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HEAT AND MASS TRANSFER CORRELATION EQUATIONS FOR SUBLIMING GRAPHITE IN HIGH SPEED FLOW.

MASTER

by L. L. PERINI

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY

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FOREWORD

The work reported herein was conducted by the Aeronautics Division of the Applied Physics Laboratory for the Atomic Energy Commission Safety Branch, Space Nuclear Systems Office. Activities of the Aeronautics Division are under the general supervision of Dr. William H. Avery. The Project Engineer for the Aerospace Nuclear Safety Program is James C. Hagan.

ABSTRACT

Current correlations for the mass loss rate of graphite in the sublimation regime are reviewed and it is concluded that the models are inappropriate for use in an aerothermal analysis of nuclear heat source reentry bodies. Employing current thermochemical data and heat and mass transfer coefficients a new set of correlation equations have been developed. The new set of correlations are valid for wall temperatures greater than 2400°R and extend from $P_w = 0.00001$ to 100.0 atm and from $h_T = 2000$ to $28,000$ Btu/lb. The correlations are accurate to $\pm 10\%$ throughout the majority of the region.

ACKNOWLEDGMENT

The author wishes to acknowledge the assistance of D. W. Conn who initiated the work and reviewed the results.

SUMMARY

In previous thermal studies of nuclear heat sources on spacecraft, correlation equations for the sublimation region of graphite have been employed. Two of the correlations (Scala and Gilbert, Fogaroli and Brant) are reviewed and it is concluded that they are inapplicable for use in an aerothermal analysis of nuclear heat source reentry bodies, primarily because the correlations are restricted to the suborbital flight regime and require extensive extrapolation. Employing current thermochemical data and correlations of the heat and mass transfer coefficients (Putz and Bartlett) a new set of correlation equations have been developed. The new correlations are felt to be an improvement over previous correlations, with respect to the nuclear safety program, in that a) the range of the correlations has been extended to cover the super-orbital regime, b) the correlations are appropriate for downstream locations for laminar and turbulent boundary layers, c) current thermochemistry is employed, d) mass loss rates, when the erosion model is included, agree with experimental data and e) the correlations extend into the diffusion limited regime, and it is not assumed that blowing off-sets exothermic heat release. The correlation is accurate to $\pm 10\%$ over the majority of the region ($P_w = 0.00001$ to 100 atm) except at the high pressure point of $P_w = 100$ atm where the errors are greater than 10% . The correlations are valid for $T_w > 2400^\circ\text{R}$. Rarefied flow effects, although not considered herein, can be approximated by appropriately modifying $\rho_e U_e C_h$.

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I. INTRODUCTION

In the evaluation of the safety aspects of nuclear heat sources employed on spacecraft a reentry thermal analysis that considers the effects of ablation is a necessity. Previous¹ and current² safety evaluations by Atomic Energy Commission (AEC) contractors have employed the Scala and Gilbert³ correlation equations for the sublimation regime of graphite. In a recent comparison with General Electric Corporation (GE)⁴ discrepancies were noted in predicted stagnation point net heat fluxes in the graphite sublimation regime between the techniques employed at the Applied Physics Laboratory (APL) and those employed by GE.

It is the purpose of this memorandum to first, outline the heat and mass transfer coefficient approach employed at APL; second, discuss two correlation equations currently in use for graphite sublimation; and third, present new correlation equations formulated on the basis of the procedures and data employed at APL. The graphite sublimation correlation described in this report was conceived in order to provide the safety contractors a means of updating their reentry analyses to include the effects of current thermochemistry and to eliminate the extrapolations of older correlations, without the burden of a more exact solution such as that provided by the detailed procedure in use at APL.

II. MASS AND HEAT TRANSFER COEFFICIENT TECHNIQUE EMPLOYED AT APL

A. SURFACE ENERGY BALANCE

The surface energy balance equation has been thoroughly discussed in a number of references, e.g., 5, 6, and 7, therefore only a superficial presentation will be given here. Figure 1 shows the energy components under consideration and the resulting balance is then

$$\left(k \frac{\partial T}{\partial y} \right)_w = \rho_e U_e C_h (h_T - h_{e,w}) + \rho_e U_e C_m \left[\sum (z_{i,e}^* - z_{i,w}^*) h_i^{T_w} \right] + \dot{m}_w (h_c - h_w) + q_{rad,in} - q_{rad,out} \quad (1)$$

