TECHNICAL MEMORANDUM

X-613

AN EVALUATION OF THERMAL PROTECTION FOR APOLLO

By William A. Brooks, Jr., Kenneth L. Wadlin,
Robert T. Swann, and Roger W. Peters

Langley Research Center
Langley Air Force Base, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON December 1961

CONFIDENTIAL

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL MEMORANDUM X-613

AN EVALUATION OF THERMAL PROTECTION FOR APOLLO* **

By William A. Brooks, Jr., Kenneth L. Wadlin,
Robert T. Swann, and Roger W. Peters

L
1
7
7
5

SUMMARY

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The experimental investigation was directed toward the evaluation of ablation materials for both convective and radiative heating and of the influence of char thickness on the performance of a charring ablator. The analytical investigation consisted of a thermal analysis to predict the required thermal protection weight for a flight condition. These investigations indicated that advanced charring ablators having low density are best suited for the thermal shield for Apollo. Such materials achieve high efficiency by combining the desirable features of ablation and reradiation. This efficiency is not seriously affected by the presence of radiative heating and is attained with only moderate char thickness. The efficiency is decreased for the vehicle afterbody because of exposure to lower heating rates which require more insulation weights.

INTRODUCTION

A survey of recent Apollo studies has indicated that thermal-protection weight for the reentry module may constitute 20 to 30 percent of the total reentry weight. Considerable effort therefore should be devoted to obtaining an understanding of the requirements for thermal-protection systems with the objective of developing and utilizing high performance systems which afford weight reduction. The discussion presented herein is centered on the analysis of some experimental investigations and on analytical predictions of thermal-protection requirements for the Apollo spacecraft.

---

*This report was one of the papers presented at the NASA-Industry Apollo Technical Conference, Washington, D.C., July 18-20, 1961.
**Title, Unclassified.

SYMBOLS

h	enthalpy, Btu/lb
k	thermal conductivity, $\frac{\text{Btu}}{\text{ft-sec-}^{\circ}\text{F}}$
P	pressure, atm
Q	total heat input, Btu/ft^2
q	heating rate, Btu/ft^2-sec
T	temperature, $^{\circ}$F
W	weight, lb/ft^2
ρ	density, lb/ft^3

Subscripts:

C	convective
R	radiative
S	stream
W	wall

L
1
7
7
5

FLIGHT THERMAL ENVIRONMENT

Figure 1 shows a typical reentry heating condition for the stagnation point of a vehicle with a small nose radius such as the M-1 configuration. The convective heating, which is characteristic of a long-range overshoot mode of operation, consists of a high, relatively short pulse followed by a low long pulse. One of the dominant features of this type of reentry is the long heating time and the resulting high convective heat input Q_C of 100,000 Btu/ft^2. Another distinguishing feature is the large amount of radiative heat transfer to the body from the hot gases.

The pulse indicated by the dashed curve in figure 1 is an estimated total radiative heating rate (equilibrium plus nonequilibrium radiation) which was obtained from some recent work of the AVCO Corporation. The nonequilibrium component of the radiative heating is several times as large as the equilibrium component. There is considerable uncertainty regarding the radiative heat input Q_R and this uncertainty undoubtedly will not be resolved until suitable flight tests have been made. Radiative heat input will be confined for the most part to the forebody of the spacecraft. For the stagnation point, the total radiative input is 27,500 Btu/ft^2.

Certain characteristics of the heat pulse in figure 1 suggest desirable properties for the thermal shield. These characteristics are listed in the following table along with the resulting shield property requirements:

Characteristic of heating	Requirement
High heating rate	Ablator
High enthalpy	Large volatile fraction
Long time at lower heating rate	High surface temperature for reradiation
Large heat input	High surface temperature and large blocking effect
Long exposure time	Efficient insulator

The initial heating rates q are too high to be handled by reradiation alone and a material that ablates is indicated. The enthalpy is also high during the first pulse and therefore mass injection into the boundary layer is very efficient in reducing the convective heating to the body. This being the case, a substantial fraction of the ablator should be volatile.

About one-half of the total heat input is accumulated at heating rates less than 100 Btu/ft^2-sec. This characteristic, plus the fact that the total input is large, indicates that materials which operate with high surface temperatures should be used to obtain the beneficial effects of reradiation. Also, because of the large input, as much convective heating as possible should be blocked. The long exposure time requires that the material be an efficient insulator in order to minimize the amount of heat that soaks through to the spacecraft interior. In other words, an ablating radiator with a small value of thermal conductivity times density ($k\rho$) is appropriate.

