Study of the Effects of Heat Load, Ablator Density and Backup Structure upon the Thermal Protection Performance of Heat Shield Systems Consisting of Phenolic Carbon Ablators

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The effects of heat load, ablator density, and backup structure, etc., upon the heat shield performance of the lightweight phenolic carbon ablators named LATS were investigated using a one-dimensional ablation analysis code. The ablator density was assumed to be from about 260 to 1000 kg/m³. Heat flux time histories of a rectangular pattern were assumed, where cases of constant heating duration time and constant accumulated heat load (up to 600 MJ/m²) were considered. The heating level was assumed to be from 1 to 10 MW/m², which means that the ablator surface is in the region of diffusion control oxidation/sublimation. The materials of the backup wall are assumed to be aluminum, stainless steel and high density CFRP. Main findings are: (1) For a low heat flux \( q \) with the same heating duration time \( t_q \), the necessary thickness, with which the maximum back surface temperature equals to the pre-determined allowable temperature, is nearly constant as the density \( \rho_v \) changes. On the other hand, the necessary thickness increases largely when \( q \) is larger and \( \rho_v \) is smaller. The ablator necessary mass increases with the increase of \( \rho_v \) and \( q \) for the same \( t_q \).
(2) When a backup wall is attached, the necessary thickness decreases and the necessary mass including the wall mass increases. (3) For a constant accumulated heat load, necessary thickness and mass decrease for a higher heat flux \( q \) especially when \( \rho_v \) is high. (4) A lower density ablator with a CFRP backup wall gives the lightest mass of the heat shield system for most of the parameter range among the three wall materials. (5) For a high heat flux, selection of a lower density ablator gives a larger necessary thickness.

Key Words: Ablator, Heat Shield System, Re-Entry Capsule, Ablation Analysis

Nomenclature

\[
\begin{align*}
C_p & : \text{specific heat, } J/(kg \text{ K}) \\
h & : \text{enthalpy, } J/kg \\
k & : \text{thermal conductivity, } W/(m \text{ K}) \\
L_1 & : \text{length of ablator, } m \\
L_2 & : \text{thickness of backup wall, } m \\
m_{ne} & : \text{necessary mass of ablator, } kg/m^2 \\
m_{ne\text{ALL}} & : m_{ne}+m_2, \text{ kg/m}^2 \\
m_2 & : \text{mass density of backup wall, } kg/m^2 \\
rh & : \text{mass flux, } kg/(m^2 \text{ s}) \\
Q & : \text{accumulated heat load, } MJ/m^2 \\
q & : \text{heat flux, } W/m^2 \\
q_{cw} & : \text{cold wall convective heat flux, } W/m^2 \\
q_{net} & : \text{net heat flux, } W/m^2 \\
S & : \text{surface recession rate, } m/s \\
T & : \text{temperature, } K \\
T_{b,\text{max}} & : \text{maximum back surface temperature, } K \\
T_{\text{ref}} & : 300K \\
T_{r,\text{max}} & : \text{maximum surface temperature, } K \\
t & : \text{thickness or time, } m \text{ or } s \\
t_{ne} & : \text{necessary thickness of ablator, } m \\
t_{ne\text{ALL}} & : t_{ne}+L_2, \text{ m} \\
t_q & : \text{heating duration time, } s \\
x & : \text{moving coordinate or in-depth distance from receding surface, } y-\Delta S, \text{ m} \\
y & : \text{stationary coordinate or in-depth distance from initial front surface, } m \\
\Delta h_{\text{pyro}} & : \text{heat of pyrolysis per gas produced, } J/kg \\
\Delta m & : \text{mass loss, } kg/m^2 \\
\Delta S & : \text{surface recession, } m \\
\varepsilon & : \text{surface emissivity} \\
\phi_{\text{blow}} & : \text{blowing correction factor} \\
\rho & : \text{density, } kg/m^3 \\
\sigma & : \text{Stefan-Boltzmann constant, } 5.67 \times 10^{-8} \text{ W/(m}^2 \text{ K}^4) \\
\text{Subscripts} & \\
\text{ab, ch} & : \text{ablation and char, respectively} \\
g, \text{ ne} & : \text{pyrolysis gas and necessary, respectively} \\
r, \text{ ref} & : \text{recovery and reference, respectively} \\
u & : \text{at wall underside} \\
v & : \text{virgin material} \\
w & : \text{at wall} \\
1, 2 & : \text{ablator and backup wall, respectively}
\end{align*}
\]
1. Introduction

A re-entry capsule has a heat shield system to protect inner equipment against the severe heating environment during re-entry. The heat shield system is mainly consisted of an ablator which has the capability to prevent conduction of heat to the inside by an ablation phenomenon. Until now various kinds of ablative materials with various densities have been developed.1, 4)

In the design of a heat shield system of a re-entry vehicle, a light-weight requirement on the ablator is very critical. The thickness constraint on the ablator is also important. For the design of a heat shield system, it is very important to evaluate quantitatively the heat shield performance such as necessary thickness, necessary mass, etc. with respect to the heat load, ablator density, the backup structure and so on.

Recently, a lightweight ablator named LATS (Lightweight Ablator series for Transfer vehicle Systems) with the densities of about 300-700kg/m³ has been developed.9) The LATS is a carbon phenolic ablator fabricated by impregnating a phenolic resin into a felt made of carbon fibers. The material properties of the LATS ablator were measured and arc-heated tests of the ablator samples with various densities were carried out.9, 10) Ablation analysis with respect to the arc-heated tests was also carried out using a one-dimensional analysis code and the measured and calculation results agreed well.10, 11)

Investigations concerning the effects of heat load and ablator density upon the necessary thickness \( t_{nc} \) and necessary mass \( m_{nc} \) of the LATS ablator were carried out using a one-dimensional ablation analysis code.11) It was found that the necessary thickness \( t_{nc} \) is nearly constant as the ablator density changes, and the necessary mass \( m_{nc} \) increases almost linearly with the increase of the density. In the study, the ablator back surface was assumed to be attached to an insulation material, and the heating level was from 1 to 3 MW/m², which means that the surface ablation is mainly in the diffusion controlled oxidation region and not in the sublimation region (Sec. 3.1.4.). In the study, effects of (1) a high heat flux which corresponds to the surface ablation of sublimation, (2) a constant accumulated heat load \( Q \) with a variable heat flux \( q \), and (3) the backup wall, upon the thermal protection performance of the ablator were not investigated yet.

