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SC-RR-68-601
December 1968

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**AEROSPACE
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ABLATION MATERIAL TESTING

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OPERATED FOR THE U. S. ATOMIC ENERGY COMMISSION BY SANDIA CORPORATION

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Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00, Microfilms \$0.65

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ABLATION MATERIAL TESTING

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ABSTRACT

This report describes the ablation material test method developed to select the exterior thermal protection for the RFD-2 reentry vehicle. Results of the RFD-2 plasma jet test series are presented.

December 1968

The cutoff date for information in this report is August 1968.

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SUMMARY

As partial fulfillment of its responsibility to the AEC for the safety analyses of nuclear power supplies to be used in space, Sandia Laboratories conducted Reentry Flight Demonstration Number Two (RFD-2) on October 9, 1964. The flight test required a reentry vehicle to provide a stable platform for the inert isotopic power supply and a housing for the telemetry and recovery gear. The test RV was required to survive throughout the entire heat pulse, although the power supply was designed to burn up during reentry.

The ablation material on the RFD-2 flight test vehicle was not required to withstand high stagnation heating because the experiment was mounted on the nose of the vehicle (Figure 1). However, the ablation material was required to withstand the long duration reentry heating, shear forces, and impact of debris from the disassembly experiment. The lack of experimental data for RFD-2 flight conditions made it necessary to conduct ablation tests to select the best material and to obtain design data.

The testing techniques described in this report were developed to provide a rapid and inexpensive means of screening ablation materials for specific flight conditions. The same testing method is also well suited for obtaining design data. The RFD-2 ablation material test series was conducted in the North American 1-Megawatt Hyperthermal Electric-Arc Tunnel. The reduced test data are presented as: heat of ablation, heat of degradation, effective heat capacity for two back side temperatures, relative char strength, and time/temperature curves.

The test method method and data presented in this report have current application for intact reentry heat sources for nuclear power supplies as well as reentry vehicles.

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NOMENCLATURE

C_p	=	specific heat, Btu/lb
f	=	fraction of liquid that vaporizes on the surface
H	=	enthalpy, Btu/lb
H_D	=	heat of degradation (Eq. 4), Btu/lb
H_E	=	effective heat capacity (Eq. 5), Btu/lb
M	=	Mach number
$\dot{m}$	=	mass loss rate, lb/ft ² sec
P_{T2}	=	stagnation pressure behind the shock, atmospheres
Q^*	=	heat of ablation (Eq. 3), Btu/lb
$\dot{q}_c$	=	convective heating rate, Btu/ft ² sec
$\dot{q}_r$	=	radiative heat loss rate, Btu/ft ² sec
T	=	temperature
T_a	=	apparent surface temperature, °R
t	=	time, seconds
TC	=	thermocouple
η	=	heat blockage coefficient
θ	=	angle between the sample surface and the flow direction, degrees

Subscripts

f	=	fusion
i	=	initial
L	=	liquid
R	=	reaction
S	=	solid
St	=	stagnation
V	=	vapor
W	=	wall

ABLATION MATERIAL TESTING

Introduction

The large number of ablation materials currently being produced makes it impractical to obtain complete design data for each mission for even a small percent of the materials. Data are available for some of the established ablation materials, but different testing methods, test conditions, and definitions of material efficiency make it difficult to compare the materials. Little or no design data are available for the new ablation materials. It is desirable to be able to select the best material for a given mission with a small number of relatively simple tests. These tests should determine ease of application, adhesion, resistance to thermal stresses, and the thermal protection offered.

After the screening process is completed, the better material or materials should be more thoroughly tested to obtain complete design data. Parameters such as heat of ablation, effective heat capacity, heat of degradation, surface temperature, and pyrolysis temperature can be obtained using the same test setup that is used for the screening tests. Test data should be obtained for the full range of enthalpies, pressures, and types of flow expected during the flight. Thermo-physical properties such as thermal conductivity, specific heat, emissivity, density, thermal expansion, strength, and elasticity can be found as functions of temperature by using conventional testing methods. The more sophisticated digital computer programs analyze ablation by separating the heat ablation into its various components. The additional input data for these programs are discussed in the Ablation Process section of this report, but methods of obtaining these data are not described. The testing method described in this report is applicable for screening tests and for obtaining total heat of ablation, heat of degradation, and effective heat capacity.

The Ablation Process

Because of the large variations in ablation terminology and in the energy terms included in the ablation process, these topics are discussed briefly before describing the tests and data reduction.

There are at least four methods of evaluating the effectiveness of ablation material:

1. Heat of ablation (Q^*), which is defined as the amount of aerodynamic heat blocked, reradiated, or absorbed per pound of ablation material lost.
2. Heat of degradation (H_D) is similar to Q^* but is based on the weight loss of virgin material instead of only the weight of the material that leaves the surface of the ablation material. H_D is a more realistic measure of the material involved in the ablation process.
3. Effective heat capacity (H_E)_T is defined as the aerodynamic heating divided by the weight of ablation material needed to keep the back side temperature below a given temperature (T). This parameter includes the insulating effects of the ablation material and is one of the best methods of selecting an ablation material for a given application.
4. The ablation process can be separated into each of its components, and each component can be evaluated separately. Provided each of the mechanisms can be defined accurately with exact numerical values assigned to each, this method is the most accurate for predicting ablation effectiveness over a large range of flight conditions. In addition, this method is the most accurate during early stages of ablation before all of the energy absorbing mechanisms are in effect. However, the testing and analysis are time consuming and expensive, and they are not practical for screening materials and for limited use applications.