In Eq. (1) the Z_i^* are modified diffusion forces and are defined in Ref. 6. For equal diffusion coefficients for all species in the summation, the diffusion forces reduce to the species mass fractions K_i . The one-dimensional computer code⁸ employed at APL has the capability of employing Eq. (1) in its general form, however, to date we have assumed that the diffusion coefficients are equal. In addition the correlation for the heat and mass transfer coefficients currently in use and discussed below also assume equal diffusion coefficients. Now

$$\left. \begin{aligned} h_w &= \sum K_{i,w} h_i^{T_w} \\ h_{e,w} &= \sum K_{i,e} h_i^{T_w} \end{aligned} \right\} \quad (2)$$

where $h_{e,w}$ is the enthalpy evaluated with the boundary layer edge composition at the wall temperature and h_w is the enthalpy evaluated at the

wall temperature and composition. Dropping the radiative flux terms since those will not be correlated, using Eqs. (2) in Eq. (1), and defining $B' = \dot{m}_w / (\rho_e U_e C_m)$ we have,

$$\left(k \frac{\partial T}{\partial y} \right)_w = \rho_e U_e C_h \left[(h_T - h_{e,w}) + \frac{C_m}{C_h} (h_{e,w} - h_w) \right] + \rho_e U_e C_m B' (h_c - h_w) \quad (3)$$

For the case $C_m = C_h$ (i.e., $Le = 1$) this reduces to the familiar form:

$$\left(k \frac{\partial T}{\partial y} \right)_w = \rho_e U_e C_h \left[(h_T - h_w) + B' (h_c - h_w) \right] \quad (4)$$

B. COUPLING OF MASS TRANSFER AND HEAT TRANSFER

Putz and Bartlett in a recent publication⁹ have employed the BLIMP¹⁰ computer program to generate stagnation point boundary layer solutions with heat and mass transfer for air flowing over graphite and charring ablaters. The analysis employed equilibrium, similar, equal diffusion coefficient assumptions. The resulting numerical solutions were correlated with

$$\left(k \frac{\partial T}{\partial y} \right)_w = \rho_e U_e C_{h_o} \psi (h_T - h_w) + \rho_e U_e C_{h_o} B' \phi (h_c - h_w) \quad (5)$$

where

$$\phi = \frac{C_m}{C_{h_o}} = \frac{1}{2\lambda_m B'} \ln (1 + 2\lambda_m B') \quad (6)$$

$$\left. \begin{aligned} \lambda_m &= (1.012 + 0.018 B'_o + 0.0814 B'^2_o)(1 - F_1) \\ F_1 &= (0.238 + 0.038 B'_o) \left(\frac{F_2 - 0.95}{0.60} \right)^{0.71} \\ F_2 &= \begin{cases} 0.95 & m_w/m_e \leq 0.95 \\ m_w/m_e & 0.95 < m_w/m_e < 1.55 \\ 1.55 & m_w/m_e \geq 1.55 \end{cases} \end{aligned} \right\} \quad (7)$$

$$\begin{aligned} \Psi = \frac{C_h}{C_{h_o}} &= 1.0 - 0.6563 B'_o + 0.01794 B'^2_o \\ &\quad + 0.06365 B'^3_o - 0.01125 B'^4_o \end{aligned} \quad (8)$$

$$B'_o = \phi B' \quad (9)$$

$$B' = \dot{m}_w / (\rho_e U_e C_m) \quad (10)$$

and

$$\rho_e U_e C_{h_o} = \dot{q}_{w,o} / (h_T - h_w) \quad (11)$$

is the non-ablating heat transfer coefficient.

The numerical solutions upon which the correlations are based were generated for flight conditions ranging from $h_T = 500$ to 13,000 Btu/lb (i.e., $U_\infty = 5000$ to 26,000 ft/sec) and stagnation pressures of 0.01 to 150 atmospheres. The Ψ correlation, however, encompasses higher enthalpy levels, as the authors employ previously published numerical solutions in these correlations encompassing the flight conditions $h_T = 40,000$ to 60,000 Btu/lb and $P_w = 0.2$ to 1.0 atm. In addition the correlations were compared

to non-similar solutions and found to give good agreement. The correlations were checked against the original calculations and it was found⁹ that for Ψ , "the errors are usually within 2 to 3 percent and seldom exceed 7 percent" and for $\emptyset$, "the correlation equation typically predicts the data within ± 2 percent."

