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RESEARCH MEMORANDUM

EXPERIMENTAL ABLATION COOLING

By Aleck C. Bond, Bernard Rashis,
and L. Ross Levin

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

This paper presents the results of an experimental investigation on the ablation of a number of promising materials for heating conditions comparable to those which may be encountered by unmanned reentry satellite vehicles, as well as for higher heating conditions comparable to those associated with reentry ballistic missiles. Materials tested included the plastics Teflon, nylon, and Lucite; the inorganic salts ammonium chloride and sodium carbonate; graphite; a phenolic resin and fiber glass composition; and the commercial material Haveg Rocketon. Results of these tests indicated heat-absorption capabilities which are several times greater than those of current metallic heat-sink materials. The results with Teflon showed that for hemispherical noses there was no apparent effect of size or stagnation-point pressure on ablation rate for the range of variables covered in the tests. For flat-faced configurations, however, there was a definite increase in the ablation rate with increased stagnation-point pressure. The results for the several materials tested at heating rates associated with reentry ballistic missiles showed considerable increase in the effective heats of ablation over the results obtained at lower heating rates. This trend of increased effectiveness with increased heating potential is in agreement with the predictions of ablation theories. Comparisons of the results for several materials tested at the higher heating rates showed graphite to have the lowest ablation rate of all materials tested.

INTRODUCTION

Ablating surface materials appear to hold considerable promise as a cooling or heat-shielding system for high-speed vehicles, from the standpoint of simplicity as well as efficiency. A theoretical treatment by Leonard Roberts of the Langley Laboratory, for ablating materials which sublime rather than melt, has indicated the desirable properties for such materials. Likewise the theoretical treatments of ablation systems with materials which exhibit the intermediate liquid phase by such investigators as Lees (ref. 1) and Sutton (ref. 2) have also indicated the prime requisites for such systems. Further, these studies have all shown that

*Title, Unclassified.

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the absorption of heat by ablation involves a number of complex mechanisms which require considerable knowledge of material properties in the various states (solid, liquid, and gaseous) for complete analytical treatment, and therefore detailed experimental investigation of the ablation phenomena is necessary. The purpose of this paper is to present some recent experimental data on the ablation of a number of promising materials for conditions of medium to high aerodynamic-heating rates. These data were obtained in three hot-air jet facilities of the Langley Laboratory.

SYMBOLS

h_{EFF} effective heat of ablation, $\frac{\bar{q}}{\bar{\dot{w}}/S}$, Btu/lb

M_∞ free-stream Mach number

$p_{t,2}$ surface pressure at model stagnation point, lb/sq in. abs

$\bar{q}$ average aerodynamic heating rate (for a nonablating surface) for flat face or hemispherical nose at a surface temperature equal to the melting or decomposition temperature of the material, Btu/(sq ft)(sec)

S surface area of flat face or hemispherical nose, sq ft

T_w surface temperature, °F

T_t stagnation temperature, °F

t time, sec

W weight, lb

$\bar{\dot{w}}$ average rate of weight loss from nose of model, $(\Delta W)_{NOSE}/\Delta t$, lb/sec

TEST FACILITIES AND MODELS

The ceramic-heated jets (laboratory scale model and pilot model) of the Langley Pilotless Aircraft Research Division and the 600-kw electric-arc-powered air jet of the Langley Structures Research Division were used to conduct the present tests. The laboratory scale model, which is a $M_\infty = 2.0$ jet (ref. 3), was utilized to make exploratory tests at moderate heating rates on the materials Teflon, Lucite, nylon, ammonium chloride, sodium carbonate, phenolic resin and fiber glass, and Haveg Rocketon. Hemispherical-nosed models 1/2 and 5/8 inch in diameter were used in these tests. The pilot model jet, which is a similar but larger facility ($M_\infty = 3.65$), was used to investigate the effect of such factors as size, shape, and surface pressure, as well as heating rate, on Teflon. Both hemispherical and flat-faced models from 1/2 to 2 inches in diameter were tested in this facility. The electric-arc-powered air jet ($M_\infty = 2.0$) was used to investigate the performance of nylon, Teflon, Rocketon, and graphite at extremely high heating rates. The test stagnation temperature was approximately 11,000° F in this facility and hemispherical-nosed models of 1/4-inch diameter were employed in the tests.