EXPERIMENTAL MATERIALS INVESTIGATION

It is not possible at present to simulate accurately the reentry environment in ground facilities. However, in view of the cost of flight tests test facilities which are available must be used to determine the processes and the parameters which influence the performance of thermal-protection systems. These results may then be extrapolated to the actual environment by analytical means with the final verification accomplished by a limited number of flight tests.

L 1 7 7 5

Because of this philosophy, a series of tests was made in the 2500 kilowatt arc jet at the Langley Research Center with the experimental arrangement shown in figure 2. The convective heating was provided by a 4-inch-diameter subsonic atmospheric pressure arc-heated air jet. A convective heating rate q_C of 100 Btu/ft^2-sec was obtained with a stream enthalpy h_S of 3,500 Btu/lb. A cylindrical graphite grid radiator, mounted directly above the arc-jet nozzle, was used to provide radiative heating rates q_R up to 200 Btu/ft^2-sec. With this arrangement combined radiative and convective heating tests could be made in addition to the familiar convective tests.

The specimens, which were supported by a water-cooled sting, were 3-inch-diameter disks with thicknesses such that all specimens had a weight W of 3 lb/ft^2. A copper calorimeter was bonded to the back face of the specimen. The calorimeter had a heat capacity of approximately 0.5 Btu/ft^2-$^\circ$F which corresponds to about 2 lb/ft^2 of aluminum structure. The principal purpose of these tests was to evaluate the test materials in terms of their ability to limit the flow of heat to the back face. The temperature of the calorimeter and mass losses were measured.

Although these test conditions do not closely simulate the flight environment, it is expected that the relative behavior of materials in flight will be substantially the same as in the test environment. Those areas where the lack of exact simulation will most likely affect the results are indicated as the test data are discussed.

Figure 3 shows the temperature rise that the calorimeter experienced when the 3 lb/ft^2 specimens were exposed to convective heating alone at a cold wall rate of 100 Btu/ft^2-sec. The tests were terminated when the calorimeter temperature rise reached 300° F which was selected as a representative structural temperature. The materials investigated can be divided into three classes and the calorimeter temperature histories are shown by bands for each of the classes: sublimers, ceramic composites, and charring composites. The sublimers tested were Teflon, nylon, and Fluorogreen which is basically Teflon with silica and other additives. These materials as a class showed the poorest ability to limit the calorimeter temperature rise, providing a maximum delay of less than 60 seconds. In addition, they experienced high mass-loss rates with the entire 3 lb/ft^2 being consumed during the tests.

The ceramic composites included foamed alumina, foamed zirconia, foamed silicon carbide, and these same foams impregnated with various resins. In all, 18 different combinations were tested. As a class, ceramic composites provided greater delay times than the sublimers. In general, the high-density unimpregnated foams provided the shortest delay times, and the low-density impregnated materials provided the longest delays. The ceramic composites experienced the smallest mass-loss rates of the three classes tested, being about 1/15 those of the sublimers. The ceramics experienced approximately a 20-percent mass loss.

The charring composites, in general, consist of phenolic, epoxy, or other resins filled with organic or inorganic materials in the form of powder, fibers, or microballoons. Fifty-five different composities were evaluated including G.E. castable ablators, AVCO Avcoat series, Emerson Electric Thermo-Lag series, NARMCO series, and NASA series. The charring composites show the best ability to limit heat flow to the back surface, limiting the calorimeter temperature rise to 300° F for times up to 260 seconds. Again, the lower density materials generally provided protection for longer times than did the higher density materials. The right boundary of the charring composite band corresponds to materials typical of which is a 50-50 mixture of phenolic-nylon with 50 percent of the phenolic in the form of microballoons. The curve in the center of the band is for a 50-50 mixture of phenolic and powdered nylon without microballoons. This material, which was compounded at the Langley Research Center, was used as a reference material for experimental and analytical studies to be discussed subsequently. The charring composites experienced moderate mass-loss rates, these rates being in general about twice those experienced by the ceramic composites. About 85 percent of the material was consumed during the tests.

As previously mentioned, these tests were made with a stream enthalpy of 3,500 Btu/lb. If the enthalpy were increased to the higher levels encountered in the Apollo reentry environment, all three bands would shift to the right. However, it is expected that the charring composites would continue to show superior performance for the Apollo conditions.

The results presented in figure 3 indicate that charring ablators are the type of thermal-protection materials appropriate for the Apollo spacecraft. The advanced charring ablators which have additives to lessen the density, to increase the integrity of the char, and to lessen shape changes should be employed.

Reentry at escape velocity is expected to result in substantial radiative heat loads as previously indicated. The prospect of radiative heat loads has caused speculation as to the performance of ablative materials under combined radiative and convective heating. In view of this, a preliminary evaluation of the influence of radiative heat loads on ablation materials was made.

