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GEORGE C. MARSHALL SPACE FLIGHT CENTER

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GAS IN MULTILAYER THERMAL INSULATION

By

Billy P. Jones

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ABSTRACT

A review is made of the effects of gas in the multilayer thermal insulation currently considered for applications in cryogenics. Some of the results from A. G. Emslie's ([4], NAS 5-664) analysis is presented and interpreted by comparison with data on outgassing and gas diffusion obtained from various sources. The steady-state pumping of the natural space vacuum is included for the cases of edge pumping of panels of stacked foils and for perforated stacked foils. The related transient pumping problem is not examined.

It is found for these conditions that diffusion of hydrogen through the tank wall is not a problem at temperatures near that of liquid hydrogen. The effects on the diffusion susceptibility of the tank walls after exposure to radiation from on-board nuclear reactors are not considered. Gassing from the foils or other materials imbedded in the foils can be a serious problem. Leaks into the foils cannot be permitted. Procedures for degassing the insulation prior to launch should be investigated and the transient space pumping problem should be studied.

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RESEARCH PROJECTS DIVISION

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SUMMARY

A review is made of the effects of gas in the multilayer thermal insulation currently considered for applications in cryogenics. Some of the results from A. G. Emslie's ([4], NAS 5-664) analysis is presented and interpreted by comparison with data on outgassing and gas diffusion obtained from various sources. The steady-state pumping of the natural space vacuum is included for the cases of edge pumping of panels of stacked foils and for perforated stacked foils. The related transient pumping problem is not examined.

It is found for these conditions that diffusion of hydrogen through the tank wall is not a problem at temperatures near that of liquid hydrogen. The effects on the diffusion susceptibility of the tank walls after exposure to radiation from on-board nuclear reactors are not considered. Gassing from the foils or other materials imbedded in the foils can be a serious problem. Leaks into the foils cannot be permitted. Procedures for degassing the insulation prior to launch should be investigated and the transient space pumping problem should be studied.

INTRODUCTION

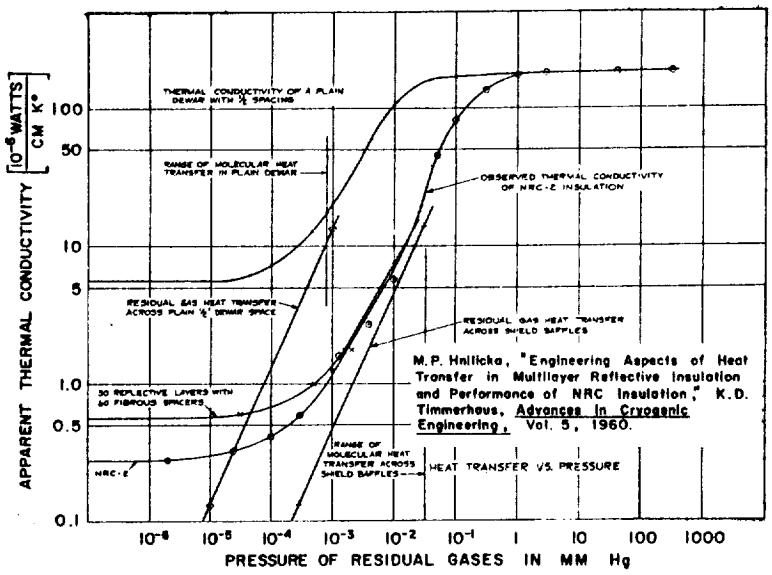
The effective conductivity of multilayer insulations shows a marked change as a function of the gas pressure between the layers at about 10^{-4} mm Hg. This is evidenced by FIGURE 1 [1, 2, 3]. For a gas at 25°K, a pressure of 1.4×10^{-4} mm Hg corresponds to a gas density of 6×10^{3} molecules per cubic centimeter. This represents a gas density at which the number of foils is such that the transfer by radiation is equal to the transfer by the gas [4]. Sources of gas can be leaks from the tank or plumbing, residual gas in the foil, gassing from materials unstable in vacuum which are imbedded in the insulation, and diffusion of hydrogen through the tank wall.