TEST TECHNIQUE AND DATA REDUCTION

The method of data reduction employed in these tests is illustrated in figure 1. The sketches at the top of the figure indicate the mode of ablation which was generally observed for both the hemispherical and flat-faced models. The hemispherical noses tended to maintain their hemispherical shape, and likewise the flat-faced models tended to maintain their flat face with some slight rounding at the corners. The weight loss of the nose was determined in most cases by weighing the model before and after testing to obtain a total weight loss and applying a correction to account for the material loss from the sides of the model. In some cases the nose weight loss was determined by calculating volumetric changes from enlargements of high-speed motion-picture film. It was found that this latter method agreed rather closely with the weighing method except for the materials which have high coefficients of expansion.

The average ablation rate of the nose $\bar{\dot{w}}$ was determined by simply dividing the nose weight loss by the elapsed test time. Test times of 2 to 7 seconds were used for the ceramic-heated jet tests, and for the electric-arc-powered-jet tests the test times were 1/2 to 2 seconds except for the graphite test which was conducted for a period of about 4 seconds. In order to compare the several materials, the data were reduced to an effective-heat-of-ablation parameter h_{EFF}, defined as $\dfrac{\bar{q}}{\bar{\dot{w}}/S}$.

Laminar heating distributions were assumed for all the ceramic-heated-jet tests since the Reynolds number (based on diameter) for the largest model tested was less than 600,000. Also, the nose surfaces eroded as would be expected with laminar heating distributions. Integration of the laminar heating distribution at $M_\infty = 2.0$ on a hemisphere gives the result that the average heating rate to a hemisphere is equal to 1/2 the stagnation-point heating value. Likewise, integration of the laminar heating distribution for a flat face at $M_\infty = 2.0$ from the results of reference 4 yielded the result that the average heating rate to the flat face is about 3/4 of the stagnation-point heating rate of a hemisphere of the same diameter. The theory of reference 5, modified for conditions behind the normal shock and including the appropriate velocity gradient, has been found to agree quite well with calorimeter measurements of the stagnation-point heating of hemispherical noses in these two facilities and was thus used to obtain the stagnation-point heating rates.

In the case of the electric-arc-powered air jet the average heating rate to the hemispherical-nosed models was obtained by converting calorimeter measurements of the heating rates to a copper model. Since the test Reynolds number (based on model diameter) is also quite low in this facility, and since the models here too eroded as would be expected with laminar heating distributions, it was assumed that the heating to these models was also of a laminar level.

Surface temperatures used in calculating heat transfer for the various materials are given in the following table:

Materials	Melting or decomposition temperature, °F
Teflon	1,000
Phenolic resin and glass	2,000
Haveg Rocketon	2,000
Nylon	600
Lucite	250
Ammonium chloride (NH_4Cl)	635
Sodium carbonate (Na_2CO_3)	1,560

Current literature on properties of Teflon (refs. 6 and 7, for example) does not give any fixed sublimation or decomposition temperature for this material, but indicates that it tends to become soft and jellylike at temperatures approaching 600° F. Some data on mass loss rate with temperature are given in reference 7, from which it may be deduced that for high heating rates the decomposition temperature may be in the range from 1,000° to 1,200° F. Some simple laboratory tests were conducted in an attempt to determine the stabilization temperature of a metallic plate heated electrically at relatively high heating rates and covered on both sides with pieces of Teflon. When this stabilization temperature was extrapolated to eliminate the effect of the gas layer produced between the heated plate and the Teflon, the resulting temperature was approximately 1,000° F.

The surface-temperature values used in the calculations for the phenolic resin and glass and for Haveg Rocketon were estimated from static-test measurements. Some recent measurements made with an optical pyrometer with models tested in the jets have substantiated the estimated values. The melting temperature of nylon was obtained through private correspondence with E. I. du Pont de Nemours & Company, Inc. Surface temperatures for the remaining materials, Lucite, ammonium chloride, and sodium carbonate, are handbook values and were obtained from reference 8.

RESULTS AND DISCUSSION

Exploratory Tests

Results of the exploratory ablation tests conducted at moderate heating rates in the laboratory scale model ceramic-heated air jet and at high heating rates in the electric-arc-powered air jet, all at a Mach number of 2.0, are shown in figure 2. The data are presented as the effective-heat-of-ablation parameter h_{EFF} plotted against the average aerodynamic heating rate and were obtained with 1/2- and 5/8-inch-diameter models in the ceramic-heated jet and 1/4-inch-diameter models in the arc-powered jet. The heating-rate scale is broken in this figure in order that the trends in the lower range of heating will not be obscured. The lower heating-rate range (75 to about 350 Btu/(sq ft)(sec)) is comparable to the heating rates which may be encountered by unmanned reentry satellite vehicles, whereas the higher heating rate ($\approx$1,570 Btu/(sq ft)(sec)) is in the category of heating rates associated with reentry ballistic missiles. Another range of heating rates exists for the manned reentry satellite vehicle, from 0 to about 75 Btu/(sq ft)(sec), as has been indicated in heating studies for such vehicles of reference 9. It is felt that caution should be used in extending the present data to this lower range of heating, since these materials may be affected by heat conduction and hence exhibit deterioration of physical strength under prolonged low heating rates.

