NASA TECHNICAL NOTE

NASA TN D-3735

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NASA TN D-3735

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1966

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SUMMARY

The results of a parametric study of a representative low-density charring ablator are presented and discussed. The results were obtained from an ablation analysis programed for solution on a high-speed digital computer. The thermal performance of the charring ablator was examined over a range of environmental conditions.

The results show that the thermal performance of a charring ablator is strongly influenced by the environmental conditions, particularly stream enthalpy and oxygen concentration. The results also show that the effect of material properties on thermal performance depends upon the stream enthalpy level.

INTRODUCTION

Charring ablation materials have been extensively studied both experimentally and theoretically. However, present ground test facility limitations have confined the experimental studies of charring ablator thermal performance in any given facility to a narrow range of thermochemical environmental conditions, and the theoretical studies have been restricted by uncertainties in material properties. One means of overcoming these restrictions is provided by the parametric study, wherein the range of environmental and material property parameters can be extended.

In the present report, the results from a parametric study of a representative low-density charring ablator are presented. A low-density material was selected because it has been shown (for example, refs. 1 to 4) that such materials, that is, those with a specific gravity of 0.65 or less, are more efficient as thermal protection systems than are the denser materials. The present study is intended to show the manner in which the thermal performance of the representative charring ablator is influenced by environmental conditions. It is also intended to indicate which material properties most influence the thermal performance and the extent to which the material properties must vary to provide significant variations in the thermal performance.

Thermal performance calculations were made for a wide range of stream enthalpy, heating rate, oxygen concentration, and material properties by using an ablation analysis described in references 5 and 6. Heating conditions typical of many ground test facilities were simulated by holding the stream enthalpy and the cold-wall convective heating rate constant for each calculation. Some of the results reported herein were also reported in reference 7.

SYMBOLS

The units used for the physical quantities defined herein are given both in the U.S. Customary Units and in the International System of Units, SI (ref. 8). An appendix is included for the purpose of explaining the relationship between these two systems of units.

A	specific reaction rate constant
B	activation temperature; ratio of activation energy to gas constant
C_e	oxygen concentration
c_p	specific heat of charred material
c_p'	specific heat of uncharred material
$\bar{c}_p$	specific heat of gaseous products of pyrolysis
E	thermal effectiveness, $\frac{q_{cw}t}{m}$
f	fraction of original material which vaporizes during pyrolysis
h	enthalpy
h_e	stream enthalpy
Δh_c	heat of combustion of char
Δh_p	effective heat of pyrolysis

K	reaction rate constant
k	thermal conductivity of charred material
k'	thermal conductivity of uncharred material
m	mass per unit area of ablation material
$\dot{m}_c$	rate of char removal
$\dot{m}_p$	rate of formation of gaseous products of pyrolysis
N_{Le}	Lewis number, $\frac{\text{Prandtl number}}{\text{Schmidt number}}$
p	pressure
Q^*	effective heat of ablation
q	heating rate
q_{cw}	cold-wall convective heating rate
$q_{c,net}$	net convective heating rate (see eq. 3(b))
q_R	radiant heating rate
T	absolute temperature
t	time
x	coordinate normal to surface
α	absorptivity
β	transpiration factor for char mass loss injection into boundary layer
ϵ	emissivity

η	transpiration factor for gaseous products of pyrolysis which are injected into boundary layer
λ	mass of char removed per unit mass of oxygen diffusing to the surface
ρ	density of charred material
ρ'	density of uncharred material
σ	Stefan-Boltzmann constant

Subscripts:

A	based on total mass loss
B	based on mass of material degraded
e	external to boundary layer
ref	reference
w	condition at wall

A dot over a symbol indicates differentiation with respect to time.

ABLATION ANALYSIS

A charring ablator in a high-temperature gas stream is shown schematically in figure 1. When a charring ablator is subjected to aerodynamic heating, this type of ablator performs qualitatively as follows: Thermal degradation of the material by convective and radiative heating produces a char layer. The char layer provides both insulation for the uncharred material and a high-temperature outer surface for reradiation of heat. The heat passing through the char layer is partially absorbed by pyrolysis at the interface

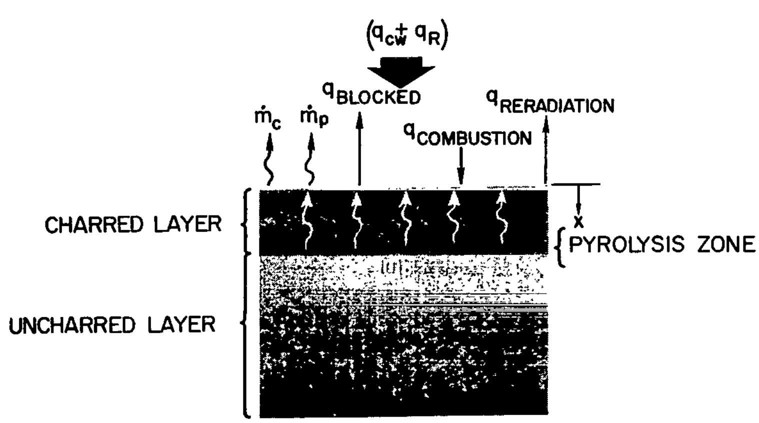


Figure 1.- Schematic diagram of charring ablator. L-2324-1

between the char layer and the uncharred material. The remaining heat is conducted into the uncharred material. The gases generated by pyrolysis are heated as they pass through the char layer which reduces the amount of heat reaching the pyrolysis interface. The gaseous products of pyrolysis, after transpiring through the char layer, are injected into the boundary layer; this injection causes a reduction in convective heat transfer. The reduction in convective heating is commonly referred to as blocking and has the same effect as that obtained with subliming ablators such as teflon. As the thickness of the char layer increases by pyrolysis, char removal may occur from thermal, chemical, and/or mechanical mechanisms. Therefore, the total char thickness may increase or decrease depending on the relative rates of char formation and removal. These various processes are related quantitatively in the following section.

In the analysis presented in references 5 and 6, it is assumed that the thermal properties of the char are functions of temperature only, that all heat flow is normal to the surface, that the gases which transpire through the char are at the char temperature, and that the pyrolysis zone is a plane between the charred and uncharred material. Reference 9 indicates that treating the pyrolysis zone as a plane is a reasonable assumption. The differential equation governing the temperature in the char is (from ref. 5)

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \dot{m}_p\bar{c}_p\frac{\partial T}{\partial x} = \rho c_p\frac{\partial T}{\partial t} \tag{1}$$

Conditions on the temperature or heating rate must be specified at each boundary to solve this equation. For a charring ablator with low rates of mass transfer into the boundary layer and with char removal by oxidation only, the necessary boundary conditions at the char surface are (from ref. 5)

$$\underbrace{q_{cw}\left(1 - \frac{h_w}{h_e}\right)\left[1 - (\beta\dot{m}_c + \eta\dot{m}_p)\frac{h_e}{q_{cw}}\right] + \alpha q_R + \dot{m}_c\,\Delta h_c}_{\text{Heat input}} = \sigma\epsilon T^4 + \left(k\frac{\partial T}{\partial x}\right)_{surface} \tag{2}$$

= Reradiation + Heat conducted into material

where the rate of char removal is

$$\dot{m}_c = \frac{1}{2}\left\{-\frac{(h_e - h_w)K^2 p_w}{q_{c,net}\lambda N_{Le}^{0.6}} + \sqrt{\left[\frac{(h_e - h_w)K^2 p_w}{q_{c,net}\lambda N_{Le}^{0.6}}\right]^2 + 4K^2 p_w C_e}\right\} \tag{3a}$$

and the net convective heating rate $q_{c,net}$ is

$$q_{c,net} = q_{cw}\left(1 - \frac{h_w}{h_e}\right)\left[1 - (\beta\dot{m}_c + \eta\dot{m}_p)\frac{h_e}{q_{cw}}\right] \tag{3b}$$

and K is the reaction rate constant

$$K = Ae^{-B/T} \tag{3c}$$

For the case where the pyrolysis zone is treated as a plane, the temperature of the char and the uncharred material must be equal at the interface. In general, the temperature at the interface will be a function of the rate of pyrolysis

$$T_{char} = T_{uncharred} = f(\dot{m}_p) \tag{4a}$$

From an energy balance at the interface

$$\left(-k\frac{\partial T}{\partial x}\right)_{char} = \dot{m}_p\,\Delta h_p - \left(k\frac{\partial T}{\partial x}\right)_{uncharred} \tag{4b}$$

Solution of these equations, together with the transient heat conduction equation in the uncharred material and in any insulation layer, provides an estimate of the heat shielding capability of a charring ablator thermal protection system. The present analysis has been extensively used to study the performance of thermal protection systems in both flight and ground tests.