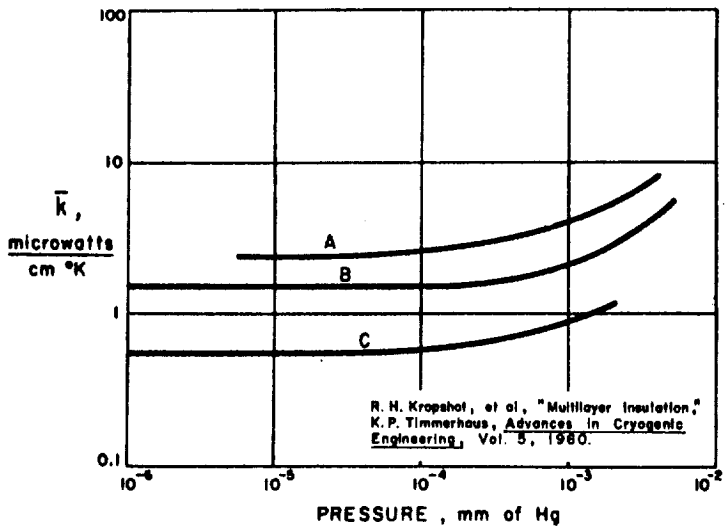
NATURAL PUMPING EFFECTS

Gas caught between layers of the insulation might escape by diffusion through the foil layers, holes through the foil, or at the edges of panels of the stacked foils. As can be seen later from data on diffusion from the tank, diffusion through several layers of foils is negligible. The other two means of gas removal have been examined by Emslie [4] and the results will be summarized here.

The analysis for gas escape through panel edges is made for the steady state case of outgassing. A maximum allowable outgassing rate, ν, is estimated to be 8×10^{8} molecules cm^{-2} sec^{-1} to maintain a pressure less than 10^{-5} mm Hg at 25°K. This assumes as typical a panel 1 meter wide composed of foils 0.002 cm thick and stacked 40 to the cm, with spacers that occupy effectively 90% of the spaces between foils. The relation used is

$$\nu = \frac{\pi \bar{c}\, a^2}{\ell^2} \cdot N_{max} \qquad (1)$$





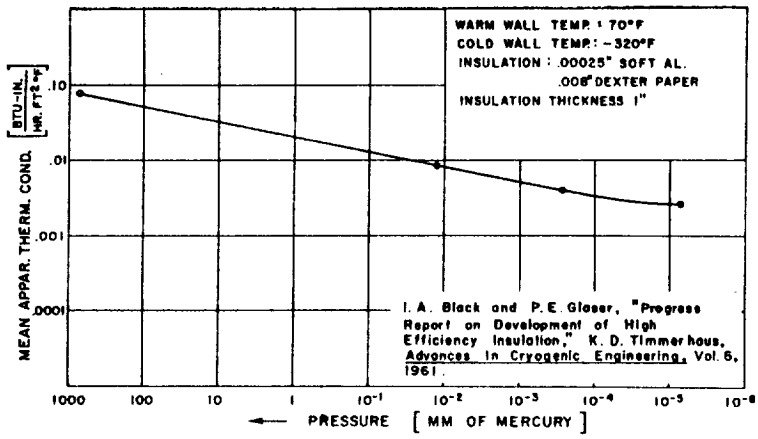


FIGURE 1. APPARENT THERMAL CONDUCTANCE AS FUNCTION OF GAS PRESSURE FOR MULTI-LAYER INSULATION

where

$\bar{c}$ = average molecule velocity, cm sec^{-1}

a = effective foil separation distance, cm

= width of panel strip, cm

N_{max} = molecule density at the center of the strip corresponding to some pressure and temperature, molecules cm^{-3}.

The analysis for gas escape through perforations in the foil is also made for the steady-state outgassing case. A maximum allowable outgassing rate, ν , is estimated to be 3×10^{11} molecules $cm^{-2} sec^{-1}$ to maintain a pressure less than 10^{-5} mm Hg at 25 °K. This assumes 100 foils with a perforation coefficient of 10%. The relation in this case is

$$\nu = \frac{c}{4} \frac{\tau}{1-\tau} n^2 \cdot N_{max} \tag{2}$$

where

τ = ratio of area perforated to total surface area

n = number of foil layers.