Shown in Fig. 2 is a plot of the blowing relationship Ψ as a function of B' as given by Eqs. (6) thru (9) for the two limiting values of $m_w/m_e = 0.95$ and 1.55. Also shown in Fig. 2 is the classic Mickley-Spalding¹¹ correlation,

$$\Psi = \frac{1}{\lambda_m B'} \ln (1 + \lambda_m B') \quad (12)$$

with $\lambda_m = 0.5$. The curve marked 'effective Scala' will be discussed below.

Shown in Fig. 3 is a plot of the mass transfer blowing relation $\emptyset$ as a function of B' from Eqs. 6 thru 9, again for the two limiting values of m_w/m_e .

C. EVALUATION OF MASS TRANSFER RATES

In order to incorporate the Putz and Bartlett coupling of mass and heat transfer into the surface energy balance, an estimate of the mass transfer rate must be provided. At high temperatures, the value for the non-dimensional mass transfer rate, B' , is dependent upon the sublimation model incorporated in the calculation. The relationship between B' , h_w , T_w , P_w and h_c that is favored at APL is generated with the EST¹³ computer code.

The calculations are based on equilibrium thermochemistry and 16 species have been considered, C_1 thru C_5 , CO, CO_2 , N_2 , N, O_2 , O, NO, CN, C_2N_2 , C_4N_2 , and C(c). The thermochemical data were from the JANAF¹⁴ tabulations and are current up to and including supplement 35.¹⁵ All enthalpies are referred to the JANAF base at $T = 298.16^\circ K$, $P = 1$ atm and the elements in their natural state. The above thermochemical model has been found to give the most realistic comparison to experimental arc-jet sublimation measurements of graphite.^{12,16} The variations of h_w with T_w and P_w is shown in Fig. 4. Also shown for comparison is the enthalpy of air at $P_w = 1$ atm. The difference between air and carbon-air enthalpies in the diffusion controlled regime $2500^\circ R < T_w < 5200^\circ R$ is due to the exothermic formation of CO for the C-air reaction resulting in an enthalpy differential ($H_{fCO}^{298} = -1748$ Btu/lb with 34.7 wt % CO) of ~ 600 Btu/lb. The variation of B' with T_w and P_w is shown in Fig. 5. The solid carbon enthalpy, h_c , is taken from the JANAF data and is shown plotted in Fig. 6.

III. PREVIOUS CORRELATIONS

A. Scala and Gilbert (1965)

Based on numerical solutions to the laminar, stagnation boundary layer equations, with a reacting graphitic surface, Scala and Gilbert³ formulated a set of correlation (curve-fit) equations to evaluate the net flux (excluding radiation) as a function of total enthalpy, total pressure, nose radius, wall temperature and wall enthalpy (based on air properties). The correlation equations are:

$$\begin{aligned}
 \frac{1}{\dot{q}_{w,o}} \left(k \frac{\partial T}{\partial y} \right)_{s,w} &= \left[1 - S (C_{c,w} - C_{c,d}) \right] \\
 \dot{q}_{w,o} &= \left(\frac{P_w}{R_N} \right)^{\frac{1}{2}} \left[33.3 + 0.0333 (h_T - h_{w,air}) \right] \\
 C_{c,w} &= 0.15 + 2.4 \times 10^6 p_w^{-\frac{2}{3}} e^{-\frac{11.1 \times 10^4}{T_w}} \\
 C_{c,d} &= 0.15 \\
 S &= a + b h_T + c h_T^2 + d h_T^3 + e h_T^4 + f h_T^5 \\
 a &= 18.68 & d &= 1.146 \times 10^{-12} \\
 b &= -0.004418 & e &= -2.057 \times 10^{-15} \\
 c &= 3.945 \times 10^{-7} & f &= 8.333 \times 10^{-20} \\
 \dot{m}_w / \dot{m}_d &= 6.67 C_{c,w}
 \end{aligned} \tag{13}$$

with P_w in atm, T_w in $^{\circ}\text{R}$, h_T and $h_{w,air}$ in Btu/lb. The correlation equations were developed for the region $3500 < h_T < 12,000$ Btu/lb (i.e., $11,000 < U_{\infty} < 24,800$ ft/sec) and $0.01 < P_w < 100$ atm. The numerical solutions assumed a laminar locally similar boundary layer with 10 species $[O, N, CO, CO_2, CN, C, C_3, N_2, O_2 \text{ and } C(c)]$. Transport properties were evaluated from statistical mechanic formulations based on then (1965) currently available force constants (i.e., no assumptions on Le or Pr were involved). Thermochemical properties for the reacting species were based on 1965 (evidently JANAF data¹⁷) information. More recent thermochemical data show some differences with the data used in this correlation, a factor that can affect the accuracy of the technique.