In this paper the effects of heat load, ablator density, backup structure, etc. upon the thermal protection performance of the LATS ablator such as the necessary thickness and the necessary mass of the ablator are investigated using a one-dimensional ablation analysis code. Heat flux time histories of a rectangular pattern are assumed. The research items of (1)-(3) mentioned above are mainly investigated in this study and are described below. (1) Effect of a high heat flux with a constant duration time which corresponds to the surface ablation of sublimation (Sec. 3.1)

In this paper, the heat flux rate \( q \) is assumed to be from 1 to 10MW/m² with a constant duration time \( t_{q} \) of 60s. In the previous research11), \( q \) was assumed to be from 1 to 3MW/m² with \( t_{q} \) of 60s. In such a low heating level, the surface temperature is well below 3000K and the surface ablation is mainly in the diffusion controlled oxidation region.12, 13) If \( q \) is on the level of about 10MW/m², the ablator surface temperature is on the level of about 3000K, which means that the surface ablation is in the sublimation region and the surface recession would become much larger than that in the diffusion controlled oxidation region or reaction controlled oxidation region. This behavior would influence the thermal protection performance of the ablator.

(2) Constant accumulated heat load \( Q \) with a variable heat flux \( q \) (Sec. 3.2)

The effects upon the heat protection performance in the case of a constant heat load \( Q \) (120 to 600MJ/m²) with a variable heat flux \( q \) (1 to 10MJ/m²) are investigated. In an arc-heated test of ablative materials, heat load of a rectangular pattern is sometimes applied to the ablator, where heat flux rate \( q \) and the accumulated heat load \( Q = q t_{q} \) are equal to the maximum heat flux and the accumulated heat load of the estimated re-entry heating environment, respectively. The study results would be useful for not only designing the heating conditions of an arc-heated test but also designing the heat load of re-entry vehicle and obtaining the basic knowledge of the effects of \( Q \) with variable \( q \) upon the heat protection performance of the ablator.

(3) Backup wall (Sec. 3.3 and Sec. 3.4)

Each material of the backup walls is assumed to be aluminum, stainless steel and high density CFRP, respectively. To obtain the effect of backup wall materials, two cases are studied: constant wall thickness (Sec. 3.3) and constant wall mass density (Sec. 3.4). The results would give valuable information in designing the candidate material of the backup wall of the heat shield system.

2. Analysis

We carried out one-dimensional ablation analysis of the LATS ablators with and without a backup wall for heating conditions of a rectangular pattern, from which the heat resistant performance of the LATS ablators with respect to the ablator densities, thicknesses, heat fluxes, accumulated heat loads and backup walls was evaluated quantitatively. Mathematical model of ablation, input data for the ablation analysis and the analysis conditions for the parametric study are shown in the following sections.

2.1. Mathematical model of ablation10, 11)

A one-dimensional computer code for charring ablation and thermal response analysis was used to calculate the heat resistant performance of the LATS ablators. The code was developed for simulation of one-dimensional transient thermal behavior of charring materials, and was successfully applied to the LATS ablators under the heating environments of arc-heated test.10) The mathematical model used in the code is described precisely in the previous papers.10, 11) Thermal model of the analysis in this paper is shown in Fig. 1. In the following, the basic equations and

![Fig. 1. Thermal model for the analysis.](image)
boundary conditions are briefly described.

The basic equations about the charring ablation are well known.\(^{10-16}\) The in-depth governing equations for one-dimensional charring ablator response are energy, mass continuity, and decomposition equations, and are expressed by

\[
\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \left[ \rho(\mu - \mu_{ch}) \right] \frac{\partial \rho}{\partial t} + S_{\text{pyro}} \frac{\partial T}{\partial y} + \dot{m}_g C_p \frac{\partial T}{\partial y} + \dot{m}_g \frac{\partial T}{\partial y}
\]

\[(1)\]

\[
\frac{\partial \rho}{\partial t} = (\partial / \partial y)_{y=0} \frac{\partial \rho}{\partial y} = (\partial / \partial y)_{y=0} \frac{\partial \rho}{\partial y}
\]

\[(2)\]

\[
\frac{\partial \rho}{\partial t} = -\sum_{i=1}^{N} A_i \rho_i (\rho - \rho_{ch}) \left( \frac{\rho - \rho_{ch}}{\rho - \rho_{ch}} \right) \exp \left( -\frac{B_i}{T} \right)
\]

\[(3)\]