For the lower heating rates the plastic materials Teflon, nylon, and Lucite show a decreasing effectiveness with increasing heating rate. The high values of effectiveness indicated for these materials at the lower heating rates are believed to be influenced somewhat by conduction into the solid and hence do not reflect values of effectiveness for steady ablation. This conduction effect was investigated experimentally for Teflon by testing a series of models at an approximately constant heating rate ($\overline{q} \approx 68$ Btu/(sq ft)(sec)) for successively longer periods of time in order to determine the elapsed time before the actual beginning of ablation. At this low heating rate it was found that approximately 0.7 second elapsed before steady ablation began. For a test time of approximately 2.0 seconds the uncorrected ablation rate was about 90 percent of the asymptotic or steady ablation rate value. Correcting the actual observed time with the time increment for beginning of ablation for the value of h_{EFF} (3,100 Btu/lb) at $\bar{q} = 76$ Btu/(sq ft)(sec) results in $h_{EFF} = 2,830$ Btu/lb. Therefore, conduction accounts for only about 10 percent of the uncorrected value of h_{EFF}. The correction for conduction would, of course, decrease with increasing heating rate and should be well within the experimental accuracy at heating rates of 200 to 300 Btu/(sq ft)(sec).

In the case of the phenolic resin and fiber glass composition and the Haveg Rocketon, which is a resin-asbestos composition, it is seen that h_{EFF} increases with increasing heating rate. This can be explained by the fact that the resin in these materials burns readily, and hence at the lower heating rates the heat of combustion of the resin must counteract a significant portion of the shielding effect. However, as the heat input is increased the shielding effect apparently also increases.

Both sodium carbonate and ammonium chloride displayed higher average effective heats of ablation than any of the other materials at the lower heating values at which they were tested. The ammonium chloride has an effectiveness more than twice as great as that of the other materials at a heating rate of about 200 Btu/(sq ft)(sec). It should be mentioned that both these materials displayed low resistance to thermal shock, possibly because of the method of manufacture, which consisted of simply cold-pressing crystals of these materials to form the test specimen. This difficulty might be overcome by the use of suitable binders or reinforcement materials during manufacture.

The values of h_{EFF} for Teflon, nylon, and Rocketon at the higher heating rates of the arc-powered jet show an increasing trend of effectiveness with heating rate. The Rocketon and nylon show more than a 200 percent increase in effectiveness over the values at lower heating rates; however, Teflon does not show such a marked increase in performance. This larger increase for nylon and Rocketon may be due to the more complete vaporization of the liquid layer which was seen to form on these materials at the lower heating rates. Teflon, on the other hand, did not display this liquid phase at any of the test heating rates but went directly from the solid to the gaseous state.[1] The trend of increased effectiveness with increased heating rate agrees with the theory of Lees

[1]These observations can be seen in a motion-picture film supplement which is available on loan. A request card form and a description of the film will be found at the back of this paper, on the page immediately preceding the abstract and index pages.

(ref. 1) which predicts increased effectiveness with higher enthalpy potentials. The trend of increased effectiveness for Teflon at higher heating rates is also predicted by the previously mentioned theory of Leonard Roberts, which was specifically developed for materials which sublime rather than melt.

A photograph showing several materials after test in the laboratory scale model ceramic-heated jet is given as figure 3. It can be seen that the plastic materials Teflon, nylon, and Lucite ablated quite uniformly with relatively small change in the hemispherical-nose shape. The Rocketon does not show as uniform ablation as the plastics and exhibits some charring at the nose due to burnout of the resin binder. The specimen of phenolic resin and fiber glass shown here was tested for a shorter period of time than the other materials and hence shows practically no effect. Other models of this material, tested for longer periods of time, showed considerable charring action as the resin binder was consumed.

The effect of the resin content of the phenolic resin and glass specimens on the average effective heat of ablation was investigated by testing specimens of different resin content for constant stagnation temperature or constant heating rate. Results of these tests for stagnation temperatures of 2,900° and 3,800° F are shown in figure 4. These results indicate decreasing effectiveness with increased resin content, due of course to the lower effectiveness of the resin binder itself. Indications are (private correspondence with the General Electric Company) that at higher heat fluxes (from 1,000 to 1,500 Btu/(sq ft)(sec)), the trend is reversed. The chemical breakdown of resin at these high heating rates apparently results in the formation of light gases which are relatively efficient in their shielding action.