Ablation materials can be divided into four categories: subliming, melting and vaporization, char forming, and combinations of the various ablation materials and nonablaters.

Sublimation

The simplest form of ablation is sublimation or depolymerization. Most thermoplastic materials are in this category. Thermal protection

is derived by the heat of phase change, sensible heat, convective heat blocked by mass injection of gas into the boundary layer, and heat being radiated from the surface. Since the reaction temperatures are usually low, radiation is low, mass losses high, and conduction to the substructure low. Although conductivity is not included in Q^* or H_D , it does affect the ablation rate and the amount of heat transferred to the substructure. Many of the materials in this category, such as Teflon, ablate cleanly and remain electrical insulators. Q^* and H_D are equal for sublimers and are defined in this report as

$$Q^* = \frac{\dot{q}_c}{\dot{m}} = C_{P_S}(T_R - T_i) + H_R + \eta(H_{St} - H_W) + \frac{\dot{q}_r}{\dot{m}} . \quad (1)$$

The Q^* in Eq. (1) is the value obtained from experimental data. Radiation is not actually part of the ablation process and is often handled separately. If radiation is included, Q^* approaches infinity at low heating rates. All of the terms in Eq. (1) can be found from the tests described in this report if the specific heat, heat of reaction, and emissivity are known. The heat blockage term (η) depends on ablation upstream and hence is a function of the configuration. η in laminar flow is approximately three times as high as in turbulent flow. If $\dot{q}_c$ is measured by a cold wall calorimeter, it is necessary to apply the hot wall correction factor

$$\left(\frac{H_{St} - H_W}{H_{St} - H_{cal}} \right)$$

when separating Q^* into its various components or if it is desired to have the efficiency parameters based on hot wall heat inputs.

Melting and Vaporization

This group of ablators is similar to the sublimers except for the additional phase change of melting before vaporization. Most ceramics and metals are in this category, and they vary greatly in thermal efficiency. Quartz is one of these materials that has been used extensively. Some of the ceramics can be used as ablating antenna windows. Q^* is

defined as

$$Q^* = C_{PS}(T_f - T_i) + C_{PL}f(T_V - T_f) + H_f + fH_V + f\eta(H_{St} - H_W) + \frac{\dot{q}_r}{\dot{m}} \quad (2)$$

The fraction of the liquid phase that vaporizes (f) is a function of the vapor pressure and viscosity of the liquid phase of the ablation material, as well as of flight conditions. Quartz and high silica glass, which have high viscosity and high vapor pressure, have high f 's that remain nearly constant for most reentry conditions. The heat carried away by the liquid phase leaving the surface is small compared to the heat blocked, absorbed, and carried away by the material that vaporizes.

Char Forming

Thermosetting plastics such as phenolics and epoxies form a carbonaceous char when heated to the pyrolysis temperature. Silicones form noncarbonaceous chars which are electrically nonconductive. The char is a porous refractory which is itself an excellent ablator. The high emissivity and high surface temperature of the char cause much of the incoming heat to be radiated to the surroundings. The gases evolved during pyrolysis cool the char by transpiration. The gases percolating through the hot char layer are cracked to their lowest molecular weights and largest volumes. The additional gas thickens the boundary layer and thereby reduces aerodynamic heating to the surface. Reinforcing materials such as nylon, asbestos, or glass fibers or honeycomb are often used to strengthen the virgin material and char and to bridge the reaction zone, which is usually the weakest part of the material during ablation. Recession of the outer char surface is caused by oxidation, melting, sublimation, aerodynamic pressure and shear forces, and spalling caused by thermal stresses and internal pressures from trapped gases.

It is convenient to discuss the internal energy balance and surface energy balance of charring ablators separately. The internal energy balance includes sensible energy stored in the virgin material and char, chemical energy accumulation, conduction through the material, energy convected by pyrolysis gas passing through the char, and energy

absorbed by pyrolysis. The surface energy balance includes convection; diffusion; losses by gas, liquid, and solid phase removal; radiation in and out; conduction inward; energy in the pyrolysis gas; and heat of phase change. The convection and diffusion terms include aeroheating and heat of combustion. The convection term is modified by gas injection into the boundary layer. The energy balance and ablation process of a charring ablator are depicted in Figure 2.

The high surface temperature of the carbonaceous and silicone-based chars radiates a substantial part of the aerodynamic heat. However, since pyrolysis takes place at a relatively low temperature, little heat is conducted into the virgin material. This large temperature gradient through the char is caused by the transpiration of gases outward partially canceling the inward conduction.

