

# Technical Notes

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## Outgas Dominated Pressure Distribution in a Multilayer Insulation System

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### I. Introduction

APPLICATION of multilayer insulation (MLI) systems to the thermal protection of fuel tanks of space vehicles has been a subject of interest for many years. It is known that an MLI system consisting of reflective shields and spacers is capable of reducing heat transfer to a negligible level when the interstitial gas pressure is below roughly  $10^{-4}$  torr. This low pressure level can be achieved before or after launch by certain pumping processes. For a long-term space mission, the self-broadside-pumping process, by which the interstitial gas is evacuated from atmospheric level after launch by the vacuum environment through perforation holes on the insulation layers, is considered favorable. As the ascent and re-entry heat leaks can be considerably reduced with rapid evacuation during ascent and effective repressurization during re-entry, the long-term on-orbit performance of the insulation composites may be dominating and of major concern. The purpose of this work is to obtain a simple way to compute the pressure distribution in an insulation composite when the ambient pressure is very low.

In a high vacuum environment, the interstitial gas pressure is caused primarily by particles outgassing from the insulation materials. There are different kinds of gas particles originally absorbed or adsorbed in the MLI materials and released from them at low pressures. However, experimental data have shown that they are mainly water vapors for the commonly used reflective shields and spacers.<sup>1</sup> Thus, both for simplicity in the way of presentation of analysis and practical application, only one outgas component (water vapor) is assumed present. Generalization to the case of a mixture of gases is straightforward.

Following the same line of reasoning as given in Ref. 2, for the case of small perforation coefficient and large number of insulation layers, gas molecules in any particular interstice are assumed to have a Maxwellian distribution with the number density and temperature associated with that interstice. In the computation of the pressure in the MLI system, cryopumping effect, i.e., removal of gas particles by the very cold layers near the cryogenic wall, is assumed not to occur.

### II. Formulation

Let  $c$  be the perforation coefficient of the insulation layers (perforation area per unit area of an insulation sheet),  $n$  the molecular number density of the interstitial gas,  $v$  the mean thermal velocity of the gas molecules, and  $A$  the total area of an insulation sheet (one side). Then, the total number flux across the insulation layer  $l$  between the interstitial spaces  $l-1$  and  $l$  is

$$F_l = -\frac{cA_l}{4}[(nv)_l - (nv)_{l-1}] = -\frac{cA_l}{4}(\Delta nv)_l \quad (1)$$

where  $l = 0, 1, \dots, L$ , which identifies the position of a certain interstitial space or that of an insulation layer, is counted from the ambient towards the tank wall in increasing order. The mean thermal velocity of the gas particles is given by

$$v = (8kT/\pi m)^{1/2} \quad (2)$$

where  $k$  is the Boltzmann constant,  $m$  the mass of a gas molecule, and  $T$  is the temperature of the gas.

The term  $(\Delta nv)_l$  in Eq. (1) is the increment of the quantity  $nv$  across the layer  $l$  from interstice  $l-1$  to  $l$ , i.e.,  $(\Delta nv)_l = \Delta(nv)/\Delta l$ . This definition applies to other quantities in exactly the same way.

Replacing  $l$  in the set of integers  $(0, 1, \dots, L)$  by  $r$  which is in the continuous interval  $[0, L]$ , then, Eq. (1) can be written as

$$f(r) = -(c/4)[d(nv)/dr] \quad (3)$$

where  $f(r)$  is the number flux per unit area and time. It should be noted that only those solutions of the differential equation which are evaluated at the integer points on  $[0, L]$  have physical meaning.

The rate of change of the total flux across interstitial space  $l$  is

$$(\Delta F)_l = \Delta F/\Delta l = 2(1-c)A_l q_l \quad (4)$$

where  $q$  is the outgassing rate in (molecules per unit area and time). In engineering applications, the total thickness of the insulation system is much smaller than the dimensions of the fuel tank, and  $A$  is nearly constant. Therefore, by replacing  $l$  by  $r$  and neglecting  $dA/dr$ , Eq. (4) becomes

$$df/dr = 2(1-c)q(r) \quad (5)$$

The boundary conditions of the problem are

$$r = 0: n = 0, T = T_o \quad (6)$$

$$r = L: f = -2(1-c)q(L), T = T_w$$

With the boundary condition for  $f$  as prescribed in Eqs. (6), Eqs. (3) and (5) give

$$\frac{d(nv)}{dr} = \frac{8(1-c)}{c} \left[ q(L) - \int_L^r q(r_1) dr_1 \right] \quad (7)$$

There are two unknown functions ( $n$  and  $v$  or  $T$ ) in Eq. (7); therefore, another equation is needed to close the system. It is noted that Eq. (7) is derived from the principle of conservation of mass. Following the same reasoning given in Ref. 2, the momentum equation can be neglected when  $c$  is small, leaving the energy equation to be considered. In an outgas dominated situation, the energy equation will be replaced by assuming a temperature distribution

$$T = (a + br)^{1/4}, \text{ where } a = T_o^4 \text{ and } b = (T_w^4 - T_o^4)/L \quad (8)$$

Equation (8) is the temperature distribution in complete vacuum,<sup>†</sup> a conservative approximation at low pressures.