PROCEDURE FOR PARAMETRIC STUDY

The present study was based on the representative set of material properties (given in table I) for a low-density charring ablator. Several of these properties were systematically varied and the resulting effect on thermal performance was determined. In compiling these properties, the thermal conductivity of the charred material was assumed to vary linearly with temperature. This assumption is at variance with the char conductivity data reported in reference 10, which was unavailable at the onset of the present study. However, inasmuch as char conductivity values have been measured in the range from the values of reference 10 to essentially constant values for all temperatures (as indicated by unpublished data), the assumed linear variation with temperature is considered reasonable. Although the values of some of the other material properties are uncertain, the values shown in table I are in satisfactory agreement with the data in reference 10, wherever comparisons could be made. Therefore, since the intent of the present paper is to show the gross effect of large changes in material properties on thermal protection capabilities, table I is considered representative of a variety of low-density charring ablation materials.

The thermal performance of the charring ablation material was evaluated in terms of the thermal effectiveness parameter E which can be defined as the product of the cold-wall convective heating rate on a nonablating surface and the time required to achieve a specified back surface temperature rise, divided by the unit area mass of ablation material,

$$E = \frac{q_{cw}t}{m}$$

The value of this parameter depends on both the mass loss characteristics and the insulating properties of materials. This parameter provides the best available method for evaluating the relative performance of various ablation materials exposed to environmental conditions ranging from ground facility combustion products to supercircular atmospheric entry. Although the parameter E does not in itself provide information on which to base heat shield designs, the parameter is useful in comparing various materials subjected to similar test environments or in investigating the effect of changes in environment on a particular material.

Another parameter often used to evaluate the performance of ablation materials is the effective heat of ablation Q^*. The effective heat of ablation is defined in this study as the ratio of the product of the cold-wall convective heating rate on a nonablating surface and exposure time to the mass loss of the material. A comparison of Q^* and E is given in a subsequent section.

The calculations were made with the thickness of material corresponding to a unit mass m of 3 lbm/ft^2 (14.6 kg/m^2) in all cases. The cold-wall convective heating rate and stream enthalpy were held constant for each calculation and thus represent heating rate and stream enthalpy conditions of many ground test facilities. For the present study, a heating rate range of 50 to 200 Btu/ft^2-sec (0.6 to 2.3 MW/m^2) and a stream enthalpy range of 1000 to 25 000 Btu/lbm (2.3 to 58 MJ/kg) were considered. The specified back surface temperature rise was 300° R (167° K) for all calculations except those noted.

The calculations were made for convective heating only. Although radiant heating is significant at enthalpies above 25 000 Btu/lbm (58 MJ/kg) on portions of bodies with large radii, the behavior of charring ablators, except for blocking, is similar whether the heating is convective or radiative. Thus, radiative heating was not considered in this study.

The oxidation char removal mechanism used in the calculations will always be applicable. The presence of other mechanisms not considered, such as removal of the char by aerodynamic shear, would have an adverse effect on the thermal performance.

RESULTS AND DISCUSSION

Effects of Environmental Conditions on Performance of Charring Ablators

Heating rate.- The effect of heating rate on the performance of the reference charring ablator in an airstream at different constant enthalpy levels is shown in figure 2.

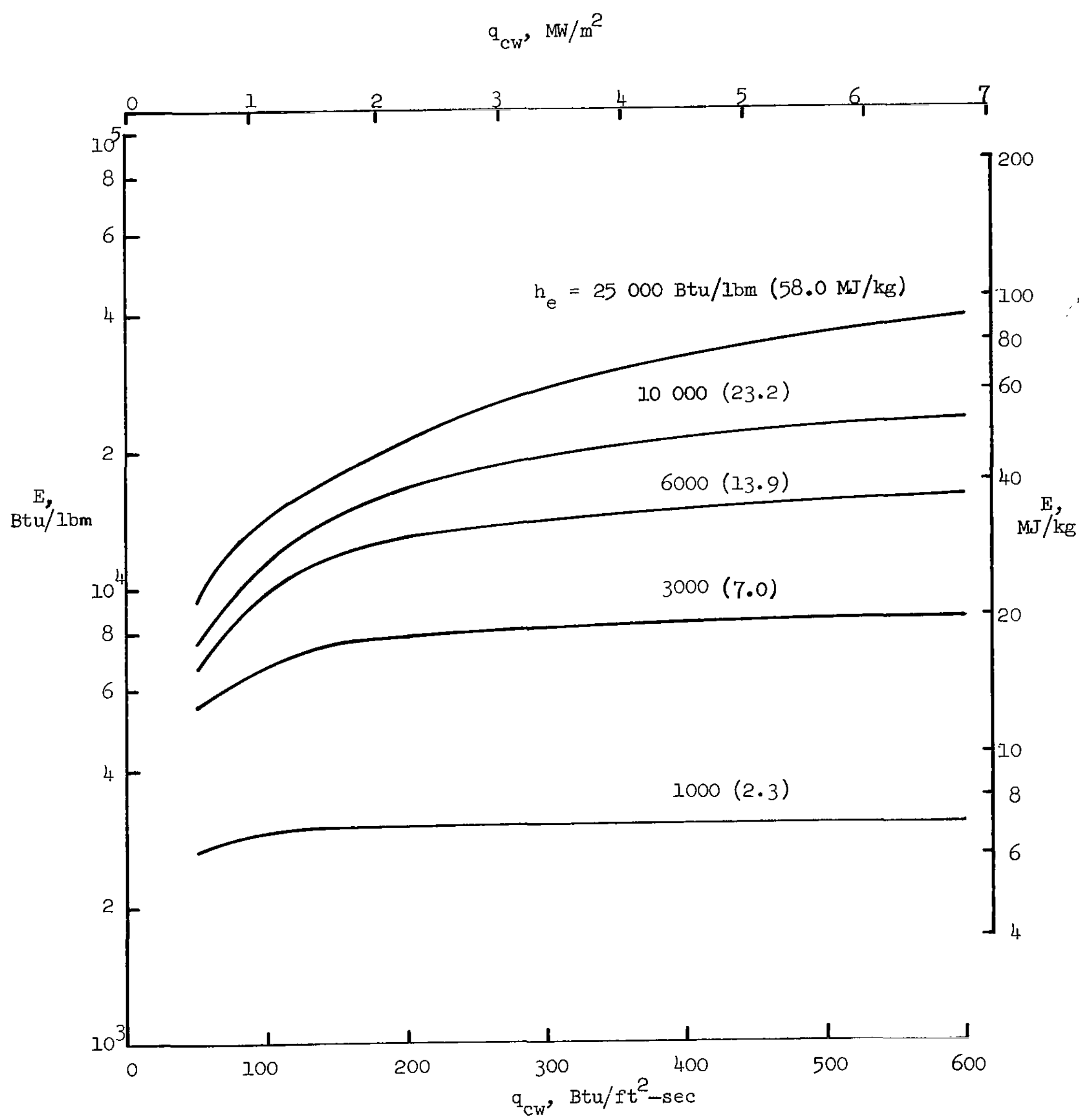


Figure 2.- Effect of heating rate on thermal effectiveness of charring ablators. $C_e = 0.232$.

The calculations show that at an enthalpy of 1000 Btu/lbm (2.3 MJ/kg) the thermal performance is relatively insensitive to heating rate over the range considered. As the stream enthalpy is increased there is a progressively greater increase in thermal performance with increases in heating rate.

At low heating rates, about 150 Btu/ft^2-sec (1.7 MW/m^2) and below, the effectiveness depends primarily on the thermal conduction characteristics of the material. At higher heating rates, the effectiveness depends primarily on the ablation characteristics of the material, such as blocking, which are beneficial at high heating rates and high enthalpy levels.

