creases; at long test times, the influence of t_0 will be negligible, and the log$t$ vs θ trace will become linear. In practice, the test time is limited to the time during which the surface temperature θ_s remains constant [see assumption (1)]. It is possible for the influence of t_0 to become negligibly small before θ_s, the surface temperature, begins to change, and K can then be calculated neglecting the t_0 correction. To determine when t_0 can be neglected in practice, it is necessary to monitor θ_6 and the linearity of log$t$ vs θ simultaneously.

Experimental Procedure

The accuracy of the line-source technique was established by comparisons with guarded-hot-plate measurements made by the National Bureau of Standards (NBS) according to the Standard Method of Test ASTM C177. The mean sample temperature during the test was 70.1°F with a 40.0°F/in. temperature gradient through the sample.

The line-source is initiated by closing a switch (Fig. 1). The voltage and current are measured and the temperature-time response is monitored using the recorder.

The material studied was NASA E4A1, a filled silicone elastomer with a density of 42.5 lb/ft^3. Slabs, 8 × 8 × 1 in., were prepared and sent to the NBS for the guarded-hot-plate measurements. Then the samples were returned to our laboratory and cut into 1 × 1 × 4 in. samples for line-source measurements. Additional line-source samples were prepared from a separate batch of heat-shield materials and used for the vacuum measurements.

Vacuum thermal conductivity measurements were made in a bell jar at 10^{-5} torr for a 9-day vacuum exposure time at 70°F. Three samples were tested simultaneously. In addition, control samples were tested at constant relative humidity (55%) and atmospheric pressure. Daily measurements were made on these control samples for comparison with vacuum-stored samples.

Discussion

The NBS measured K to be 0.0754 Btu/hr-ft °F (the average K of the 8 × 8 × 1 in. sample). Since the t_0 correction could influence the line-source accuracy to a large extent, tests were performed to determine the maximum test times (thus minimizing t_0) and yet not violate the assumption concerning no change in surface temperatures [see assumption (1)]. The intent was to go to long test times and thus eliminate the necessity of determining t_0. By placing thermocouples on the surface of the samples during line-source measurements, it was found that it took about 2 min before θ_s changed. This would indicate that measurements should be taken prior to 2 min so as to avoid violating the surface temperature boundary condition.

Typical line-source experimental data are shown in Fig. 2; the curves for log$t$ vs θ are nearly linear, indicating that $t_0 \approx 0$. The values of K calculated from the linear portions of the curves in Fig. 2 for the three samples are 0.076, 0.080, and 0.074 Btu/hr-ft °F. The average value measured using the line-source technique is within 2% of the NBS value. The maximum deviation for any one of the line-source samples was less than 7% of the NBS value.

Figure 3 shows K vs storage time for the vacuum and ambient control samples; each data point is the average value from the three samples tested at the same conditions. For the vacuum samples, K decreased about 15% after 1-day exposure and remained approximately 15% lower than the ambient samples for the 9-day duration of the test. At the end of the 9 days, the bell jar was vented to the atmosphere where the relative humidity was about 30% and K for the re-exposed samples was measured daily for the next 3 days. After 1-day re-exposure, K reverted to approximately its original value and remained at this value for the remainder of the tests.

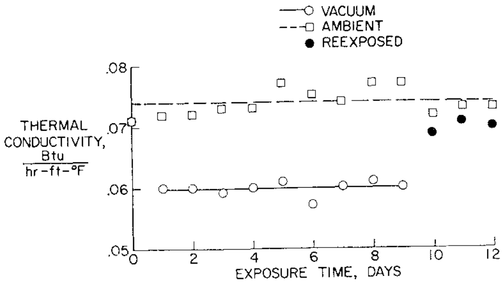

Fig. 3 **Effects of vacuum on the thermal conductivity of heat-shield material.**

Conclusions

The line-source technique measured the average thermal conductivity of a heat shield material to within 2% of the guarded-hot-plate value, with a maximum deviation for any one sample of less than 7%. The technique appears to be well suited for use in vacuum. For the E4A1 material, a vacuum-induced decrease in thermal conductivity of 15% was observed after 24 hr in the vacuum environment.

