the dust cover. From the perfect gas law,

$$n = \frac{p_{N2} V_2}{RT} ,$$

$$n = \frac{p_{N1} V_N}{RT} ,$$

or

$$n = \frac{p_{X1} V_X}{RT} , \quad (7)$$

where

$p_{N2}$  = the partial pressure, in atmospheres, of nitrogen in the dust cover

$R$  = the gas constant

$T$  = the absolute temperature.

Substituting Equation (7) into Equation (6), one obtains

$$A_2 N_{N2} = \frac{V_2}{RT} \frac{dp_{N2}}{dt} . \quad (8)$$

For equimolar counterdiffusion through crack  $A_2$ , Fick's First Law gives

$$N_{N2} = -cD \frac{dx_N}{dz} , \quad (9)$$

where

$c$  = the total gas concentration in moles  $\text{cm}^{-3}$

$D$  = the diffusivity of the nitrogen-xenon pair in  $\text{cm}^2 \text{sec}^{-1}$

$dx_N/dz$  = the mole fraction gradient of nitrogen in the crack  $A_2$  in  $\text{cm}^{-1}$ . ( $x_N$  is mole fraction of nitrogen,  $z$  is length along the crack.)

Substituting Equation (9) into Equation (8) yields

$$\frac{V_2}{RT} \frac{dp_{N2}}{dt} = -A_2 cD \frac{dx_N}{dz} . \quad (10)$$



From the perfect gas law,

$$c = \frac{p(\text{total})}{RT} = \frac{1(\text{atm})}{RT} \quad (11)$$

An average value of the mole fraction gradient of nitrogen is simply the difference in partial pressures at each end of the crack, divided by the crack length.

$$\left. \frac{dx_N}{dz} \right|_{AV} = \frac{p_{N2} - 1}{L_c} \quad (12)$$

Substitute Equations (11) and (12) into Equation (10) and rearrange.

$$\frac{dp_{N2}}{1 - p_{N2}} = \frac{A_2 D}{V_2 L_c} dt \quad (13)$$

Integrate Equation (13), with the initial condition: when  $t = 0$ ,  $p_{N2} = 0$ . (Initially, there is no nitrogen pressure in the dust cover.) This results in

$$p_{N2} = 1 - e^{\frac{-A_2 D t}{V_2 L_c}} \quad (14)$$

For Equation (14) to be of use, values are needed for  $A_2$ ,  $D$ ,  $V_2$ , and  $L_c$ . These are as follows:

$$D = 0.125 \text{ cm}^2 \text{ sec}^{-1} = 3.942 \times 10^6 \text{ cm}^2 \text{ year}^{-1}$$

$$V_2 = 130 \text{ cm}^3$$

$$L_c = 0.1 \text{ cm (estimated)}$$

$$A_2 = \sqrt{\frac{8\pi\mu_{He} L_c Q}{\Delta p_{He}}} \quad (15)$$

The value for  $A_2$  is obtained by helium leak testing the dust cover and substituting the values in Equation (15) (Hagen-Poiseuille equation). In Equation (15),

$\mu_{\text{He}}$  = the viscosity of helium in poises.

$Q$  = the leak rate in  $\text{cm}^3 \text{sec}^{-1}$ .

$\Delta p_{\text{He}}$  = pressure difference in dynes  $\text{cm}^{-2}$ .

Since there are only two gases in the dust cover and the pressure is one atmosphere, the partial pressure of xenon is

$$p_{\text{X2}} = 1 - p_{\text{N2}} \quad (16)$$

Thus, Equation (14) can be substituted into Equation (16) to get the partial pressure for xenon,

$$p_{\text{X2}} = e^{-\frac{A_2 D t}{V_2 L_c}} \quad (17)$$

Next, a nitrogen balance is performed on the accelerometer in the same manner as Equation (6).

Assumption: Diffusion through the oil is slower than the nitrogen transport through the crack; this is the rate limiting step.

Assumption: Nitrogen and xenon act independently in the oil. This is because the quantity of nitrogen (or xenon) dissolved in the oil does not effect the volume available to the other gas. Also, the probability of molecular collisions between nitrogen and xenon traveling in opposite directions in the oil is low [5].

The result of the balance is

$$-A_1 N_{\text{N1}} = \frac{dn}{dt} \quad (18)$$

where  $N_{\text{N1}}$  is the flux of nitrogen in crack  $A_1$  in moles  $\text{cm}^{-2} \text{sec}^{-1}$ . If Equation (9) (Fick's First Law) is integrated, a value for  $N_{\text{N1}}$  is obtained,

$$N_{\text{N1}} = -K_N (p_{\text{N2}} - p_{\text{N1}}) \quad (19)$$

where all constants have been incorporated into the single constant  $K_N$ . Substitute Equations (7), (14), and (19) into Equation (18) and rearrange to obtain

$$\frac{dp_{N1}}{dt} + G_N p_{N1} = G_N - G_N e^{-Ft} \quad , \quad (20)$$

where  $G_N = K_N A_1 RT/V_N$  and  $F = A_2 D/V_2 L_c$ . If the differential equation, Equation (20), is solved with the initial condition: when  $t = 0$ ,  $p_{N1} = p_{Ni}$  ( $p_{Ni}$  is the equilibrium pressure of nitrogen in the oil at the time of backfill), the following expression for nitrogen pressure in the oil is obtained

$$p_{N1} = 1 - \frac{G_N}{G_N - F} e^{-Ft} + \left( p_{Ni} + \frac{G_N}{G_N - F} - 1 \right) e^{-G_N t} \quad . \quad (25)$$