Stream enthalpy.- Figure 3 shows the effect of changes in stream enthalpy on the performance of the reference charring ablator for several heating rates and two back

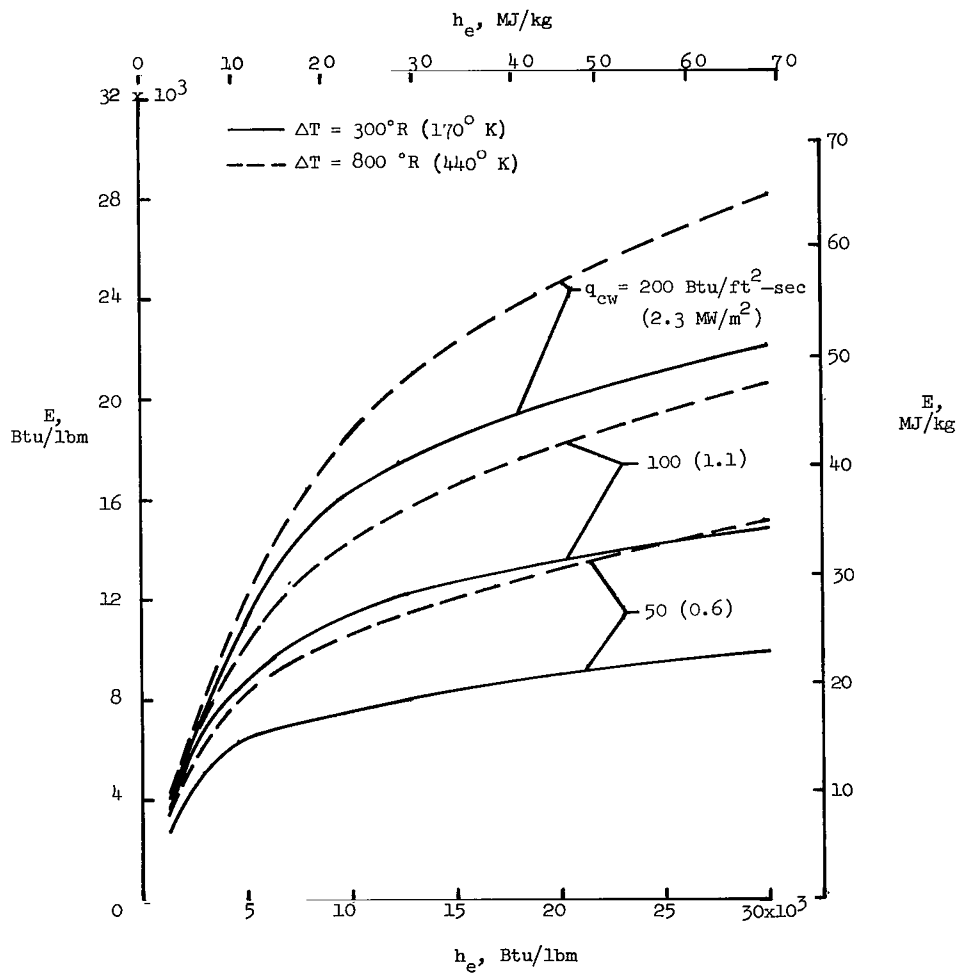


Figure 3.- Effect of stream enthalpy on thermal effectiveness of charring ablators. C_e = 0.232.

surface temperatures. At all heating rates, an increase in stream enthalpy results in increased thermal performance. The increase in thermal performance is particularly rapid at stream enthalpies of 6000 Btu/lbm (14 MJ/kg) or less. This increase in performance results from two factors. First, as the enthalpy of the stream is increased, there is an increase in the blocking effectiveness of the gases of pyrolysis. Second, as the stream enthalpy increases at a constant cold-wall convective heating rate, the flow of oxygen to the char surface decreases in relation to the flow of energy from the stream. This decrease reduces the rate of char oxidation.

Also shown in figure 3 is the increase in thermal performance which may be obtained if the temperature rise at the back surface of the uncharred material is changed from 300° R (170° K) to 800° R (440° K). The increase in performance is particularly significant at the higher enthalpies. The magnitude of this increase in performance at high enthalpies would not be indicated by tests at low enthalpies.

Stream oxygen concentration.- Stream oxygen concentration affects the thermal performance of the reference charring ablation material as shown in figure 4. The

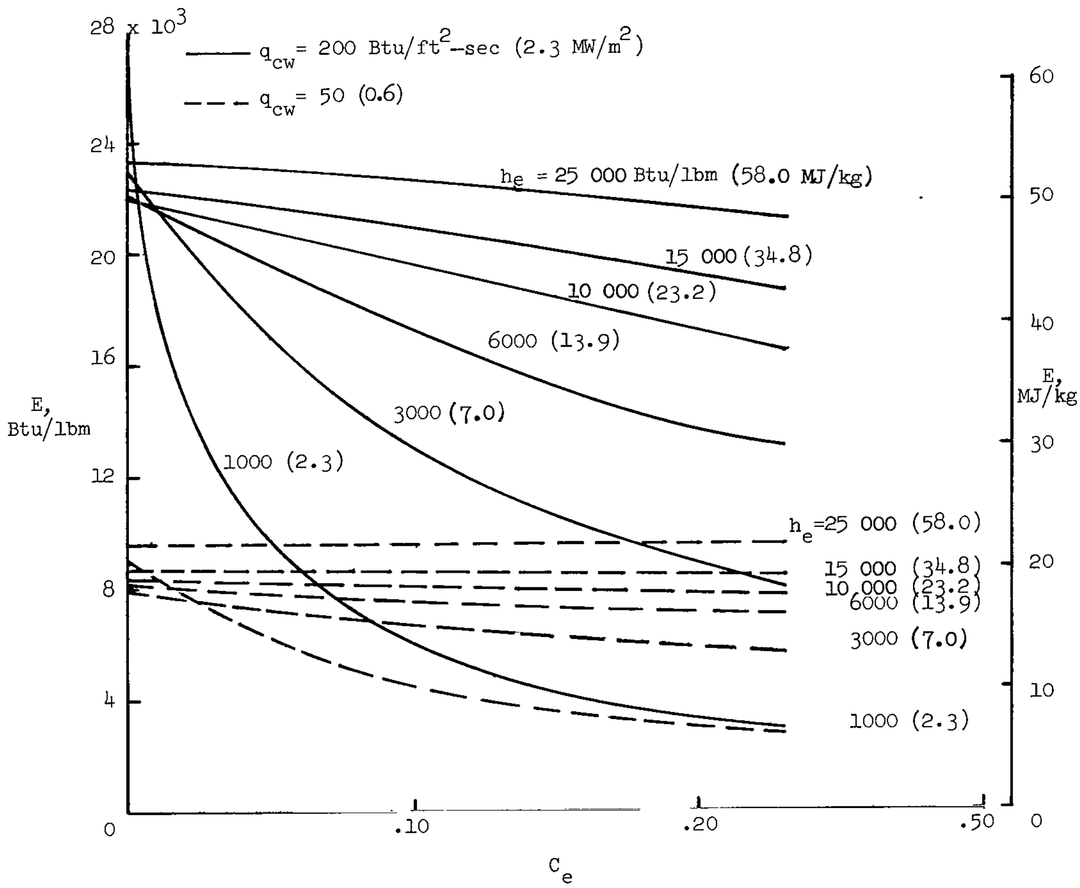


Figure 4.- Effect of stream oxygen concentration on thermal effectiveness of charring ablators.

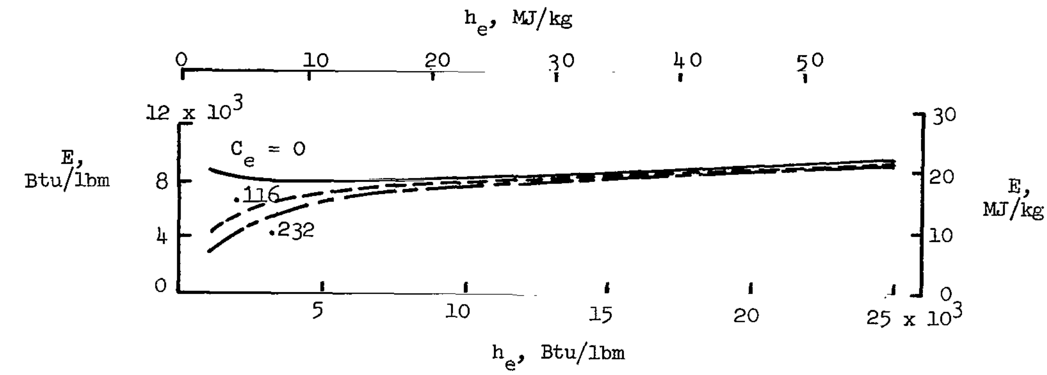
calculations were made for constant cold-wall heating rates of 50 Btu/ft^2-sec (0.6 MW/m^2) and 200 Btu/ft^2-sec (2.3 MW/m^2). The stream enthalpy was varied from 1000 to 25 000 Btu/lbm (2.3 to 58 MJ/kg) and the oxygen concentration of the stream was varied from 0 to 23.2 percent by mass. The curves of figure 4 indicate that the thermal performance is strongly influenced by the oxygen concentration of the test stream at enthalpies less than 10 000 Btu/lbm (23.2 MJ/kg) over the range of heating rates considered. The reduction in thermal performance with increases in the stream oxygen concentration is more severe at the higher heating rate than at the lower heating rate. The severe oxidation of the char layer at low stream enthalpies is the major factor causing the reduction of thermal performance. Oxidation reduces the thickness of the char layer, thus reducing the amount of insulation afforded the uncharred material, and causes excessive consumption of ablation material.

The strong influence of the stream oxygen concentration on the thermal performance at enthalpies less than 10 000 Btu/lbm (23.2 MJ/kg) indicates that ground tests in air at enthalpies less than 10 000 Btu/lbm (23.2 MJ/kg) are unduly severe as regards oxidation of the char layer in comparison with high enthalpy performance.

