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ABLATION PERFORMANCE CHARACTERIZATION OF THERMAL PROTECTION MATERIALS USING A MACH 4.4 SLED TEST

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Abstract

Sled Tests are often used to evaluate ablation *performance and to provide design parameters for* predicting thermal protection requirements for missile structures. This paper presents a discussion of such a test, performed to determine values of heats of ablation versus ablation temperatures for six materials which are *candidates for use in external thermal protection* schemes. These relations can then be used to predict ablation performance of these materials when being subjected to aero-heating environments having heating regimes which are reasonably similar to those of the test.

Nomenclature

$\dot{a}$	Ablation rate (in/sec)
Cp	Specific heat (Btu/lbm-°F)
H	Heat of ablation (Btu/lbm)
h	Heat transfer coefficient (Btu/ft^2-hr-°F)
k	*Thermal conductivity* (Btu/ft-hr-°F)
q	Heating rate (Btu/ft^2-hr)
T	Temperature (°F)
t	Time (sec)
ρ	Density (lbm/ft^3)

Subscripts

c	Convective
eff	Effective value
m	ablation condition
r	Recovery condition
T	Total integrated value

Introduction

When subjected to aerodynamic heating during high *speed flight, missiles require exterior thermal* protection to maintain structural integrity of the load-carrying structures. Constraints, such as ease of application, low-cost, well defined thermal properties, low-weight, and good ablative/insulative performance, are *normally placed on the thermal protection.*

A test program was developed to identify, test, and evaluate the performance of several materials, for use as ablative/insulative thermal protection layers (TPL) for high-velocity, low-altitude missile systems. A sled test was performed at the Hypervelocity Sled Track Facility at Holloman Air Force Base, New Mexico[1] in which the selected materials were evaluated. The sled test provided a means of correlating ablation depths with an aero-heating environment in the range of interest. This makes possible the determination of an empirical relationship between heat of ablation and effective ablation temperature for each material tested.

The purpose of this paper is to present the details of the test methods and conditions, measured test values, and the method and results of the ablation performance evaluation.

Discussion

Materials

The selected materials tested are shown in Table 1. *This table includes a description of the material* composition, the process in which the materials can be

Table 1. Selected Materials

Materials	Composition	Process	Function	Vendor
1 Chartek	Fiber-reinforced epoxy	Troweled Sprayed Molded	Intumescent	AVCO/MICOM
2 RX-2390	Two-part epoxy	Troweled Molded	Intumescent	PFIZER INC.
3 ARI-2820B	Aramid-silica-Hypalon composite	Laminated	Ablator	Atlantic Research Corp.
4 RX-2376	Two-part urethane	Sprayed	Low-temperature abltor	PFIZER INC.
5 NSX	Glass and cork-filled epoxy	Troweled Molded	Cork substitute	NASA
6 Korotherm	Epoxy-urethane	Sprayed	Low-temperature ablator	Desoto/LTV

Table 2. Material Thermal Properties

Material	ρ (lbm/ft^3)	Cp (Btu/lbm-°F)	k (Btu/ft-hr-°F)
1 Chartek	77.2	0.47	0.14
2 RX-2390	81.7	0.39	0.17
3 ARI-2820B	79.7	0.47	0.18
4 RX-2376	67.9	0.41	0.21
5 NSX	39.3	0.43	0.11
6 Korotherm	62.1	0.52	0.17

applied, the thermal protection function, and the vendor from which the materials can be procured. These candidate materials were selected from a larger list of materials which have been and are currently being evaluated on other programs under similar conditions.

The thermal properties for each of the candidate materials are given in Table 2. These properties were evaluated as a secondary effort to obtain temperature-dependent thermal properties[2]. The values in Table 2 represent average effective properties for use in the associated heat-conduction calculations which were coupled to the aeroheating/ablation routines.

