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THE PERFORMANCE OF MULTILAYER INSULATION IN A RAPIDLY DEPRESSURIZING ENVIRONMENT*

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ABSTRACT

The performance of multilayer insulation in a rapidly depressurizing environment is determined by the variation of heat transfer with internal pressure and the pressure history of the interstitial gas. Measurements of thermal performance were made on three multilayer insulation configurations at room temperature and steady-state pressures form 10^{-6} to 10^{-1} torr. The heat transfer due to gas conduction alone correlated with the kinetic theory of gases in the molecular flow regime. Pressure histories were measured in a unique apparatus which simulated the depressurization rate of a boost vehicle. The pressure histories on both sides of two of the configurations were measured to bound the actual interstitial pressure. The results of the two types of measurements agreed with earlier work and were combined to make performance predictions using an actual ascent pressure history.

INTRODUCTION

The performance of multilayer insulation (MLI) in a rapidly depresssurizing environment is of interest in some ballistic missile applications. This performance is determined by the variation of heat transfer with internal pressure and the pressure history of the interstitial gas. If both of these relationships are known, the insulation performance can be predicted for all times. The objectives of this study were to quantify the pressure dependence and determine pressure histories of some typical MLI configurations.

Thermal conductivity and effective emissivity are measures of the rate of heat transfer through a material. At low internal pressures, heat is transferred through MLI by a combination of radiation between adjacent layers and conduction through material contact points. At higher internal pressures, heat is also conducted by molecular collisions with the layers. To determine the contribution due to gas conduction alone, the heat transfer rates through three multilayer configurations were measured at room temperature, at a series of steady-state pressures between 10^{-6} and 10^{-1} torr. A ten layer, a four layer, and a two layer configuration were investigated.

To determine the pressure history of the interstitial gas in broadside venting MLI, the ascent pressure history of a boost vehicle was simulated. The pressures on both sides of the MLI were measured during the rapid depressurization of one side. The actual interstitial pressure was thus bounded by the two measured pressures. The ten layer and four layer blankets were investigated, and pressures between atmospheric and 10^{-6} torr were recorded.

After a brief comparison of the measures of thermal performance, the kinetic theory of gas conduction in the molecular flow regime will be presented. The two types of measurements performed will then be described. Finally, some predictions of MLI performance will be made using an actual ascent pressure history.

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HEAT TRANSFER THEORY

THERMAL PERFORMANCE

The performance of MLI can be expressed in three ways, each of which has advantages and disadvantages. If the sample configuration and boundary conditions are known, each can be calculated from the other.

The effective thermal conductivity (k_{eff}) between parallel plates is defined in terms of the total heat flux (Q/A), whose units are power per unit area, as

$$k_{eff} = (Q/A)\, t \,/\, (T_H - T_C)$$

where t is the thickness of the sample and T_H and T_C are the hot and cold boundary temperatures respectively. Effective thermal conductivity has the same units as, and therefore is comparable to, the thermal conductivity of other insulations and materials. However, the thickness of the sample must be known accurately and the thickness of MLI is usually variable. This parameter is useful for comparing materials whose properties vary linearly with thickness but it does not take into account the fourth-power dependence on temperature of radiation heat transfer. Effective thermal conductivity was used originally by the cryogenic industry in the comparison of MLI with similar boundary temperatures.

The effective heat transfer coefficient (h_{eff}) is simply the effective thermal conductivity per unit thickness.

$$h_{eff} = (Q/A) \,/\, (T_H - T_C)$$

This parameter has the units of a heat transfer coefficient and has the advantage of not depending explicitly on material thickness. It should be used for comparing materials of equal thickness or, in the case of MLI, equal numbers of layers.

Since the number of applications for MLI at different boundary temperatures has increased, effective emissivity (ε_{eff}) has been used for performance comparison[1]. It is defined as

$$\varepsilon_{eff} = (Q/A) \,/\, \sigma\, (T_H^4 - T_C^4)$$

where σ is the Stefan-Boltzmann constant. Effective emissivity includes the temperature variation of radiant heat transfer and should be used to compare configurations with dissimilar boundary temperatures and the same thickness or number of layers. It should be noted that at higher internal pressures, effective emissivity can be greater than one, and its use is therefore more appropriate at lower pressures. In keeping with the current trend, and to avoid explicit use of material thickness, effective emissivity will be used here.

PRESSURE DEPENDENCE

The pressure dependence of MLI thermal performance is determined by the variation with pressure of the total heat transfer through the insulation. Under high vacuum, below 10^{-6} torr, heat is transferred by a combination of solid conduction ($(Q/A)_{sc}$) and radiation ($(Q/A)_{rad}$). At higher internal pressures, heat is also conducted by molecular collisions ($(Q/A)_{gc}$) with the layers. The total heat transferred is the sum of the heat transferred by each of these three modes.

$$Q/A = (Q/A)_{sc} + (Q/A)_{rad} + (Q/A)_{gc}$$

For given boundary temperatures, the amount of heat conducted through material contact points has been assumed to be constant, independent of the pressure of the interstitial gas. The amount of heat radiated between adjacent layers was also assumed to be constant for given boundary temperatures. This assumption is valid because the change in radiative heat flux resulting from a change in the layer temperature profile would be much smaller than the heat flux causing the change in the temperature profile. The pressure dependence of the thermal performance is therefore entirely due to the variation of gas conduction.

When the mean free path of the gas molecules is greater than the characteristic dimensions of the configuration, the gas is characterized by molecular flow. In a ten layer blanket 2.5 mm thick, the distance between radiation shields is about .25 mm. The mean free path of an air molecule is greater than this dimension for any pressure less than .2 torr. For a two layer configuration of the same thickness, the onset of the transition to continuum flow occurs at .02 torr. Therefore, the flow was assumed to be in the molecular regime for the pressures investigated here.