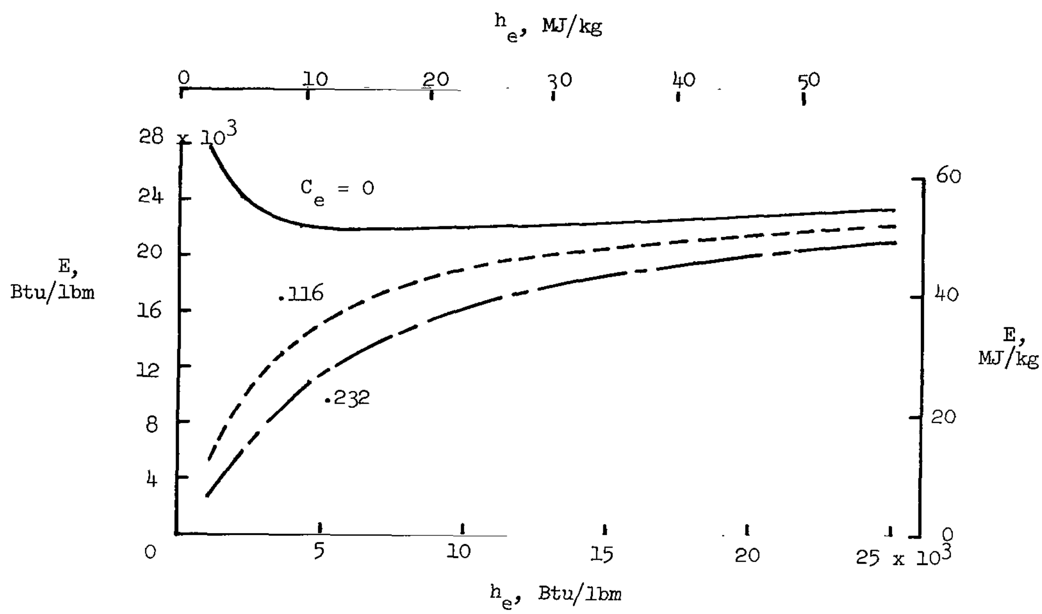
The curves of figure 4 show that as the oxygen concentration approaches zero the thermal performance at low enthalpies is better than at the higher enthalpies. This effect is shown more clearly in figure 5. At zero oxygen concentration, the thermal performance decreases to a minimum at an enthalpy level of about 6000 Btu/lbm (14 MJ/kg) and then gradually increases. This decrease in thermal performance with increase in enthalpy is due to the reduction in the hot-wall correction term $1 - \frac{h_w}{h_e}$, which produces an increase in the net convective heat input. At enthalpies higher than 6000 Btu/lbm (13.9 MJ/kg), the increased blocking effectiveness of the gaseous products of pyrolysis results in increased thermal performance. In a stream containing appreciable oxygen, the increased severity of oxidation at low enthalpies more than offsets the effect of the hot-wall correction, and the effectiveness increases monotonically with increasing enthalpy.

Effects of Changes in Material Properties on Thermal Performance of Charring Ablators

Char thermal conductivity.- The effects on the thermal performance due to changes in the char thermal conductivity of the reference material exposed to an airstream are shown in figure 6. The char conductivity was varied from 0.5 to 10 times the values shown in table I. The value of $k/k_{ref} = 1$ in figure 6 corresponds to the reference material. The curves of figure 6 show that the thermal performance of the charring ablator is strongly dependent on the char conductivity. As can be seen the thermal



(a) $q_{cw} = 50$ Btu/ft^2-sec (0.6 MW/m^2).



(b) $q_{cw} = 200$ Btu/ft^2-sec (2.3 MW/m^2).

Figure 5.- Effect of stream enthalpy and oxygen concentration on thermal effectiveness of charring ablators.

effectiveness decreases with increasing char conductivity. This effect of char conductivity becomes more pronounced as the enthalpy is increased. Thus it appears that the char conductivity is an extremely important material property which can greatly influence the thermal performance of a charring ablator.

The effectiveness of the char layer depends on the char conductivity, surface temperature, and char thickness. For a given environment, increasing the char conductivity increases the char thickness and lowers the surface temperature. Since material is consumed to produce the thicker char and since reradiation from the surface decreases with

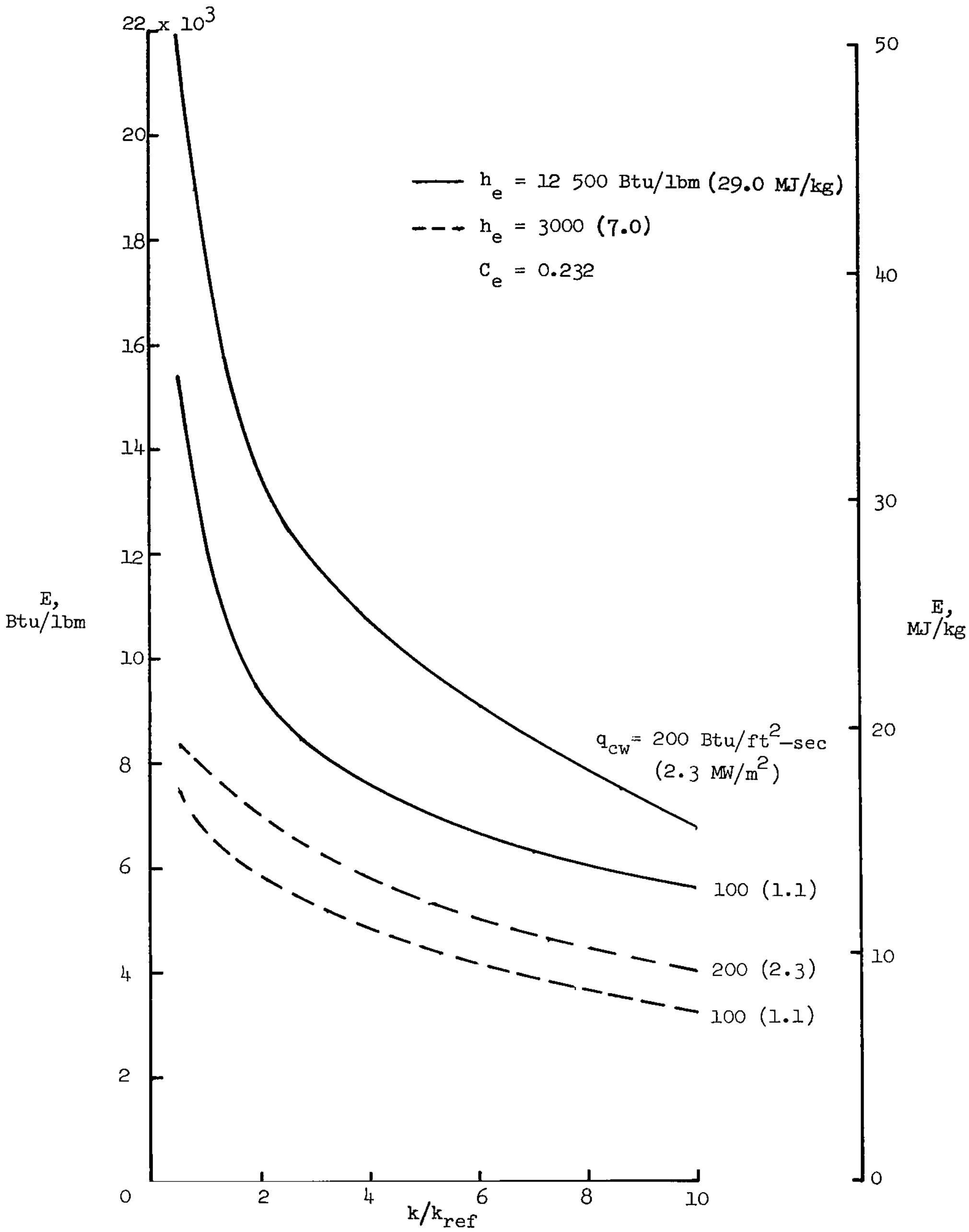


Figure 6.- Effect of char thermal conductivity on thermal effectiveness of charring ablators. $C_e = 0.232$.

lower surface temperature, the overall material effectiveness is decreased. Decreasing the char conductivity, however, decreases the rate of material consumption and increases the surface temperature, thus an increase in thermal performance results. At low enthalpy, for low values of char conductivity, char surface oxidation and material consumption are so severe that there is no large increase in thermal performance such as was obtained at high enthalpy.