Eq. (1) is the in-depth energy equation of the ablator, where \( \dot{m}_g \) is the gas flow rate (mass flux) and \( C_{\text{pyro}} \) is the specific heat of the pyrolysis gas. Eq. (2) expresses the mass conservation when the ablator yields the pyrolysis gas. Eq. (3) expresses the Arrhenius type expression for the decomposition rate, where \( \mu \) is the reaction order, \( A_i \) is the weighting factor, \( B_i \) is thecollision frequency (1/s), and \( T_b \) is the activation temperature (K). These values are assumed to be constant.\(^{11,12,17}\) The virgin and char densities, \( \rho \) and \( \rho_{ch} \), are considered constant. The density of the ablator yields decreases from the value of \( \rho \) according to Eq. (3), and always takes a value between \( \rho \) and \( \rho_{ch} \). \( k \) and \( C_p \) are calculated by

\[
k = \omega(\rho / \rho_{ch}) k_{ch} + (1 - \omega)(\rho / \rho_{ch}) k_{ch}
\]

\[(4a)\]

\[
\omega = (\rho - \rho_{ch}) / (\rho - \rho_{ch})
\]

\[(4b)\]

\[
C_p = \omega(\rho / \rho_{ch}) C_{p,ch} + (1 - \omega)(\rho / \rho_{ch}) C_{p,\text{pyro}}
\]

\[(5)\]

where \( k \) and \( k_{ch} \) are the thermal conductivities of the virgin and char materials, and \( C_{p,ch} \) and \( C_{p,\text{pyro}} \) are the specific heats of the virgin and char materials, respectively. Thermal properties of \( k \), \( k_{ch} \), \( C_{p,\text{pyro}} \), and \( C_{p,\text{ch}} \) are functions of the temperature. \( k \) and \( k_{ch} \) for ablators with various densities \( \rho \) are also functions of \( \rho \). (See Sec. 2.2.)

We assume three kinds of materials for the backup wall: aluminum (AL), stainless steel (SUS), and high density CFRP. For the calculation of the wall temperature, the classical heat conduction equation is used. As for the CFRP wall, the wall is treated as a non-ablating material, because the wall temperature is low (less than 250°C). (See Sec. 2.3.)

The energy balance at the ablator surface yields the surface boundary condition, in which aerodynamic heating, block effect of heating due to the mass ejection, radiation cooling, and enthalpy change when the char recedes, enthalpy change of pyrolysis gas and the heat conduction in the ablator are considered. We also assume that the pyrolysis gases are chemically inert with respect to the boundary layer gases.\(^{13}\) Thus the surface boundary condition is obtained and is shown below:\(^{13}\)

\[
q_{\text{net}} = q_{\text{cw}} \left( 1 - h_a / h_b \right) \phi_{\text{blow}} - \sigma \left( T_s^4 - T_{\text{ref}}^4 \right) - \dot{m}_g \left( h_a - h_b \right)
\]

\[6\]

where \( h_a \) is the enthalpy of the gas adjacent to the surface, \( h_b \) is the recovery enthalpy of the flow, \( T_s \) is the temperature of the char surface, \( T_{\text{ref}} \) is 300 K, \( \dot{m}_g \) is the mass flux due to the thermochemical ablation of the char, and \( h_s \) is the enthalpy of the char at the surface. \( \phi_{\text{blow}} \) is the blowing correction factor, which means the ratio of heat transfer coefficient with and without ablation mass injection into the boundary layer from the ablator surface. The factor \( \phi_{\text{blow}} \) also means the correction (reduction) factor of heat flux due to the mass injection into the boundary layer.\(^{13,14}\)

As for the back surface boundary condition, radiation heat exchange between the back surface and the back environment is assumed.

The temperature and the density distributions in the ablator and backup wall are calculated by the use of the equations mentioned above. Calculation is carried out using the finite difference method considering the boundary conditions. For each time step, \( \rho \) is calculated by Eq. (3). Integration of Eq. (2) gives \( \dot{m}_g \) with the assumption that the pyrolysis gas flow is zero at the back surface of the ablator. \( T \) is calculated by Eq. (1), in which the calculation results of \( \rho \) and \( \dot{m}_g \) are used. The front surface condition of Eq. (6) and the back surface condition (attached to the back-up wall or exposed to the back environment) are also considered. In the calculation, \( \dot{m}_g \) is obtained considering oxidation (reaction controlled or diffusion controlled oxidation) and sublimation of the surface char.\(^{12,13}\) \( \dot{S} \) is obtained by the relation of \( \dot{S} = \dot{m}_g / \rho_{ch} \). \( C_{\text{pyro}} \) and \( \Delta H_{\text{pyro}} \) are assumed to be constant values of 1674.6 J/(kg K) and 3.313x10^7 J/kg, respectively.\(^{10,11}\) For each time step, output parameters are obtained simultaneously for both the ablator and the backup wall.

### 2.2. Input data for the calculation

- Input data for the calculation of the thermal behavior of the ablator model using the one-dimensional ablation analysis program include parameters such as heating environment conditions, ablator thickness and material properties. Input data for the ablator material properties are the same as those in the previous paper.\(^{11}\) These data were determined based on the measured and the literature data.\(^{4,9,10,11,13,14,17}\)

- Among them, thermal conductivity data of the LATS ablator were tuned based on the matching of the measured and calculated temperatures.\(^{10,11}\) In which the measured temperatures were obtained by the arc-heated tests of the ablators.

Simulations of the ablators in the arc-heated tests were carried out using the tuned data and simulation results of the surface and the back surface temperature time histories by the analysis program agreed well with the measured results. The simulation results of mass loss by the analysis program also agreed well with the measured results.\(^{11}\)

### 2.3. Parametric study and conditions of the analysis

The LATS ablator with or without a backup wall is assumed as shown in Fig. 1. It is assumed that the backup wall is attached to the back surface of the ablator by an adhesive, where the allowable maximum temperature value of the adhesive \( T_{\text{allow}} \) is 250°C (=523.15K=480°F).\(^{18}\) (The allowable maximum temperatures of the backup wall and the ablator are assumed more than \( T_{\text{allow}} \).) Because the thickness of the adhesive is assumed to be very small, the adhesive was neglected in the analysis and the calculated ablator back surface temperature is regarded as the adiabatic temperature.
Where $T_{\text{b,max}}$ is the maximum back surface temperature evaluated at the end of the heating time $t_h$. $T_{\text{b,allow}}$ is the maximum back surface temperature which corresponds to the maximum adhesives temperature between the ablator and the backup wall. $\Delta m$ is the mass loss, and $\Delta S$ is the surface recession evaluated at $t=600s$ in Sec. 3.1 and $t_h=600s$ in Sec. 3.2, respectively. For the time more than the evaluation time, the calculated results are approximately the same, which means that the results do not change much during the time more than the evaluation time. The necessary thickness $t_{\text{ne}}$ or mass $m_{\text{ne}}$ is defined to be the ablator thickness or mass per unit area in which $T_{\text{b,max}}$ is equal to $T_{\text{b,allow}}$. $t_{\text{ne}}$ or $m_{\text{ne}}$ is also defined to be the necessary thickness or mass added by the wall thickness $L_2$ or the wall mass $m_2$, and expressed by $t_{\text{ne}}=t_{\text{ne}}+L_2$ or $m_{\text{ne}}=m_{\text{ne}}+m_2$, respectively.