GAS CONDUCTION

In the molecular flow regime, the heat transferred between two surfaces is expressed by Knudsen's theory of free molecular conduction[2].

$$(Q/A)_{gc} = \frac{1}{2}\,\frac{\alpha}{2-\alpha}\,\frac{\gamma+1}{\gamma-1}\left(\frac{R}{2\pi M T_C}\right)^{\frac{1}{2}} P\,\Delta T$$

where α is the accommodation coefficient of the surfaces
γ is the ratio of specific heats at constant pressure and volume
R is the universal gas constant
M is the molecular weight of the air
P is the pressure of the interstitial gas
and ΔT is the temperature difference between the two surfaces. The accommodation coefficient was taken to be an average value of .9 [2,3,4].

The temperature difference used to calculate this heat flux is the temperature difference between two adjacent surfaces. It is related to the total temperature difference between the hot and cold boundary surfaces by the number of surface pairs (n), or spaces, between the boundary surfaces. Simply dividing the total temperature difference by the number of spaces in between,

$$\Delta T = (T_H - T_C)/n$$

assumes a linear temperature profile, which is sufficiently accurate to first order. This illustrates the effect of layers as barriers to molecular flow.

For the ten layer blanket tested, the number of spaces was taken to be 9 plus 1 additional space on top, between the blanket and a temperature controlled surface. Similarly, n was taken to be 4 for the four layer blanket. For the two layer configuration tested, the total temperature difference was used because each of the two layers was in contact with one of the temperature controlled surfaces.

A measurement of the heat flux under high vacuum represented a measure of radiation and solid conduction without a contribution from gas conduction. By measuring the heat flux at higher pressures, the theoretical pressure dependence of thermal conductivity could be verified.

EFFECTIVE EMISSIVITY MEASUREMENTS

PROCEDURE

The heat flux through samples of MLI was measured in a guarded hot-plate calorimeter mounted in a bell-jar vacuum system. The test setup is shown schematically in Figure 1. The main heater was held at about 40 C and the liquid cooled heat sinks at about 0 C so that the sample average was near room temperature. The temperature controlled surfaces were separated by small fiberglass spacers at three locations around the guard heater circumference.

The temperature of the guard heater was maintained within 2 C of the main heater temperature to minimize the heat leak in the radial direction. No extra guard heater was required around the test samples because the radiation leak to the room temperature surroundings was small. Two samples, of each configuration tested, and two heat sinks were used so that all power into the main heater flowed out axially through sample material. Hence, the area of the main heater and only half of the measured power to it were used in the calculation of effective emissivity. The samples tested were 20 cm in diameter, and the main heater was 10 cm in diameter.

To control the pressure, a provision for nitrogen gas to be introduced into the bell jar through a needle valve was included. By adjusting the gate valve to the vacuum pump and the needle valve controlling the nitrogen flow rate, any pressure above 7×10^{-6} torr could be maintained. An ionization vacuum gauge measured pressures below 4×10^{-2} torr.

Three MLI configurations were measured. The first was a ten layer blanket with mesh spacers. The layers were 8 micron thick Kapton* film, aluminized on both sides, perforated with 1.3 mm diameter holes which accounted for 2.2% of the area. The mesh consisted of pairs of 25 micron diameter Dacron* fibers in a 3 mm grid pattern. The blanket was approximately 2.5 mm thick so the temperature controlled surfaces were separated by 2.9 mm thick spacers.

The second configuration tested was a four layer blanket made of the same materials. It was approximately .9 mm thick, and 1.5 mm thick fiberglass spacers were used.

The third configuration consisted of two layers of 130 micron thick Kapton film, aluminized on one side, separated by the 2.9 mm spacers. The first layer was laid on the lower temperature controlled surface, aluminum side up, and the fiberglass spacers were placed around the edge. The second layer was then held in place by the upper temperature controlled surface, aluminum side down. The layer separation varied across the sample, but the aluminized surfaces did not touch at any point. Two samples of each configuration were assembled.

Each measurement required from 3 to 5 days to equilibrate in both pressure and temperature. This was due to the large outgassing surface area, low pumping speed, low powers, relatively large thermal masses, and low conductivities involved. Equilibrium was reached when the average boundary temperatures had not changed more than .1 C in four hours and the pressure had not changed more than 1/100 of the current decade. Measurements were made at a low pressure, increasingly higher pressures, intermediate pressures to check reproducibility, and finally the lowest pressure.

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*Kapton polyimide film and Dacron polyester fibers, manufactured by E. I. du Pont de Nemours & Co., Inc.

RESULTS

The effective emissivities at various pressures are shown in Figure 2 for the three configurations tested. The squares, triangles and circles represent measurements of the two, four and ten layer configurations respectively. Effective emissivities were calculated from measured heat fluxes and boundary temperatures. The curves were calculated by adding the heat flux given by the theory of free molecular gas conduction to the lowest measured heat flux, in each case, and then converting to effective emissivity. Thus, the theoretical curves are forced to fit the experimental data at their lowest points and the theory describes only the increase in heat transfer due to gas conduction.

DISCUSSION

The variation in performance with pressure of any multilayer configuration can be predicted given a value of effective emissivity at high vacuum. The effective emissivity in the absence of gas molecules is a measure of the heat transfer by radiation and solid conduction alone. The kinetic theory of gas conduction describes well the increase in heat transfer with increasing pressure.