A xenon balance is now performed on the accelerometer and the result is

$$A_1 N_{X1} = \frac{dn}{dt} \quad , \quad (26)$$

where  $N_{X1}$  is the flux of xenon in crack  $A_1$ , in moles  $\text{cm}^{-2} \text{sec}^{-1}$ . Again, Fick's First Law, Equation (9), yields for xenon

$$N_{X1} = -K_X (p_{X1} - p_{X2}) \quad . \quad (27)$$

Substituting Equations (7), (27), and (17) into Equation (26) results in

$$\frac{dp_{X1}}{dt} + G_X p_{X1} = G_X e^{-Ft} \quad , \quad (28)$$

where  $G_X = K_X A_1 RT/V_X$ . The solution to the differential equation, Equation (28), with the initial conditions: when  $t = 0$ ,  $p_{X1} = 0$  (no xenon in the oil at the time of backfill), results in the following expression for xenon pressure in the oil:

$$p_{X1} = \frac{G_X}{G_X - F} \left( e^{-Ft} - e^{-G_X t} \right) \quad . \quad (29)$$

The total equilibrium pressure of both gases in the oil is the sum of the individual pressures.

$$p_{\text{total}} = p_{X1} + p_{N1} \quad . \quad (30)$$



Finding a realistic value for F with the use of the Hagen-Poiseuille equation and several given constants has already been described. A value for  $G_N$  may be obtained from the penetration rate of nitrogen into the accelerometer before the xenon backfill, i.e., while the dust cover is filled with nitrogen. In this case the nitrogen balance on the accelerometer is

$$A_1 N_{N1} = \frac{dn}{dt} \quad (31)$$

Substituting Equation (19) into Equation (31) and using a value of one atmosphere for  $p_{N2}$ , the following differential equation is obtained.

$$\frac{dp_{N1}}{1 - p_{N1}} = G_N t \quad (32)$$

If Equation (32) is integrated with the initial condition: when  $t = 0$ ,  $p_{N1} = 0$  (initially there is no nitrogen in the oil), then rearranged, an expression for  $G_N$  results.

$$G_N = \frac{-\ln(1 - p_{N1})}{t} \quad (33)$$

The equilibrium nitrogen pressure is experimentally measureable and is known as the pressure drift point (PDP). The time  $t$  can also be known from the age of the accelerometer as determined by the serial number of the sensor. Experimental values necessary for determining  $G_X$  are lacking, but an indirect method may be used. Dividing  $G_X$  by  $G_N$ , one obtains

$$\frac{G_X}{G_N} = \frac{K_X V_N}{K_N V_X} \quad (34)$$

Since the geometry of the system is constant,  $K_X$  and  $K_N$  are directly proportional to the "effective overall diffusivities" of the two gases through the crack-oil system. This relationship is substituted into Equation (34) to obtain the following:

$$G_X = G_N \frac{D_X V_N}{D_N V_X} \quad (35)$$

By gas dynamic theory, the velocity of a gas through a crack is proportional to the inverse square root of its molecular weight, thus

$$G_X = \frac{G_N V_N}{V_X} \sqrt{\frac{M_N}{M_X}}, \quad (36)$$

where  $M_N$  and  $M_X$  are the molecular weights of nitrogen and xenon, respectively. Using Equations (25), (29), and (30) the equilibrium pressures inside the sensor for various leak rates in the dust cover are shown in Figure 4. This graph is based on an example where the accelerometer accumulated nitrogen before the xenon backfill at such a rate that a nitrogen equilibrium pressure in the oil (PDP) of 17 in. of mercury was reached after two years. Using 17 in. mercury as an initial condition at backfill, the total equilibrium pressure versus time was plotted for five different leak rates in the dust cover. The plot is shown in Figure 4.

This analysis was also performed in a manner to reflect the effect of nitrogen entering the dust cover by one crack while xenon is exiting by a separate crack, or stated differently, the two gases are acting independently. Diffusion theory would indicate this to be an unlikely case, i.e., equimolar counterdiffusion should prevail since there is no sound physical reason why xenon should not tend to exit through the same channel that nitrogen enters. However, to make the study complete and to present the effects of such an independently acting system, the analysis was made. The only significant difference between this analytical treatment and the previous one is the dust cover balance; therefore, Equation (6) is still true.

$$A_2 N_{N2} = \frac{dn}{dt} \quad (6)$$

If the gases act independently, each behaves as though the other did not exist and  $N_{N2}$  then becomes the rate that nitrogen would flow through the crack  $A_2$  into an initially empty dust cover.

$$\frac{298}{273} \times 22,400 A_2 N_{N2} = Q = \frac{1.0133 \times 10^6 A_2^2 (1 - p_{N2})}{8\pi\mu_N L_c} \quad (37)$$