Analytical Methodology

A simple analytical model for predicting ablation performance, widely used in missile design[3], assumes that while ablating, the material ablation rate, $\dot{a}$, is related to the convective heating rate, q_c, by the following relation:

$$\rho\ \dot{a}\ H = q_c = h\ (T_r - T_m)$$

The density, ρ, is assumed constant. Here the ablation depth, a, is defined as the distance from the original (non-ablated) surface down to the virgin material. The heat transfer coefficient, h, and the recovery temperature, T_r, are basically time-dependent functions of velocity, altitude, and geometry and are quantitative indicators of the convective heating environment. T_m is specified as a fixed ablation (modeling) temperature and may be characteristic of the surface temperature of a sublimer or the pyrolysis zone temperature of a charring ablator. The parameter H, relating the recession rate of a material to the heating rate is here called the heat of ablation. It incorporates a multitude of "hidden" energy components such as latent heat of vaporization, heat of reaction, blowing, sensible heat increases, radiation, and errors in convective heating calculations.

Now, over the period that ablation is occurring,

$$\int \rho \dot{a} H dt = \int h(T_r - T_m)\, dt.$$

If the range of the heating regime encountered during the period is limited within reason, one may then use a constant effective heat of ablation, H_{eff}, to obtain:

$$H_{eff} = \frac{\int h(T_r - T_m)\, dt}{\rho \int \dot{a} dt} = \frac{1}{\rho a_T} \int h(T_r - T_m)\, dt$$

Thus, the total measured ablation (a_T) during a sled test, along with computer-calculated convective heating rates during the corresponding period of ablation, yield a parameter which may be used to calculate ablation rates of a material for application in flights with similar convective heating regimes.

Test Facility

The Hypersonic Rocket Sled Facility at Holloman Air Force Base (HAFB), New Mexico was chosen to subject the materials to a severe, accurately determined thermal environment. The advantages of using the sled facility to characterize the ablation performance of each material are:

(a) The test occurs in air with an even, well-characterized free-stream.

(b) Velocity and pressure are accurately known.

(c) The flow occurs over a simple, symmetrical geometry for which local flow values and heating rates can be calculated with confidence.

(d) The materials are expected to behave as they would on an actual missile flight having the same trajectory.

(e) All the samples are subjected to the same conditions at the same time, giving a good indication of relative performance.

Some of the disadvantages of using the sled facility are:

(a) Due to short sled times, the tests have a highly transient nature.

(b) No indication of ablation temperature can be obtained from these tests.

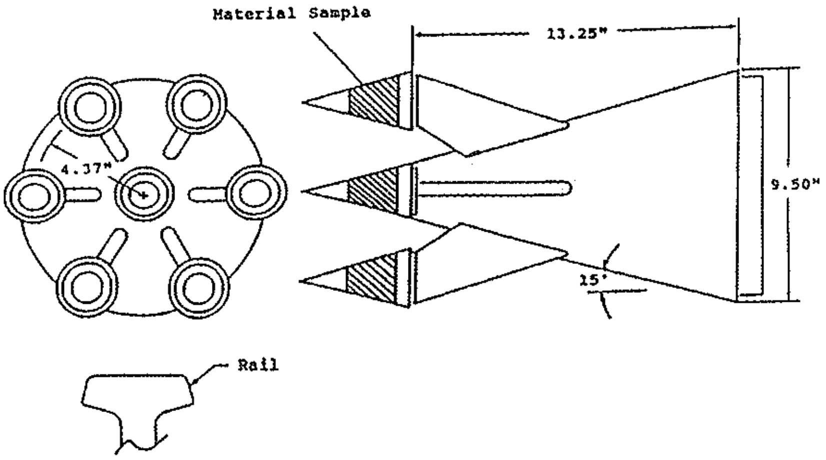

Figure 1. Seven-arm test sting.