$T_{\text{s, max}}$, $T_{\text{b, max}}$, $\Delta m$, and $\Delta S$ are calculated as functions of virgin density $\rho_s$, ablator thickness $L_1$, heat flux $q$, and so on. $t_{\text{ne}}$ and $m_{\text{ne}}$ are also calculated as functions of $\rho_s$, $q$, accumulated heat load $Q$ and the backup wall.

Calculated parameters mentioned above are useful for various design aspects: $T_{\text{s, max}}$ can be used for estimating the in-depth temperature, $T_{\text{b, max}}$ can be used for the design requirement of the heat shield system, $\Delta m$ is related to the mass and movement of the center of gravity of the re-entry vehicle, $\Delta S$ influences the aerodynamic characteristics of the re-entry vehicle, and $t_{\text{ne}}$ and $m_{\text{ne}}$ influence the outer geometry and the mass of the re-entry vehicle, respectively. Among these parameters, $t_{\text{ne}}$ and $m_{\text{ne}}$ seem to be most important with respect to the heat shield design.

For the parametric calculation, heat flux time histories of rectangular patterns of constant heating duration time and constant accumulated heat load are considered, examples of which are shown in Fig. 2. The rectangular heating pattern is usually used in the arc-heated test of ablators. The heating level is assumed to be from 1 to 10MW/m², which corresponds to the regions of diffusion controlled oxidation/sublimation (see 3.1.4.). The impact pressure of 1930 Pa and enthalpy of 12.8 MJ/m², the values of which are derived from those of the arc-heated test shown in Sec. 2.2, are used for the calculation. The ablator virgin density $\rho_s$ is assumed to be from 264 to 1000 kg/m³. The Char density is calculated by $\rho_{\text{ch}}=\rho_s \times 0.7$ (7)

Material properties of AL and SUS used for the analysis are based on the literature. Material properties of the high density CFRP are estimated by means of those of the LATS ablator.

The emissivity of the front surface is taken as $\varepsilon=0.85$. The back surface and equipment in the back environment are assumed to be painted black, where radiant heat exchange between the back surface and the equipment in the back environment is assumed. The radiant energy flux is calculated by assuming the radiation between parallel plates, in which the emissivity of the back surface and back environment was assumed to be 0.9 and 0.9, respectively. (The emissivity of the black painted surface is assumed to be 0.9).

Conditions of the analysis are shown in Fig. 1 and Table 1. In this paper, Sec. 3.1 is regarded as a baseline section, where various calculated parameters are evaluated. In other sections of 3.2 - 3.4, important parameters of necessary thickness and mass are evaluated, and other parameters are omitted. (Sec. 3.2 includes also $T_{\text{b, max}}$, which is related to the necessary thickness and mass.)

3. Results and Discussion

Effects of heat load, ablator density, backup structure, etc. upon the thermal protection performance of the LATS ablators such as the necessary thickness and necessary mass of the ablator system are investigated using a one-dimensional ablation analysis code.

3.1. Constant heating duration time

In this section, thermal protection performance of the LATS ablator is examined for a constant $t_h$ of 60s with or without an aluminum backup wall of $L_2=2\times10^{-3}$m, with the heat flux $q$ of 1 to 10MW/m².

3.1.1. Maximum surface temperature $T_{\text{s, max}}$

Figure 3a shows the relation between the maximum surface temperature $T_{\text{s, max}}$ and $\rho_s$ for various values of heat flux $q$ with a constant $t_h$ of 60s. It is seen that for $q=5$, 7.5 and 10MW/m², $T_{\text{s, max}}$ is nearly constant independent of the values of $\rho_s$, whereas $T_{\text{s, max}}$ decreases slightly as $\rho_s$ increases for $q=1$MW/m². Figure 3b shows the relation between $T_{\text{s, max}}$ and $q$ for several values of $\rho_s$. $T_{\text{s, max}}$ increases as $q$ increases. Deviations of $T_{\text{s, max}}$ due to the density decrease as $q$ increases.

Additional calculations show that longer $t_h$ of more than 60s
tends to raise $T_{b_{\text{max}}}$ especially for high $\rho_v$ and low $q$. and each curve of constant $q$ approaches the parallel line with respect to the $\rho_v$ axis. This means that the ablator is not in a steady state condition but is still in a transient condition especially for high $\rho_v$ and low $q$. Deviations of $T_{b_{\text{max}}}$ due to the density which is shown in Fig. 3b also decrease as $t_i$ increases.

With the following assumptions and by using a simple model, we can show that each term of surface energy balance equation Eq. (6) is the same irrespective of the ablator density, which is shown below.

We assume the LATS ablators with various densities, and that each ablator is in a steady state condition under the same heating load. We also assume that the surface temperature $T_s$, mass loss rate of the ablator surface $\dot{m}_{ab}$, mass loss rate of the pyrolysis gas $\dot{m}_p$, and total mass loss rate $\dot{m}_{\text{tot}}(=\dot{m}_{ab}+\dot{m}_p)$ of each ablator are the same, respectively. (It can be shown by simple consideration that these assumptions of a steady state condition, and the same heating load, $T_i$ and mass loss rate do not contradict each other.)

