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# Evaluation of a Polyurethane Foam for Ablative Protection at Low Heating Rates

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## Introduction

The surfaces of many entry vehicles, such as the cone frustum afterbody of the Apollo vehicle, are exposed to heating rates that do not exceed 200 kw/m². Proposed missions where entry vehicles will have similar low heating environments include "out-of-orbit" probes into Mars and the upper surfaces of some lifting entry bodies. Nevertheless, these heating environments are sufficiently severe that ablative heat protection is attractive, provided that the ablative material 1) produces a char for radiating energy from the surface, 2) has a low thermal conductivity to minimize heat conducted to the vehicle structure, 3) has a low density to minimize heat-shield weight, and 4) is sufficiently strong to preclude damage before entry and can resist surface removal by oxidation or shear during entry. Many available ablative materials satisfy all but the low-density requirement (e.g., see Ref. 1).

This Note describes briefly the development and evaluation of a low-density (54-kg/m³) modified polyurethane foam that can be used as an ablator. Panels of this material were, in fact, evaluated as part of the afterbody heat shield on the Apollo 502 entry vehicle, and they performed satisfactorily. Performance of the foam, both with and without honeycomb, is compared with those of two other materials: Avco 5026-39HCG and Martin SLA-561.

## Material

The modified polyurethane foam, designated 5-I, was initially developed for arresting fuel fires in aircraft. Details of its development and theoretical material decomposition mechanisms are given in Ref. 2. It is formulated as follows: 1) the basic polyurethane binder system is derived from the reaction of $\alpha$-methylglucoside propyleneoxide polyol and polymeric isocyanate; 2) an alkyl halide polymer [VMCH polyvinyl chloride-acetate polymer (Union Carbide)] and a dissociating inorganic salt (potassium fluoroborate) are

Table 1 Material properties

| Material | Ames 5-I | Ames 5I-HC | Martin SLA-561 | Avco 5026-39HCG |
|---|---|---|---|---|
| Bulk density, kg/m³ | 54 | 74 | 225 | 512 |
| Open cell porosity, % | 3.3 | 4.3 | 43.5 | 54.6 |
| Compressive strength, $N \times 10^{-4}/m^2$ | 21.03 | 129.12 | 47.56[a] | 1576.60 |
| TGA char yield at 873°K under $N_2$, % | 26.7[b] | 26.7[b] | 51.0 | 49.0[c] |
| Initiation temperature of decomposition, °K | 498 | 498 | 523 | 593 |

[a] Ultimate compressive strength.
[b] Corrected for initial loss of Freon 11 from cells.
[c] Includes E-glass and quartz.

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Table 2 Test conditions

| Condition | I | II | III |
|---|---|---|---|
| Gas mixture (mass fraction) | | | |
| $O_2$ | 0.23 | 0.23 | |
| $N_2$ | 0.55 | 0.77 | 1.00 |
| Ar | 0.22 | | |
| Total stream enthalpy, Mjoules/kg | 1.3 | 4.3 | 4.0 |
| Stagnation-point pressure, atm | 0.010 | 0.011 | 0.008 |
| Convective heating rate, kw/m$^2$ | 70 | 170 | 170 |
| Model-exposure time, sec | 100 | 42 | 42 |
| Total heating, kjoules/m$^2$ | 7000 | 6940 | 6940 |

added, each in amounts of 10% by weight; and 3) a foaming agent (trichlorofluoromethane), a surfactant (Dow Corning 195), and a catalyst (triethylene diamine) are used. The alkyl halide polymer and inorganic salt enhance the injection of low-molecular-weight species into the boundary layer and contribute to char formation and strength.

Because of its char-forming characteristic and low density, it was decided to evaluate 5-I for thermal protection in low-heating-rate environments. A stronger system, 5I-HC, was formed by forming 5-I within a 35-kg/m$^3$ honeycomb (Hexel Corp., HRP $\frac{3}{8}$ GF-11 2.2 reinforced plastic honeycomb). The measured properties of 5-I and 5I-HC are compared with the properties of the other two materials in Table 1. The data obtained with thermogravimetric analyses for both the 5I-HC and the Avco 5026-39HCG are only for the filler, without the honeycomb. Note that, although the density of 5I-HC is $\frac{1}{3}$ that of SLA-561, the compressive strength is greater. The compressive strength of the SLA-561 is an ultimate strength, since the material is elastomeric as compared to the 5-I foam.

### Experiment

Ablative performance was evaluated by convectively heating blunted ablation specimens in arc-heated supersonic flows in the Ames planetary entry ablation facility. Details of the equipment and testing procedure are given in Ref. 3. The three test conditions used are summarized in Table 2. To obtain the low enthalpy and low heating rate of condition I, Ar was heated in the arc heater and unheated $N_2$ and $O_2$ were added in the arc-jet reservoir. Similarly, only part of the $N_2$ was heated for conditions II and III, and the remaining $N_2$ (and $O_2$ for II) was added in the reservoir. All ablative specimens were exposed to a total heat load of about 7000 kjoules/m$^2$ (which approximates the Apollo afterbody heat load).

The test specimens were flat-faced cylinders, 3 cm in diameter, supported on a sting by three small stainless-steel pins at the rear face to minimize heat loss to the sting. The rear face of each specimen was instrumented on the centerline with a chromel-alumel thermocouple held in place by a micarta disk, 0.05 cm thick, bonded to the material with Epoxylite no. 8839 adhesive (Epoxylite Corp.). The initial mass per unit area $\rho x_0$ was varied from 0.5 to 16.0 kg/m$^2$ by changing the thickness of the specimens.