<u>Volatile fraction</u>.- The effect of changes in the volatile fraction on the thermal performance of the reference material in air are shown in figure 7. The volatile fraction is that part of the ablation material which is converted to gaseous products at the pyrolysis

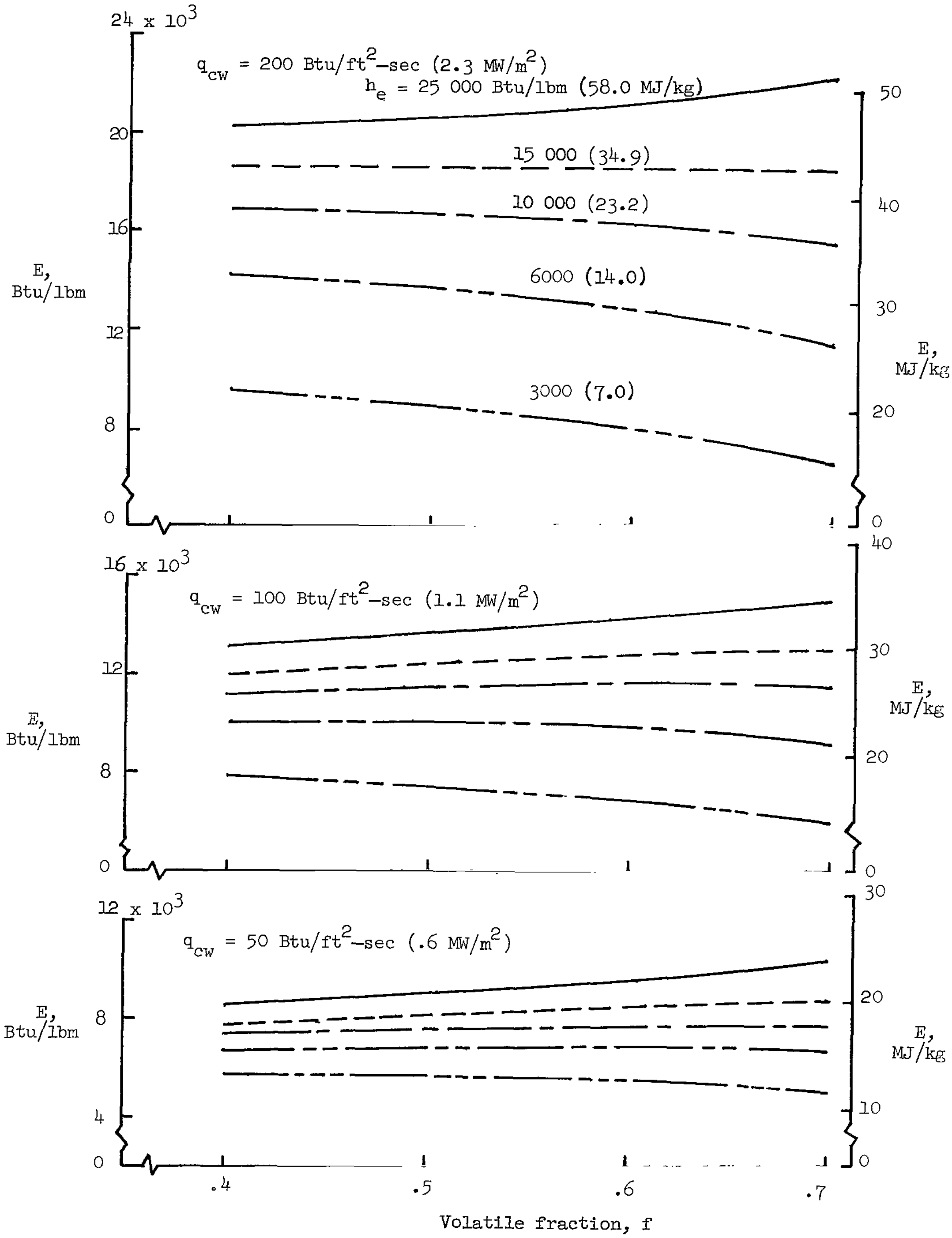


Figure 7.- Effect of volatile fraction on thermal effectiveness of charring ablators. C_e = 0.232.

interface. For a constant-density uncharred ablation material, an increase in the volatile fraction corresponds to a decrease in char density since a smaller amount of residue remains as char. The calculations were made for three levels of cold-wall heating rate and over a range of enthalpies from 3000 to 25 000 Btu/lbm (7 to 58 MJ/kg).

The results, as shown in figure 7, indicate that the thermal performance increases with increasing volatile fraction at enthalpies above 15 000 Btu/lbm (34.8 MJ/kg) for a heating rate of 200 Btu/ft^2-sec (2.3 MW/m^2). At heating rates of 50 and 100 Btu/ft^2-sec (0.57 and 1.14 MW/m^2), the performance increases with increases in volatile fraction at enthalpies above 10 000 Btu/lbm (23.2 MJ/kg). The increase in thermal performance is due to the blocking of the gaseous products of pyrolysis which is more effective at high enthalpy levels. At the lower enthalpy levels, oxidation is severe and blocking effectiveness is reduced so that an increase in the volume of the gaseous products of pyrolysis generated by an increase in the volatile fraction is more than offset by increased oxidation of the resulting low-density char. The results show that the qualitative effect of volatile fraction is dependent upon the environment.

Specific heat of char.- The consequence of changes in the specific heat of the char layer on the thermal performance is shown in figure 8. The specific heat of the char was varied from 0.5 to 2 times the value used for the reference material. (See table I.) Calculations were made at high and low enthalpy levels for one heating rate.

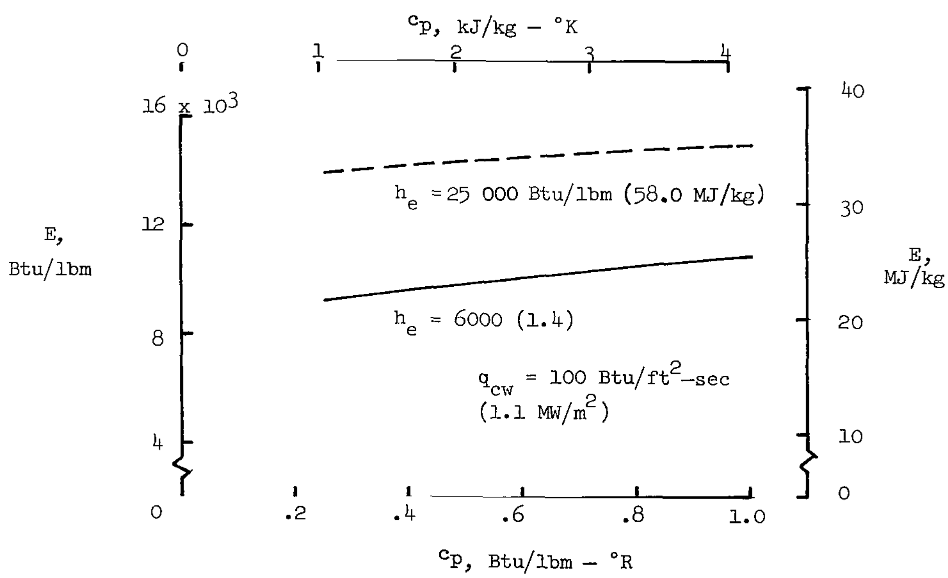


Figure 8.- Effect of specific heat of char on thermal effectiveness of charring ablators. C_e = 0.232.

At both high and low stream enthalpy, the amount of heat absorbed in the char layer is small in comparison to the amount of heat which is blocked by the gaseous products of pyrolysis and reradiated from the char surface. Thus large changes in the specific heat of the char have little effect on the overall thermal performance of charring ablators. The absorption of heat in the char layer is a relatively unimportant mechanism of heat accommodation because of the small amount of char normally available and the large heat flow through the char. Therefore, the formulation of materials which would produce chars with high values of specific heat is an ineffective means of significantly increasing thermal performance.

Thermal diffusivity of uncharred ablation material.- Changes in the thermal diffusivity of the uncharred ablation material affects the thermal performance as shown in figure 9. The thermal diffusivity values were varied from 0.5 to 2 times the value used for the reference material. (See table I.) Calculations were made at the same environmental conditions as for the specific heat of the char layer.