Equation (37) is the Hagen-Poiseuille equation. Substituting Equations (7) and (37) into Equation (6) results in the differential equation, Equation (38),

$$\frac{dp_{N2}}{1 - p_{N2}} = B_N dt \quad (38)$$

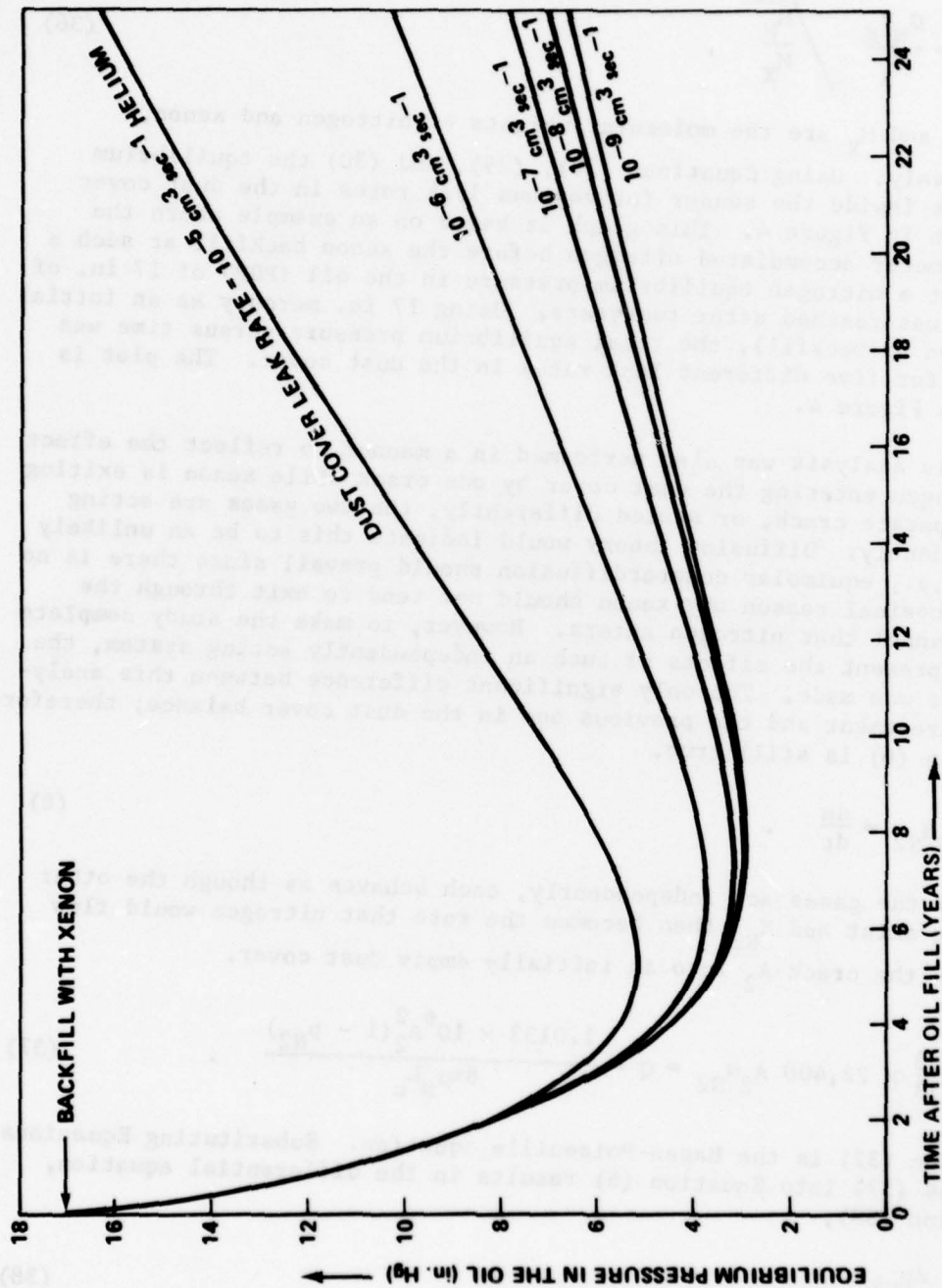


Figure 4. Equilibrium gas pressures in the oil for various dust cover leak rates.

where

$$B_N = \frac{41.44 A_2^2 RT}{8\pi\mu_N L_c V_2} \quad (39)$$

Solving Equation (38) with the initial condition: when  $t=0$ ,  $p_{N2}=0$ , there results the expression for the nitrogen pressure in the dust cover.

$$p_{N2} = 1 - e^{-B_N t} \quad (40)$$

Similarly, the expression for the xenon pressure is

$$p_{X2} = e^{-B_X t} \quad (41)$$

If these two equations are used in place of Equations (14) and (17), respectively, a more conservative answer results. This is to be expected since gas will enter and leave the dust cover faster if there are no "traffic problems" with gas molecules going in the opposite direction in a narrow passageway. Although analytically not as realistic as equimolar counterdiffusion, the "one-way cracks" had a certain amount of usefulness as far as exploring the most pessimistic hypothesis. One further difference between the solution for one-way cracks and for equimolar counterdiffusion is that the transport in the former would be accomplished by pressure driven laminar flow while the mechanism for the latter would be strictly molecular counterdiffusion. The counterdiffusion solution, predicts no change in pressure inside the dust cover. Thus, "breathing" through the cracks caused by atmospheric temperature and pressure changes could present a lower-than-expected lifetime, while such derived pressure changes would have a negligible effect on one-way cracks. Xenon percentages in the dust cover resulting from counterdiffusion are shown in Figure 5.