The heat of ablation computed from the tests described in this report combines all of the energy absorbing, dissipating, and blocking terms. The heat of ablation can easily be separated into the various components for subliming ablators, but this cannot be done for charring ablators. Separate tests must be conducted to obtain input data for ablation computer programs, such as Sandia's CMA,¹ which handle each energy term separately. The pyrolysis temperature of charring ablators must be known regardless of the method used to design an ablation system. Some virgin material should remain after the reentry heat pulse to ensure the integrity of the char/virgin material interface. Ablation material effectiveness is greatly reduced after all the material has pyrolyzed.

Graphite based ablation materials can be classified as a special class of charring ablators that are charred prior to reentry. Although graphite does not have the advantages of pyrolysis and the evolved gas, the "char" is stronger and more uniform than charring ablators.

Composite Materials

Composite materials usually consist of a refractory matrix filled with either subliming or melting and vaporizing materials. The composites can be tailored to specific applications. Reaction temperatures, surface temperatures, and mass injection rates of composite

materials can be controlled better than can the temperatures and rates of homogeneous ablation materials. The porosity of matrix materials, such as ceramics and refractory metals, can be varied to obtain different gas flow rates. Both metals and plastics have been used as fillers. Testing methods and required data are similar to charring ablatators.

The surface temperature of many ablating materials varies with pressure and enthalpy. Materials with vapor pressures that do not vary greatly with temperature, such as high silica glass, have a nearly constant outer surface temperature for most reentry conditions.

Testing Methods and Analysis

The test method, instrumentation, and data reduction described in this report were initially proposed in Reference 2 and were used to select the ablation material and provide design data for the RFD-2 reentry vehicle.^{3,4} Subsequently, the test method, instrumentation, and some of the data reduction techniques were used for a series of high pressure ablation tests at Sandia.⁵⁻⁸

This method of determining ablation efficiency has several distinct advantages over measuring the weight loss of a small sphere-cone or the recession rate of the end of a flat-faced cylinder when heated by an arc jet or rocket exhaust. The Q^* measured on the sphere-cone is an average over a large range of heat inputs and flow conditions ranging from the stagnation point to the skirt of the cone. This wide variation in heating (at least a factor of 5) makes accurate calibration of the total heat input to the sample difficult. Test samples are expensive, and laminated materials cannot be made with the reinforcing fabrics in the proper orientation.

A better method is to measure the recession rate of the end of a flat-faced cylinder. If readings are taken after the ablation rate is constant, the startup effects can be eliminated. The primary drawback of this method is that Q^* can only be measured near the stagnation region where pressures are high and average shear forces are low. These

conditions do not simulate the reentry environment over most of the reentry vehicle. In addition, heat of degradation and effective heat capacity cannot be computed from the surface recession rate.

It would be desirable to measure all ablation efficiency parameters in all types of flow conditions from the stagnation point to the wake. However, because of the size and power limitations of plasma jets, ablation is difficult to measure accurately on exterior surfaces which are parallel to flow. Ablation can be measured in simulated wake conditions using radiant heaters.⁹

Test samples can be inclined at any angle to the flow between $\theta = 90$ degrees (stagnation) and $\theta \cong 20$ degrees using the method described in this report. These samples are inexpensive and easy to fabricate with any desired fabric orientation. Data reduction is simple, and all efficiency parameters can be computed. In addition, pyrolysis temperature, surface temperature, and electrical conduction of the char can be measured directly.

A typical test setup is shown in Figure 3. The sample holder can have either a fixed or variable angle of inclination. The fixed angle mount shown in Figure 4 was used for the RFD-2 test series. Instrumentation leads are routed through the sting and into the cavity behind the sample. The recessed area behind the sample reduces back side heat losses, which improves the accuracy of effective heat capacity measurements. Care should be taken to assure that the sample seals this cavity. The mounting slots can accommodate a range of material sample sizes and shapes. The mount shown in Figure 4 can be used with the standard 3 x 6 inch samples provided by many suppliers. This is a desirable feature when screening tests must be conducted on short time scales.

Whenever inclination angles (θ) and pressures are low, the test samples of most materials can be simple rectangular sheets. Figure 5 shows the uniform surface recession of a phenolic fiberglass sample which was inclined at a 30-degree angle during the test. Materials with highly viscous liquid phases and materials that have a high threshold ablation heating rate will ablate only in the direct flow impingement area. Large inclination angles can also cause cratering of rectangular

samples. The local ablation will change the shape of the sample and the resulting local flow field change precludes accurate calibration. Figure 6 shows the deep crater in a viscous material tested at high pressure with an inclination angle of 45 degrees. The cratering can be reduced by shaping the downstream end of the sample to an ellipse which matches the core of the free jet (Figure 7). The sample width must not exceed the diameter of the free jet. At inclination angles approaching 90 degrees, the leading end of the sample must also be shaped to match the jet because the gas flows over all sides of the sample.