Further Teflon Tests

In the initial tests at the moderate heating rates of the laboratory model ceramic-heated jet, the models utilized were all essentially the same size (1/2 and 5/8 inch in diameter), the stream total pressure was maintained constant for all the tests, and the aerodynamic heating rate was varied simply by changing the stagnation temperature. In order to investigate the effect of such test conditions as temperature, pressure, and model size and shape, a program was laid out for a somewhat systematic variation of these test conditions. Teflon was chosen as the material, since it is relatively easy to handle and fabricate, it ablates rather uniformly, and it also has the characteristic of going directly from the solid to the gaseous state without any intermediate liquid phase. The program as outlined for this series of tests is shown in figure 5, and includes the previously discussed initial tests. As previously stated, the initial tests in the laboratory scale model ceramic-heated jet were all conducted at constant stream total pressure, and hence $p_{t,2}$, which is the surface pressure at the model stagnation point, is constant in all of these tests. In the pilot model ceramic-heated jet, systematic variations of heating rate were accomplished for 1-inch-diameter flat-faced models by varying stagnation temperature for two levels of stagnation pressure. Likewise the effect of size on both flat-faced and hemispherical-nosed models was investigated at the higher pressure level and at near-constant stagnation temperature. The test conditions for the electric-arc-powered air jet are also included here.

The data from these various tests on Teflon are presented in figure 6 as the average rate of ablation per unit surface area as a function of the average aerodynamic heating rate. The open symbols denote the data for hemispherical-nosed models and the partially and completely filled symbols denote the data for the flat-faced models. In general, the points for the hemispherical-nosed models tend to lie along one line without any discernible effects resulting from changes in model size or stagnation-point pressure. It should be noted that here again the heating-rate scale has been broken and, hence, the one data point for the highest test heating rate, if plotted on an unbroken scale, would show a reduction in slope of the average rate of ablation at the higher heating rates. The points for the flat-faced models at the lower pressure level (denoted by the half-filled squares) also tend to agree with the trend of the data for the hemispherical-nosed models; however, the data for the flat-faced models at the higher pressure level show a pronounced effect of pressure on ablation rate.

The ablation-rate data of figure 6 have been reduced to the effective-heat-of-ablation parameter h_{EFF} and are presented in figure 7 again as a function of the average aerodynamic heating rate $\overline{q}$. All the data for the hemispherical-nosed models show essentially the same trend with $\overline{q}$, and the flat-faced models tested at the lower stagnation-pressure level (denoted by the half-filled squares) also agree with this trend. The three points for the flat-faced models at the higher stagnation-point pressure (denoted by the filled squares) gave lower values of h_{EFF}, but tend to approach the trend established by the other data at the higher heating rates. The data point at the higher heating rate of the electric-arc-powered jet, which is the same as that presented previously for Teflon in figure 2, indicates the gradually increasing trend of effectiveness with heating rate for rates greater than about 250 Btu/(sq ft)(sec).

It is known that the heat of depolymerization of Teflon decreases with increased pressure, and hence the reduction in effectiveness for the flat-faced models at the lower heating rates may possibly be a result of the higher pressure loading on the flat face. As heating rate is increased the heat of depolymerization becomes a less significant part of the total effectiveness, since the shielding effect is becoming more predominant.

Photographs of several typical Teflon models after test in the pilot model ceramic-heated jet are shown in figure 8. In general, these photographs show that the smaller models, up to 1 inch in diameter, ablated quite uniformly with little change in basic shape. Both the flat-faced and the hemispherical-nosed model of 2-inch diameter showed some local pitting or cratering which may be attributed to transition to turbulent flow, or possibly to increased heating due to impact of ceramic dust with the model surface.

As a matter of interest a comparison is made in figure 9 of the experimental effective heat of ablation of Teflon (presented in fig. 7 for hemispherical-nosed models) with the effectiveness for a nitrogen-transpiration-cooled hemispherical nose shape of the same diameter as the Teflon models. The lower curve for nitrogen was calculated for a surface temperature of 1,000° F, the temperature used in the calculation of heating rates for Teflon. The upper transpiration-cooling curve was calculated for a surface temperature of 1,500° F, which is considered a practical limit of surface temperature for porous stainless-steel materials employed in transpiration cooling systems, and thus represents the most effective cooling that can be achieved with nitrogen for the aerodynamic heat fluxes to which the Teflon models were subjected.