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A System for Removing Contaminants from Spacecraft Optical Systems

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BEGINNING early in the Mercury Program and continuing through the orbit of Apollo IX, manned spacecraft of the United States have encountered the problem of window filming to varying degrees. It was initially thought that the film might be caused by materials blowing back from the nose cone during the launch phase. Postflight chemical analysis of the contaminant, performed by Manned Spacecraft Center (MSC) personnel, revealed the residue to be composed mainly of silicones. As the manned spaceflight program continued it became increasingly evident that the RTV silicon impregnated gasket material used in securing the window to the spacecraft was responsible for the problem. The reader is referred to NASA document TND-4916

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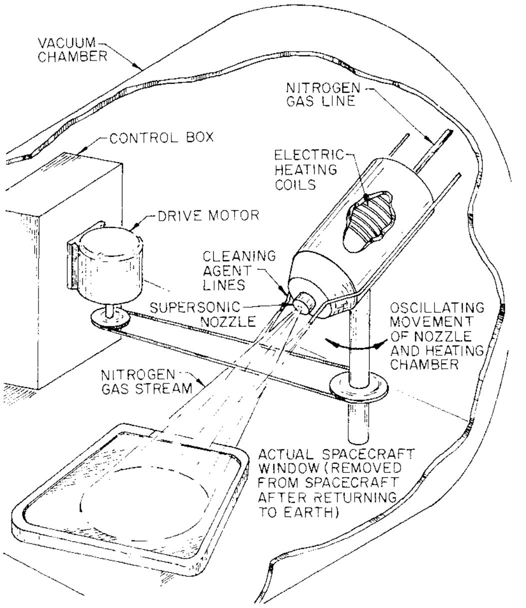

Fig. 1 Experiment set-up used in development of window cleaning technique.

for a detailed discussion of the problem. Since optical quality windows are essential for a variety of reasons, it was necessary either to eliminate or minimize the problem or to examine methods of removing the film in flight.

In response to this situation the Structures and Mechanics Branch of MSC was able to reduce the problem of window filming by a prolonged curing time of the RTV seals. The windows of subsequent flights were then entirely adequate from an operations point of view. They certainly did not pose a navigation hazard. From a scientific point of view, it was desirable to improve optical transmission still more. A program was then undertaken by the Optical Experiments Section to compile a method to improve this situation further.

An attempt was made to use a high-velocity stream of nitrogen gas, but because it was chilled after expanding at the exit of the nozzle, it was ineffective; in fact, the oil was made more difficult to remove by the cold gas. The oil that was used to simulate the film on the windows of Apollo was Dow Corning 705 Silicone based diffusion pump oil.

A system was designed including a heater and a supersonic nozzle that would provide a 5500 fps flow at temperatures over 200°F. A 1-kw, nicrome wire heater was used to heat the gas. The tests were conducted in a 3-ft-diam, 5-ft-long cylindrical vacuum tunnel. With the hot jet (1.7 standard ft^3/min) placed 1 to 2 in. from the "window" at a 45° angle, the area cleaned was still only a little over 3 in.^{2}, and the time required was almost 5 min (see Fig. 1).

The final and more successful step in the authors' attempt to develop some method to clean the Apollo command module's window was to introduce a liquid cleaning agent into the nitrogen stream. Acetone, methyl ethyl ketone, Freon 152, ethyl alcohol, and methyl alcohol were tried. In addition to using a liquid agent a mechanical drive mechanism was evaluated to scan a larger area. The drive was designed so that the blower was free to rotate about a vertical axis while still being held at a 45° angle with respect to the horizontal.

During the last set of experiments one of the side windows from an early unmanned Apollo spacecraft was used for a target surface. The gas temperature was again 220°–230°F. The gas nozzle was held 1.0–1.3 in. from the surface of the window as measured along a line through the center of the nozzle. Back pressure from the nitrogen reservoir was varied from 60 psig down to 5 psig during the series of tests. Gas flow rates were varied from 1.7–0.08 standard ft^3/min, and the duration was varied from $\sim$15 sec to 1 min in an attempt to find the optimum balance. With ketone, $\sim$20 in.^{2} of silicone oil was cleaned, but the ketone left a film that was almost as bad as the silicone oil. Both ethyl alcohol and Freon 152 froze when leaving the end of the $\frac{1}{8}$-in.-o.d. copper line through which the agents entered the vacuum chamber. Acetone did not freeze but really was not very effective as a cleaning agent.

Success was finally attained by using methyl alcohol in conjunction with low-pressure nitrogen. Areas as large as 50 in.^{2} were cleaned to the point that no film could be visually detected, and an increase in spectral transmission of 30% in the visible portion of the spectrum. The test procedure for the most successful result was to introduce 0.41 oz of methyl alcohol into a flow stream of 210°F nitrogen gas. The gas pressure was 15 psig, and the total time required was less than 30 sec for each 10 in.^{2} of surface area cleaned. The results shown in Fig. 2 were acquired by using the previously described technique repeated in three positions across the travel arc of the blower thus requiring all told 1.27 oz of methanol during 90 sec.