Holes in the insulation increase the heat transfer by radiation while decreasing that transferred by the gas. Thus, an optimum perforation should exist to minimize the net over-all energy transfer. The equation for the total flux through the perforated insulation is

$$q = \frac{\sigma (T_2^4 - T_1^4)}{\left(\frac{2}{\varepsilon} - 1\right) \cdot n} + \frac{2}{2-\varepsilon} \sigma (T_2^4 - T_1^4) \frac{\tau}{(1-\tau) n} + \frac{3}{2} \nu k (T_2 - T_1) \frac{(1-\tau)n}{\tau} \tag{3}$$

where

T_2 ; T_1 = temperature of outermost and innermost foil, respectively, °K

σ = Stefan-Boltzmann radiation constant, 5.672×10^{-5} erg cm^{-2} sec^{-1} deg^{-1}

ε = emissivity of foil

k = Boltzmann constant, 1.38×10^{-16} erg deg^{-1}

In order for q to be a minimum in the above equation, it is necessary that $\frac{\partial q}{\partial \tau}$ equal zero. If the operation is performed, the following equation is obtained:

$$\frac{1-\tau}{\tau} = \frac{1}{n}\left[\frac{\left(\frac{2}{2-\varepsilon}\right)\sigma\,(T_2^4 - T_1^4)}{\frac{3}{2}\,\nu\,k\,(T_2 - T_1)}\right]^{\frac{1}{2}} \tag{4}$$

If the values $T_2 = 300°K$, $T_1 = 25°K$, $\varepsilon = 0.05$ and an allowable $\nu = 10^{10}$ molecules cm^{-2} sec^{-1} are assumed, the relation between n and τ is obtained. Using this relation and the data on insulation given in [5], Table 1 is constructed. The results are plotted in FIGURES 2 and 3, with insulation thickness as a function of optimum perforation.

OUTGASSING

If Eq. (4) is substituted into Eq. (3), the expression for minimum q thus obtained is [4]:

$$q_{min}(n) = \frac{\sigma\,(T_2^4 - T_1^4)}{\left(\frac{2}{\varepsilon} - 1\right)n} + \left[6\,\nu k\,(T_2 - T_1)\,\sigma\,(T_2^4 - T_1^4)\left(\frac{2}{2-\varepsilon}\right)\right]^{\frac{1}{2}}. \tag{5}$$

As n approaches infinity, the first term approaches zero. On this basis, Emslie gives the data in Table II.