Both nitrogen curves indicate less cooling effectiveness than those for Teflon for the range of $\bar{q}$ from about 75 to 225 Btu/(sq ft)(sec). At the very high heating rate of 1,570 Btu/(sq ft)(sec), however, the nitrogen transpiration effectiveness is calculated to be more than twice the effectiveness of Teflon. It should be noted that the calculations of the nitrogen values were based on the theoretical curve of Stanton number ratio as a function of the flow-rate parameter given in Lees' analysis (ref. 1) and not on experimental values. The theoretical curves are based on the assumption that the exiting coolant has properties identical to those of the local stream flow. For the electric-arc-powered air jet, the local stream properties may very well be substantially different from those of the transpired coolant.

If a lighter gas such as helium had been chosen for the comparison, it would have been shown to be considerably more effective than the Teflon ablating system. Nitrogen was chosen for the comparison since it was estimated that the properties of the Teflon gas resemble those of nitrogen. Likewise, the comparison could have been made with some of the other ablating materials which show considerably higher effectiveness than Teflon.

Graphite Test

Considerable interest has been expressed in the use of carbon as an ablating material in view of its extremely high heat of vaporization. Reference 10 indicates values of about 26,000 Btu/lb for the heat of vaporization of carbon. In order to take advantage of these high heats of vaporization, carbon or graphite should be used at conditions where the surface can reach the vaporization or sublimation temperature of these materials. Test temperatures in the ceramic-heated jets are not high enough to achieve surface vaporization; however, the test temperature ($\approx$11,000° F) of the electric-arc-powered air jet is more than adequate. A test was conducted in this facility with a 1/4-inch-diameter hemisphere-cylinder model, made of AGR graphite, and the measured ablation-rate data are shown in figure 10 and are compared with the previously discussed ablation-rate data for the several other materials tested in this facility. The graphite model was tested for a period of 4 seconds in order to obtain a measurable weight loss. As can be seen from this bar-graph presentation, the graphite is considerably better than any of the other materials tested at these high heating conditions. It has only about 1/8 the erosion rate of the better of the other materials, Rocketon.

Some additional tests conducted with graphite in the laboratory scale model ceramic-heated jet at a stagnation temperature of 4,000° F showed that in spite of the fact that graphite suffers from oxidation at such temperatures, the ablation rate was only about 1/2 that measured in the arc-powered jet.

CONCLUDING REMARKS

The experimental results given in this paper have indicated several ablating materials that have effective heat-absorption capabilities several times greater than those of current metallic heat-sink materials. Since the ablating materials investigated herein are rather unconventional, the choice of a given material for application to an actual vehicle should, of course, involve consideration of strength, workability, ease of manufacture and handling, and so forth. The results with Teflon showed that for hemispherical-shaped noses there was no apparent effect of size or stagnation-point pressure on the trend of ablation rate for the range of variables covered in the tests. For the flat-faced configuration, however, there was a definite increase in the magnitude of ablation rate with increased stagnation-point pressure. The results for the several materials tested at heating rates comparable to those encountered by a reentry ballistic missile showed considerable increase in the effective heats of ablation over the results obtained at lower heating rates. This trend of increased effectiveness with increased heating potential is in agreement with the prediction of theory. Comparisons of the results for several materials tested at the higher heating rates of the electric-arc-powered air jet showed graphite to have the lowest ablation rate of all materials tested in this facility.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 19, 1958.

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DATA REDUCTION

$$(\Delta W)_{NOSE} = (\Delta W)_{TOTAL} - (\Delta W)_{SIDES}$$

$$\bar{\dot{w}} = (\Delta W)_{NOSE} / \Delta t$$

$$h_{EFF} = \frac{(\bar{q})_{NOSE}}{\left(\frac{\bar{\dot{w}}}{S}\right)_{NOSE}}$$

Figure 1

EFFECTIVE HEATS OF ABLATION OF SEVERAL MATERIALS

$\frac{1}{4}$-IN., $\frac{1}{2}$-IN. AND $\frac{5}{8}$-IN. DIAM. HEMISPHERE NOSES