When we assume the assumptions mentioned above, each term on the right side of Eq. (6) has the same value for different densities, because each term is a function of the heat load/surface temperature/mass loss rate, and not of the ablator density.\(^{13}\) The term of left side means the net heat conduction into the ablator, which is roughly approximated by using a simple model of a steady state semi-infinite receding solid of constant properties with constant $T_s$, $T_i$ (initial temperature), and mass loss rate. Thus we obtain $q_{\text{net}} = \dot{m}_{ab} C_p (T_s - T_i)$.\(^{21}\)

Assuming $C_p$ is the same, this relation means the same value of $q_{\text{net}}$ for different densities.

The above results, although roughly estimated, do not contradict the tendency that the surface temperature is nearly equal irrespective of the ablator density, as shown in Figs. 3a and 3b.

### 3.1.2. Maximum back surface temperature $T_{b_{\text{max}}}$

Figures 4a and 4b show the relations between $T_{b_{\text{max}}}$ and $\rho_v$ with and without an aluminum backup wall of $L_2=2\times10^{-3}$m, for $q=1$ and 10MW/m$^2$, with $L_1$ of $40\times10^{-3}$ and $60\times10^{-3}$m, respectively.

In both figures, for low $q$, $T_{b_{\text{max}}}$ is nearly constant with various $\rho_v$. Main factors that influence $T_{b_{\text{max}}}$ would be the thermal diffusivity of the ablator $\alpha$ and the surface recession $\Delta S$,\(^{11}\) $\alpha$ of the LATS ablator is nearly equal for different densities (For example, the difference of $\alpha$ between $\rho_v=400$ and 1000kg/m$^3$ is about 10%). When $\Delta S$ is relatively small, nearly equal $\alpha$ determines nearly equal $T_{b_{\text{max}}}$. Low $q$ yields relatively small $\Delta S$ (See 3.1.4.) and nearly equal $T_{b_{\text{max}}}$ is obtained.

It is seen that $T_{b_{\text{max}}}$ slightly increases as $\rho_v$ increases for low $q$, the reason of which would be due to the combination of small $\Delta S$, nearly equal $\alpha$, and other factors of the surface temperature $T_i$ (during heating) and the heat capacity $pC_p$. (For precise discussion of the mechanism, see Ref. 11.) It is seen that the dependency of $T_{b_{\text{max}}}$ upon $\rho_v$ is smaller when $q$ is lower, $L_1$ is larger and $\rho_v$ is larger. Lower $q$, larger $L_1$ and larger $\rho_v$ correspond to relatively smaller $\Delta S$ (See 3.1.4.), which contribute the small dependency of $T_{b_{\text{max}}}$ upon $\rho_v$. It is also seen that $T_{b_{\text{max}}}$ increases when $q$ increases, $L_i$ decreases, or the backup wall is not attached. Larger $q$ and smaller $L_1$ correspond to relatively larger $\Delta S$, which contribute to increase $T_{b_{\text{max}}}$. As for the backup wall, the wall heat capacity decreases $T_{b_{\text{max}}}$. In these figures, with $q=10$MW/m$^2$, $T_{b_{\text{max}}}$ increases rapidly as $\rho_v$ decreases in the range of low density. In this case, $\Delta S$ increases largely for a low density ablator, which increases $T_{b_{\text{max}}}$.

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**Fig. 3a.** Relation between $T_{b_{\text{max}}}$ and $\rho_v$ for various $q$.

**Fig. 3b.** Relation between $T_{b_{\text{max}}}$ and $q$ for various $\rho_v$.

**Fig. 4a.** Relation between $T_{b_{\text{max}}}$ and $\rho_v$.

**Fig. 4b.** Relation between $T_{b_{\text{max}}}$ and $\rho_v$. 

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Pe_99
3.1.3. Mass loss of ablator $\Delta m$

Figure 5 shows the relation between the mass loss $\Delta m$ and ablator density $\rho_a$ with several $q$ for $t_0$ of 60s. It is seen that $\Delta m$ increases almost linearly as $\rho_a$ increases. In the previous paper [11] it was shown that for a relatively low value of $q$ with diffusion controlled oxidation, the mass loss $\Delta m (=\Delta m_{ab,s}+\Delta m_{g})$ mass loss of surface recession due to diffusion controlled oxidation, $\Delta m_{g}$ mass loss due to pyrolysis gas) has a linear relation with $\rho_a$ by using a simple model. For a high value of $q$, additional effect of sublimation should be considered. In the sublimation range, when $q$ is the same, each surface temperature of ablators with different densities is nearly equal (See 3.1.1.). The same surface temperature gives the same mass loss due to sublimation.[13] Thus the mass loss of surface recession due to sublimation $\Delta m_{ab,s}$ is also the same, which means that the relation of $\Delta m (=\Delta m_{ab,s}+\Delta m_{g})$ and $\rho_a$ is also linear in the sublimation region.

3.1.4. Surface recession $\Delta S$

Figure 6a shows the relations between the surface recession of the ablator $\Delta S$ and $\rho_a$ with several $q$ for $t_0$ of 60s. Figure 6b shows the relation between $\Delta S$ and $\rho_a$ with several $\rho_a$. In these figures, solid curves ($\Delta S_{ab}$) are calculated considering diffusion controlled oxidation/sublimation [12, 13] and dotted curves ($\Delta S_d$) are calculated considering only diffusion controlled oxidation. It is seen that $\Delta S_{ab}$ increases with the decrease of $\rho_a$ or the increase of $q$. When $q$ is higher and $\rho_a$ is lower, $\Delta S_{ab}$ increases largely. For low $q$ the difference between $\Delta S_{ab}$ and $\Delta S_d$ is small, which means that the surface recession is mainly due to diffusion controlled oxidation. For high $q$, the difference between $\Delta S_{ab}$ and $\Delta S_d$ becomes larger, which means that the effect of sublimation upon the surface recession becomes larger and the surface recession is promoted.[12, 13]

3.1.5. Necessary thickness $t_{\text{neAll}}$

Figure 7 shows the relation between the necessary thickness of the ablator $t_{\text{neAll}}$ and the density $\rho_a$ for various $q$ of a constant heating time $t_0$ of 60s, with and without an aluminum backup wall of $L_2=2 \times 10^{-3} \, \text{m}$. (Necessary thickness $t_{\text{neAll}}$ is defined to be $t_{\text{neAll}}=t_{\text{ne}}+t_{\text{L}}$.) $t_{\text{neAll}}$ increases with the increase of $q$.