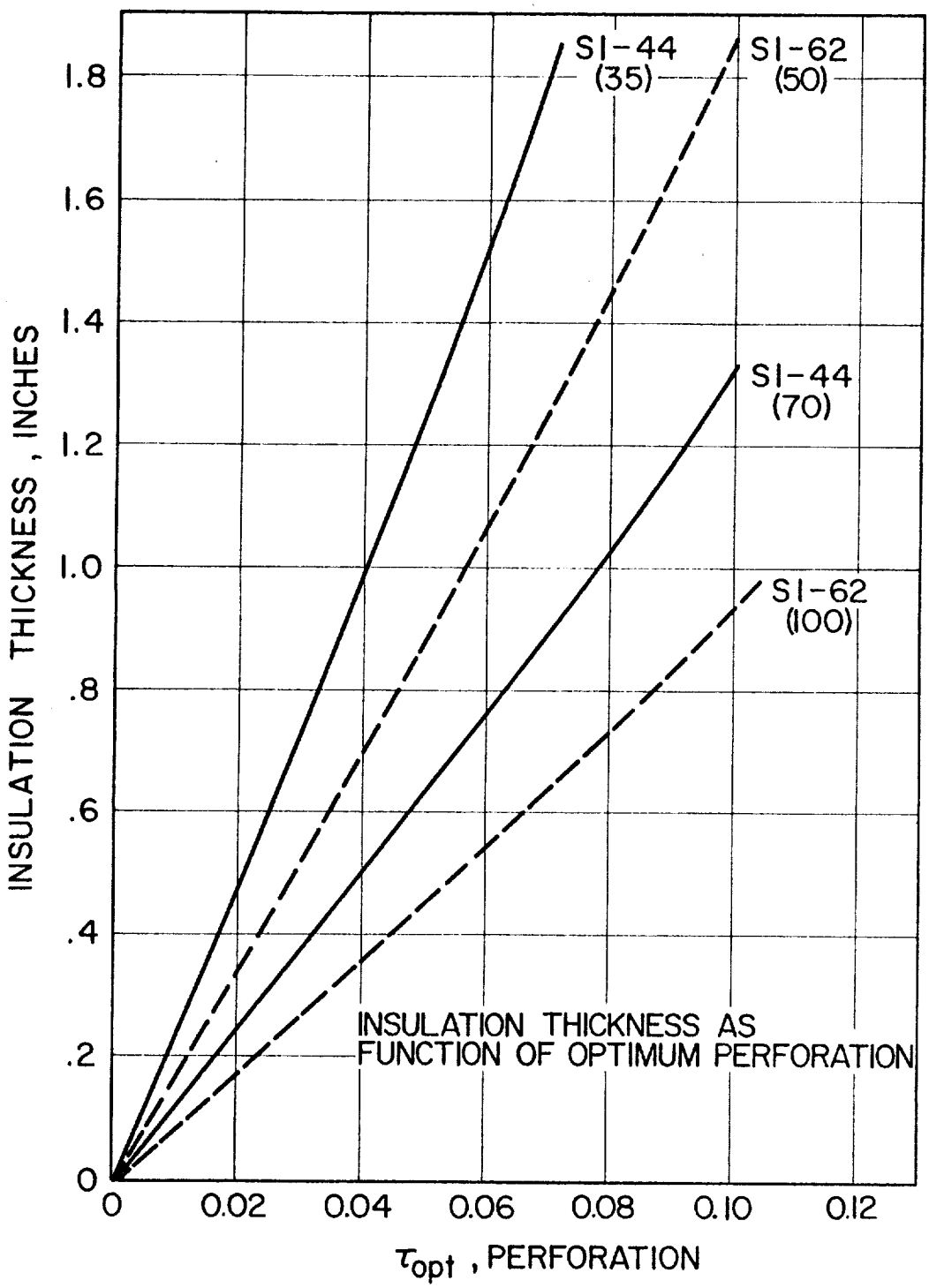


FIGURE 2. OPTIMUM FOIL PERFORATION WITH RESPECT TO NET OVER-ALL HEAT TRANSFER

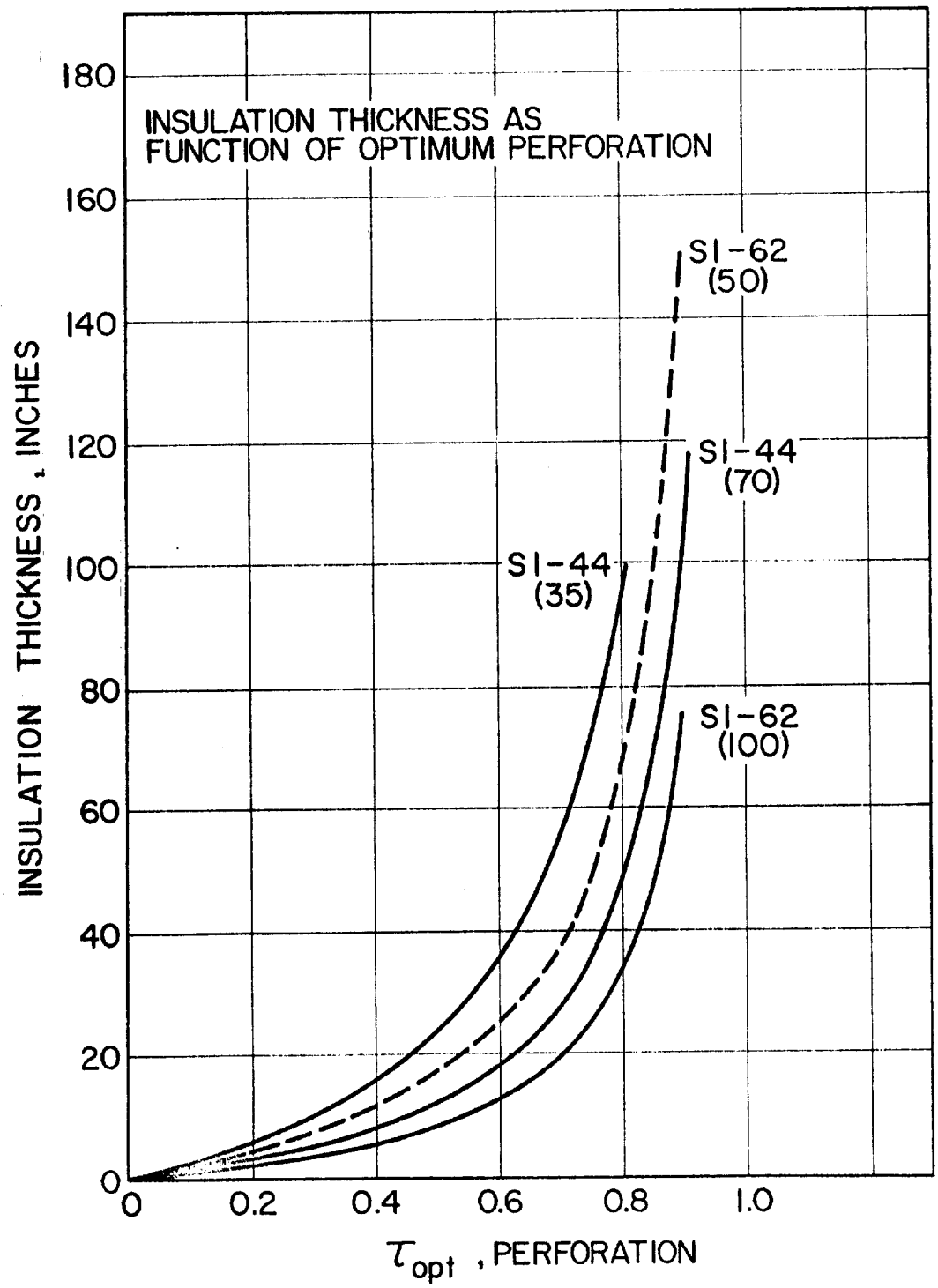


FIGURE 3. OPTIMUM FOIL PERFORATION WITH RESPECT TO NET OVER-ALL HEAT TRANSFER

TABLE I

Optimum Perforation as Function of Insulation Thickness

τ	n	SI-44		SI-62	
		min.	max.	min.	max.
0.01	8.5	0.243	0.122	0.170	0.085
0.02	17.1	0.488	0.244	0.342	0.171
0.03	26.0	0.743	0.372	0.520	0.260
0.04	35.0	1.00	0.500	0.700	0.350
0.05	44.2	1.26	0.630	0.884	0.442
0.06	53.7	1.53	0.767	1.074	0.537
0.07	63.3	1.81	0.905	1.266	0.633
0.08	73.1	2.09	1.05	1.462	0.731
0.09	83.1	2.37	1.18	1.662	0.831
0.10	93.4	2.66	1.33	1.868	0.934
0.20	210	6.00	3.00	4.20	2.10
0.30	360	10.0	5.00	7.20	3.60
0.40	560	16.0	8.00	11.20	5.60

Table II

Minimum Heat Flux as a Function of Outgassing Rate

ν (molecules cm^{-2} sec^{-1})	$q_{min}(\infty)$ (erg cm^{-2} sec^{-1})
10^{10}	33
10^{11}	105
10^{12}	330
10^{13}	1050

Available experimental data on the outgassing of various materials have been collected recently by Dayton [6] for use in analyzing requirements for vacuum equipment speed and chamber size relations. The data for aluminum are given in Table III.

Table III

Outgassing from Aluminum

Material (25°C)	$10^7 K_1$*	$10^7 K_4$	$10^7 K_{10}$
Aluminum	15	3.7	—
Aluminum, bright rolled (cleaned in Stergene)	—	0.22	0.075
Aluminum, anodized	—	3.6	1.1