L
1
7
7
5

The initial results of this program are presented in figure 4. The efficiencies Q/W of three materials - Teflon, Fluorogreen, and phenolic-nylon - are given as a function of the total cold-wall heating rate. Efficiency is defined as the total cold-wall heat input to the specimen, before the calorimeter experienced a 300° F temperature rise, divided by the initial specimen weight, which was 3 lb/ft^2. Tests have also been made with initial specimen weights of $1\frac{1}{2}$ and 6 lb/ft^2. These tests indicated that the initial weight has a small influence on efficiency with the larger weights leading to a slight increase in efficiency. Data are shown for radiative heating alone, convective heating alone, and combined radiative and convective heating.

For Teflon, the efficiency for convective heating only is about 1,900 Btu/lb. With radiative heating only the efficiency drops to essentially zero. This radical change in efficiency is caused by the transparency of Teflon to thermal radiation. When the convective heating is held approximately constant and the radiative component is increased, the efficiency again drops to a low level. The addition of only a small amount of radiative heating causes most of the decrease.

For Fluorogreen, which is essentially Teflon with additives that increase the opaqueness to thermal radiation, the efficiency for convective heating alone is the same as for Teflon. However, pure radiative heating does not decrease efficiency as much as it did in the case of Teflon. The series of tests with combined radiative and convective heating produced higher efficiency than in the case of Teflon.

For phenolic-nylon, a series of convective tests shows an increase in efficiency with increasing heating rate. At a comparable heating rate, phenolic-nylon has a much greater efficiency, 5,600 Btu/lb, than Teflon and Fluorogreen. The substantial increase in efficiency is caused by the char formation which reradiates heat.

A series of tests involving radiative heating alone shows the same level of efficiency and rate of increasing efficiency that was obtained in the convective tests. Tests of combined radiative and convective heating with the convective component approximately equal to 100 Btu/ft^2-sec and with increasing amounts of radiative heating also produced about the same trend in efficiency. In all cases, as the total heating rate was increased, surface temperatures increased and caused increased reradiation and efficiency.

The point that can be made with these test results is that, for the test environment, phenolic-nylon has the same efficiency for convective or radiative heating. The presence of radiative heating does not cause a degradation in the performance of the material.

It has been established that the high surface temperatures, which are possible when chars are present, result in increased efficiency. There is, however, some question as to the amount of char required. Figure 5 shows the results of a preliminary study of char thickness. Chars were developed with a convective heating rate of 110 Btu/ft^2-sec. Thick specimens, weighing 9 lb/ft^2, were used in this phase of the study to provide for long test times and thick char layers. The char thickness in inches and the mass-loss rate in lb/ft^2-sec are plotted as functions of time. Experimental points have been fitted with a faired line to show the growth of the char thickness. The char thickness grew rapidly at first; however, the rate of the growth diminished with time and the char approached a thickness of about 0.25 to 0.3 inch under these test conditions with a slight decrease in thickness occurring after 240 seconds.

The mass-loss rate is shown by a curve which was derived from measurements of the mass losses. The mass-loss rate decreased rapidly with time when the char layer was thin and was rapidly building up. After the initial rapid decrease, the mass-loss rate changed very slowly and became constant. This shows that the mass-loss rate is strongly influenced by the initial char formation but not influenced as significantly by further development of thick chars.

It is interesting to note that the specimen surface temperature T_W, shown on the char-thickness curve, increased from 3,060° F after an exposure of 30 seconds to 3,460° F after 120 seconds and remained essentially constant thereafter. The period of increasing temperature corresponds to the transient period in mass-loss rate.

The conclusion that can be drawn here is that char formation is important but the benefits diminish rapidly after a certain thickness is obtained. For phenolic-nylon this thickness appears to be about 0.2 of an inch, but it may differ for other materials. Although the test environment does not exactly simulate the flight environment, it is expected that the same conclusion applies to the flight environment - that is, in flight only a moderate thickness of char layer will be required to derive the major benefits.

ANALYTICAL PREDICTIONS

The thermal analysis which must be used to predict the required
thermal-protection weight for Apollo is now discussed. Figure 6 shows
one of the models which is currently being analyzed. The model incor- L
porates a char layer and a layer of virgin material bonded to a honey- 1
comb structural panel. A cooling system is utilized to maintain the 7
interior wall at temperatures less than 100° F. 7
5

The mechanism of char removal is not at present well understood so provisions have been made in the computer program for either oxidation, which removes char at a calculated rate, or mechanical erosion, which produces a char layer of constant thickness. Test results obtained for charring ablators have indicated that combustion of the char or the gases of pyrolysis may be a significant factor in the performance of these materials. At the present time, this phenomenon is not understood well enough to be included in these calculations. The computer program has a provision for a variable temperature of pyrolysis but, in the results to be presented subsequently for phenolic-nylon, a constant pyrolysis temperature of 1,250° F was used.