### C. Effect of a Leaky Float

The Model 4841 accelerometer has one moving part which consists of a sensing element mounted on jeweled bearings. This piece of hardware has a coil at one end supported by two pendulum arms, and these are counterbalanced by a hollow float box. The float box is machined from aluminum with an aluminum lid held in place and sealed by an epoxy cement. This part is built and assembled under ambient conditions so that the float is filled with air at one atmosphere pressure. If the epoxy seal develops an infinitesimal leak, the contents of the float box would become an additional source of gas which would dissolve in the damping oil and, at the same time, exhibit a pressure less than that at the time of assembly. This decrease in the



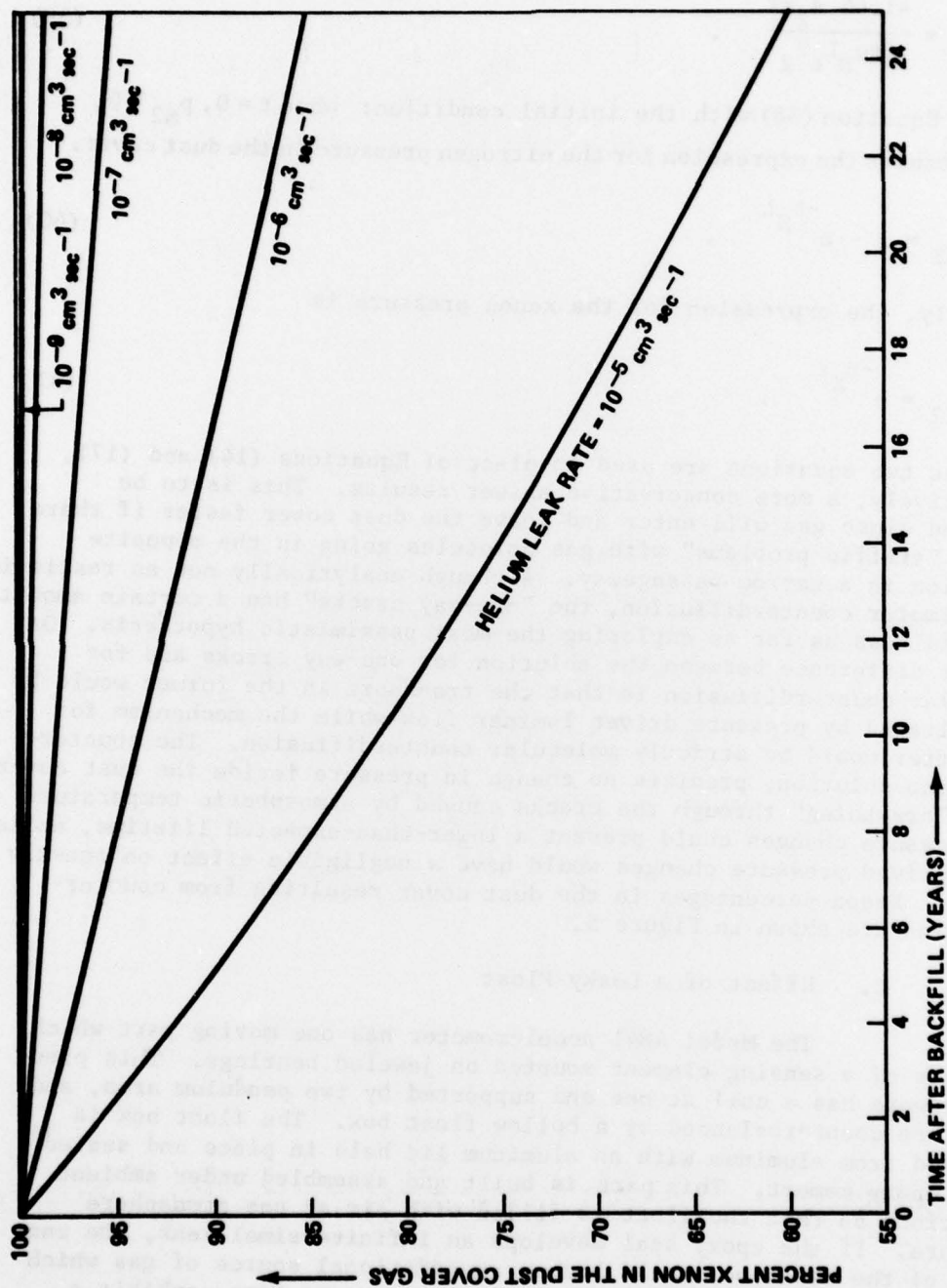


Figure 5. Percent xenon in the dust cover gas for various dust cover leak rates.

internal pressure of the float could possibly cause stresses on the aluminum walls which would result in permanent deformation and damage.