The dependency of $t_{\text{neAll}}$ upon $\rho_a$ is small for $q=1$ and 5MW/m$^2$. Considering the tendency of $t_{\text{neAll}}$ is the same as that of $T_{\text{w, max}}$ in 3.1.2, the reason of small dependency on $\rho_a$ is due to small $\Delta S$ and nearly equal $\alpha$ as shown in 3.1.2. For $q=1$ and 5MW/m$^2$ with more than about 600kg/m$^3$, $t_{\text{neAll}}$ is seen to increase slightly as $\rho_a$ increases. The slight increase would be due to the combination of a relatively small value of $\Delta S$, nearly equal $\alpha$ and other factors of surface temperature and heat capacity of the ablator as described in 3.1.2.

For $q=10$MW/m$^2$, $t_{\text{neAll}}$ increases monotonously as the density decreases. The increasing rate also increases as the density decreases. The reason why $t_{\text{neAll}}$ is large especially for low density and high heat flux is as follows: When $\rho_a$ is lower and $q$ is higher, $\Delta S$ increases. Especially when $q$ is around 10MW/m$^2$, the surface recession increases largely due to the combination of diffusion controlled oxidation and sublimation, which causes the thickness of the ablator shorter, and $t_{\text{neAll}}$ becomes larger. This tendency is slightly seen also with $q=5$MW/m$^2$ for low density.

When a backup wall is attached to the ablator, $t_{\text{neAll}}$ decreases. (It is seen that $t_{\text{ne}}$ decreases with a backup wall)
attached.) Because $L_2$ has a constant value for each of the wall conditions, the tendency of $t_{\text{ne}}$ is similar to that of $t_{\text{neALL}}$.

### 3.1.6. Necessary mass $m_{\text{neALL}}$

The necessary mass $m_{\text{neALL}}$ is defined to be $m_{\text{neALL}} = m_\text{av} + m_\text{e}$, where $m_\text{e}$ is the necessary mass expressed by $m_\text{e} = t_{\text{neAll}} \times \rho_\text{e}$ and $m_\text{e}$ is the wall mass expressed by $m_\text{e} = L_2 \rho_\text{e}$. Accordingly, $m_{\text{neALL}}$ is expressed by

$$m_{\text{neALL}} = t_{\text{neAll}} + L_2 \rho_\text{e}$$

(8)

When $L_2$ is constant, $L_2 \rho_\text{e} = (m_2)$ also has a constant value for the same wall material. Eq. (8) means that $t_{\text{neAll}}$ determine the value of $m_{\text{neALL}}$. So, $t_{\text{neALL}} = (t_{\text{ne}} + L_2)$ in Fig. 7 determines $m_{\text{neALL}}$. Figure 8 shows the relations between the necessary mass of the ablator $m_{\text{neALL}}$ and the virgin density $\rho_\text{e}$ with several kinds of $q$ for a constant heating time $t_\text{h}$ of 60s, with and without an aluminum backup wall of $L_2 = 2 \times 10^{-3}$m. It is seen that $m_{\text{neALL}}$ increases as $\rho_\text{e}$ increases, and the relation is nearly linear for the low heat flux. For low $q$, $t_{\text{neALL}}(t_\text{h})$ is nearly constant in Fig. 7, which gives the nearly linear relation of $m_{\text{neALL}}$ and $\rho_\text{e}$ in Fig. 8. While as shown in Fig. 7, $t_{\text{neALL}}$ (and $t_{\text{ne}}$) with $q = 10 \text{MW/m}^2$ decreases as $\rho_\text{e}$ increases in the low density region, $m_{\text{neALL}}$ (and $m_\text{e}$) increases as $\rho_\text{e}$ increases. This is because $m_\text{e}$ is the product of $t_{\text{ne}}$ and $\rho_\text{e}$. It is also seen that $m_{\text{neALL}}$ increases as $q$ increases. When $\rho_\text{e}$ is high, the value of $m_{\text{neALL}}$ for $q = 5 \text{MW/m}^2$ is relatively near that for 10MW/m$^2$. This tendency corresponds to that of $t_{\text{neALL}}$ shown in Fig. 7. When an aluminum backup wall is attached to the ablator, $m_{\text{neALL}}$ increases. (Based on Fig. 7, it is also seen that $m_\text{e}$ decreases with a backup wall attached).

Because $m_2$ has a constant value for each of the wall conditions, the tendency of $t_{\text{ne}}$ is similar to that of $t_{\text{neALL}}$.

In order to satisfy the back surface temperature requirement, selection of a lower density ablator is more advantageous than that of a higher density ablator from the point of reducing the ablator mass. However, selection of a low density ablator gives a larger necessary thickness.

### 3.2. Constant accumulated heat load

In this section, thermal protection performance of the LATS ablator is examined for the case of constant accumulated heat load $Q (Q = q \times t_\text{h})$ from 120 to 600MJ/m$^2$, where $q$ is from 1 to 10MW/m$^2$ and $t_\text{h}$ is calculated by $t_\text{h} = Q/q$.