This relationship is shown graphically in Figure 3 for the case of ten layer blankets. The effective emissivity as a function of pressure of the blanket tested, both experiment and theory, is shown along with the theoretical predictions for two hypothetical higher performance blankets. A configuration with higher performance has lower radiation and solid conduction heat transfer and a lower high-vacuum effective emissivity. The straight line is the effective emissivity resulting from gas conduction alone. The theoretical curves are simply the sum of this straight line and the various high-vacuum effective emissivities. As the interstitial gas pressure increases, gas conduction dominates radiation and solid conduction, and the performance of all ten layer blankets converge.

A comparison of these results with those found originally in reference 5, is shown in Figure 4. The circles are the present measurements of a ten layer blanket. The curves are equivalent emissivity calculated for a .25 cm thickness of two types of MLI from reference 5. The kinetic theory of gas conduction, the solid line, fits the present data better (for pressures above $2x10^{-3}$ torr where gas conduction dominates) than that of the earlier work.

A pressure of 10^{-4} torr or less is sufficient to ensure the minimum effective emissivity for any particular ten layer blanket. This is true for any practical configuration of ten layers. But, for the configuration tested, a pressure of about 10^{-3} torr is sufficient. This pressure is probably applicable to any easily attainable configuration of ten layers.

PRESSURE HISTORY MEASUREMENTS

PROCEDURE

The four and ten layer blankets described above were tested to determine the interstitial pressure as a function of time during broadside venting. A single sample was mounted in the stainless steel chamber shown schematically in Figure 5. The volume of this chamber, 8 liters, was minimized to make the vacuum pumping rate as fast as possible.

The blanket sample was mounted so as to divide the chamber into two volumes. The sample was clamped around the circumference with an aluminum ring as shown in Figure 5. The volume on one side, the pumped region, was evacuated in three stages: a carbon vane mechanical pump, a liquid nitrogen sorption pump, and the opening of an 18 cm diameter gate valve. The gate valve opened to a 40,000 liter vacuum chamber and its liquid helium cryogenic pump. The pressure in this large chamber was less than $2x10^{-6}$ torr at the start of each test run. The actual volume on the other side of the sample, the enclosed region, was 4 liters.

The pressures on both sides of the test sample were measured using thermocouple gauges and ionization vacuum gauges with 2.5 cm diameter inlet ports. These gauges were located as close as possible to the sample as shown in Figure 5. The pressures measured by the sets of gauges in each region tracked closely when the chamber was evacuated without any sample in place.

No clean-room procedures were followed when handling the sample materials. They were handled without gloves, in a normally humid environment, just prior to mounting in the test chamber. The test samples represented materials that may have been in storage for some time and that were handled without any particular precautions.

RESULTS AND DISCUSSION

Representative measured pressure histories are shown in Figure 6. The lower curves show the pressures measured in the pumped region outside the four or ten layer test blanket. The other curves are the corresponding pressures measured in the region enclosed by the sample blanket. The pressures measured on either side of the blanket bounded the actual interstitial pressure within the blanket, which would have had a gradient from layer to layer. The pressure measured in the enclosed region was thus higher than any pressure within the blanket. The tests were repeatable. The results shown in Figure 6 are similar to many other runs performed under similar conditions.

The pressure in the enclosed region was always higher than the pressure in the pumped region due to the presence of the blanket. Any delay in pressure change during the initial rapid depressurization was due to resistance to the flow of gas passing through the blanket from the enclosed region. Delays are evident in both of the cases shown in Figure 6. Delay times from 0 to 15 seconds were observed. The delay time is related to the conductance of the blanket.

In each test, the rate of depressurization slowed after about one minute. The pressure and the rate of pressure change in the enclosed region at this time, depended on the number of layers in the sample being tested. These are the effects of material outgassing and its dependence on surface area. In general, water vapor is the major contributor to outgassing[6] followed by contamination. These results agree with those of reference 7 in which pressures leveled out around 10^{-3} torr and material outgassing was indicated.

The results of three consecutive tests of the ten layer blanket are shown in Figure 7. The chamber was blackfilled with dry nitrogen between runs. The pressures shown were measured in the enclosed region. When repeated in succession, some residual water vapor and contaminants were removed and each test resulted in lower pressures. The apparent continuation of the same pressure profile, after initial rapid depressurization, indicates that outgassing limited the interstitial pressure.

When pumped overnight, the pressure in the region enclosed by the ten layer blanket dropped to the 10^{-5} torr range but was still one decade higher than that on the pumped side. This residual pressure could still be the effect of outgassing.

PERFORMANCE PREDICTIONS

The results of the two types of measurements were combined to predict the performance of a multilayer configuration in a rapidly depressurizing environment. It was assumed that the blanket performance measured at steady-state pressure would result at each time during a pressure transient. Also, the pressure history measured in the region enclosed by the test blanket was assumed to be a conservative estimate of the actual interstitial pressure. These two assumptions allow the blanket performance to be estimated as a function of time.

As an example, Figure 8 shows the actual ascent pressure history of a boost vehicle and the estimated interstitial pressure within a ten layer blanket during the first five minutes of flight. The maximum measured delay time of 15 seconds was applied down to 5×10^{-3} torr after which the pressure history of Figure 6 measured in the enclosed region was assumed.

Values of effective emissivity from the theoretical curve of Figure 2 were inserted for each pressure. The resulting predicted performance of the ten layer blanket is shown in Figure 9. The ultimate performance of the blanket is also indicated for comparison.

Once the pressure within the ten layer blanket reaches 10^{-3} torr, the effective emissivity will be within 15% of its ultimate value. This will occur in about five minutes. In the same time, the pressure inside the four layer blanket would have reached 2×10^{-4} torr and its performance would be within 5% of its ultimate.