To study the effect of a leaky float, a three-compartment model is proposed as shown in Figure 6. Initially, before any xenon backfill, one considers the dust cover volume  $V_2$  to be filled with nitrogen which leaks into the sensor oil through crack  $A_1$  with a flux of  $N_{N1}$  moles  $\text{cm}^{-2} \text{sec}^{-1}$ . Also the float volume  $V_F$  is filled with air (nitrogen) which leaks into the sensor through crack  $A_F$  with a flux of  $N_{NF}$  where  $N_{NF} = N_{N1}$  by definition. These combined fluxes are such that they will produce an equilibrium nitrogen pressure (PDP) in the oil of 17 in. of mercury after 2 years. A nitrogen balance on the float is performed first.

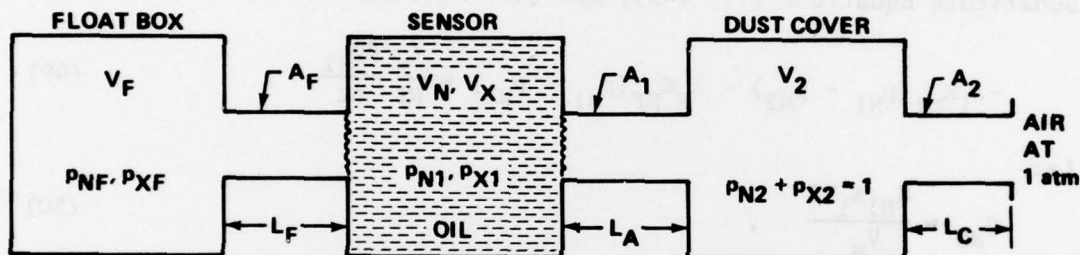


Figure 6. Model of the float-accelerometer dust cover system.

$$\begin{array}{l} \text{Rate in} \\ 0 \end{array} - \begin{array}{l} \text{Rate out} \\ A_F N_{NF} \end{array} = \begin{array}{l} \text{Rate of accumulation} \\ \frac{dn}{dt} \end{array} \quad (42)$$

Again, use the relationship based on Fick's First Law,

$$N_{NF} = -K_{NF}(P_{N1} - P_{NF}) \quad (43)$$

where all constants have been incorporated into the single constant  $K_{NF}$ . Substitute Equations (7) and (43) into Equation (42) to obtain

$$A_F K_{NF}(P_{N1} - P_{NF}) = \frac{V_F}{RT} \frac{dp_{NF}}{dt} \quad (44)$$

Let

$$G_{NF} = \frac{K_{NF} A_F RT}{V_F} \quad (45)$$

and substitute Equation (45) into Equation (44) to get

$$\boxed{\frac{dp_{NF}}{dt} = G_{NF}(p_{N1} - p_{NF})} \quad (46)$$

Equation (46) cannot be integrated immediately because  $p_{N1}$  as well as  $p_{NF}$  is a function of time. Now, another nitrogen balance is performed on the sensor. This results in

$$A_1 N_{N1} + A_F N_{NF} = \frac{dn}{dt} \quad (47)$$

Let

$$N_{N1} = -K_{N1}(p_{N1} - p_{N2}) \quad (48)$$

Substitute Equations (7), (43), and (48) into Equation (47) to obtain

$$-A_1 K_{N1}(p_{N1} - p_{N2}) - A_F K_{NF}(p_{N1} - p_{NF}) = \frac{V_N}{RT} \frac{dp_{N1}}{dt} \quad (49)$$

Let

$$G_{NO} = \frac{K_{N1} A_1 RT}{V_N} \quad (50)$$

$$Y_{NF} = \frac{K_{NF} A_F RT}{V_N} \quad (51)$$

and

$$p_{N2} = 1 \text{ atm} \quad (52)$$

Place Equations (50), (51), and (52) into Equation (49) and rearrange to obtain

$$\boxed{\frac{dp_{N1}}{dt} = G_{NO}(1 - p_{N1}) - Y_{NF}(p_{N1} - p_{NF})} \quad (53)$$

Equations (46) and (53) are coupled and must be solved numerically. From Equations (45), (50), and (51) it may be seen that the following relationships apply:

$$G_{NF} = \frac{K_{NF} A_F V_N}{K_{N1} A_1 V_F} G_{NO} \quad (54)$$



and

$$Y_{NF} = \frac{V_F}{V_N} G_{NF} = \frac{K_{NF} A_F}{K_{N1} A_1} G_{NO} \quad (55)$$

To find a value for  $G_{NO}$ , a computer program was written for solving the coupled equations, Equations (46) and (53), numerically with an estimated value for  $G_{NO}$ . If the equilibrium pressure of nitrogen in the oil,  $p_{N1}$ , did not reach a value of 17 in. of mercury after 730 days (2 years), a new  $G_{NO}$  was substituted and the process was repeated. This trial-and-error procedure led to a value of  $0.00069 \text{ days}^{-1}$  for  $G_{NO}$ . Other values are:

$$V_N = 0.882 \text{ cm}^3$$

$$V_F = 0.718 \text{ cm}^3$$

The remaining constants in Equations (54) and (55) need not be known. The reason is that the original assumption considered the nitrogen fluxes from the dust cover to the oil and from the float to the oil to be equal. In this case all values in the numerator and denominator in Equations (54) and (55) cancel except  $V_N$  and  $V_F$ .