Table 3 Test results

| | | | $\Delta T_{\max}$, °K | | |
|---|---|---|---|---|---|
| | | | Condition | | |
| Material | $x^0$, cm | $\rho x_0$, kg/m$^2$ | I | II | III |
| Ames 5-I | 1.75 | 0.95 | 75 | 180 | 37 |
| | 3.12 | 1.68 | 42 | 39 | 22 |
| Ames 5I-HC | 0.67 | 0.50 | 349 | 260 | 157 |
| | 1.35 | 1.00 | 158 | 131 | 84 |
| | 2.54 | 1.90 | 68 | 50 | 32 |
| Martin SLA-561 | 0.26 | 0.58 | 255 | 255 | 232 |
| | 0.51 | 1.15 | 166 | 154 | 138 |
| | 1.01 | 2.28 | 89 | 78 | 65 |
| Avco 5026-39HCG | 0.19 | 1.00 | 478 | 358 | 379 |
| | 0.78 | 4.00 | 128 | 108 | 88 |
| | 1.56 | 8.00 | 58 | 52 | 40 |
| | 3.13 | 16.00 | 30 | 29 | 19 |

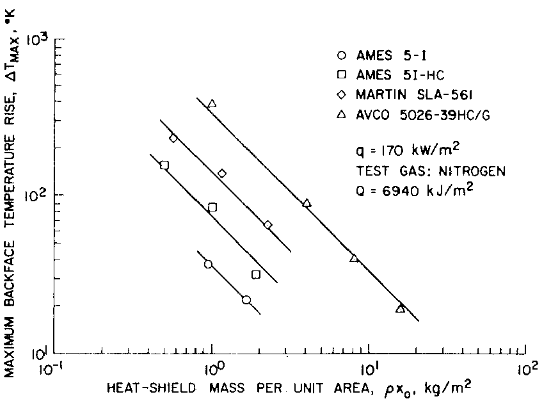

Fig. 1 Test results for condition III.

### Results and Discussion

Table 3 shows the measured maximum backface temperature rise $\Delta T_{\max}$, initial thickness $x_0$, and test condition. The maximum temperature rise occurred at the termination of heating, or at some time thereafter.

Let us first consider ablative performance in $N_2$ (condition III). A simplified analysis shows that, for each material and for a given heating rate and total heat load, $\Delta T_{\max}$ should be proportional to $(\rho x_0)^{-1}$ if combustion and erosion are negligible. The solid lines in Fig. 1 show that this is the case for all four materials, and that the use of Martin SLA-561, 5I-HC, and 5-I, rather than Avco 5026-39HCG, would permit heat-shield weight reductions of 55, 77, and 89%, respectively.

In oxidizing environments, the $\Delta T_{\max}$ for 5-I, 5I-HC, and SLA-561 was not proportional to $(\rho x_0)^{-1}$, indicating that the material performance was affected by the presence of oxygen in the boundary layer. For a heating rate of 70 kw/m$^2$ (condition I), no surface recession was observed with any of the materials. However, when exposed to a heating rate of 170 kw/m$^2$, the surfaces of both 5-I and 5I-HC were severely eroded by as much as 1.75 cm. In contrast, the surfaces of Avco 5026-39HCG and Martin SLA-561 receded no more than 0.025 cm.

The effect of oxidation on the insulative capabilities can be seen by comparing the results for conditions II and III; the only difference in the tests was the presence of oxygen for condition II. The increase in $\Delta T_{\max}$ by oxidation was 10–20% for Martin SLA-561, as much as 50% for Avco 5026-39HCG, and about 60% for 5I-HC. With 5-I, $\Delta T_{\max}$ was increased 77% by oxidation for $\rho x_0 = 1.68$, whereas $\Delta T_{\max}$ was increased 400% for $\rho x_0 = 0.95$. For the latter case, the ablative material was completely removed. With 5I-HC, the honeycomb retained the char sufficiently to prevent complete removal.

A comparison of the results for conditions I and II shows that, for a fixed total heat load, the $\Delta T_{\max}$ decreases with increasing heating rate. Two reasons for this phenomenon are 1) the surface temperature is higher for the higher heating rate, thereby allowing more energy to be radiated from the surface and also allowing the ablative gases to carry away more energy and 2) the high-temperature material removed at the higher heating rate carries with it the intrinsic heat that would otherwise be conducted to the rear of the heat shield. This phenomenon is discussed in greater detail in Ref. 4.

The panel of 5-I material, which was part of the windward afterbody heat shield on the Apollo 502 vehicle, performed satisfactorily during entry. The panel was initially 3.2 cm thick. We estimate that the heating rate did not exceed 120 kw/m$^2$, and the total heat load was about 8000 kjoules/m$^2$. Postflight inspection indicated that at least 1.3 cm of undegraded foam remained, and the backface temperature did not exceed 370°K.

## Conclusions

The low-density 5-I foam is an excellent heat-shield material for protection at low heating rates. Despite the large removal rates in air at 170 kw/m$^2$, the backface temperature increase was small except when the material was completely removed. The large surface-removal rates are apparently caused by oxidation. Resistance to oxidative removal may be improved by the addition of other materials to the foam system. Compositions of 5-I with various filler additives will be evaluated in the future. The strength of the 5-I foam or future composite foams can be enhanced with honeycomb while acceptable insulative capability is maintained.

## References

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