CONCLUSIONS

The effective emissivity of a ten layer insulation blanket was found to be nearly constant up to 10^{-3} torr, a pressure higher than has been reported previously. The effective emissivity of a similar four layer blanket was nearly constant up to 10^{-4} torr. As pressure increases from high vacuum, insulation layers act not only as radiation shields but also as shields to molecular flow. The increase in heat transfer with increasing pressure correlated with the kinetic theory of gas conduction in the molecular flow regime. Therefore, the performance of a multilayer configuration at any pressure can be determined from the effective emissivity of the particular configuration under high vacuum.

The interstitial gas pressure inside each test configuration was bounded by measuring the pressures on both sides during the rapid depressurization of one side. The pressure inside the ten layer blanket was at most 10^{-3} torr after three minutes. The pressure inside the four layer blanket was less than 2×10^{-4} torr in the same time. The measurements indicated that outgassing, rather than restriction to flow, limits the performance of multilayer insulation. These results were combined with the measurements of effective emissivity to provide performance predictions. For example, on an actual boost vehicle, either of the multilayer blankets tested could attain within 15% of their ultimate performance in about five minutes.

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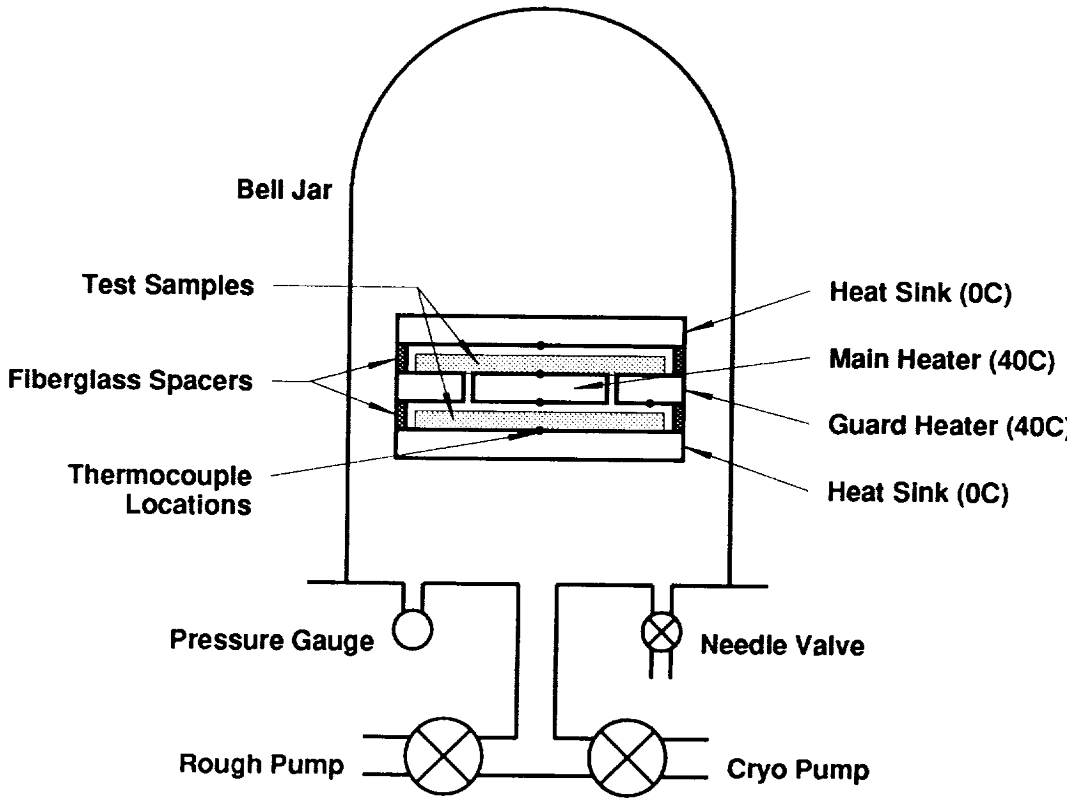