Using the boundary condition for  $n$  at  $r = 0$ , Eq. (7) is integrated to give

$$nv = \frac{8(1-c)}{c} \left[ q(L)r - \int_0^r \int_L^{r_1} q(r_2) dr_2 dr_1 \right] \quad (9)$$

Since the pressure  $p = nkT$ , it follows from Eqs. (2) and (9) that

$$p = \left( \frac{1-c}{c} \right) (8\pi mkT)^{1/2} \left[ q(L)r - \int_0^r \int_L^{r_1} q(r_2) dr_2 dr_1 \right] \quad (10)$$

Equation (10) is the explicit solution of the pressure distribution provided  $q$  is a known function of  $r$ .

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† Assumption is made here that the insulation layers are gray surfaces.

The outgassing rate  $q$  is determined experimentally. It is a function of the temperature, pressure, and time. It also depends on the materials, manufacturing process, and preconditioning of the insulation sheets and spacers. Thus, for a specific insulation composite with prescribed preconditioning,  $q = q(T, p, t)$ . At extremely low pressure ranges, however,  $q$  may be written as  $q = q(T, t)$ , since its dependence on  $p$  is weak in this case.

Outgassing rates of some typical insulation materials measured against the time at room temperature and constant pressure are available in the literature.<sup>1,3-5</sup> However, to the knowledge of the author, systematic measurement of outgassing rates vs the time at different temperatures can only be found in Ref. 1. According to the experimental data reported in this reference, the temperature dependence of the outgassing rate of double-aluminized Mylar (from 262 K to 297 K), in the early diffusion stage of the outgassing process, can be written as

$$Q = e^{d-\alpha/T} \equiv Q_1 e^{-\alpha/T} \quad (11)$$

where  $d$  and  $\alpha$  are experimental constants and  $\alpha$  has the dimension of the temperature and is positive. The unit of  $Q$  is in pressure times volume per unit area and time (torr-liters/cm<sup>2</sup>-sec). From Eq. (11), one sees that  $Q$  increases with the temperature and that  $\log Q$  has a linear dependence on the reciprocal of  $T$ .

Equation (11) may not represent the outgassing rate at very low temperatures, say, the temperature of liquid hydrogen. However, as some commonly used insulation materials have negligibly small outgassing rates at temperatures way above the liquid oxygen temperature,<sup>1,3</sup> the discrepancy at low temperatures between the actual  $Q$  and that expressed by Eq. (11) will not appreciably affect the computed pressure distribution in the MLI. On the other hand, although  $Q$  has a limit  $Q_1$  at large  $T$  according to Eq. (11), it is likely that there exists an upper limit of  $T$  beyond which this equation does not apply. And, unlike the low temperature case, the computed pressure distribution depends strongly on the accuracy of Eq. (11) at high temperatures. Unfortunately, how far this equation can go on the high temperature side is not known without further experimental study.

When the outgassing rate is expressed in the unit of molecules per unit area and time, Eq. (11) can be written as

$$q = s e^{-\alpha/T/kT} \quad (12)$$

where  $q$  is in (molecules/area-time) and  $s$  in (force/length-time). If the outgassing rates of other insulation materials in the early diffusion period also obey Eq. (12), then the evaluation of  $q$  vs  $T$  in this period reduces to the determination of the two experimental constants  $s$  and  $\alpha$  for different materials.

It should be noted that Eq. (11) gives  $Q$  a monotonically increasing function of  $T$ , while  $q$ , which has an exact physical meaning of the outgassing rate, possesses a maximum value at  $T = \alpha$  by Eq. (12). If the actual outgassing rate increases with  $T$  for all  $T$  in this period of time, the upper limit of  $T$  for the validity of Eq. (11) or (12) must be less than or equal to  $\alpha$ .