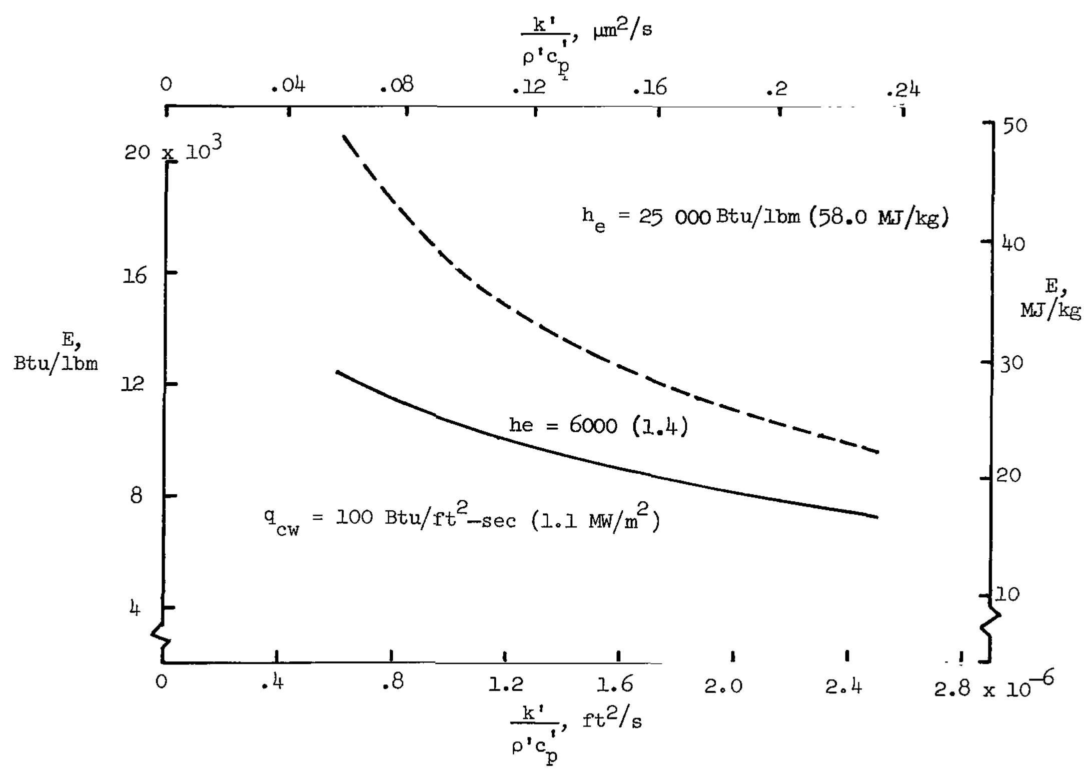


Figure 9.- Effect of thermal diffusivity of uncharred material on thermal effectiveness of charring ablators. $C_e = 0.232$.

The results indicate that changes in the thermal diffusivity of the uncharred ablation material can have significant effects on the thermal performance of charring ablators because the rate of heat conduction through the uncharred material, though small, is important. Therefore, changes in the thermal diffusivity in the uncharred material strongly influence the amount of time required for a given temperature rise to occur at the back surface of the uncharred material. The effect of changes in thermal diffusivity of the uncharred material is more pronounced at high stream enthalpy than at low stream enthalpy. At high stream enthalpy, the various heat accommodation mechanisms function more effectively and result in a lower rate of material consumption than at low stream enthalpy. Therefore, at a given time during heating there is more uncharred material remaining for absorption and insulation.

Specific heat of the gaseous products of pyrolysis.- Figure 10 shows the effect of changes in the specific heat of the gaseous products of pyrolysis $\bar{c}_p$ on the thermal performance of the reference charring ablation material. The calculations were made at one heating rate and at high and low stream enthalpies. In the calculations, a constant value of $\bar{c}_p$ was used but in actuality $\bar{c}_p$ is a complicated function of temperature. The use of a constant value of $\bar{c}_p$ can be justified in this parametric study since the intent is to show the gross effect of large changes in $\bar{c}_p$ on the thermal performance of the charring ablator.

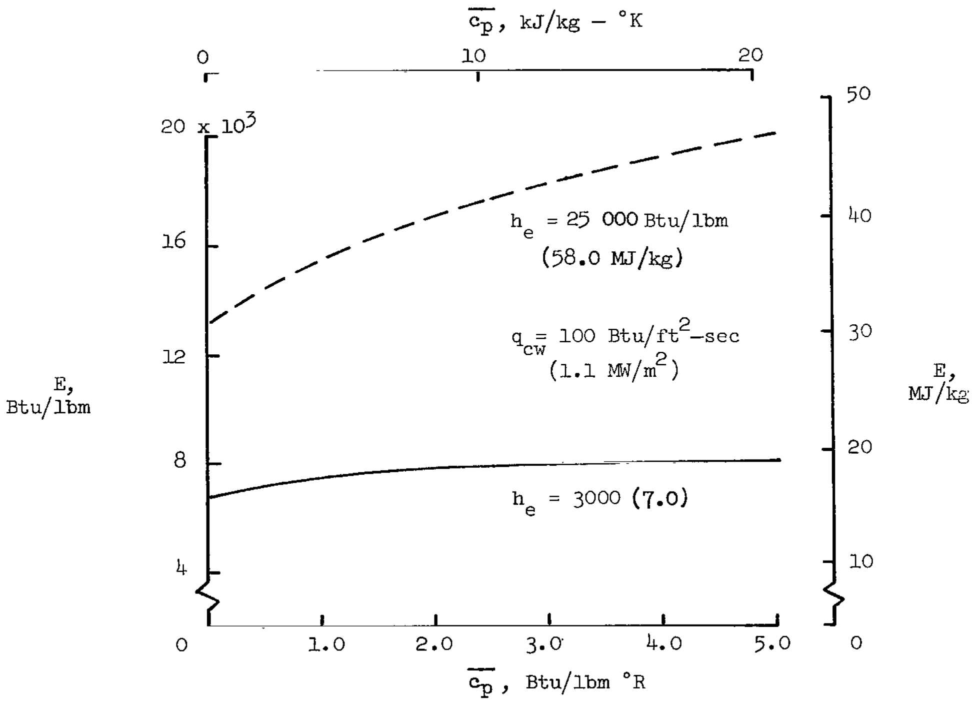


Figure 10.- Effect of specific heat of gaseous products of pyrolysis on thermal effectiveness of charring ablators. $C_e = 0.232$.

The curves of figure 10 indicate that changes in the value of $\bar{c}_p$ do not significantly influence the material performance at low stream enthalpy where the char layer is thin and the rate of char consumption is high. The heat input due to char combustion is relatively large and the resulting increase in the amount of heat absorbed by the gaseous products of pyrolysis in the thin char layer do not greatly affect the temperature at the pyrolysis interface and the rate of ablator consumption. Therefore the time required to reach a specified back surface temperature is not significantly affected and there is little variation in thermal performance.

At high stream enthalpy, a change in $\bar{c}_p$ is more effective than at low enthalpy. The increased char temperature, which results from the high enthalpy stream, causes an increase in ablator consumption but this effect is nearly offset by the increased reradiation and blocking by the gaseous products of pyrolysis. As the value of $\bar{c}_p$ is increased above the value of $\bar{c}_{p,ref}$, the thermal performance improves. The increased amount of heat absorbed in the char layer reduces the temperature at the pyrolysis interface and, in turn, reduces the amount of material pyrolysis. Since the uncharred material is an effective insulator, even slight increases in the thickness of the uncharred material can greatly affect thermal performance.

Char emissivity.- The thermal performance of the reference material varies with the char emissivity as shown in figure 11. The curves of figure 11 show that large changes in emissivity affect the thermal performance more at high than at low stream enthalpy, but for both cases the effect is relatively small. Consideration of the heat accommodation mechanism in the high enthalpy stream shows that reradiation and blocking are the dominant mechanisms, but that the effect of changes in char emissivity on the thermal performance is small since a slight change in surface temperature compensates for large changes in emissivity.

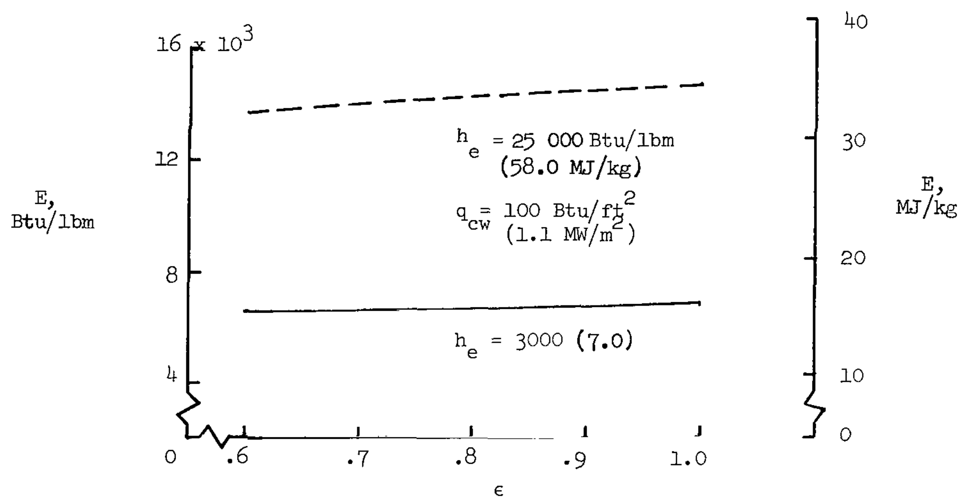


Figure 11.- Effect of surface emissivity on thermal effectiveness of charring ablators. $C_e = 0.232$.