Figure 1. Guarded Hot Plate Calorimeter in Vacuum System

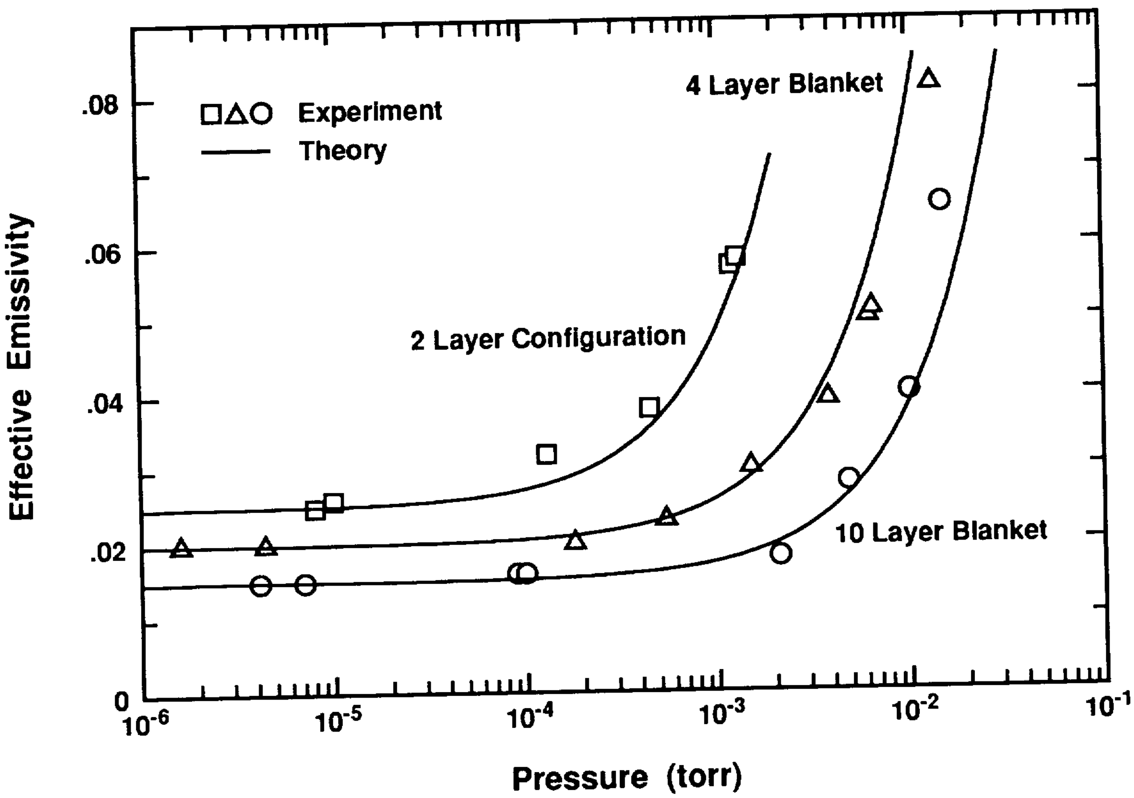

Figure 2. The Variation of Effective Emissivity with Pressure

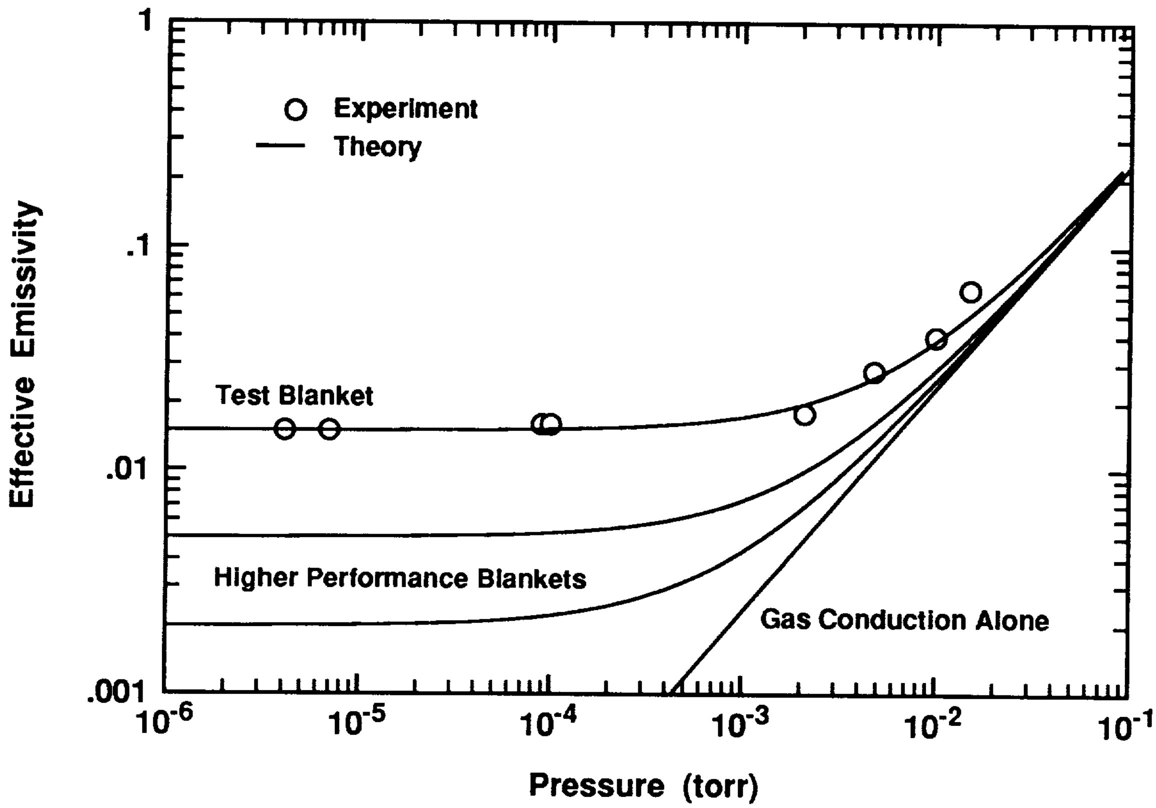

Figure 3. Ten Layer Blanket Performance With Gas Conduction

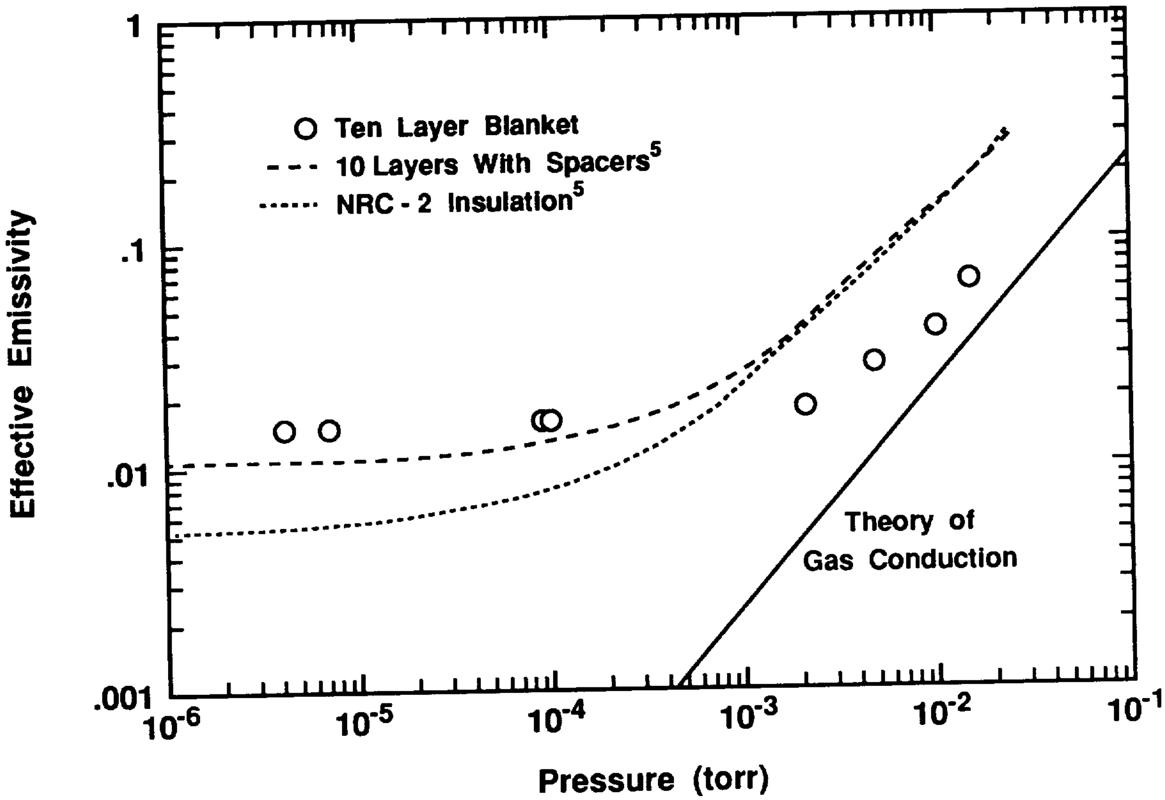

Figure 4. A Comparison of Blanket Performance.