When several materials are being screened for a specific application, it is often desirable to make all the samples the same weight per unit surface area. This will give an indication of the comparative thermal protection of the various materials for a given weight and can be used with the effective heat capacity as selection criteria. Materials that are too weak to be self supporting can be applied to a simulated structural member for the tests. Self bonding materials should be molded on the structure, and those that are not self bonding should be bonded to the structure with the same adhesive that will be used on the reentry vehicle.

Instrumentation consists of two thermocouples and a radiation pyrometer and can be supplemented by a pyrolysis depth gage. Both thermocouples are mounted near the center of the flow impingement area of the sample, which is also the calibration point. TC-2 (Figure 3) is attached to the back face of the sample and is used to compute the effective heat capacity. Thermocouple number 1 is located just below the exposed surface at a known depth. TC-1 should be molded in place whenever possible, but it can be inserted in a small hole and bonded in place. The reaction zone temperature can be obtained from TC-1. The temperature of TC-1 will rise steadily until the reaction temperature is reached. Then the slope of the time-temperature curve will decrease as energy is absorbed by the reaction. TC-1 will then read the char temperature until either the surface recedes down to the thermocouple or the operating temperature of the thermocouple is exceeded. Surface temperatures of low ablation temperature materials can be determined by TC-1. When the surface reaches TC-1, the temperature reading will increase rapidly, followed by erratic readings as the thermocouple

melts. The use of a pyrolysis depth gage at the same distance from the surface as TC-1 (Figure 8) will aid in determining the pyrolysis temperature. The gage consists of two thin conducting rods separated by the nonconducting virgin ablation material. When the pyrolysis level reaches the ends of the rods, the circuit is completed through the electrically conducting char. The reaction temperature is then taken from TC-1. The gage can also be used to determine if a char is conductive at ablation temperatures.

Surface temperatures of the samples can be measured during the tests with a radiation pyrometer. Optical pyrometers conventionally measure radiation intensity at the 0.65- μm wavelength. Measurements in a plasma jet show that optical pyrometers respond to the plasma and do not give accurate readings of the sample surface temperature. Figure 9, from Reference 10, shows the radiation intensity of high temperature air. It can be seen that the gas radiation is substantial in the 0.65- μm range but is negligible in the 2.0- μm range typical of ablation material surface temperatures. A total radiation pyrometer with filters to allow passage of radiation from approximately 0.8 to 3.0 μm will read sample surface temperatures but will not be affected by the plasma. This type of pyrometer gave accurate temperature readings of a cold wall calorimeter in the plasma. Apparent temperatures (T_a) read by pyrometers without built-in emissivity compensators must be corrected to account for the emissivity of the sample surface. Figure 10 gives the factors for correcting absolute temperatures.

Ablation efficiency is a function of gas composition, pressure, and enthalpy. Shear forces that are large enough to remove part or all of the char layer will reduce the overall efficiency of the ablation material. These flight parameters can usually be matched in a plasma jet for orbital and suborbital reentries. Heat blockage is dependent upon ablation upstream and cannot be matched exactly in a tunnel. However, there is some ablation upstream of the test location on an inclined flat-plate sample. Heating rates can be measured with a flat-plate calorimeter which is the same shape as the samples. The calorimeter sensing element is located in the center of the plate, corresponding to the location on the material sample where the instrumentation is located and the ablation measurements are made. Heating rates vary greatly over the surface of a test sample, and the location and size of the sensing element is critical.

The heat absorbed by ablation material before the surface starts to recede is included in the effective heat capacity $(H_E)_T$ but should not be included in heat of ablation (Q^*) or heat of degradation (H_D). The start-up effects can be eliminated from Q^* and H_D by making two runs at the same conditions but for different time durations and basing the computations on the differences in the two runs.

Data acquisition can be summarized as follows.

Before Test

1. Measure or compute Mach number, stagnation pressure, and stagnation enthalpy in the test section at the point where the test samples will be centered; measure or compute the shear force on the sample surface.
2. Measure the heating rate at the center of the flow impingement area with an inclined flat-plate calorimeter.
3. Record ablation material fabrication procedures and machinability or ease of application.
4. Measure the thickness of each sample.
5. Measure the weight per unit surface area of each sample.
6. Take still photographs of the test setup in the test chamber and of each sample.

During Test

1. Record the temperatures of thermocouples 1 and 2 versus time.
2. Record the surface temperature of the center of the test sample with a pyrometer.
3. Record the continuity of the pyrolysis depth gage if one is used.
4. Take high speed motion pictures of the samples.

After Test

1. Take still photographs of the samples.
2. Note the char condition, including the strength and surface roughness.
3. Carefully cut either a small square parallelepiped or a cylindrical core from the center of the flow impingement area of the sample. The parallelepiped cannot contain any instrumentation or lead wires. If the char layer is "mudcaked," select an area of average thickness.
4. Take cross section photographs of either the core or a cut through the center of the entire sample.
5. Note the bond condition of samples supported by structural members.
6. Weigh the core.
7. Measure the cross sectional area of the core.
8. Measure the overall thickness of the core.
9. Measure the thickness of the core from the inner surface to the reaction zone.
10. Remove the char and weigh the virgin material remaining in the core.