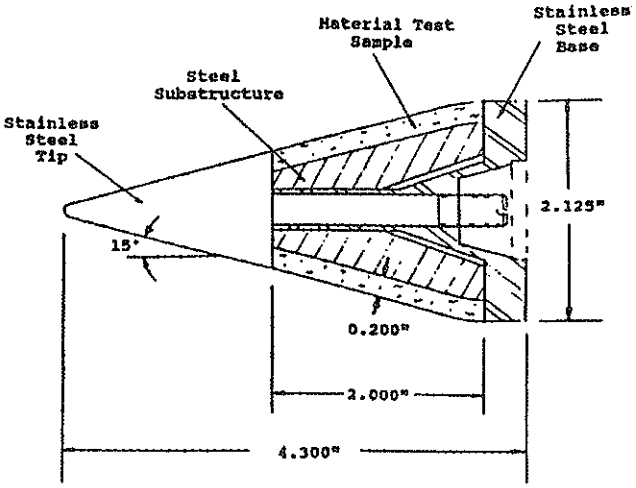

Figure 2. Sample material cone configuration.

Test Set-Up

The seven-arm test-sting upon which the test cones were mounted for the sled test is shown in Figure 1. The candidate materials were applied to 15° sharp-nose cones as shown in Figure 2. A 22.5° blunt-nose cone Duroid sample was used to fill in the seventh position (center) on the test-sting. Figure 3 shows the test vehicle and sled system located on the sled track shortly before the test. As can be seen in this figure, the test-sting is attached to the rocket system and ensures the material samples will be exposed to the freestream environment and not affected by any adverse flow or shock structure.

Figure 3. Sled test vehicle on track.

Thermal Environment

The target velocity for the sled test was 4800 ft/sec. This value was chosen so that the corresponding recovery temperatures would be approximately equal to the range of recovery temperatures encountered during missile flight environments of interest. Figure 4 shows a plot of the velocity history actually achieved during the sled test[4]. A peak velocity of 4950 ft/sec was obtained. The recovery temperature and heat transfer coefficient histories are shown in Figure 5. As can be seen, the peak values are 1600°F and 850 Btu/ft^2-hr-°F for the recovery temperature and heat transfer coefficient, respectively. These values represent the aerothermal boundary conditions which define the heating rate imparted to the materials. The cold-wall heating rate, with a peak value of 175 Btu/ft^2-sec is shown in Figure 6.

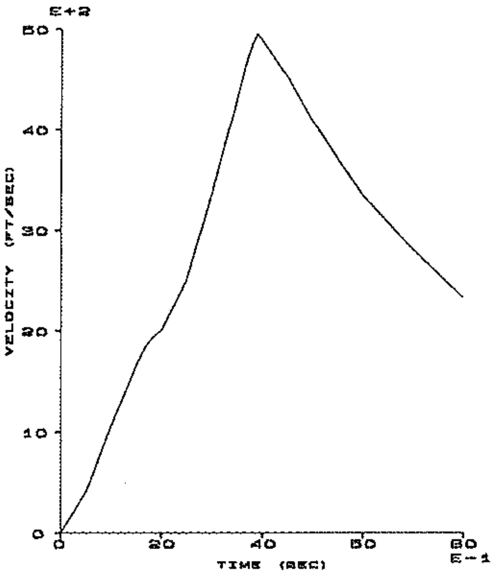

Figure 4. Sled test velocity history.