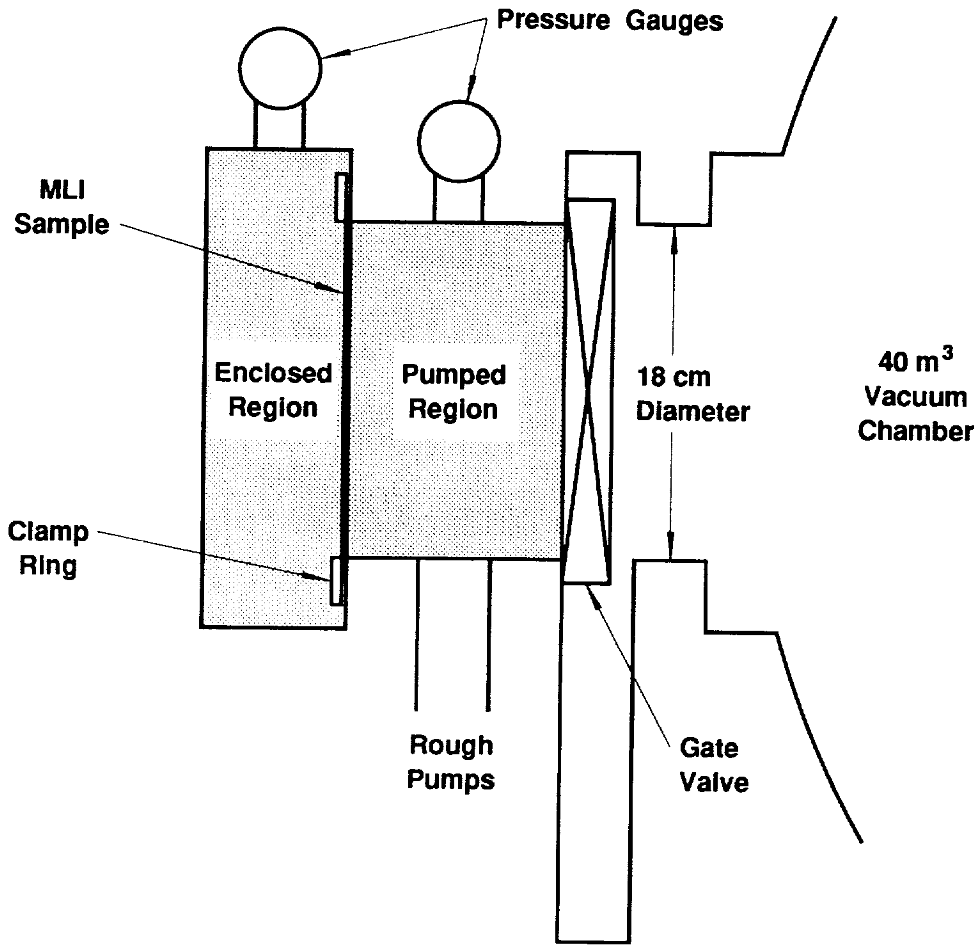

Figure 5. Pressure History Measurement Chamber

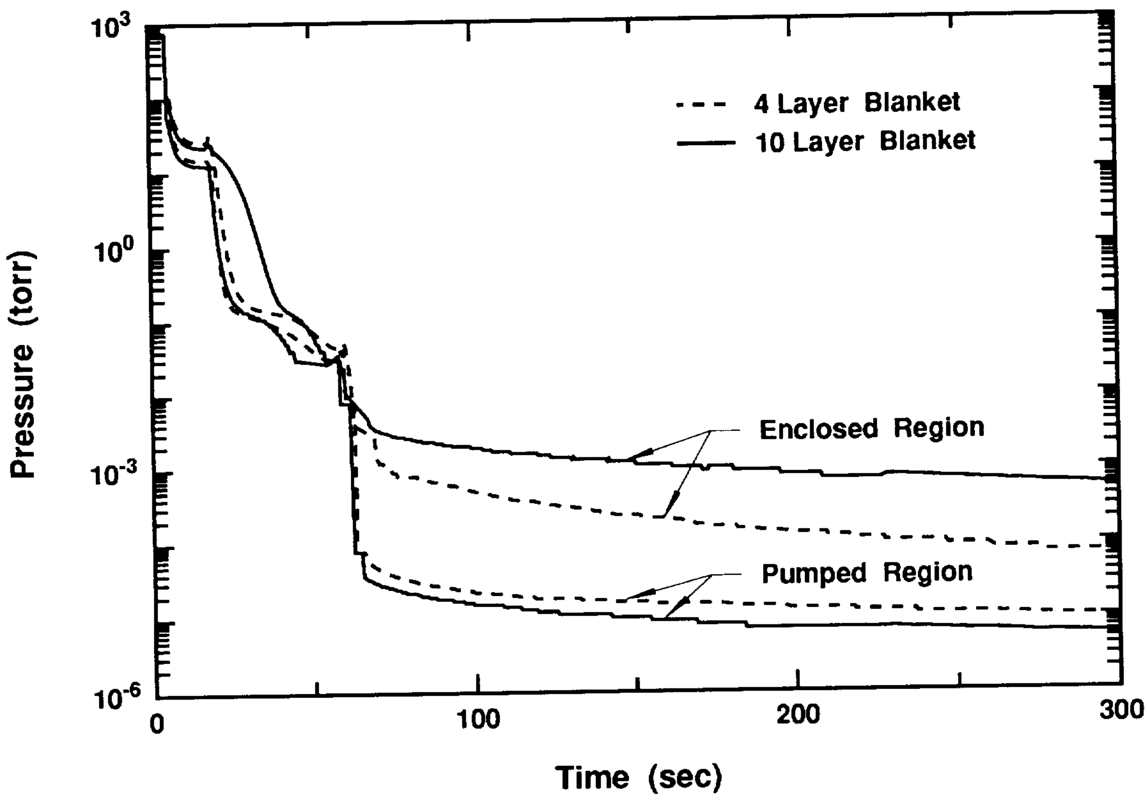

Figure 6. Measured Pressure Response