The time-temperature plot of thermocouple number 2, the heating rate, and the weights per unit area of the samples before and after the test are needed to compute Q^* , H_D , and H_E . Many of the ablation materials designed for long duration, low heating rate application are intumescent when heated. Some of these materials are actually thicker after ablation than before. Posttest weights of any intumescent material cannot be computed from the dimensions of the core. Since expansion may be undetectable, all weight losses should be based on direct measurement rather than computed values.

The heat of ablation is given by Eq. (3). Final weights are based on the core.

$$Q^* = \frac{\text{Heating rate per unit area} \times \text{run time of test}}{\text{Initial weight of sample per unit area} - \text{final weight of core per unit area}} \quad (3)$$

The heat of degradation is computed using Eq. (4).

$$H_D = \frac{\text{Heating rate per unit area} \times \text{run time of test}}{\text{Initial weight of sample per unit area} - \text{final weight of virgin material per unit area}} \quad (4)$$

The effective heat capacity as given in Eq. (5) is based on the run time required for the back side thermocouple (TC-2) to reach a specified temperature (T).

$$(H_E)_T = \frac{\text{Heating rate per unit area} \times \text{time for TC-2 to reach T}}{\text{Initial weight of sample per unit area}} \quad (5)$$

An example of this testing and data reduction method and resulting design information is given in the RFD-2 Test Series section of this report.

RFD-2 Test Series

The ablation material requirements for the RFD-2 reentry vehicle, with a reentry angle of -6 degrees, were between those of a vehicle designed for orbital reentry and a vehicle designed for ballistic reentry. In addition to a high heat of ablation and a low thermal conductivity, the RFD-2 ablation material had to be impact resistant to withstand the impact of the debris from the disassembling generator. Tests of 14 widely differing ablation materials were conducted in the North American 1-Megawatt Hyperthermal Electric-Arc Tunnel to aid in the selection of the best ablation material for this flight.

A schematic sketch of the various operating components of the North American tunnel is shown in Figure 11. Oxygen was added to the primary nitrogen gas in the plenum chamber to produce air as the gas in the test section. Tunnel conditions remained constant during the test, and the samples were inserted into the free jet with a movable sting mount. Samples were inclined at a 30-degree angle with the flow. Tests were conducted with the two sets of tunnel conditions given in Table I. All materials were tested at the higher heat flux; the five

most promising materials were also tested at the lower heat flux. The RFD-2 reentry vehicle experienced higher heating rates and pressures than either of these tests, but tunnel limitations precluded simulation of the high heating rate portion of the trajectory. Details of the tunnel calibration can be found in Reference 11.

TABLE I
Tunnel Conditions

<u>Series</u>	<u>Mach Number</u>	<u>Stagnation Pressure (atm)</u>	<u>Stagnation Enthalpy (Btu/lb)</u>	<u>Heating Rate at Center of Sample (Btu/ft²-sec)</u>
1	3.23	0.19	6500	70
2	3.20	0.08	7300	50

The structural member of the RFD-2 vehicle was a flat layup of phenolic fiberglass. The ablation material was bonded to the structure to form a single shell. This composite was simulated in the ablation tests by attaching the sample ablation materials to 0.125-inch phenolic fiberglass bases. The three exceptions were the two Fiberite samples which were acquired just before the tests and the silicone-fiberglass which was used as thermal protection on the base of the stub antenna. All samples were 3 x 6 inches in size, and the laminates were layed up with the optimum fabric orientation. Most samples were approximately the same weight per unit surface area to aid in evaluating the relative specific efficiency.

Instrumentation consisted of two chromel-alumel thermocouples in the sample and a pyrometer. TC-1 was located 0.125 inch below the outer surface of the ablation material, and TC-2 was located on the inner surface of the phenolic fiberglass base. The outer surface temperature was measured by a Thermodot TD-9H optical pyrometer. Color motion pictures taken during the tests recorded the surface texture of the char, spallation, mudcaking, fracturing, and flow of the liquid phase.

Table II contains all the pertinent data for each of the runs. Included are materials, tunnel conditions, times, dimensions, weights,

and design information. Runs 1 through 14 were at the higher heat flux, and runs 15 through 19 were the lower heating rate tests of the five materials best suited for the RFD-2 vehicle. A 1/2-inch-square parallelepiped was cut from the center of each sample after the tests, and the data were reduced using Eqs. (3), (4), and (5). The surface temperatures given were those read by the pyrometer, assuming a black-body radiating surface. Emissivities of the chars were not known, and the corrections given by Figure 10 were not made. Surface and internal temperatures versus run time are presented in Figures 12 through 30. Surface temperatures were not obtained during runs 1 and 2. Apparent changes in surface temperature could be the result of emissivity changes as well as actual temperature changes. The slope changes in the TC-1 temperature plots indicate the beginnings of the virgin material decomposition. These are the pyrolysis temperatures given in Table II. Actually, the pyrolysis takes place over a temperature range when the ablation material is heated rapidly.

The following is a brief discussion of each material, the responses during the test, and an evaluation of each as it pertained to the RFD-2 vehicle.