#### 3.2.1. Maximum back surface temperature $T_{\text{b max}}$

Figure 9 shows the relation between $T_{\text{b max}}$ and $\rho_\text{e}$ of the ablator of $L_1 = 40 \times 10^{-3}$m, with and without an aluminum backup wall of $L_2 = 2 \times 10^{-3}$m, for $Q = 240 \text{MJ/m}^2$ with several $q$. It is seen that $T_{\text{b max}}$ decreases as $q$ increases. For constant $Q$, when $q$ is lower or higher, $t_\text{h}$ becomes longer or shorter, respectively. Different $q$ and $t_\text{h}$ give different temperature distributions in the ablator. This would be the reason of the relation between $T_{\text{b max}}$ and $q$. When a backup wall is attached, $T_{\text{b max}}$ decreases. Dependency of $T_{\text{b max}}$ upon $\rho_\text{e}$ is not so large for a constant value of $q$, the main reason of which would be relatively small value of $\Delta S$, and nearly equal $\alpha$ for different densities (See 3.1.2.)

#### 3.2.2. Necessary thickness $t_{\text{neALL}}$

Figures 10a and 10b show the relations between the necessary thickness of the ablator $t_{\text{neALL}}$ and $\rho_\text{e}$ with and without...
an aluminum backup wall of $L_2=2\times10^{-3}$m with several $q$, for $Q$ of 120 and 600 MJ/m$^2$ respectively. In Fig. 10a, it is seen that for a constant $Q$ of 120MJ/m$^2$, at least except for the case of low density, $m_{ne\text{ALL}}$ decreases as $q$ increases. $m_{ne\text{ALL}}$ also decreases when a backup wall is attached. In Fig. 10b, it is seen that for a constant $Q$ of 600MJ/m$^2$, $m_{ne\text{ALL}}$ decreases as $q$ increases for relatively high density ablators. In the range of relatively low density, $m_{ne\text{ALL}}$ decreases as $\rho_v$ increases. Except for the case of $\rho_v=1000$kg/m$^3$, $m_{ne\text{ALL}}$ decreases when a backup wall is attached. ($m_{ne}$ also decreases with a backup wall attached.) In both figures, $m_{ne\text{ALL}}$ decreases as $q$ increases with the exception of some conditions. As mentioned in 3.2.1, this would be because of the different temperature distributions in the ablator due to the different $q$ and $t_q$. In Fig. 10b, $m_{ne\text{ALL}}$ in the low density region increases for high $q$, the reason of which would be due to the large surface recession in this region.

Because $L_2$ has a constant value for each of the wall conditions, the tendency of $m_{ne}$ is similar to that of $m_{ne\text{ALL}}$.

### 3.2.3. Necessary mass $m_{ne\text{ALL}}$

Figures 11a and 11b show the relations between the necessary mass $m_{ne\text{ALL}}$ and $\rho_v$ with and without an aluminum backup wall of $L_2=2\times10^{-3}$m with several $q$ for $Q$ of 120 and 600 MJ/m$^2$, respectively. In Fig. 11a, it is seen that for $Q=120$MJ/m$^2$, $m_{ne\text{ALL}}$ increases as $\rho_v$ increases. When a backup wall is attached, $m_{ne\text{ALL}}$ increases. (Based on Figs. 10a and 10b, it is also expected that $m_{ne}$ decreases when a backup wall is attached.) Except for the case of very low density, $m_{ne\text{ALL}}$ decreases as $q$ increases. In Fig. 11b, it is seen that with $Q=600$MJ/m$^2$, for a relatively high density ablator $m_{ne\text{ALL}}$ increases as $\rho_v$ increases, $q$ decreases or when a backup wall is attached.}

In both figures, except for some conditions $m_{ne\text{ALL}}$ decreases as $q$ increases. As discussed in 3.2.1 and 3.2.2, this would be because of the different temperature distributions in the ablator due to the different $q$ and $t_q$. It is also seen that, $m_{ne\text{ALL}}$ increases as $\rho_v$ increases, the tendency of which is different from that of $m_{ne}$ in high density. As discussed in Sec. 3.1.6, this is because $m_{ne}$ is the product of $t_{ne}$ and $\rho_v$.

Because $m_2$ has a constant value for each of the wall conditions, the tendency of $m_{ne}$ is similar to that of $m_{ne\text{ALL}}$.

#### 3.3. Effect of backup wall material (constant wall thickness $L_2$ and constant heating duration time $t_q$)

Figure 12 shows the relation between the necessary thickness $l_{ne\text{ALL}}$ and $\rho_v$ for various $q$ with $t_q$ of 60s, with backup walls of $L_2=2\times10^{-3}$m, materials of which are aluminum (AL), stainless steel (SUS), and high density CFRP. Each density of AL, SUS and CFRP is assumed to be $2713$, $7833$, and $1450$ kg/m$^3$, respectively. It is seen that SUS gives the minimum thickness of $l_{ne\text{ALL}}$, AL and CFRP give the second and the third minimum, respectively for most of the parameter range. The ratios of heat capacity $\rho C_p$ of SUS and AL with respect to CFRP are, $(\rho C_p)_{SUS}/(\rho C_p)_{CFRP}\approx 2.0$ and $(\rho C_p)_{AL}/(\rho C_p)_{CFRP}\approx 1.4$ (average values between RT and 250°C) respectively, from which SUS has the maximum heat capacity. The maximum heat capacity of a wall gives the minimum $t_{ne}$ and thus $l_{ne\text{ALL}}$. This is the reason why SUS gives the minimum $l_{ne\text{ALL}}$.

$l_{ne\text{ALL}}$ is expressed by $l_{ne\text{ALL}}=t_{ne}+L_2$ and $L_2$ is constant ($2\times10^{-3}$m). This means that the tendency of $t_{ne}$ is similar to that of $l_{ne\text{ALL}}$.