There are a number of weaknesses in the experimental procedure that should be presented. First, the pressures in the vacuum chambers in which the experiments were run rose sharply when the nitrogen flow was turned on, and the "space" simulation was poor. The pressure was 1×10^{-5} torr to start and rose to 10^{-2} torr. Also, the films on which the authors had success were on the order of 0.39×10^{-3} oz/in.^{2} in surface density. However, from experimental observations one can see that a film of much greater thickness can be removed by the nitrogen-methanol system at the expense of greater methanol consumption. The uncertainty in the methanol consumption is ±10%, and on the nitrogen consumption approximately 20%. Extrapolating this result to use on an Apollo-type vehicle, the weight of the methanol required to clean 40 in.^{2} on each of five surfaces plus 15 in.^{2} on each of two smaller windows once a day for ten days should run $\sim$11.6 lb. The nitrogen consumed for the same cleaning results should approach 8.1 ft^3. The figures quoted are based on the experimental data taken during the project being discussed.

If only 15–20 in.^{2} of cleaned area for five windows are required, then the weight of methanol consumed would be $\sim$4 lb, and the nitrogen consumed would be $\sim$2.7 ft^3. Further, if the window gasket outgassing problem is sufficiently reduced so that cleanings are not required every day, the weight of consumables will be down proportionally.

It needs to be re-emphasized that the slight window filming problem still present in the Apollo spacecraft does not present the slightest danger to the flight crews. The system proposed in this report is only meant to improve the transmission sufficiently to allow more sophisticated optical experiments to be performed through the windows.

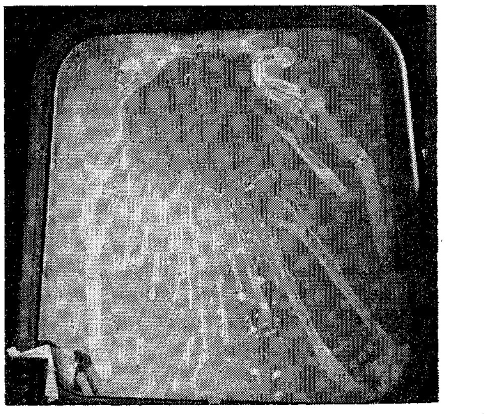

Fig. 2 Spacecraft window cleaned using N_2-methanol technique.

It is felt by the authors that actual flight hardware development based on the results of the work presented in this note could be simple and reliable. Scaled down versions of the system discussed could be suspended over the surfaces which display the more serious outgassing problem. Each of these small jets could be mounted so that it could sweep across the window surfaces. In this manner a small jet could be used to clean a large area, by cleaning one area, then moving to another. However, the principal purpose of this effort was to establish a feasible method of removing contaminants similar to those encountered and little effort was expended on development of optimum hardware.

Quasi-Steady Solution for Ablation-Erosion Heat Transfer

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THE quasi-steady temperature distribution and surface recession rate ($\dot{S}$) for a material undergoing internal decomposition and surface ablation and erosion are rapidly approached when a vehicle travels at hypersonic speeds and when the rate ($\dot{S}$) is high. By "quasi-steady state" we mean that changes in the temperature distribution in the material, as measured from the moving surface, are small with respect to time. Erosion here refers to material removal due to chemical reaction, aerodynamic force, and particle impact (if a vehicle enters a rain, ice, or dust environment); whereas ablation refers to phase change such as sublimation. The erosion rate, heat rate, and surface temperature are interdependent and hence must be calculated simultaneously. Erosion thus differs from ablation which occurs at a unique known surface temperature. The present analysis treats erosion alone and combined erosion/ablation.

The solution presented not only allows for rapid estimation for engineering purposes, but it also provides a means to verify computer solutions that include a transient period. In fact, it is shown in this Note that ordinary numerical methods using finite-difference techniques to solve problems of this type are subject to two severe limitations on the maximum size of the space interval.