During Rapid Depressurization

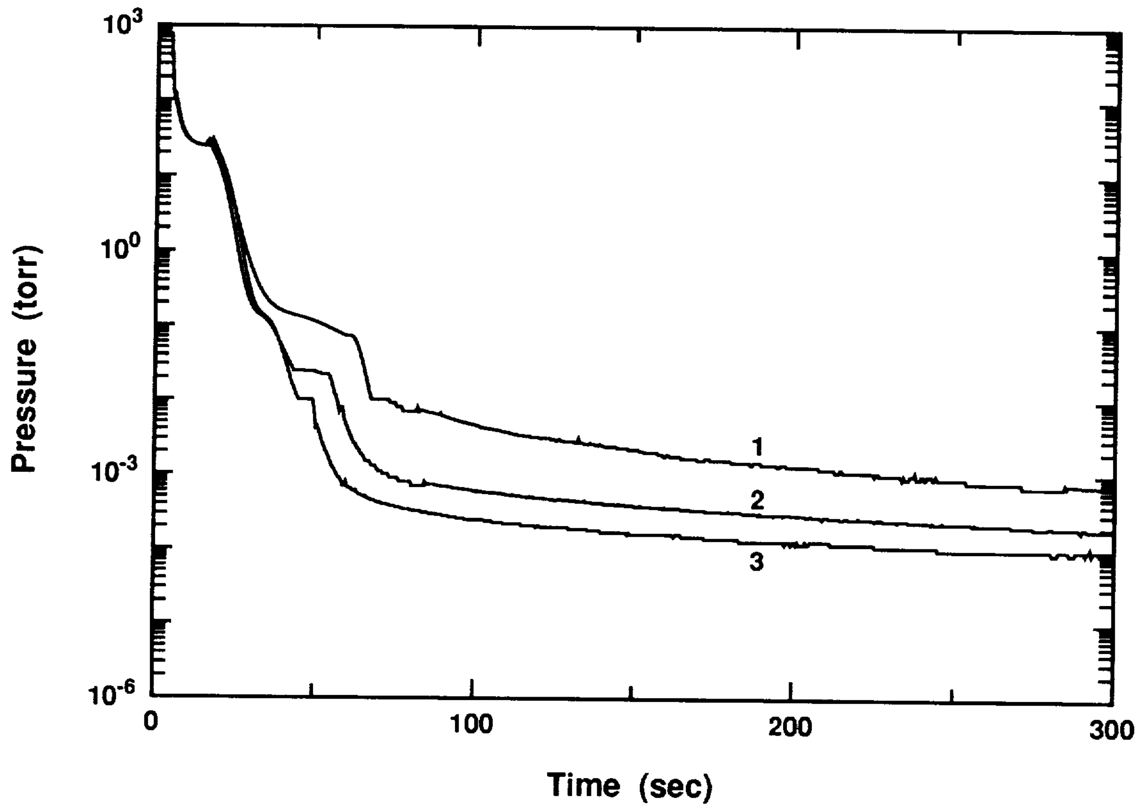

Figure 7. Consecutive Depressurizations of a Ten Layer Blanket

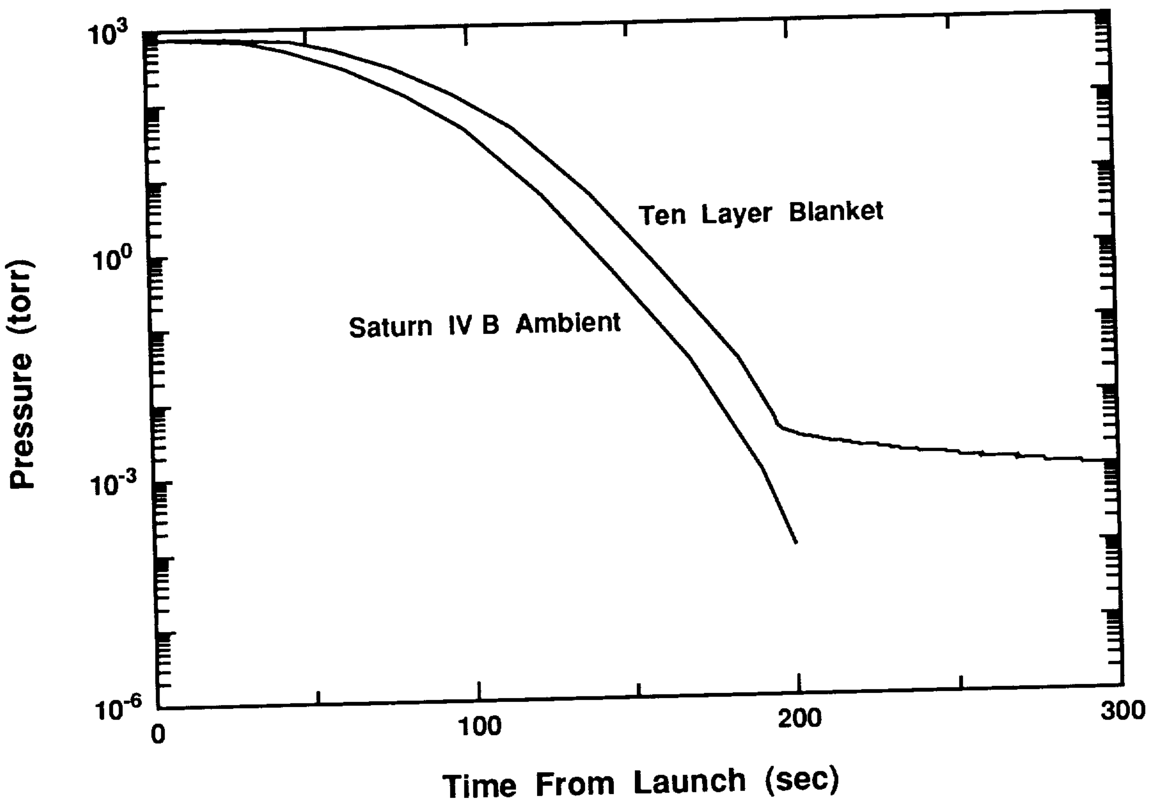