Heat of pyrolysis.- The effect of changes in the heat of pyrolysis on the thermal performance of the reference charring ablator in an air atmosphere at a cold-wall heating rate of 100 Btu/ft^2-sec (1.1 MW/m^2) is shown in figure 12. The heat of pyrolysis is the heat absorbed per pound mass of material pyrolyzed. The calculations were made at high

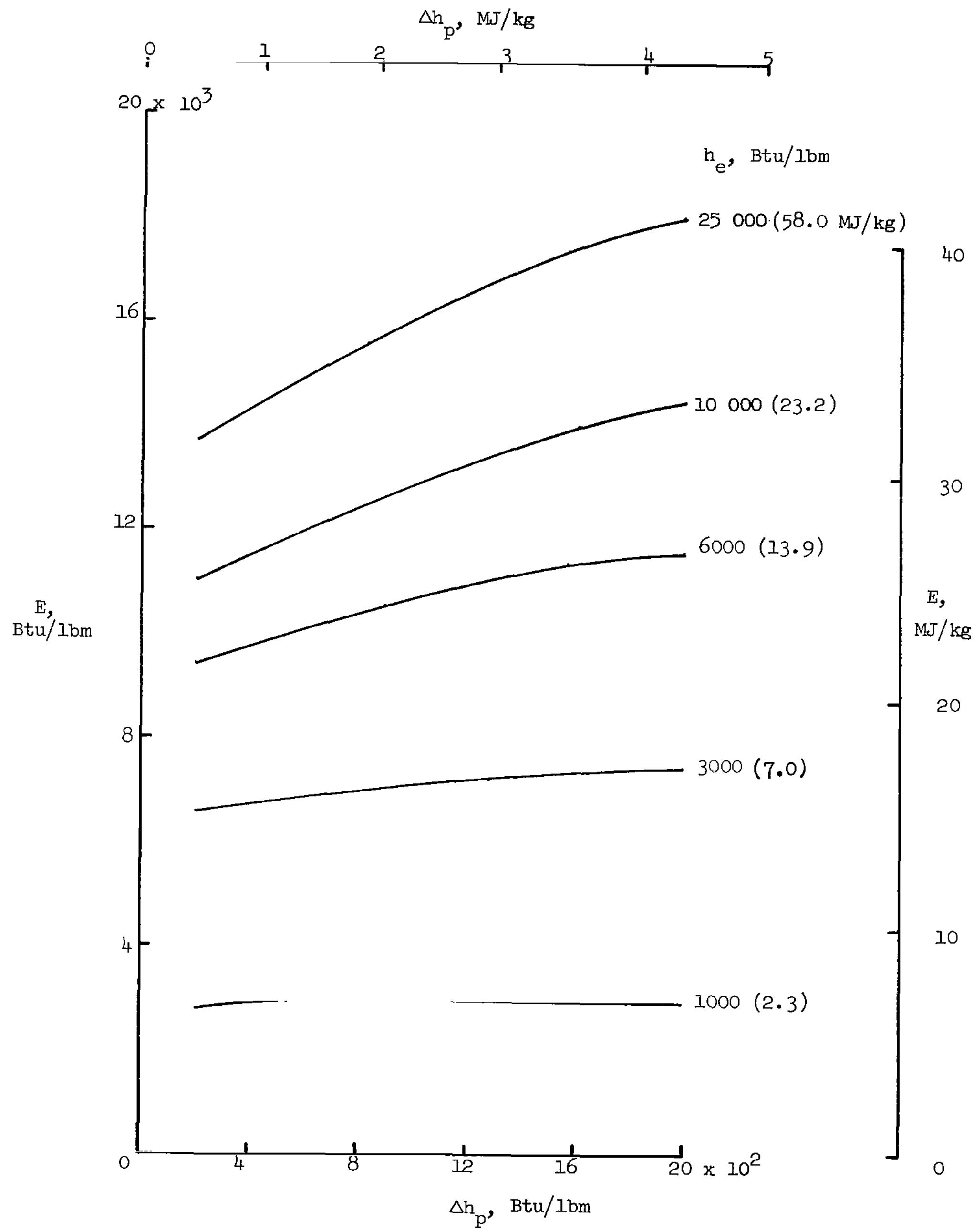


Figure 12.- Effect of heat of pyrolysis on thermal effectiveness of charring ablators. C_e = 0.232; q_{cw} = 100 Btu/ft^2-sec (1.1 MW/m^2).

and low values of stream enthalpy. The heat of pyrolysis was varied from 200 to 2000 Btu/lbm (0.5 to 4.7 MJ/kg).

The results show that at low values of stream enthalpy the thermal performance is not significantly increased by large increases in the heat of pyrolysis. Because of char oxidation at low stream enthalpy, the char layer is extremely thin and the uncharred material is rapidly consumed. Large increases in the amount of heat required to raise the ablation material to the pyrolysis temperature did not appreciably increase the time required for a specified temperature rise to occur at the back surface of the uncharred material. The results obtained at higher values of stream enthalpy with more efficient blocking and less severe oxidation show the expected increases in thermal performance with increases in the heat of pyrolysis. It is possible that an experimental investigation of the effect of increases in the heat of pyrolysis conducted in facilities with stream enthalpies of 3000 Btu/lbm (7 MJ/kg) or less would not show the increased thermal performance which would be obtained at the stream enthalpy levels encountered in atmospheric entry. Again, it can be seen that the effects of material properties on thermal performance cannot be considered apart from the environmental conditions, particularly stream enthalpy.

Effective Heat of Ablation

As previously mentioned, the effective heat of ablation Q^* is another parameter often used to evaluate the performance of ablation materials. The mass loss used to calculate Q^* may be determined by two methods. By one method, the mass loss is based on the total mass change; that is, the initial total mass minus the final total mass equals the mass loss. This method assumes the char to be available material. The second method bases the mass loss on the total thickness of material degraded. This method treats the char as unavailable material. The heat input may or may not include radiation heating. The parameter Q^* depends only on the mass loss characteristics of the material whereas the parameter E depends on the insulating properties of the material as well. It is believed that, for most heating conditions, a parameter that considers both the insulative properties and the ablation characteristics of a material is the most appropriate for evaluating ablation material performance.

A comparison of the results obtained with these two parameters is shown in figure 13. When the parameter Q^* includes the char as available material, Q^* may be 90 percent greater than the parameter E at low heating rates and high enthalpy. The ratio $(Q^*/E)_A$ increases with increasing enthalpy and decreasing heating rate.

When the parameter Q^* is based on the thickness of material degraded, Q^* is at most 20 percent greater than the parameter E. The ratio $(Q^*/E)_B$ is fairly insensitive to heating rate and enthalpy.

The value of Q^* in figure 13 is based on the mass loss during the time required for the back surface temperature to increase 300° R (170° K). If Q^* is based on greater or less test time, the values could be less or greater, respectively, than those shown in figure 13.

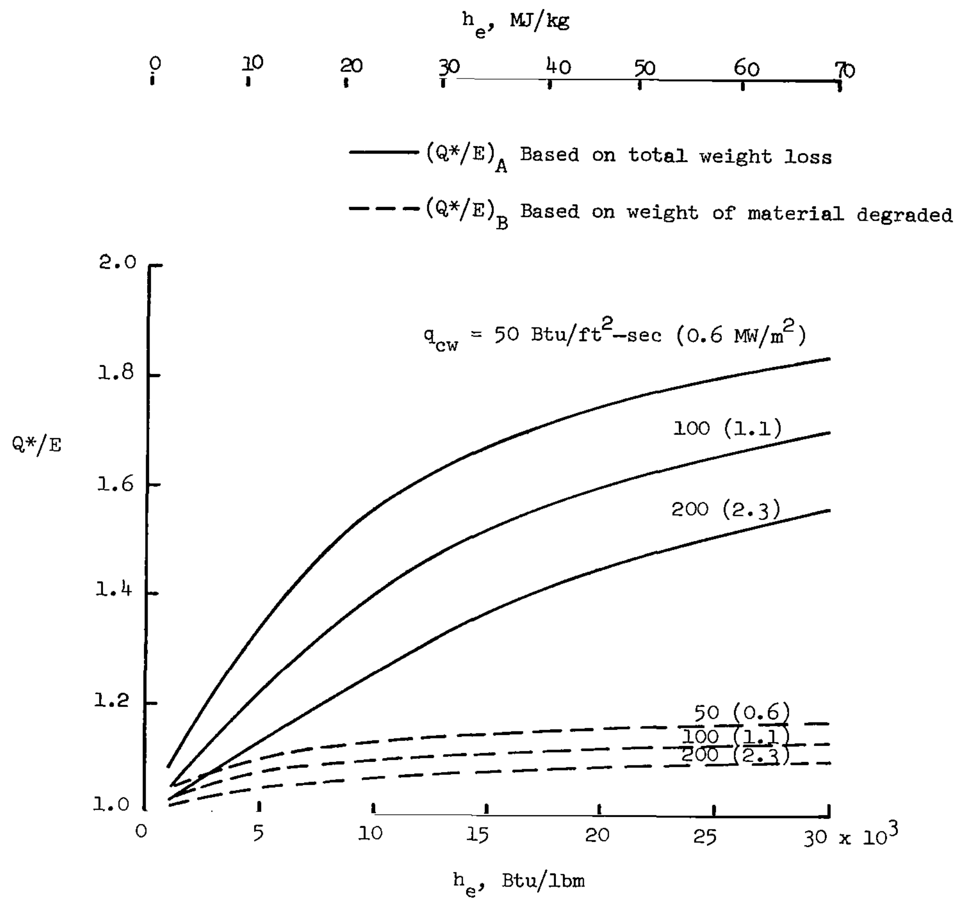


Figure 13.- Comparison of effective heat of ablation and parameter E.