*K_h= air equivalent outgassing rate after h hours pumping, Torr-liter sec^{-1} cm^{-2}. Using this data the gassing rate, ν, is shown in Table IV with the corresponding minimum heat flux rate.

Table IV

Aluminum Outgassing Rate and Minimum Heat Flux

10^7K	ν , molecules cm^{-2} sec^{-1}	$q_{min}(\infty)$, erg cm^{-2} sec^{-1}
0.075	2.4×10^{11}	160
0.22	0.72×10^{12}	280
3.7	1.2×10^{13}	1150
15	4.8×10^{13}	2290

DIFFUSION THROUGH TANK WALL*

Emslie [4] also derives the equation for the total heat flux through perforated insulation that is subject to a steady diffusion of molecules through the tank wall. The equation is the same as Eq. (3), except for the last term which is replaced by $(3/2)\nu_o k\,(T_2 - T_1)(1/\tau)$; the resulting expression for optimum perforation is the same as Eq. (4) except that the factor $1/n$ is replaced by $\left(1/n\right)^{1/2}$. The minimum total heat flux in the case of diffusion from the tank then becomes

$$q_{min}(n) = \frac{\sigma(T_2^4 - T_1^4)}{\left(\frac{2}{\varepsilon} - 1\right) n} + \frac{3}{2}\,\nu_o k\,(T_2 - T_1) + \left[6\,\nu_o k\,(T_2 - T_1)\,\sigma(T_2^4 - T_1^4)\left(\frac{2}{2-\varepsilon}\right)\frac{1}{n}\right]^{\frac{1}{2}}. \qquad (6)$$

For $\varepsilon = 0.05$; $n = 100$, $T_2 = 300°K$; $T_1 = 25°K$, and an area equivalent to the cylindrical portion of one version of the S-IVB fuel tank, Table V is constructed.