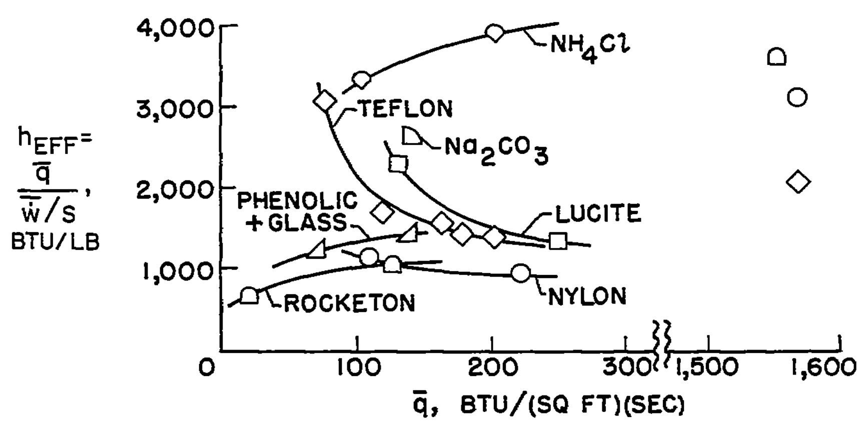

Figure 2

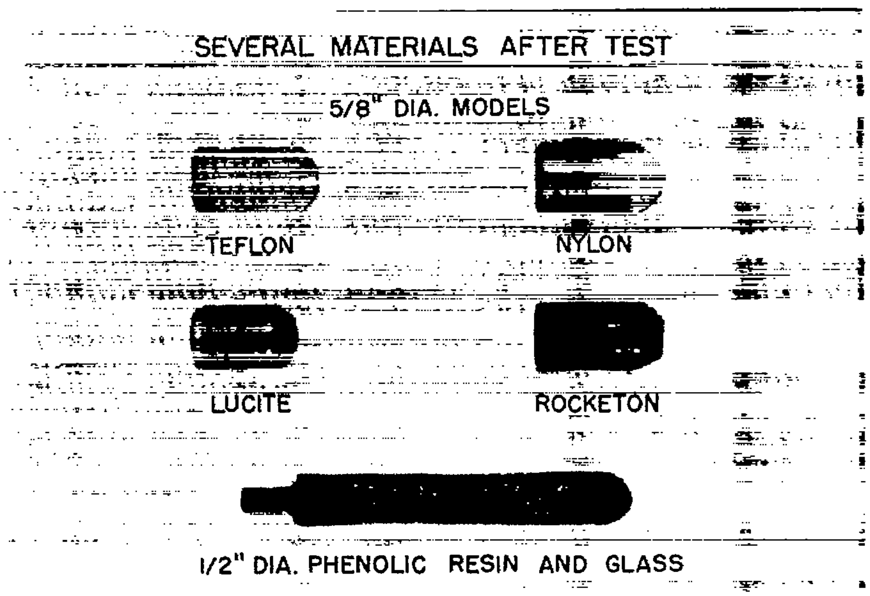

Figure 3 L-58-1671

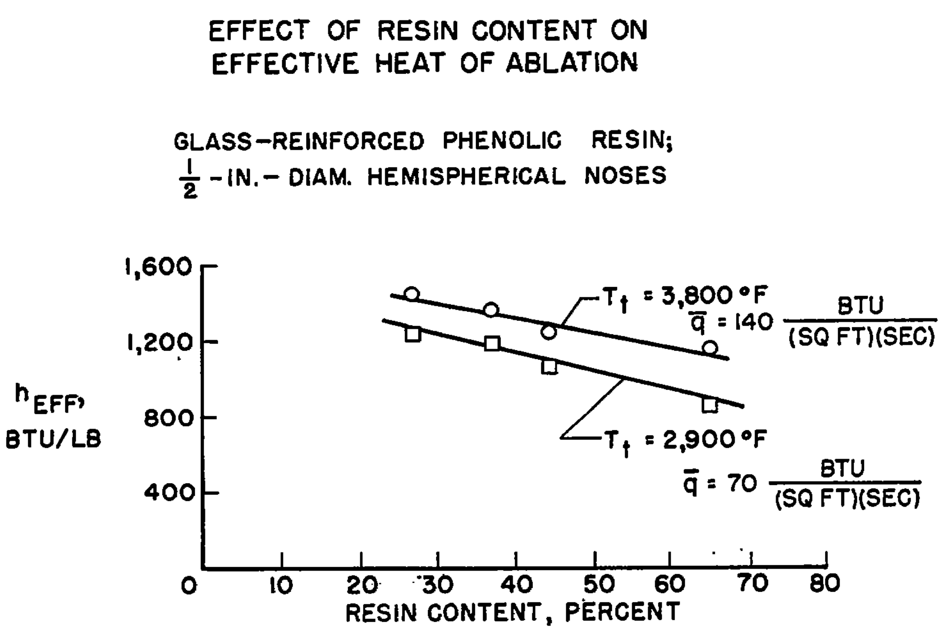

Figure 4

SUMMARY OF TEST CONDITIONS FOR TEFLON

FACILITY	M_∞	MODEL CONFIG.	MODEL DIAM., IN.	T_t, °F	$p_{t,2}$, PSIA	SYMBOL
LAB. SCALE CERAMIC-HEATED AIR JET	2.0		5/8	3,755 3,550 2,840 2,245	75	◇
			1/2	3,800	75	△
PILOT MODEL CERAMIC-HEATED AIR JET	3.65		1	3,700 2,820 2,200	116	■
			1	3,740 2,900 2,000	58	◪
			2 1/2	3,700 3,700	116	● ▲
			2 1 1/2	3,710 3,710 3,730	116	○ □ △
ELEC.-ARC-POWERED JET	2.0		1/4	11,000	70	⊿