91-LD Phenolic-Refrasil (runs 1 and 18)

This material consisted of 33 percent phenolic with a high silica glass cloth (C-100-48 Refrasil) laminate. The cloth was shingle wrapped with the slope 20 degrees from the surface. Machining was very difficult. During the test, the erosion of the char was the least of any material tested. There was no indication of the liquid phase leaving the surface. The samples charred down to the bond line in each test. The chars were very strong, with a smooth glassy outer surface. Figure 31 shows the sample during run 1, and Figure 32 shows a cross section after the test. The heat of ablation was higher in series 2 because of the large percentage of heat radiated from the surface at the lower heat flux.

TABLE II

Test Data

Run No.	Material	Test Conditions				Times			Thicknesses Including Base			Weights Including Base						Design Information								Run No.
		H _S (Btu/lb)	P _{T2} (atm)	M	q̇ (Btu/ft ² -sec)	Run Time (sec)	Time For Back Side to Reach 400°F (sec)	Time for Back Side to Reach 150°F (sec)	Initial Thickness (in.)	Final Thickness of Virgin Material (in.)	Char Layer Thickness (in.)	Density of Ablation Material (lb/in. ³)	Initial Weight (lb/in. ²)	Final Weight (lb/in. ²)	Final Weight of Virgin Material (lb/in. ²)	Weight Loss (lb/in. ²)	Weight Loss of Virgin Material (lb/in. ²)	Q* (Btu/lb)	H _D (Btu/lb)	(H _E) 400°F (Btu/lb)	(H _E) 150°F (Btu/lb)	Surface Temperature, ε = 1.0 (°F)	Pyrolysis Temperature (°F)	Electrical Conductivity of Char	Char Condition	
1	91-LD phenolic-Reirasil	6200	0.188	3.23	66	163	147	50	0.543	0.104	0.350	0.0605	0.034	0.0227	0.007	0.011	0.027	6,800	2760	1980	675	-	680	Conductive	Very strong, low erosion	1
2	Scotchply XP 1400	6200	0.190	3.23	66	86	82	53	0.524	0.025	0.097	0.0660	0.034	0.00867	0.0017	0.025	0.032	1,580	1230	1105	715	-	600	Conductive	Strong, badly eroded	2
3	91-LD phenolic-181 fiberglass	6200	0.188	3.23	66	102	98	58	0.534	0.039	0.081	0.0667	0.036	0.00830	0.0026	0.028	0.033	1,670	1420	1250	740	3400	610	Conductive	Strong, badly eroded	3
4	E-300	6300	0.190	3.23	67	167	167	127	0.700	0.168	0.088	0.0433	0.034	0.0126	0.0103	0.021	0.024	3,700	3330	2290	1740	3100	730	Conductive	Weak, mudcaked, eroded	4
5	E-300 - 5% glass fibers	6200	0.187	3.23	66	192	193	147	0.693	0.163	0.125	0.0445	0.034	0.0136	0.0101	0.020	0.024	4,400	3670	2600	1980	3150	730	Conductive	Strong, moderate erosion	5
6	E-300 - 5% asbestos	6300	0.190	3.23	67	182	185	151	0.738	0.168	0.088	0.0435	0.035	0.0126	0.0103	0.022	0.025	3,860	3390	2460	2000	3100	750	Conductive	Weak, eroded	6
7	Rosette phenolic-fiberglass	6700	0.190	3.23	71	91	90	59	0.518	0.030	0.147	0.0667	0.034	0.0118	0.002	0.022	0.032	2,040	1400	1300	855	3400	670	Conductive	Strong, badly eroded	7
8	Phenolic-asbestos	6500	0.190	3.23	69	186	191	84	0.628	0.119	0.121	0.0600	0.038	0.0129	0.0079	0.025	0.030	3,580	2970	2400	1060	3400	715	Conductive	Very strong, eroded	8
9	RTV-325	6600	0.191	3.23	70	196	211	143	0.729	0.182	0.316	0.0314	0.027	0.0150	0.0102	0.012	0.017	7,940	5600	3790	2570	3350	-	Conductive	Very weak, mudcaked, eroded	9
10	RTV-325 - 1-1/4% asbestos	6600	0.192	3.23	70	190	192	137	0.738	0.200	0.490	0.0316	0.028	0.0156	0.0108	0.012	0.017	7,700	5430	3340	2440	3200	-	Conductive	Weak, mudcaked, eroded	10
11	MX-5700 phenolic-asbestos†	6600	0.191	3.23	70	32	-	32	0.479	0.248	0.122	0.0325	0.015	0.0092	0.0081	0.0058	0.0069	2,690	2260	-	1020	3200	500	Conductive	Very weak, delaminated, badly eroded	11
12	MX-7500 phenolic-nylon†	6600	0.191	3.23	70	61	-	49	0.443	0.205	0.135	0.0318	0.014	0.0079	0.0065	0.0061	0.0075	4,860	3950	-	1700	4000	625	Conductive	Weak, mudcaked, badly eroded	12
13	Sandia epoxy "C"	6600	0.191	3.23	70	56††	-	-	0.654	0.435	0.130	0.0490	0.035	0.0264	0.0236	0.0086	0.0114	3,170	2390	-	-	3900	750	Conductive	Strong, mudcaked	13
14	Silicone-fiberglass†	6600	0.191	3.23	70	156	173	111	0.553	0.190	0.205	0.0665	0.037	0.0196	0.0126	0.017	0.024	4,450	3160	2280	1460	3150	675	Nonconductive	Strong, eroded	14
15	E-300	7200	0.0825	3.20	50	222	-	205	0.691	0.437	0.220	0.0433	0.033	0.0268	0.0219	0.0062	0.0111	12,400	8550	-	2160	2900	735	Conductive	Weak, mudcaked	15
16	E-300 - 5% glass fibers	7300	0.0825	3.20	50	245	-	140	0.641	0.430	0.202	0.0450	0.032	0.0266	0.0208	0.0054	0.0112	15,700	9500	-	1520	2900	725	Conductive	Strong	16
17	Phenolic asbestos	7200	0.0827	3.20	50	72	-	72	0.628	0.475	0.135	0.0600	0.038	0.0340	0.0294	0.0040	0.0086	6,240	2900	-	660	3150	760	Conductive	Very strong	17
18	Phenolic-Reirasil	7400	0.0823	3.20	51	136	124	49	0.555	0.135	0.430	0.0605	0.034	0.0296	0.0145	0.0044	0.0195	10,900	2470	1290	510	2900	720	Conductive	Very strong	18
19	RTV-325	7400	0.0825	3.20	51	242	-	160	0.715	0.350	0.600	0.0314	0.027	0.0225	0.0155	0.0045	0.0115	19,000	7450	-	2100	3100	-	Conductive	Very weak, mudcaked	19