Figure 13a shows the relation between $m_{ne}$ and $\rho_v$ for various $q$ with $t_q$ of 60s, with backup walls of $L_2=2\times10^{-3}$m, materials of which are AL, SUS, and CFRP. It is seen that SUS gives the minimum $m_{ne}$. AL and CFRP give the second and the third minimum, respectively for most of the parameter range. Although $m_{ne}$ for CFRP is the maximum and that for SUS is the minimum as shown in Fig. 13a, the wall mass $m_2=(\rho L_2)$ of CFRP is the minimum and that of SUS is the maximum. Thus, $m_{ne\text{ALL}}=(m_{ne}+m_2)$ of CFRP becomes the minimum and that of SUS becomes the maximum.
3.4. Effect of backup wall material (Constant wall mass density $m_2$ and constant heating duration time $t_0$)

Figure 14 shows the relation between $t_{ne}$ and $\rho_2$ for various $q$ with $t_q$ of 60s, with backup walls of $m_2=5.4$ kg/m$^2$. The thickness $L_2$ of each material of AL, SUS, and CFRP is $2 \times 10^{-3}$, $0.693 \times 10^{-3}$, and $3.74 \times 10^{-3}$ m, respectively. It is seen that CFRP gives the minimum $t_{ne}$, AL and SUS give the second and the third minimum, respectively for most of the parameter range. Because the wall mass density $m_2$ is the same for each material, specific heat of the material plays an important role for the necessary thickness. The ratio of specific heat $C_p$ of SUS and AL with respect to CFRP is, $(C_p)_{\text{SUS}}/(C_p)_{\text{CFRP}} \cong 0.4$, $(C_p)_{\text{AL}}/(C_p)_{\text{CFRP}} \cong 0.7$ (average values between RT and $250^\circ\text{C}$), from which CFRP has the maximum specific heat. The maximum specific heat gives the minimum $t_{ne}$. This is the reason why CFRP gives the minimum $t_{ne}$.

Figure 15 shows the relation between the necessary mass of the ablator $m_a$ and $\rho_2$ for various $q$ with $t_q$ of 60s, with a backup wall of $m_2=5.4$ kg/m$^2$, each material of which is AL, SUS, and CFRP, respectively. It is seen that CFRP gives the minimum $m_a$, AL gives the second minimum and SUS gives the third minimum, for most of the parameter range.

Because $m_2$ is the same for each material, the tendency of $m_{\text{neALL}}$ is similar to that of $m_{\text{ne}}$ in Fig.15.

3.5. Important results of the analysis

Among the calculated parameters, the thickness and mass of the ablator system is very important in the design of the heat shield system. Here, main results of the analysis with respect to the necessary thickness and mass are summarized as follows:
(1) When a backup wall is attached, $t_{ne}$ and $t_{ne\text{ALL}}$ decrease and $m_{\text{neALL}}$ increase for most of the parameter range.
(2) For a low heating level with a constant $t_q$, $t_{ne}$ is nearly constant as the density changes. On the other hand, $t_{ne\text{ALL}}$ increases largely when $q$ is larger and $\rho_2$ is smaller. $m_{\text{ne}}$ increases with the increase of $\rho_2$ and $q$.
(3) For a constant $Q$, $t_{ne\text{ALL}}$, $m_{\text{neALL}}$ decrease and for a higher $q$ especially when $\rho_2$ is high.
(4) When $L_2$ is the same, the CFRP backup wall gives the minimum $m_{\text{neALL}}$, but gives the maximum $t_{ne\text{ALL}}$ (and $t_{ne}$) for most of the parameter range. The SUS wall gives the maximum $m_{\text{neALL}}$, and the minimum $t_{ne\text{ALL}}$ (and $t_{ne}$).
(5) When $m_2$ is the same, the CFRP backup wall gives the minimum $m_{\text{ne}}$ (and $m_{\text{neALL}}$) and minimum $t_{ne}$ for most of the parameter range. The SUS wall gives the maximum $m_{\text{ne}}$ (and $m_{\text{neALL}}$), and the maximum $t_{ne}$.
(6) Selection of a lower density ablator with a CFRP backup wall is more advantageous than that of a higher density ablator with other walls (AL, SUS) from the point of mass reduction of the heat shield system for most of the parameter range.
(7) For a high heat flux, selection of a lower density ablator gives a larger necessary thickness.
In the previous study \(^{11}\) with a relatively low heating load (region of diffusion controlled oxidation), it was found that the calculated results of thermal protection performance of the LATS ablator based on the arc-heated test conditions (rectangular heating pattern) are similar to those based on the re-entry conditions. The study in this paper is based on the high heating load of a rectangular pattern (arc-heated test heating condition), which includes the region of sublimation. The surface degradation mechanisms of diffusion controlled oxidation and sublimation are quite different. Therefore it is not so clear that the study results of this paper based on the high heating load of a rectangular pattern would be similar to those based on the re-entry conditions, as in the case of low heating conditions. \(^{11}\) This should be confirmed in the future study.

4. Conclusions

Main findings within the range of parameters investigated in this paper are:

1. The dependency of the maximum surface temperature upon the ablator density is small especially when \(q\) is high.

2. The dependency of the maximum back surface temperature \(T_{b_{\text{max}}}\) upon the ablator density is small especially for a large ablator thickness, a low heat flux and a high density, whereas for a small thickness, a large heat flux and a low density, \(T_{b_{\text{max}}}\) increases largely especially when the ablator density is small.

3. For high \(q\), the effect of sublimation upon the surface recession is relatively large.

4. The main results of the analysis with respect to the necessary thickness and mass are summarized in Sec. 3.5.

The study results in this paper would give important information in selecting, designing and testing the candidate ablator to be used for the heat shield system of a newly developed re-entry capsule in the near future.

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References


19) MIL-HDBK-5F, Nov. 1990