Figure 8. Actual Ascent Pressure History and Estimated MLI Response

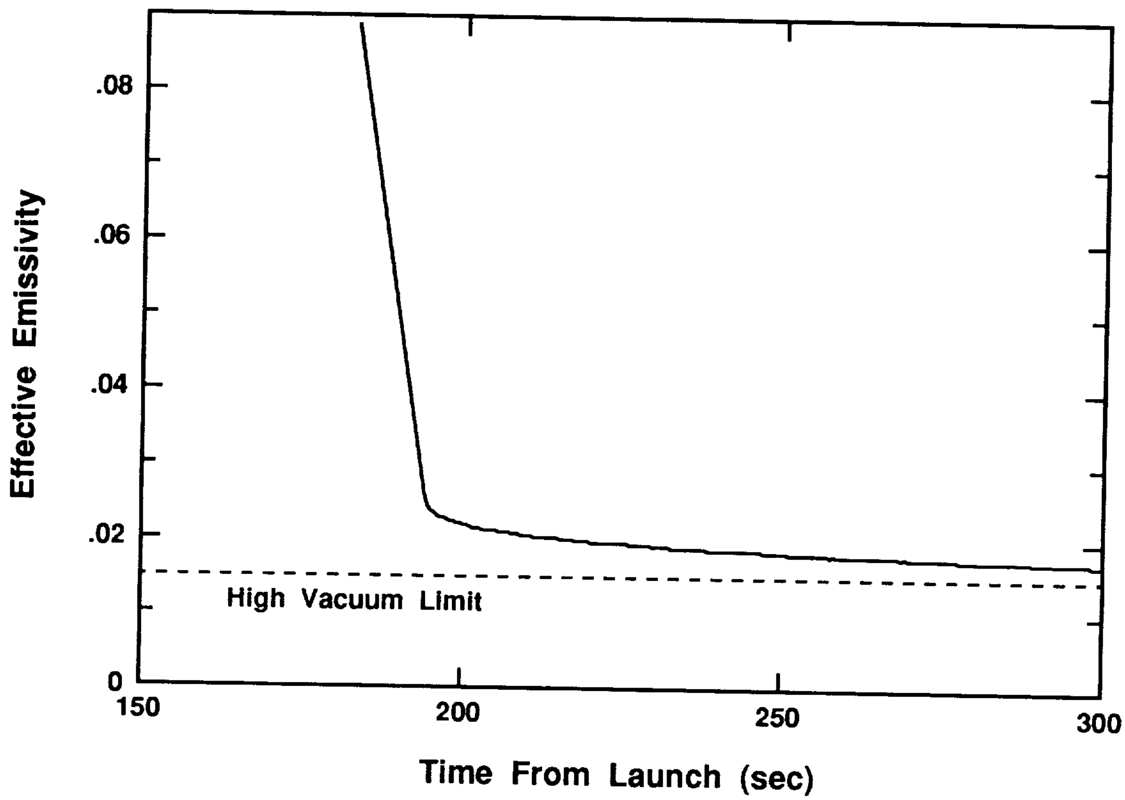

Figure 9. Predicted Ten Layer Blanket Performance