Next, a nitrogen balance is performed on the sensor after the xenon backfill. This results in

$$A_F N_{NF} - A_1 N_{N1} = \frac{dn}{dt} \quad (56)$$

Substituting Equations (7), (43), and (48) into Equation (56) one obtains

$$-A_F K_{NF} (p_{N1} - p_{NF}) + A_1 K_{N1} (p_{N2} - p_{N1}) = \frac{V_N}{RT} \frac{dp_{N1}}{dt} \quad (57)$$

Substituting Equations (14), (50), and (51) into Equation (57) the following is obtained:

$$\boxed{\frac{dp_{N1}}{dt} = G_{NO} (1 - e^{-Ft} - p_{N1}) - Y_{NF} (p_{N1} - p_{NF})} \quad (58)$$

A nitrogen balance performed on the float box after the xenon backfill is identical to that performed before the xenon backfill because nitrogen can leak only in one direction in either case, i.e., from the float

into the oil. Therefore, Equation (46) is true as a result of such a nitrogen balance. Now, for the case where internal pressure of the float is sought after the xenon backfill, Equations (58) and (46) are coupled and must be solved numerically on the computer.

After the xenon backfill, one may expect xenon to leak into the oil from the dust cover and from the oil into the float. A xenon balance on the oil after the backfill results in

$$A_1 N_{X1} - A_F N_{XF} = \frac{dn}{dt} \quad (59)$$

If the relationship for  $N_{XF}$  is used,

$$N_{XF} = -K_{XF}(p_{XF} - p_{X1}) \quad (60)$$

Then Equations (7), (27), and (60) can be substituted into Equation (59) to give

$$-A_1 K_{X1}(p_{X1} - p_{X2}) + A_F K_{XF}(p_{XF} - p_{X1}) = \frac{V_X}{RT} \frac{dp_{X1}}{dt} \quad (61)$$

By defining

$$Y_{XF} = \frac{K_{XF} A_F RT}{V_X} \quad (62)$$

and

$$G_{XO} = \frac{K_{X1} A_1 RT}{V_X} \quad (63)$$

Equation (61) may be rearranged and Equations (17), (62), and (63) substituted to give

$$\frac{dp_{X1}}{dt} = Y_{XF}(p_{XF} - p_{X1}) - G_{XO}(p_{X1} - e^{-Ft}) \quad (64)$$

A xenon balance on the float box gives

$$A_F N_{XF} = \frac{dn}{dt} \quad (65)$$

Using Equations (7) and (60) in Equation (65), one obtains

$$-A_F K_{XF} (p_{XF} - p_{X1}) = \frac{V_F}{RT} \frac{dp_{XF}}{dt} \quad (66)$$

Finally, by defining

$$G_{XF} = \frac{K_{XF} A_F RT}{V_F} \quad (67)$$

Equation (67) is placed in Equation (66) to give

$$\boxed{\frac{dp_{XF}}{dt} = G_{XF} (p_{X1} - p_{XF})} \quad (68)$$

To obtain the xenon pressure in the float, Equations (64) and (68) must be coupled and solved numerically. The nitrogen and xenon partial pressures in the oil and float were calculated as a function of time and then added to get the total pressures in the oil and float, respectively. These are plotted in Figure 7.

The relationship between  $G_{XO}$  and  $G_N$  is identical to the relationship between  $G_X$  and  $G_N$  given in Equation (36), i.e.,

$$G_{XO} = \frac{G_{NO} V_N}{V_X} \sqrt{\frac{M_N}{M_X}} \quad (69)$$

Also, by definition

$$G_{XF} = \frac{V_X}{V_N} G_{XO} \quad (70)$$

and

$$Y_{XF} = \frac{V_F}{V_X} G_{XF} \quad (71)$$

A value was obtained for  $V_X$  by analyses performed in the MIRADCOM laboratories on the xenon solubility in DC-510 oil. This value was:  
 $V_X = 17.04 \text{ cm}^3$ .