The bond-line temperature was assumed not to exceed 600° F which is a representative maximum temperature for organic bonding materials. With the 600° F limitation on bond-line temperature, only small amounts of heat reached the interior wall because of the insulating qualities of the honeycomb panel (ref. 1).

The computer program permits both convective and radiative heating inputs. Both forms of heating contribute to the rate of pyrolysis. However, when the gases produced by pyrolysis are injected into the boundary layer, they block only the aerodynamic heating. The extent of the blocking has been determined from solutions of the boundary-layer equations (ref. 2) and has been programed into the routine.

The behavior of charring ablators is very complex and one might anticipate difficulties when attempting to analytically match experimental results. This was found to be the case, particularly during rapidly changing transient situations. A great deal of the difficulty arises because of the many unknown properties, such as the char conductivity, the specific heat of the gases resulting from pyrolysis, the heat of pyrolysis, and the temperature of pyrolysis.

When the test environment was programed into the calculating routine, analytical results were obtained which are in good agreement with the experimental data shown in figure 4 for phenolic-nylon. Agreement has been obtained for the three heating conditions: radiative heating only, convective heating only, and combined heating.

The analytical routine has also been used to determine that the decrease in char layer thickness, shown in figure 5, is caused by an increase in char removal rate. Experimentally determined char-loss rates were programed into the routine producing char-thickness curves similar to those shown in the figure.

For the most part, effort has been concentrated on determining the variation of char conductivity with temperature that would result in the measured char thickness and that would match experimentally determined internal temperatures. Figure 7 shows a comparison of calculated and experimental temperature histories obtained with phenolic-nylon heated at a rate of about 100 Btu/ft^2-sec. Temperature is plotted as a function of time for several stations measured from the back surface. The solid curves are experimental temperature traces and the dashed curves are calculated results. The dashed curves shown in figure 7 are the best fit to the experimental results that has been obtained. It was found that the conductivity providing the best fit was a cubic function of temperatures with values as high as forty times the conductivity of the virgin material.

The approach that has been taken in the present program is to determine what properties must be used to bring about good agreement between analytical and experimental results and to use these properties to analytically extrapolate to the flight conditions. With this estimate of the char properties of phenolic-nylon, predictions were made of the weight of thermal protection required to protect the stagnation area from the heat pulse shown in figure 1. The results are shown in figure 8 where the required weight per square foot for maintenance of a maximum bond-line temperature of 600° F is plotted as a function of maximum char layer thickness. In the computations, when the char thickness increased to a desired amount, it was thereafter assumed to remain constant. The required weight is shown by a band whose lower edge corresponds to the analytically determined conductivity and whose upper edge corresponds to twice that conductivity. Doubling the conductivity produces about a 30-percent increase in weight for the entire range of char thickness. In general, weight decreases as the char layer thickness increases. However, the most substantial decreases occur at the thinner char layers. At the right, the tick mark indicates the weight corresponding to the limiting case of a continuous buildup of char thickness.

There are no available experimental data relating char removal to the basic mechanisms which are currently postulated. In the high-dynamic-pressure flight environment associated with intercontinental ballistic missiles, char thickness of the order of 0.05 inch has been reported. At the present time, very little can be said about the thicknesses of char layers that will be obtained in the Apollo reentry environment.

However, char layers of about 0.1 inch appear to be a reasonable assumption for the Apollo environment. With this char thickness, the required weight of thermal protection given by the lower edge of the band is 13 lb/ft^2. With the convective component of heating only, the weight is 10 lb/ft^2. The radiative component of heating causes an increase of 3 lb/ft^2 or 30 percent. The 30-percent increase is almost equal to the increase in total heat input caused by the radiative component. This means that the weight increase results primarily because of an increase in total heat input and not because of the type of heating.

L1775

Thermal protection for the afterbody was considered and the results are shown in figure 9. The required weight per square foot is plotted as a function of the local heat input. Up to 100,000 Btu/ft^2, the heating is assumed to be convective only. Beyond 100,000 Btu/ft^2, the heat input is increased to the stagnation-point value of 127,000 Btu/ft^2 by adding a radiative component. Efficiency, defined as the heat input divided by the required weight, is also shown. The significant point to be made is that weight reduction is not proportional to the reduction in heat input. Because of the long exposure to lower heating rates more ablation material is required for self-insulation on areas aft of the stagnation point. More self-insulation weight leads to decreased efficiency, as can be seen in the figure. For total heat input greater than 100,000 Btu/ft^2, there is a small reduction in efficiency caused by the radiative component of heating. This is contrary to the previously presented experimental data and may result from the differences in the heating environments.