CONCLUSIONS

A parametric study of the thermal performance of a representative low-density charring ablator has been made over a range of environmental conditions and material properties by means of an ablation analysis. A constant cold-wall convective heating rate and stream enthalpy were used in each calculation. It should be emphasized that the intent of the present study is to show the manner in which the thermal performance of a low-density charring ablator is influenced by environmental conditions. Hence, caution should be used in applying these data in the design of heat shields for flight environments. For the present study, a heating rate range of 50 to 200 Btu/ft^2-sec (0.6 to 2.3 MW/m^2) and a stream enthalpy range of 1000 to 25 000 Btu/lbm (2.3 to 58 MJ/kg) were considered. For these conditions, the following conclusions are made:

1. The thermal performance increases rapidly with heating rate at all enthalpy levels for heating rates of less than 150 Btu/ft^2-sec (1.7 MW/m^2). At higher heating rates, the thermal performance is relatively insensitive to heating rate for stream enthalpies of less than 6000 Btu/lbm (13.9 MJ/kg).

2. At all heating rates, the thermal performance increased with increasing stream enthalpy particularly at stream enthalpies of 6000 Btu/lbm (13.9 MJ/kg) and less. Stream enthalpy interacts with other parameters to affect the thermal performance.

3. The effect of oxygen concentration on thermal performance depended on both stream enthalpy and heating rate. Large reductions in thermal performance with increased stream oxygen concentration were obtained at stream enthalpies of less than 10 000 Btu/lbm (23.2 MJ/kg).

4. The thermal performance was strongly influenced by variations in char thermal conductivity at both high and low stream enthalpy. The thermal performance of the reference charring ablator was reduced with increases in char conductivity.

5. The thermal performance was markedly increased with decreases in the thermal diffusivity of the uncharred material, particularly at high stream enthalpy.

6. At high heating rates and low stream enthalpy, significant reductions in thermal performance were obtained with increasing volatile fraction. The thermal performance was relatively insensitive to changes in the volatile fraction at high stream enthalpy over the range of heating rates considered.

7. Thermal performance increases with increases in the heat of pyrolysis at high stream enthalpy. However, extremely large values of the heat of pyrolysis were required to obtain significant increases in thermal performance.

8. The specific heat of the gaseous products of pyrolysis had little effect on thermal performance at low stream enthalpy. At high stream enthalpy the thermal performance was significantly increased with increases in this parameter.

9. The thermal performance was insensitive to the char emissivity and specific heat at both high and low stream enthalpy.

10. The material properties that have the most effect on the overall thermal performance of a low-density charring ablator, for the indicated environments, were found to be the char conductivity and the thermal diffusivity of the uncharred material.

11. The present study shows that a wide spread (up to 90 percent) exists in estimates of the thermal performance of ablation materials. This wide spread depends on the performance parameter used. Therefore, care must be taken in choosing the performance parameter to be used. For most heating conditions the parameter should consider both the insulative properties and the ablation characteristics of the material.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 7, 1966,
124-08-03-16-23.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in resolution 12 (ref. 8). Conversion factors required for units used herein are given in the following table:

Physical quantity	U.S. Customary Units	Conversion factor (*)	SI Unit
Density	lbm/ft^3	16.018463	kilograms/meter^3 (kg/m^3)
Effectiveness	Btu/lbm	2.324444×10^3	joules/kilogram (J/kg)
Heating rate	Btu/ft^2-sec	1.134893×10^4	watts/meter^2 (W/m^2)
Mass distribution	lbm/ft^2	4.882	kilograms/meter^2 (kg/m^2)
Specific heat	Btu/lbm-^oR	4.184×10^3	joules/kilogram-degree Kelvin (J/kg-^oK)
Specific reaction	lbm/ft^2-sec-atm$^{1/2}$	4.882428	kilograms/meter^2-second-atmosphere$^{1/2}$ (kg/m^2-s-atm$^{1/2}$)
Temperature	^oR	5/9	degrees Kelvin (^oK)
Thermal conductivity	Btu/ft-sec-^oR	6.24×10^3	watts/meter-degree Kelvin (W/m-^oK)
Thermal diffusivity	ft^2/sec	9.29×10^{-2}	meters^2/second (m^2/s)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI unit.

Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
kilo (k)	10^3
mega (M)	10^6
micro (μ)	10^{-6}

REFERENCES

1. Chapman, Andrew J.: An Experimental Evaluation of Three Types of Thermal Protection Materials at Moderate Heating Rates and High Total Heat Loads. NASA TN D-1814, 1963.

2. Farmer, Rex W.: Ablative Behavior of Plastics in Subsonic and Supersonic Hyperthermal Flow. WADD Tech. Rept. 60-648, U.S. Air Force, Nov. 1960.

3. Chapman, Andrew J.: Effect of Weight, Density, and Heat Load on Thermal-Shielding Performance of Phenolic Nylon. NASA TN D-2196, 1964.

4. Clark, Ronald K.: Effect of Environmental Parameters on the Performance of Low-Density Silicone-Resin and Phenolic-Nylon Ablation Materials. NASA TN D-2543, 1965.

5. Swann, Robert T.; and Pittman, Claud M.: Numerical Analysis of the Transient Response of Advanced Thermal Protection Systems for Atmospheric Entry. NASA TN D-1370, 1962.

6. Swann, Robert T.; Pittman, Claud M.; and Smith, James C.: One-Dimensional Numerical Analysis of the Transient Response of Thermal Protection Systems. NASA TN D-2976, 1965.

7. Swann, Robert T.; Dow, Marvin B.; and Tompkins, Stephen S.: Analysis of the Effects of Environmental Conditions on the Performance of Charring Ablators. J. Spacecraft Rockets, vol. 3, no. 1, Jan. 1966, pp. 61-67.

8. Mechtly, E. A.: The International System of Units – Physical Constants and Conversion Factors. NASA SP-7012, 1964.

9. Stroud, C. W.: A Study of the Chemical Reaction Zone in Charring Ablators During Thermal Degradation. NASA paper presented at the Meeting of the American Institute of Chemical Engineers (Dallas, Texas), Feb. 6-9, 1966.

10. Wilson, R. Gale (Compiler): Thermophysical Properties of Six Charring Ablators From 140° to 700° K and Two Chars From 800° to 3000° K. NASA TN D-2991, 1965.

TABLE I.- MATERIAL PROPERTIES OF REFERENCE CHARRING ABLATOR

Uncharred material		
Density, ρ'	40 lbm/ft^3	(640 kg/m^3)
Specific heat, c_p'	0.4 Btu/lbm-$^\circ$R	(1.7 kJ/kg-$^\circ$K)
Specific heat of gaseous products of pyrolysis, $\bar{c}_p$	0.5 Btu/lbm-$^\circ$R	(2.1 kJ/kg-$^\circ$K)
Effective heat of pyrolysis, Δh_p	400 Btu/lbm	(0.9 MJ/kg)
Thermal conductivity, k'	2.0×10^{-5} Btu/ft-sec-$^\circ$R	(0.13 W/m-$^\circ$K)
Volatile fraction, f	0.6	
Charred material		
Density, ρ	16 lbm/ft^3	(256 kg/m^3)
Specific heat, c_p	0.5 Btu/lbm-$^\circ$R	(2.1 kJ/kg-$^\circ$K)
Emissivity, ϵ	0.8	
λ	0.75	
A	1.74×10^5 lbm/ft^2-sec-atm$^{1/2}$	(850 Mg/m^2-s-atm$^{1/2}$)
B	3.62×10^4 $^\circ$R	(2.01×10^4 $^\circ$K)

Thermal conductivity, k	Btu/ft-sec-$^\circ$R	W/m-$^\circ$K
At 500° R (278° K)	2.0×10^{-5}	0.12
At 1200° R (666° K)	4.0×10^{-5}	0.25
At 1900° R (1055° K)	6.0×10^{-5}	0.37
At 2600° R (1445° K)	8.0×10^{-5}	0.50
At 3300° R (1835° K)	10.0×10^{-5}	0.62
At 4000° R (2200° K)	12.0×10^{-5}	0.75

NASA-Langley, 1966 L-4775

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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