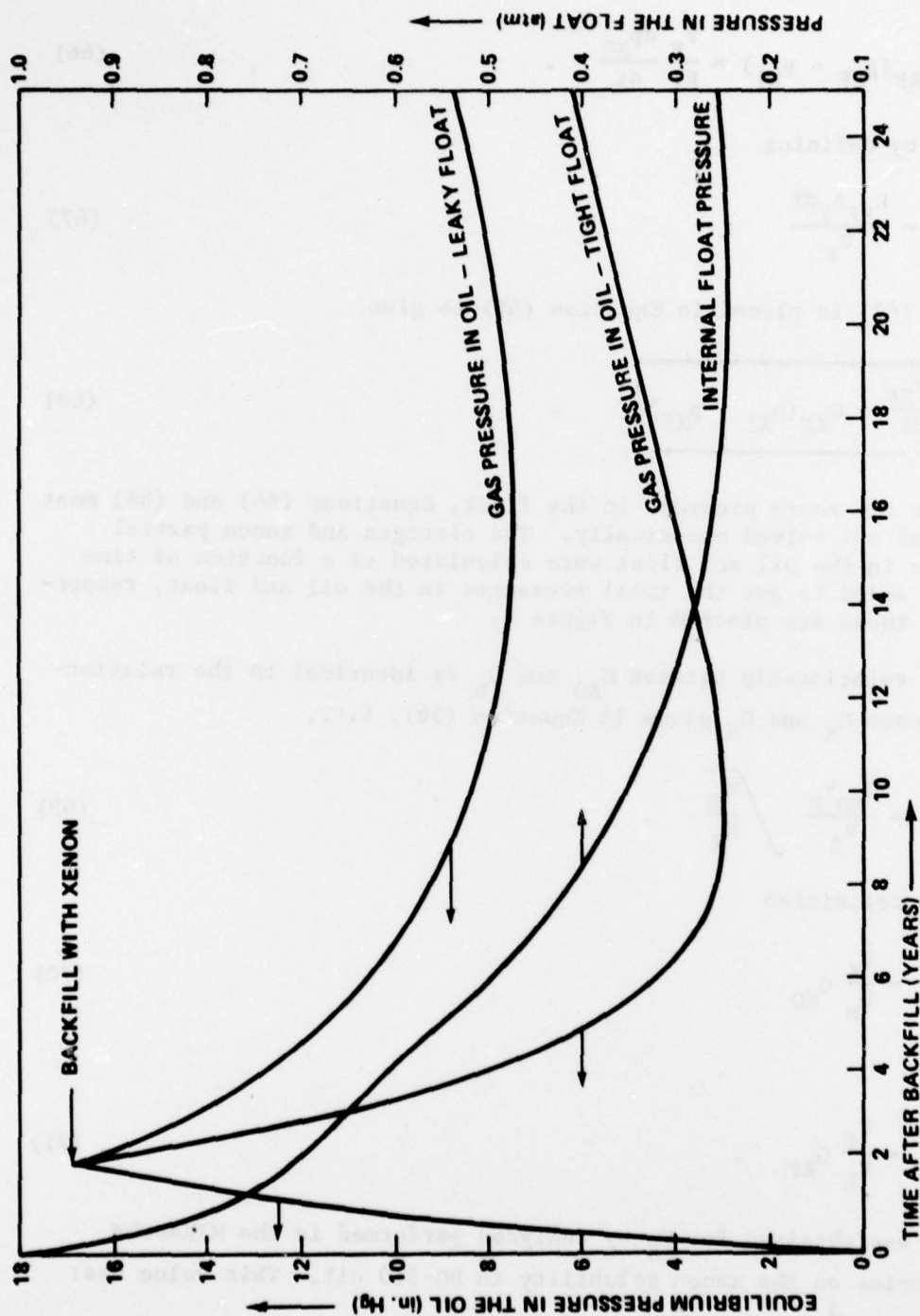


Figure 7. Equilibrium gas pressure in the oil and internal pressure attending a leaky float.



### III. CONCLUSIONS

Based on the preceding study, the following conclusions can be made:

- a) On accelerometers sealed by an O-ring and Loctite, the Loctite furnishes most of the seal.
- b) Thermal shocking degrades the Loctite seal.
- c) The diffusion analysis on the dust cover shows that the xenon percentage will drop to the following values in 15 years after backfilling with xenon.

<u>Dust Cover Leak Rate (helium, 1 atm <math>\Delta p</math>)</u>	<u>Xenon Percentage in Dust Cover Gas</u>
$10^{-9} \text{ cm}^3 \text{ sec}^{-1}$	99.7
$10^{-8}$	99.0
$10^{-7}$	97.0
$10^{-6}$	90.7
$10^{-5}$	73.5

The relationship between time and xenon percentage in the dust cover gas is shown in Figure 5.

d) If the predicted lifetime is defined as the number of years between xenon backfill and that time when the equilibrium pressure rises back to the original 17 in. of mercury, then all cases examined gave adequate extention of lifetime; i.e., all dust cover leak rates including  $10^{-5} \text{ cm}^3 \text{ sec}^{-1}$  of helium would be acceptable. However, if the source of gas is not known, i.e., if it can be principally or largely from the float, then the larger leak rates in the dust cover may not be acceptable.

e) If the float leaks equally with the dust cover at such a rate that the equilibrium gas pressure in the oil is 17 in. of mercury after 2 years, then the two smaller leaks are worse than one large equivalent leak in the dust cover only. Figure 7 shows two such cases where the leaky float allows the equilibrium gas pressure in the oil to drop no lower than 7.5 in. of mercury, while the single equivalent dust cover leak allows a drop to 3 in. of mercury.

f) For the case described in e), the pressure inside the float drops to 0.24 atmosphere in 21 years before rising.