CONCLUSIONS

Although the presented experimental data and analytical predictions are at present limited in scope, they are believed to support the following conclusions regarding a thermal shield for Apollo:

1. An ablating radiator approach which achieves high efficiency by combining the desirable features of ablation and reradiation is appropriate.

2. In particular, advanced charring ablators which have low density and produce strong chars provide best efficiency.

3. A char layer is essential to the efficiency of charring ablators but only moderate thicknesses of char with good integrity appear to be required.

4. The presence of radiative heating in the Apollo reentry environment does not seriously affect the efficiency of charring ablators.

5. The efficiency of the thermal protection required for the afterbody is decreased because of exposure to lower heating rates which require more insulation weight.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., July 19, 1961.

REFERENCES

1. Swann, Robert T., and Pittman, Claud M.: Analysis of Effective Thermal Conductivities of Honeycomb-Core and Corrugated-Core Sandwich Panels. NASA TN D-714, 1961.

2. Swann, Robert T.: Effect of Thermal Radiation From a Hot Gas Layer on Heat of Ablation. Jour. Aerospace Sci. (Readers' Forum), vol. 28, no. 7, July 1961, pp. 582-583.

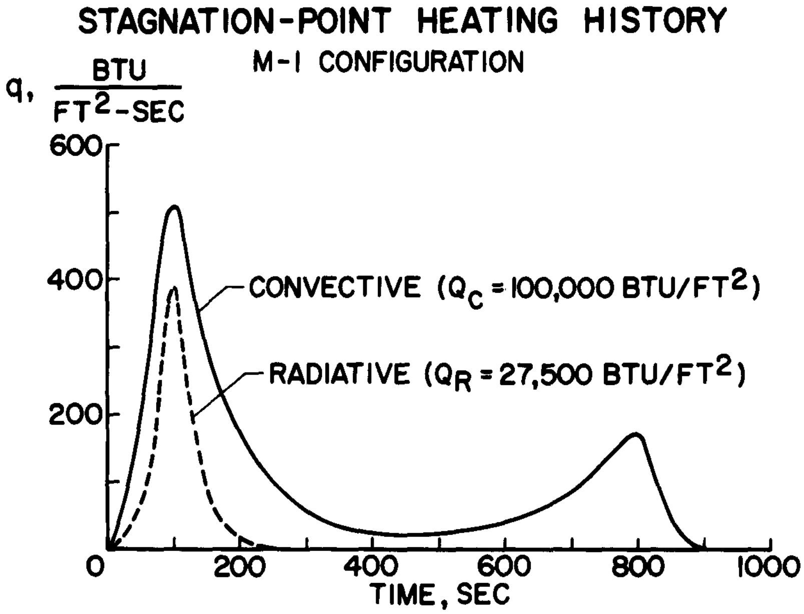

Figure 1

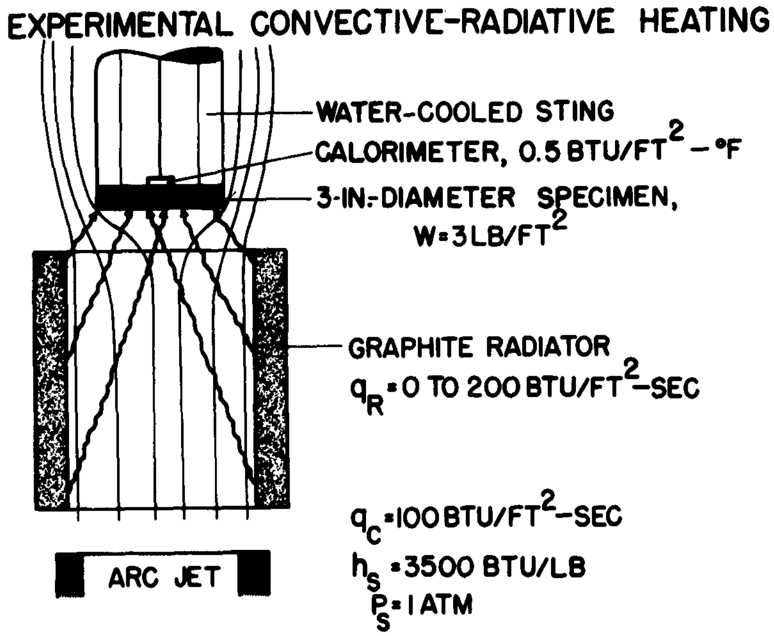

Figure 2

L-1775

L-1775

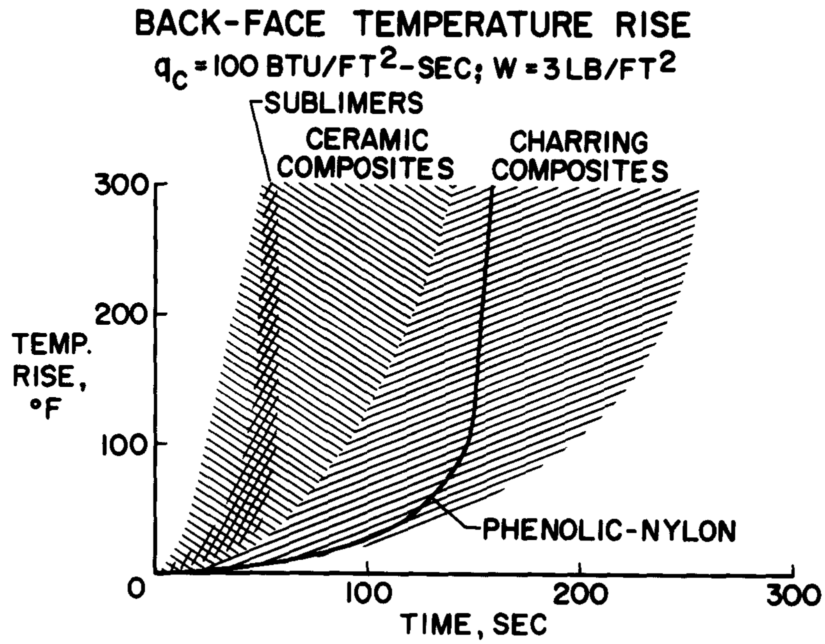

Figure 3

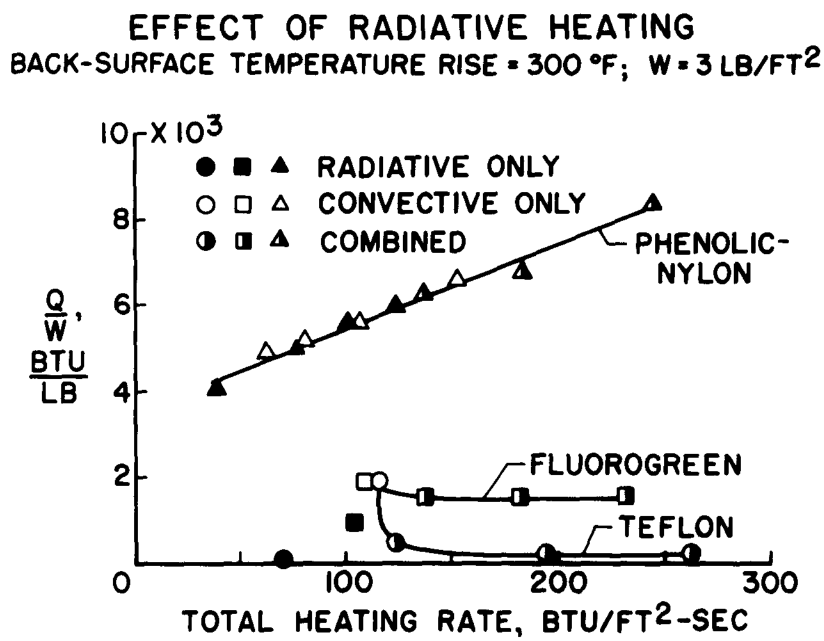

Figure 4

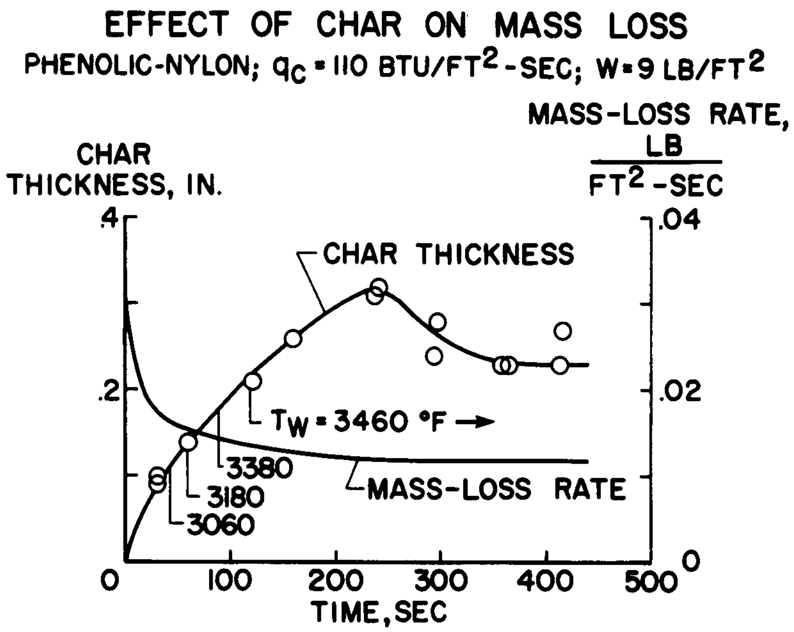

Figure 5

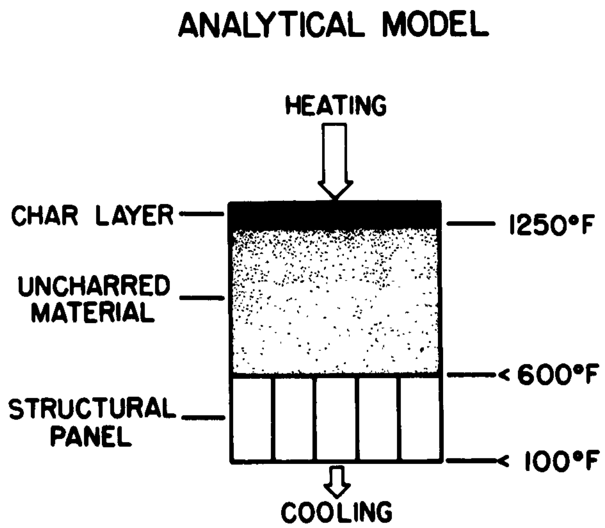

Figure 6

L-1775

L-1775

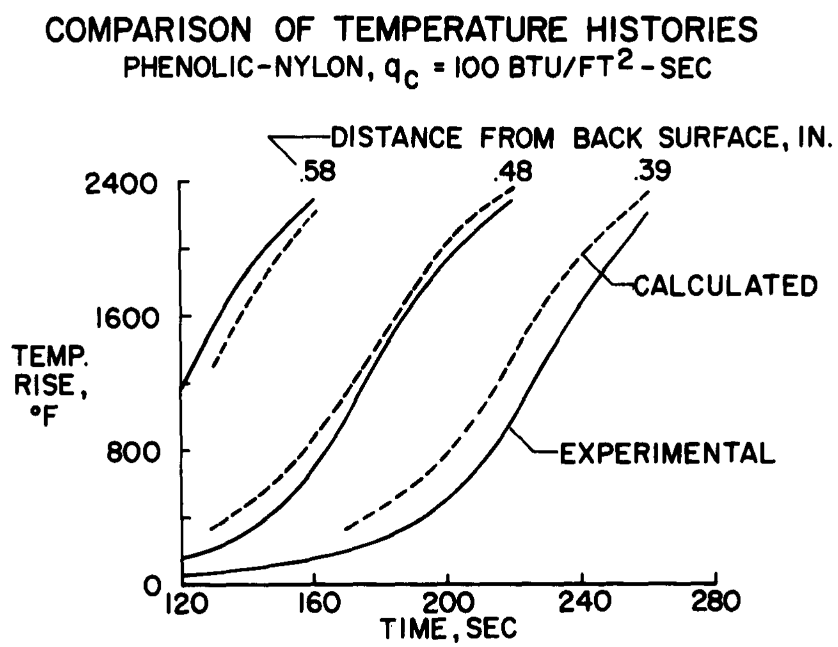

Figure 7

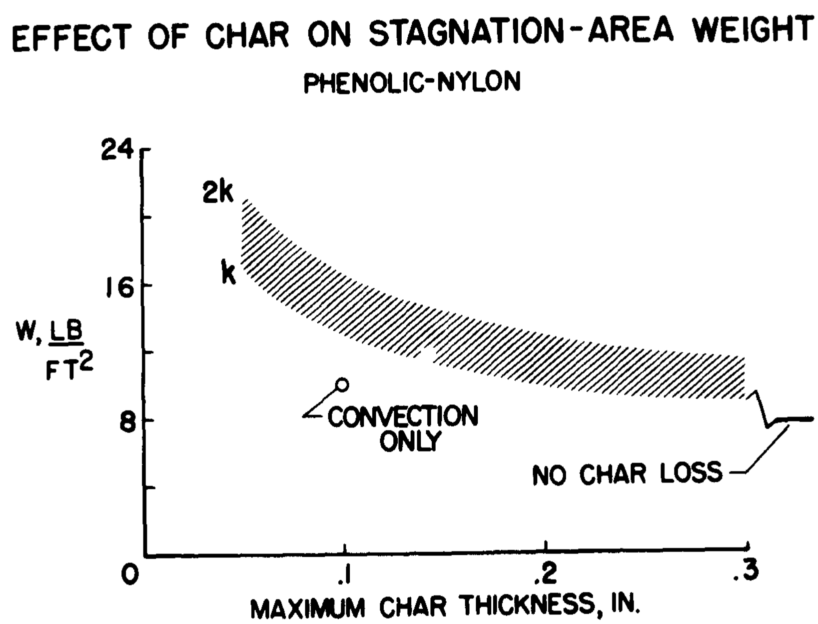

Figure 8

L-1775

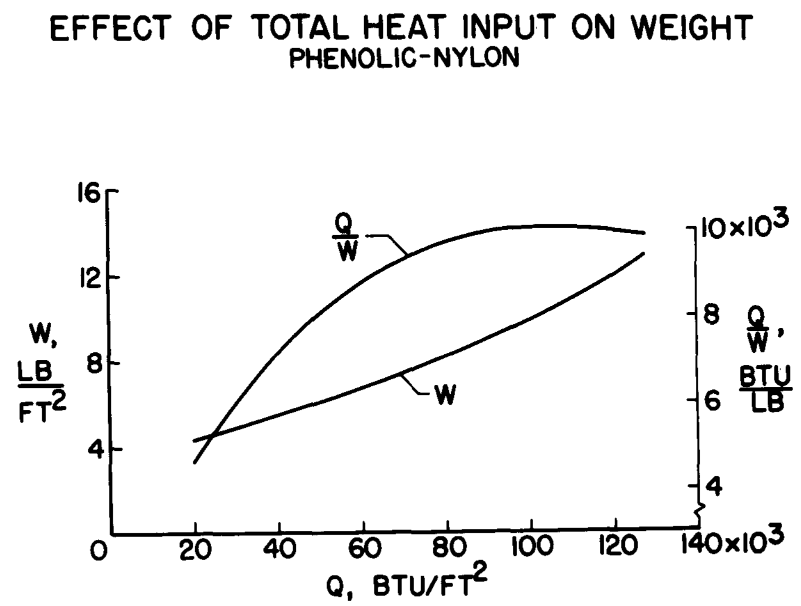

Figure 9

NASA-Langley, 1961 L-1775

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution: 2, Aerodynamics, missiles and space vehicles; 5, Atmospheric entry; 20, Fluid mechanics; 26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution: 2, Aerodynamics, missiles and space vehicles; 5, Atmospheric entry; 20, Fluid mechanics; 26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution: 2, Aerodynamics, missiles and space vehicles; 5, Atmospheric entry; 