†No phenolic fiberglass base
††Sample fractured.

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3M Scotchply XP 1400 (run 2)

This was a phenolic fiberglass laminate which was shingle wrapped at a 20-degree angle. The phenolic fiberglass machines much easier than does the phenolic-Refrasil. The erosion rate was high, with most of the material leaving the sample in the liquid phase.

91-LD Phenolic-181 Fiberglass (run 3)

This material was layed up the same as was Scotchply XP 1400 and was only slightly more efficient. Figure 33 shows the flowing of the liquid glass during the test.

Dyna-Therm E-300 (runs 4 and 15)

This elastomeric epoxy based material was molded on the base. Machining was very easy. At the low heating rates of these tests, the E-300 was more efficient than any of the phenolics. Insulating properties were also better. The char was strong but mudcaked (large irregular cracks), and the reaction zone was very weak, which results in local loss of the char (Figure 34). The periodic loss of the thin char layer reduces the efficiency but would not cause a catastrophic failure.

Dyna-Therm E-300 with 5-Percent Glass Fibers (runs 5 and 16)

Previous tests⁹ with E-300 showed that the char loss could be eliminated by adding 1/4-inch-long glass fibers to the E-300. The fibers not only strengthened the pyrolysis zone, but the glass also prevented mudcaking of the outer char. Five percent by weight was found to be the optimum amount of glass fibers. Figure 35 shows the smoother char of the glass filled E-300. There was a slight loss of liquid glass from the surface. The cross section view of the sample after the test (Figure 36) shows the fibers bridging the pyrolysis zone and the uniform char layer. The stronger char layer increased the heat of ablation up to 26 percent over the plain E-300.

Dyna-Therm E-300 with 5-Percent Asbestos (run 6)

The addition of asbestos to E-300 was far less effective than fiberglass. The char was strengthened but there was still a small amount of spalling.

Rosette Phenolic-Fiberglass (run 7)

This material is the same as the run 3 sample except that the laminates are layed up in a rosette pattern parallel to the flow. The ablation efficiency of these two samples was nearly the same.

Raybestos-Manhattan 41-RPD Phenolic-Asbestos (runs 8 and 17)

This material was shingle wrapped with the laminates parallel to flow. Liquid losses were not as large as they appear in Figure 37. The liquid phase solidified as soon as it was out of the free jet and formed thin rods on the downstream side of the sample. As a comparison, the lines on the downstream side of the phenolic-fiberglass samples (Figure 33) were rivulets of molten glass leaving the sample. The char is smooth and uniform (Figure 38). The erosion rate and char layer thickness were between that of the phenolic-fiberglass and the phenolic-Refrasil.

Dow RTV-325 (runs 9 and 19)

This low density silicone rubber was molded to the base. The char was rough, mudcaked, and weak, but the reaction zone was strong and there was no spalling of the char (Figures 39 and 40). There was a small liquid loss from the surface. This was the most efficient material tested at heating rates from 50 to 70 Btu/ft²-sec.

Dow RTV-325 with 1-1/4 Percent Asbestos (run 10)

The most filler that could be added to RTV-325 without affecting the moldability was 1-1/4 percent. The addition of asbestos decreased the efficiency of this material.