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# NOMENCLATURE

$A_1$	Accelerometer leak cross-sectional area, $\text{cm}^2$
$A_2$	Dust cover leak cross-sectional area, $\text{cm}^2$
$A_F$	Float box leak cross-sectional area, $\text{cm}^2$
$B_N$	Nitrogen leak parameter, independent action, $\text{sec}^{-1}$
$B_X$	Xenon leak parameter, independent action, $\text{sec}^{-1}$
$c$	Gas concentration, $\text{moles-cm}^{-3}$
$D$	Diffusivity, nitrogen-xenon pair, $\text{cm}^2 \text{sec}^{-1}$
$D_N$	Nitrogen effective diffusivity, crack-oil system, $\text{cm}^2 \text{sec}^{-1}$
$D_X$	Xenon effective diffusivity, crack-oil system, $\text{cm}^2 \text{sec}^{-1}$
$F$	Nitrogen-xenon counterdiffusion parameter, $\text{sec}^{-1}$
$G_N$	Accelerometer leak parameter for nitrogen, $\text{sec}^{-1}$
$G_{NF}$	Float leak parameter for nitrogen, $\text{sec}^{-1}$
$G_{NO}$	Accelerometer leak parameter for nitrogen, $\text{sec}^{-1}$
$G_{XF}$	Float leak parameter for xenon, $\text{sec}^{-1}$
$G_{XO}$	Accelerometer leak parameter for xenon, $\text{sec}^{-1}$
$K_N$	Nitrogen leak rate, $\text{moles cm}^{-2} \text{sec}^{-1} \text{atm}^{-1}$
$K_{N1}$	Nitrogen leak rate from the accelerometer, $\text{moles cm}^{-2} \text{sec}^{-1} \text{atm}^{-1}$
$K_{NF}$	Nitrogen leak rate into the float, $\text{moles cm}^{-2} \text{sec}^{-1} \text{atm}^{-1}$
$K_X$	Xenon leak rate, $\text{moles cm}^{-2} \text{sec}^{-1} \text{atm}^{-1}$
$K_{XF}$	Xenon leak rate into the float, $\text{moles cm}^{-2} \text{sec}^{-1} \text{atm}^{-1}$
$L_A$	Crack length into the accelerometer from the dust cover, cm
$L_C$	Crack length into the dust cover from the outside, cm
$L_F$	Crack length into the float from the oil, cm
$M_N$	Molecular weight of nitrogen, $\text{g mole}^{-1}$



$M_X$	Molecular weight of xenon, g mole <sup>-1</sup>
$n$	Amount of gas, moles
$N_{N1}$	Nitrogen flux into or out of the accelerometer, moles cm <sup>-2</sup> sec <sup>-1</sup>
$N_{N2}$	Nitrogen flux into the dust cover, moles cm <sup>-2</sup> sec <sup>-1</sup>
$N_{NF}$	Nitrogen flux out of the float, moles cm <sup>-2</sup> sec <sup>-1</sup>
$N_{X1}$	Xenon flux into the accelerometer, moles cm <sup>-2</sup> sec <sup>-1</sup>
$N_{XF}$	Xenon flux into the float, moles cm <sup>-2</sup> sec <sup>-1</sup>
$P_{L1}$	Gas penetration rate through Loctite seal before cycling, cm <sup>3</sup> sec <sup>-1</sup>
$P_{L2}$	Gas penetration rate through Loctite seal after cycling, cm <sup>3</sup> sec <sup>-1</sup>
$P_O$	Gas penetration rate through O-ring seal, cm <sup>3</sup> sec <sup>-1</sup>
$P_{O1}$	Gas penetration rate through O-ring seal before cycling, cm <sup>3</sup> sec <sup>-1</sup>
$P_{O2}$	Gas penetration rate through O-ring seal after cycling, cm <sup>3</sup> sec <sup>-1</sup>
$P_{T1}$	Gas penetration rate through both seals before cycling, cm <sup>3</sup> sec <sup>-1</sup>
$P_{T2}$	Gas penetration rate through both seals after cycling, cm <sup>3</sup> sec <sup>-1</sup>
$P_{He}$	Helium pressure, dynes cm <sup>-2</sup>
$P_{NF}$	Nitrogen partial pressure in the float, atm
$P_{N1}$	Nitrogen equilibrium pressure in the oil, atm
$P_{N2}$	Nitrogen partial pressure in the dust cover, atm
$P_{X1}$	Xenon equilibrium pressure in the oil, atm
$P_{X2}$	Xenon partial pressure in the dust cover, atm

Q	Volumetric gas flow rate, $\text{cm}^3 \text{sec}^{-1}$
R	Gas constant, $82.057 \text{ cm}^3 \text{ atm mole}^{-1} \text{ }^\circ\text{K}^{-1}$
T	Temperature, $^\circ\text{K}$
t	Time, sec
$V_F$	Internal volume of the float, $0.718 \text{ cm}^3$
$V_N$	Volume available to nitrogen in the oil, $0.882 \text{ cm}^3$
$V_X$	Volume available to xenon in the oil, $17.04 \text{ cm}^3$
$V_2$	Internal volume of the dust cover, $130 \text{ cm}^3$
$x_N$	Mole fraction of nitrogen, dimensionless
$Y_{NF}$	Float leak parameter for nitrogen, $\text{sec}^{-1}$
$Y_{XF}$	Float leak parameter for xenon, $\text{sec}^{-1}$
z	Distance lengthwise along crack $A_2$ , cm
$\mu_{\text{He}}$	Helium viscosity, 0.000184 poise
$\mu_N$	Nitrogen viscosity, 0.000178 poise

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