Figure 5

AVERAGE RATE OF ABLATION OF TEFLON

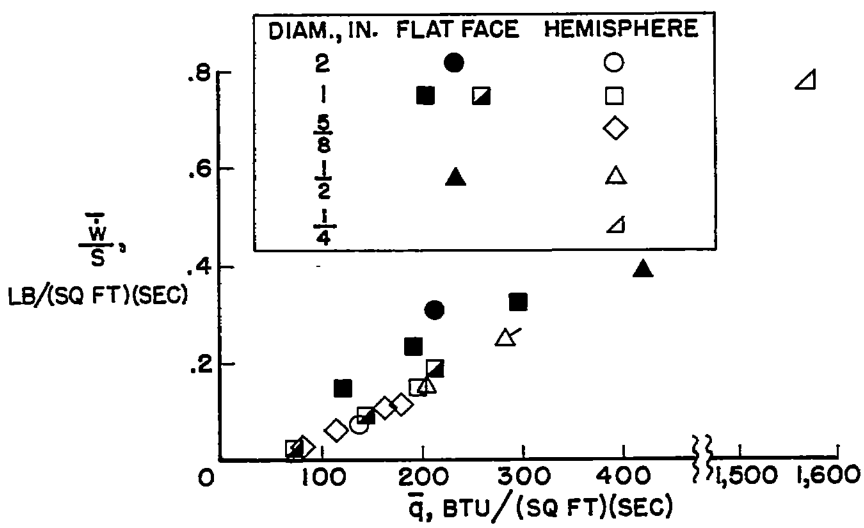

Figure 6

EFFECTIVE HEAT OF ABLATION OF TEFLON

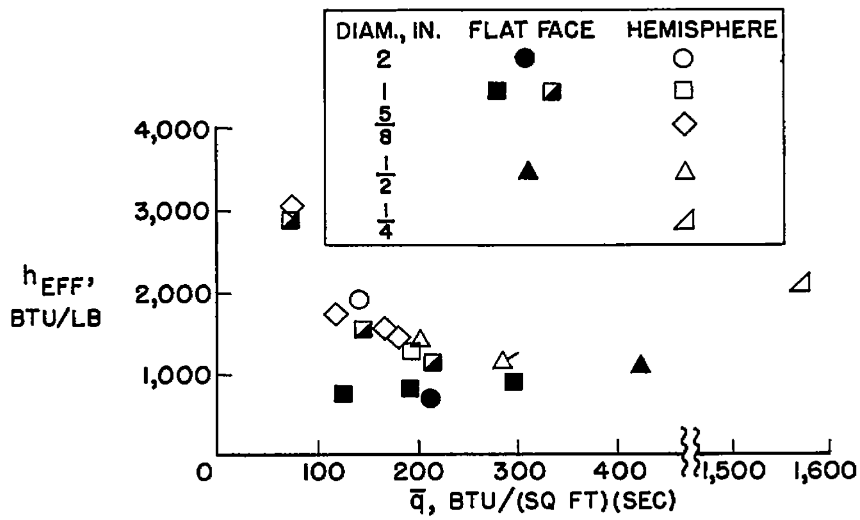

Figure 7

SEVERAL TYPICAL TEFLON MODELS AFTER TEST

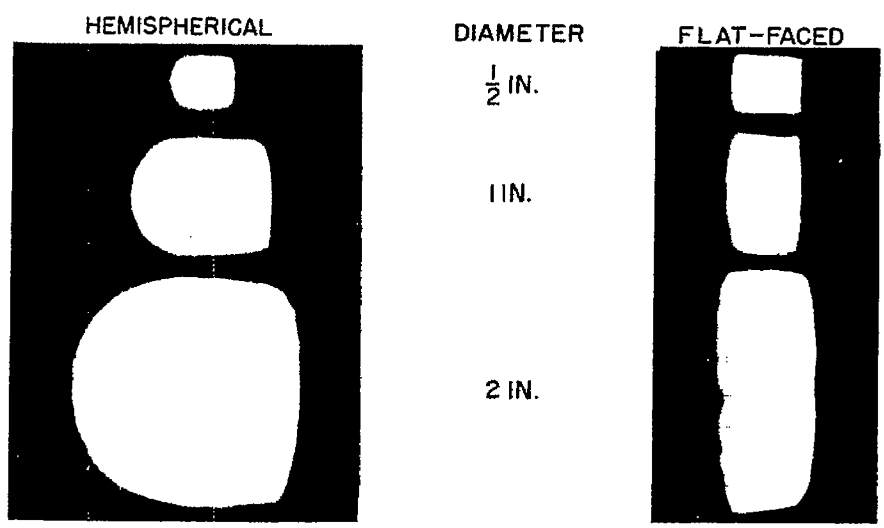

Figure 8 L-58-1672

COMPARISON OF EFFECTIVENESS OF ABLATION AND TRANSPIRATION COOLING

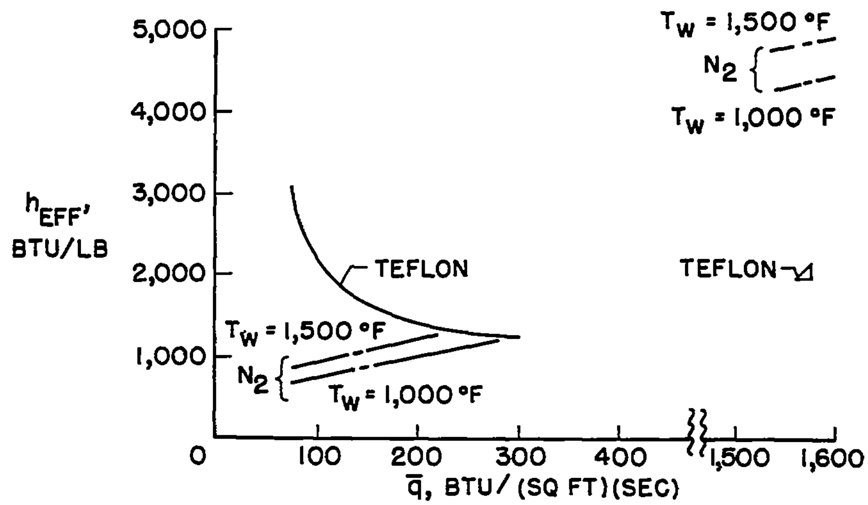

Figure 9

AVERAGE RATE OF ABLATION OF SEVERAL MATERIALS IN ELECTRIC-ARC-POWERED AIR JET

$M_\infty \approx 2.0$; $T_t \approx 11{,}000$ °F

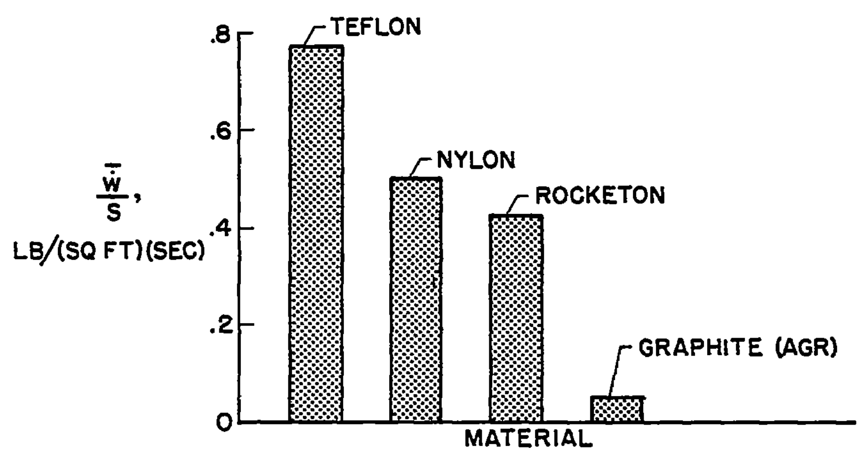

Figure 10

A motion-picture film supplement, carrying the same classification as the report, is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm., 9 min. at 24 frames per sec., color, silent) shows ablation tests of the materials Teflon, nylon, phenolic resin and fiber glass, graphite, and Haveg Rocketon, for which data are presented in the report.

Requests for the film should be addressed to the

Division of Research Information
National Advisory Committee for Aeronautics
1512 H Street, N. W.
Washington 25, D. C.

NOTE: It will expedite the handling of requests for this classified film if application for the loan is made by the individual to whom this copy of the report was issued. In line with established policy, classified material is sent only to previously designated individuals. Your cooperation in this regard will be appreciated.

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