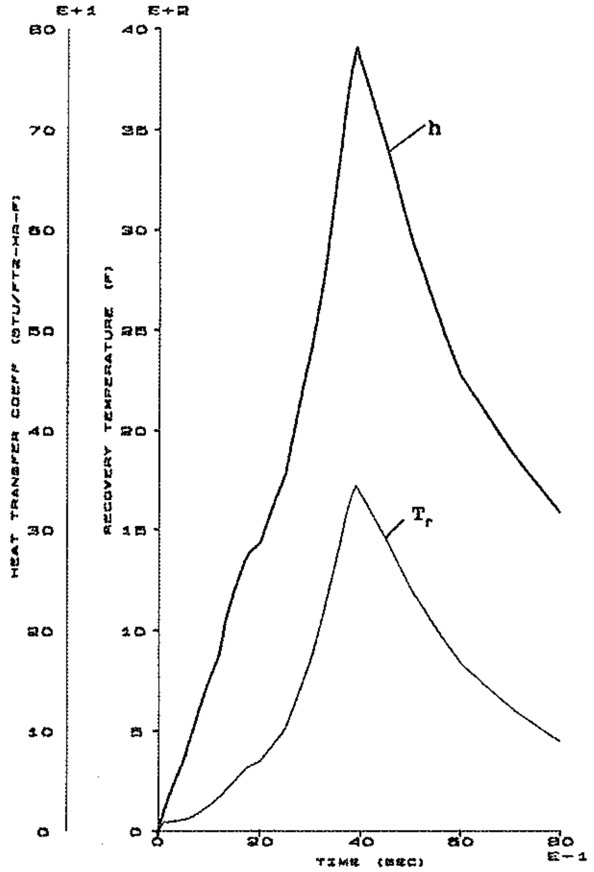

Figure 5. Sled test recovery temperature and heat transfer coefficient histories.

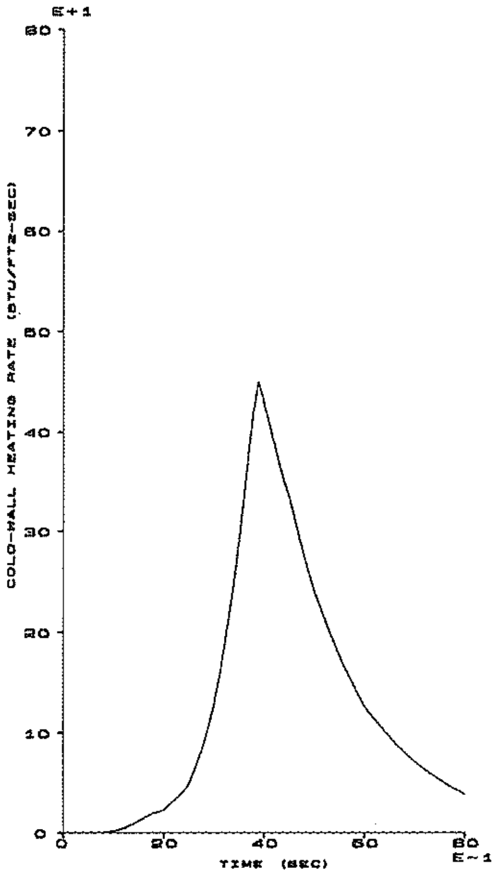

Figure 6. Sled test cold-wall heating rate.

Table 3. Measured Ablation Depths.

Material	Recession Depth to Outer Char Surface (in.)	Char Thickness (in.)	Total Ablation Depth a_T (in.)
1 Chartek	0.024	≤0.005	0.029
2 RX-2390	-0.020*	~0.015	NA
3 ARI-2820B	0.014	≤0.005	0.019
4 RX-2376	0.067	0.000	0.067
5 NSX	0.104	≤0.010	0.114
6 Korotherm	0.098	0.000	0.098

* - negative sign implies swelling; material behaved as a true intumescent

Results

Ablation Measurements

Figure 7 shows the candidate materials on the sled vehicle after the test was conducted. As can be seen, significant ablation occurred on several material samples. Measurements of ablation depths were principally made with an optical comparator (10X magnification), using pre- and posttest X-ray photographs and weight measurements as verification of results. The total ablation depths were determined by scraping down to the virgin material (through the char and reaction zones). These results are provided in Table 3.