Fiberite MX-5700 Phenolic-Asbestos (run 11)

This is a very low density material filled with phenolic micro-balloons. It is designed for low heating rates and shear forces and did not hold up under the test conditions of series 1. Figure 41 shows the erosion and delamination during the test.

Fiberite MX-7500 Phenolic-Nylon (run 12)

This material is similar to MX-5700 except the fabric is nylon instead of asbestos. The MX-7500 did not delaminate but the erosion rate was high and the char was mudcaked. Efficiency was better than MX-5700 but not as high as some of the other materials tested.

Sandia Epoxy "C" (run 13)

This is a moldable epoxy with a fire retardant but with no fiber reinforcement. The char was finely mudcaked (Figure 42). The reaction zone was moderately weak, and some spalling took place. Efficiency was good until the sample fractured. Fiber reinforcing material should improve the reaction zone strength and the thermal stress resistance.

Silicone-Fiberglass (run 14)

This material forms a low carbon content char which is nonconductive and can be used for the thermal protection of antennas. The reinforcing material is fiberglass roving. The char was rough and delaminated (Figure 43) but was strong. The ablation efficiency was high in spite of the large liquid losses.

These tests, supplemented by other test data at higher heating rates,¹²⁻¹⁴ formed the basis for selecting the RFD-2 ablation material. The RTV-325 had the highest efficiency at the low heating and shear rates, but the efficiency was lower than some of the other materials during peak heating, and the char was too weak to withstand the impact of the disassembling experiment. Glass filled E-300 was efficient and had a strong char, but there was no high heating rate data available and this material had never been used before. Phenolic-Refrasil was selected as the ablation material for the nose and sides of the RFD-2

RV because of its strong char and high thermal efficiency at the high heat fluxes representative of the greater portion of the flight. Also, phenolic-Refrasil had been used successfully on several other reentry vehicles, and ground test data had been verified by flight test data.

Conclusions

The method of ablation material testing presented in this report provides a quick and inexpensive way of selecting the best material for a wide range of configurations and flight conditions. The data obtained from these tests can be used with several design and analysis techniques. Predictions of the RFD-2 ablation rate and temperature response, using data from the tests described in the RFD-2 Test Series section, were in excellent agreement with flight test data.

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Figure 1. RFD-2 flight test vehicle

Figure 2. Cross section of reinforced phenolic during ablation

Figure 3. Typical test setup

Figure 4. Material sample mount

Flow →

Figure 5. Phenolic-fiberglass sample after ablation test

Figure 6. High pressure test of phenolic-Refrasil

Figure 7. Sample configuration to reduce cratering

Figure 8. Instrumentation to determine reaction zone level and pyrolysis temperature of materials with conducting chars

Figure 9. Radiation from air at 8000K and normal density

Figure 10. Emissivity correction for pyrometer measurements $T/T_a = (1/\epsilon)^{1/4}$

Figure 11. Schematic of North American 1-MW hyperthermal electric arc tunnel

Figure 12. Model temperatures--run No. 1,
91-LD phenolic-Refrasil

Figure 13. Model temperatures--
run No. 2, Scotchply
XP 1400

Figure 14. Model temperatures--run No. 3,
91-LD phenolic-181 fiberglass

Figure 15. Model temperatures--
run No. 4, E-300

Figure 16. Model temperatures--run No. 5,
E-300 with 5% glass fibers

Figure 17. Model temperatures--run No. 6,
E-300 with 5% asbestos

Figure 18. Model temperatures--
run No. 7, rosette
phenolic fiberglass

Figure 19. Model temperatures--run No. 8,
phenolic asbestos

Figure 20. Model temperatures--
run No. 9, RTV-325

Figure 21. Model temperatures--run No. 10,
RTV-325 with 1-1/4% asbestos

Figure 22. Model temperatures--
run No. 11, MX 5700A
phenolic asbestos

Figure 23. Model temperatures--
run No. 12, MX 7500
phenolic nylon

Figure 24. Model temperatures--
run No. 13, Sandia
epoxy C

Figure 25. Model temperatures--run No. 14, silicone-fiberglass

Figure 26. Model temperatures--run No. 15, E-300

Figure 27. Model temperatures--run No. 16,
E-300 with 5% glass fibers

Figure 28. Model temperatures--run No. 17,
phenolic asbestos

Figure 29. Model temperatures--run No. 18,
91-LD phenolic-Refrasil

Figure 30. Model temperatures--
run No. 19, RTV-325

Figure 31. Phenolic-Refrasil during test

Figure 32. Phenolic-Refrasil after test

Figure 33. Phenolic-fiberglass during test showing liquid loss

Figure 34. E-300 during test showing loss of mudcaked char

Figure 35. Glass filled E-300 during test

Figure 36. Glass filled E-300 after test

Figure 37. Phenolic-asbestos during test

Figure 38. Phenolic-asbestos after test

Figure 39. RTV-325 during test

Figure 40. RTV-325 after test

Figure 41. MX-5700 during test showing delamination

Figure 42. Sandia epoxy C during test

Figure 43. Silicone-fiberglass after test

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