* The effects on the diffusion susceptibility of the tank walls after exposure to radiation from on-board nuclear reactors are not considered.

Table V

Minimum Heat Flux as Function of Diffusion Rate

ν_o (molecules cm^{-2} sec^{-1})	$q_{min}(100)$ (erg cm^{-2} sec^{-1})	q_{min} S-IV B Fuel Tank (watts)
10^{11}*	130	241
10^{12}	150	278
10^{13}	220	408
10^{14}	450	835
10^{15}	1200	2226
10^{16}	4000	7420

* 1 kg/yr for an area of $1.855 \times 10^7 cm^2$ is equivalent to 5.11×10^{11} molecules cm^{-2} sec^{-1}. That is, S-IV B could allow not more than 1 kg/yr, on this basis.

The simplest equation accepted as describing the rate that a gas passes from one side of a metal to the other is (7):

$$d = \frac{k_o}{\ell} \cdot P^{\frac{1}{2}} \cdot e^{b_o/T}, \qquad (7)$$

where

d = diffusion rate, (atm · cm^3) cm^{-2} sec^{-1}

k_o, b_o = constants for gas - metal system

ℓ = metal thickness, mm

P = gas pressure, mm Hg

T = temperature, °K

Dushman gives $b_o = \frac{E_o}{2R_o}$, where E_o is the heat of diffusion, cal mole^{-1}, [8]. The heat of diffusion for a 300-series stainless steel is 38,000 cal mole^{-1} and the value for k_o is 10^{-2} for nickel (value for stainless steel is not available) which is considered to be a little high, as given in the Hydrogen Handbook [9]. Using these data as a basis, the second column of Table VI resulted for a pressure of 1 atmosphere. The third column is obtained by converting units and using a pressure of 3 atmospheres.

Table VI

Diffusion of Hydrogen Gas Through 300-Series Stainless Steel

T (°K)	Diffusion Rate, 1 atm (gm-moles/yr-cm²/mm)	Diffusion Rate, 3 atm* (molecules/cm²-sec/mm)
21	9.76×10^{-196}	3.23×10^{-179}
100	1.23×10^{-39}	4.09×10^{-23}
200	6.91×10^{-19}	2.28×10^{-2}
300	5.75×10^{-12}	1.90×10^{5}
373	2.82×10^{-9}	9.33×10^{7}

* The $\sqrt{P}$ relation holds for $P \geq 1$ atm.

Experimental data taken by MSFC at 300°K for the diffusion of hydrogen through several materials are given in Table VII (converted to 3 atm. pressure differential [10]).

Table VII

Diffusion of Hydrogen Through Several Tank Materials

Material	Diffusion Rate, 3 atm. (molecules $cm^2 \cdot sec^{-1} mm^{-1}$)
Nickel	6.64×10^6
301-SS	1.22×10^6
Aluminum	1.01×10^6
302-SS	1.01×10^6

The above data on diffusion assume a smooth tank wall and do not apply for local joints and welds. In the case of welds, it is likely that the diffusion would be different due to modifications of the crystal structure, increased imperfections in the structure and increase in impurities due to the welding process. All of these effects tend to increase diffusion. The welds could be an additional source of both outgassing and diffusion.

CONCLUSIONS

On the basis of the above data and analysis it appears that:

(1) Diffusion of hydrogen through the tank wall will not be a problem at temperatures near that of liquid hydrogen.

(2) Gassing of the foils can be a serious problem if the insulation is not evacuated prior to launch. However, the analysis here was for the steady-state case. The transient problem is still not thoroughly analyzed.

(3) Materials that gas profusely, such as some plastics and organic materials should not be installed in such a way that the gas escapes into the multilayer insulation.

(4) Direct leaks into the insulation should be eliminated.

(5) Procedures for degassing the insulation prior to launch should be investigated, if use of the multilayer insulation is contemplated.

(6) Data on gassing of the various insulations should be obtained.

(7) The theory of gassing in vacuum and of the diffusion of gases through solids needs to be extended.

(8) Localized diffusion and gassing of welds should be considered in further investigations.

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Officer. This report, in its entirety has been determined to be unclassified.

Gerhard Heller
for ERNST STUHLINGER
Director, Research Projects Division

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