Once the relationship between  $q$  and  $T$  is known, the integral in Eq. (10) can be evaluated, and the pressure distribution across the insulation system at a given time is obtained. For instance, by using Eqs. (8) and (12) in Eq. (10), and after considerable amount of manipulations, we obtain

$$p = s \left( \frac{1-c}{c} \right) \left( \frac{8\pi m T}{k} \right)^{1/2} \left[ (e^{-x_w/T_w} r) + \frac{16\alpha^7}{b^2} (G(x) - G(x_0)) \right] \quad (13)$$

where  $T$  and  $b$  are given in Eq. (8), and

$$x = \alpha/T, \quad x_0 = \alpha/T_0, \quad \text{and} \quad x_w = \alpha/T_w \quad (14)$$

The function  $G$  is defined as

$$G(x) = \frac{e^{-x}}{7x} \left[ \frac{1}{(4)6!} - \frac{1}{(4)6!x} + \frac{1}{(2)6!x^2} - \frac{1}{(4)5!x^3} - \frac{17}{60x^4} + \frac{1}{4x^5} - \frac{1}{3x^6} \right] + \frac{E_1(x)}{24} \left[ -\frac{1}{(7)5!} + \frac{1}{x^4} \right] + \frac{E_4(x_w)}{4x_w^3} \frac{1}{x^4} \quad (15)$$

where

$$E_n(x) = \int_1^\infty \frac{e^{-xt}}{t^n} dt \quad (n = 0, 1, \dots; x > 0) \quad (16)$$

is a well-known exponential integral whose values are tabulated in common mathematical handbooks (e.g., Ref. 6).

It should be noted that Eq. (11), hence Eq. (13), only applies to the early stage of the diffusion-controlled outgassing process. The duration of this period, for double-aluminized Mylar, is roughly 1.5 hr following the period for the fast removal of the loosely bound adsorbed gas molecules which lasts about 10 min after evacuation.<sup>1</sup> As two identical insulation materials with the same preconditioning process contain about the same amount of adsorbed and absorbed gases, the one which outgases more in the early stage must have a smaller outgassing rate at later times. Thus, when an insulation composite with a temperature distribution is evacuated, the outgassing rate first increases with the temperature, and after a few minutes when all loosely bound gas particles are removed, Eq. (11) assumes the role in relating  $Q$  and  $T$ . As time goes on, however, the outgassing rate will eventually decrease with increasing temperature and the validity of Eqs. (11) and (13) ends. At such times, one must find another expression for  $q$  as function of  $T$ , and go back to Eq. (10) to compute the pressure.

### III. Numerical Examples

Since nonisothermal outgassing data are only available for double-aluminized Mylars (DAM), numerical examples for the computation of pressure distribution will therefore be given for the MLI composites having DAM as radiation shields. Experimental data for the outgassing rates of the off-shelf DAM at different temperatures at 40 min of the pumping time, typical outgassing stage when Eq. (12) applies, are given in Ref. 1. From these data, the values of the two constants appearing in Eq. (12) are evaluated in the c.g.s. system as  $s = 2.04 \times 10^4$  dynes/cm-sec and  $\alpha = 3600$  K.

Outgassing experiments on a number of spacer materials have shown that, with only simple preconditioning process, Dacron net B4A exhibits essentially no outgassing.<sup>3</sup> If no interaction effect on outgassing exists between DAM and Dacron net B4A, insulation composites consisting of alternate layers of these two materials (DAM/B4A) will have the same outgassing rates as those of DAM. This assumption is made here.

When the value of  $x$  is in  $10 \leq x < \infty$ , the function  $E_1(x)$  in Eq. (15) can be approximated by the formula<sup>7</sup>

$$xe^x E_1(x) = \frac{x^2 + a_1 x + a_2}{x^2 + b_1 x + b_2} + \varepsilon(x) \quad (17)$$

with  $a_1 = 4.03640$ ,  $a_2 = 1.15198$ ,  $b_1 = 5.03637$ , and  $b_2 = 4.19160$ . The magnitude of the remainder in Eq. (17) is  $|\varepsilon(x)| < 10^{-7}$ , which is small enough to give satisfactory accuracy for our computation.<sup>8</sup> Approximation formulas for  $E_1(x)$  when  $x$  is in  $[0, 1]$  and  $[1, \infty)$  are available in the literature.<sup>6</sup> Furthermore, when  $x_w$  is considerably larger than  $x_0$ , the term involving  $E_4(x_w)$  can be dropped from Eq. (15) without introducing appreciable error to the solution for the pressure.

Computation for the pressure distribution in the DAM/B4A composites consisting of a variety of number of layer pairs has been made with water vapor as the outgas material. The ambient and wall temperatures and the perforation coefficient were given as  $T_0 = 300$  K,  $T_w = 20$  K (roughly the liquid hydrogen temperature), and  $c = 0.015$ . The results are shown in Fig. 1, where  $p$  is plotted against  $l/L$ , so that the solutions for several composites can be conveniently presented in one diagram.

<sup>8</sup> The requirement of the accuracy of the  $E_1(x)$  values depends mainly on the number  $L$ . Larger  $L$  requires better  $E_1$  values. Comparison with results obtained from using more accurate  $E_1$  values shows that Eq. (17) is not adequate for the pressures in the first one or two interstices when  $L = 80$  and 100, while results from the third layer on are still good. Thus, better approximation formula or more accurate interpolation from the tabulated  $E_1$  values in Ref. 6 is required for cases when  $L > 100$ .