Ablation Performance

Using these measured total ablation depths, a_T, and the procedures presented above, the effective heat of ablation, H_{eff}, was obtained as a function of assigned ablation temperature, T_w, for each material. The resulting H_{eff} versus T_w curves are shown in Figure 8. Two materials are not represented by the performance curves. RX-2390 is not included because the material swelled, behaving as a true intumescent. Duroid was not included because it did not suffer significant ablation. For a given material, values of H_{eff} and T_w taken from any point on the corresponding curve in Figure 8 will result in the correct value of a_T predicted for the test. Curves located up and to the right in Figure 8 represent better ablation performance. It should be noted that, in general, this test gives only a relationship between H_{eff} and T_w; one cannot ascertain a unique value for H_{eff} without first knowing a unique value for T_w. Once a reasonable value of T_w is assumed, the corresponding value of H_{eff} can be determined and used for an actual flight environment (similar to the tested environment) to predict required thermal protection thicknesses. While the method discussed above provides a means of comparison for material ablation performance, it does not necessarily mean that the best ablation performer provides the best thermal protection with respect to in-depth effects. Once the ablation performance has been properly characterized, in-depth effects must then be analyzed so as to provide the best thermal protection scheme for the load-carrying structure. Reasonable values of T_w have recently been determined from another series of tests[5]. Table 4 provides these recommended

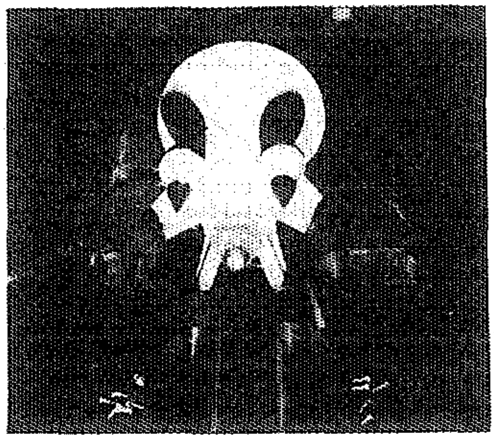

Figure 7. Posttest material samples on sled vehicle.

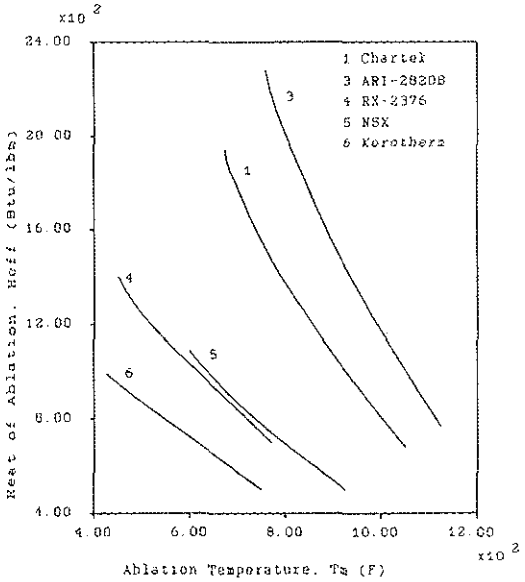

Figure 8. Ablation performance parameters.

Table 4. Recommended Values of T_m and H_{eff}.

Material	T_m (°F) (from Ref. 5)	H_{eff} (Btu/lbm) (from sled test)
1 Chartek	815	1320
2 RX-2390*	NA	NA
3 ARI-2820B	875	1650
4 RX-2376	550	1140
5 NSX	875	610
6 Korotherm	610	700

* - material behaved as a true intumescent

ablation temperatures along with corresponding heats of ablation obtained from Figure 8. These values are recommended for predicting ablation performance of thermal protection schemes for missiles subject to similar aero-heating regimes.

Conclusions

The investigation presented above provides design ablation performance parameters as well as a ranking of recession performance for six candidate ablation materials.

Using measured ablation depths along with computer-calculated integrated heating rates for the test, quantitative relationships between heat of ablation and ablation temperature were obtained for each material.

The RX-2390, while providing excellent thermal protection performance, behaved as a true intumescent and is not modeled well using the method discussed above.

Of the five remaining materials, ARI-2820B gave the best ablation performance. Chartek provided the next best performance, with the other materials performing considerably worse.

Using values of ablation temperature, T_m, determined from other tests, corresponding values of effective heat of ablation, H_{eff}, were taken from the sled test results and are presented as recommended values for use in predicting design performance in missile flight applications.

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