20, Fluid mechanics; 26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution: 2, Aerodynamics, missiles and space vehicles; 5, Atmospheric entry; 20, Fluid mechanics; 26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution:
2, Aerodynamics, missiles and space vehicles;
5, Atmospheric entry;
20, Fluid mechanics;
26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution:
2, Aerodynamics, missiles and space vehicles;
5, Atmospheric entry;
20, Fluid mechanics;
26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution:
2, Aerodynamics, missiles and space vehicles;
5, Atmospheric entry;
20, Fluid mechanics;
26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution:
2, Aerodynamics, missiles and space vehicles;
5, Atmospheric entry;
20, Fluid mechanics;
26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution:
2, Aerodynamics, missiles and space vehicles;
5, Atmospheric entry;
20, Fluid mechanics;
26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution:
2, Aerodynamics, missiles and space vehicles;
5, Atmospheric entry;
20, Fluid mechanics;
26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution:
2, Aerodynamics, missiles and space vehicles;
5, Atmospheric entry;
20, Fluid mechanics;
26, Materials, other.)

NASA

CONFIDENTIAL

NASA TM X-613
National Aeronautics and Space Administration.
AN EVALUATION OF THERMAL PROTECTION FOR APOLLO. William A. Brooks, Jr., Kenneth L. Wadlin, Robert T. Swann, and Roger W. Peters. December 1961. 16p.
(NASA TECHNICAL MEMORANDUM X-613)
CONFIDENTIAL

(Title, Unclassified)

Results of experimental and analytical investigations associated with thermal protection for Apollo are presented. The investigations indicated that advanced charring ablators having low density and producing strong chars are best suited. The efficiency achieved by such materials is indicated. This efficiency is attained with only moderate char thickness and is not seriously affected by the presence of radiative heating.

Copies obtainable from NASA, Washington

CONFIDENTIAL

I. Brooks, William A., Jr.
II. Wadlin, Kenneth L.
III. Swann, Robert T.
IV. Peters, Roger W.
V. NASA TM X-613

(Initial NASA distribution:
2, Aerodynamics, missiles and space vehicles;
5, Atmospheric entry;
20, Fluid mechanics;
26, Materials, other.)

NASA

CONFIDENTIAL