Heat-Transfer Model

The one-dimensional heat-transfer equation for a material that undergoes internal decomposition, or charring, is well known[1] and can be written in the form

$$\frac{\partial}{\partial t}(\rho h) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}[W(H_c + h_g)] \qquad (1)$$

where ρ is the density of the material, h the specific enthalpy, k the thermal conductivity, W the gas flux due to decomposition, H_c the heat of decomposition, and h_g the specific enthalpy of the gas. The temperature T is a function of distance x and time t.

The density is given by

$$\rho = \rho_1 + \rho_2 \qquad (2)$$

where subscript 1 refers to the decomposable resin and 2 to the char matrix. It is assumed that the density of the gas is negligible, ρ_2 is constant, and ρ_1 varies in accordance with a nth-order decomposition law,

$$\partial\rho_1/\partial t = -\rho_1{}^n A \exp(-B/T) \qquad (3)$$

where n, A, and B are empirical constants.

The enthalpy is taken as

$$\rho h = (\rho_1 c_1 + \rho_2 c_2)T \qquad (4)$$

where the specific heats c_1 and c_2 are assumed constant. The conductivity is assumed to follow a linear relation of the form

$$k = C\rho_1 + D \qquad (5)$$

where $C = (k_\infty - k_2)/\rho_{1\infty}$, and $D = k_2$ are constants, and the subscript ∞ referring to virgin state.

The gas flux is related to ρ_1 by the continuity equation of

$$\partial W/\partial x = \partial\rho_1/\partial t \qquad (6)$$

Assuming the gas to be in thermal equilibrium with the solid and to have a constant specific heat c_g, one may write

$$h_g = c_g T \qquad (7)$$

Equations (1–7) completely define the mathematical model for heat transfer in a charring material. The quasi-steady analysis and the boundary conditions involving a receding surface are given in the next section.

Analysis for Quasi-Steady State

By introducing the transformation of

$$z = x - S \qquad (8)$$

Eqs. (1, 3, and 6) become

$$\left(\frac{\partial}{\partial t}\rho h\right)_z - \dot{S}\left(\frac{\partial}{\partial z}\rho h\right)_t = \frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z} + W(H_c + h_g)\right]_t \qquad (9)$$

$$(\partial\rho_1/\partial t)_z - \dot{S}(\partial\rho_1/\partial z)_t = -\rho_1{}^n A \exp(-B/T) \qquad (10)$$

$$(\partial W/\partial z)_t = (\partial\rho_1/\partial t)_z - \dot{S}(\partial\rho_1/\partial z)_t \qquad (11)$$

where S is the distance from $x = 0$ to the surface at time t, and $\dot{S} \equiv dS/dt$ is the surface recession rate.

In the quasi-steady analysis, it is assumed that $(\partial T/\partial t)_z$ and $(\partial\rho_1/\partial t)_z$ are negligible. This is acceptable when the heating rate Q and $\dot{S}$ are high. Physically, this implies that heat storage is negligible compared to heat conduction and convection and that the local density change is small compared to mass convection. This situation actually occurs at hypersonic flight speeds at which the heat penetration depth and $\dot{S}$ are on the orders of 0.01 in. and 0.1 in./sec, respectively. If the vehicle enters a time-dependent environment, the present solution is still applicable if one assumes the material to adjust to the present condition instantaneously. It is further assumed that $\dot{S}$ is constant over a time interval. Using the boundary conditions of $T = T_\infty$, $\rho_1 = \rho_{1\infty}$, and $W = 0$ at $z \to \infty$, Eqs. (9) and (11) can be integrated to yield

$$(C\rho_1 + D)(dT/dz) + W(H_c + c_g T) + \dot{S}[(\rho_1 c_1 + \rho_2 c_2)T - (\rho_{1\infty} c_1 + \rho_2 c_2)T_\infty] = 0 \qquad (12)$$

$$W = \dot{S}(\rho_{1\infty} - \rho_1) \qquad (13)$$

Using Eq. (13) to eliminate W, Eq. (12) becomes

$$dT/dz = -\dot{S}\zeta(T,\rho_1)/(C\rho_1 + D) \qquad (14)$$

where

$$\zeta(T,\rho_1) \equiv [(\rho_{1\infty} - \rho_1)(H_c + c_g T) + (\rho_1 c_1 + \rho_2 c_2)T - (\rho_{1\infty} c_1 + \rho_2 c_2)T_\infty] \qquad (15)$$

Equations (10) can be written as

$$d\rho_1/dz = (A/\dot{S})\rho_1{}^n \exp(-B/T) \qquad (16)$$

Equations (14) and (16) show that $d\rho_1/dT \to \infty$ as $T \to T_\infty$,

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