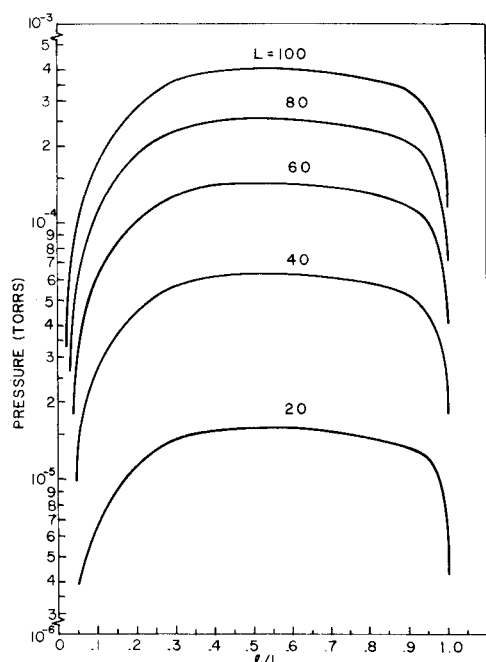


Fig. 1 Pressure distribution in the DAM/B4A composites at 40 min of pumping time ( $T_o = 300$  K,  $T_w = 20$  K,  $c = 0.015$ ).

It can be seen from Fig. 1 that the pressure increases with the total number of layers of the MLI. For a fixed  $L$ , the pressure first increases from the vacuum ambient towards the inner layers, reaches a maximum, then decreases towards the wall. This is because the temperature decreases rapidly near the wall. With the same boundary conditions, results for other values of  $c$  can be obtained from Fig. 1 by the multiplication factor  $[0.015/(1-0.015)](1-c)/c$ .

Since the temperature drops rapidly only near the wall, the maximum pressure in an MLI depends only weakly on  $T_w$ . Thus, the maximum pressures shown in Fig. 1 remain roughly the same for the liquid oxygen tanks with a wall temperature of 100 K. Experimental measurements of pressure in a non-isothermal MLI are not available for comparison.

#### IV. Conclusions

The solution for the outgas dominated pressure distribution in a DAM/B4A multilayer insulation system given by Eq. (13) only applies to the early stage of the diffusion phase of outgassing. However, this stage represents a rather important period of time as the outgassing rate in this period is large, resulting in a high pressure inside the insulation composite. Thus, the pressure prevailing in the MLI in this period can be used as a reference regarding the thermal performance of the insulation composite. At later times when the validity of Eq. (12) no longer holds, further computation of the pressure distribution, if necessary, must be obtained from Eq. (10) by using other realistic  $q-T$  relations. As the relaxation time of the gases in the MLI usually is short,<sup>2</sup> the system can be considered "quasi-steady." By using the outgassing rate and boundary conditions at any given time, the problem can be solved as time independent. The solutions for a chosen sequence of time then constitute the solution as function of the time.

The cryopumping effect of the very cold layers near the wall has not been included in this analysis. It should be noted that when cryopumping occurs, the number density decreases near the wall, and the maximum pressure in the MLI is lower than that computed from the present method.

The numerical examples presented are for the MLI composites using double-aluminized Mylars for radiation shields with Dacron net B4A as spacers, as the  $q-T$  data for these composites are better known. Since the outgassing rate is a rapidly decreasing function of the time, it can be seen from Fig. 1

that all the composites considered are adequate for long-term space missions. However, from previous experience of Apollo flights, it was learned that aluminized Mylars could not stand moisture and high temperature (considerably exceeding the room temperature). For such environments, goldized Kapton is more suitable for radiation shields.<sup>3</sup> Therefore, further experimental study of the outgassing rates of this and other potential candidate materials is desirable.

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## Debris Shielding during High-Speed Erosion

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#### Nomenclature

- $B$  = dimensionless empirical constant  
 $C_d$  = debris particle drag coefficient  
 $G$  = ratio of mass eroded to rain mass encountered; the mass loss ratio  $m/M$   
 $G_o$  = ratio of mass eroded to rain mass reaching surface  
 $G'$  = drop mass loss ratio  
 $L$  = rain field length  
 $M$  = total mass encountered  
 $m$  = mass eroded  
 $R$  = body radius  
 $r$  = drop radius  
 $r'$  = debris particle radius  
 $U$  = debris efflux speed  
 $u$  = body speed  
 $u'$  = air speed over body  
 $w$  = rain-field concentration  
 $x$  = distance along body from stagnation point  
 $\delta$  = debris layer thickness  
 $\epsilon$  = density ratio  
 $\eta$  = modified debris shielding parameter  
 $\eta'$  = debris shielding parameter  
 $\rho$  = ambient air density

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