The influence of the thermochemical properties was recognized by Scala and Gilbert where it was found that reducing $\log K_p$ for CN by an order of magnitude reduced the mass transfer by 24% and increased the heat transfer rate by 146%. In addition, reducing $\log K_p$ for C_3 by three orders of magnitude resulted in a 32% reduction in the mass loss and an increase of 120% in the heat transfer.

Shown in Table I are comparisons with current JANAF data of the heat of formation ΔH_f^{298} , the sensible enthalpy h_i at $7000^\circ R$ and the $\log_{10} K_p$ at $7000^\circ R$ for the nine gaseous chemical species considered by Scala and Gilbert. The ΔH_f^{298} were taken from Table I of Ref. 3. The Scala sensible enthalpies were read from Fig. 8 of Ref. 3, where a linear relationship of h_i with T is shown for all nine species, implying constant values of C_{p_i} . In order to compare the equilibrium constants, K_p , to the JANAF values the relations documented by Scala and Gilbert in Table 2 of their paper were transformed such that the species were formed from the JANAF 'standard states' of O_2 , N_2 and $C(c)$.

The chemical composition at $P_w = 1$ atm as a function of T_w is shown in Fig. 7 as the dashed curves, taken from Scala and Gilbert's paper. Also shown in Fig. 7, solid curves, is the chemical composition based on the current JANAF thermochemical data.

To further compare the Scala assumptions with the APL procedure the Scala values for heats of formation, specific heats and equilibrium constants shown in Table I were input into the EST¹³ computer program.

Resulting concentrations are shown by circles (o) in Fig. 7. As noted, there is excellent agreement with the Scala curves attesting to the validity of the calculations. Comparisons of B' and h_w between the JANAF(71) values and the resulting Scala curves are shown in Figs. 8 and 9. As noted the agreement is fair.

Having obtained the $B'-T_w$ relationship from the Scala data, an attempt was made to 'backout' the effective blowing relationship. Scala gave a correlation equation for the mass loss ratio $\dot{m}_w/\dot{m}_d$ (see Eq. (13)). The mass loss ratio can also be written in terms of the mass transfer coefficient, B' , and the blowing relationship, C_h/C_{h0} , as;

$$\frac{\dot{m}_w}{\dot{m}_d} = \frac{B'}{B'_d} \frac{C_h/C_{h0}}{(C_h/C_{h0})_d} \quad (14)$$

or

$$\frac{C_h}{C_{h0}} = \left(\frac{\dot{m}_w}{\dot{m}_d} \right) \left(\frac{C_h}{C_{h0}} \right)_d \left(\frac{B'_d}{B'} \right) \quad (15)$$

For a given value of P_w , T_w and B' , Eqs. (13) and (15) were solved for C_h/C_{h0} . The resulting values were essentially independent of P_w (0.00001 to 10.0 atm). Values of $B'_d = 0.17491$ and $\left(\frac{C_h}{C_{h0}} \right)_d = 0.90$ for the diffusion limits were assumed. The resulting blowing values are compared to the Mickley-Spalding,¹¹ and Putz and Bartlett⁹ correlations in Fig. 2. As noted the Scala blowing relationship is substantially lower than either of the other correlations.

B. Fogaroli and Brant (1968)

Following the suggestions of Scala and Gilbert,³ that the "mass-transfer rates for arbitrary ablation systems for the hypersonic stagnation region may be approximated by the solution of a set of algebraic thermochemical equations which yields the quantity $\sum_k C_{<k>w}$." Fogaroli and Brant¹⁷ employed a 27 component thermal model [$C_1 \rightarrow C_{16}$, O_2 , O , N_2 , N , NO , NO_2 , CO , CO_2 , C_3O_2 , CN and C_2N_2] to evaluate the equilibrium relationship between B' , T_w , P_w and h_w for pressures of $P_w = 1, 10, 100$ and 1000 atm. The thermodynamic properties for the sixteen ($C_1 \rightarrow C_{16}$) sublimating species were obtained from the Dalton¹⁸ theoretical calculations. The thermochemical data for the remaining species were obtained from the JANAF tabulation. The correlation values were obtained under the assumption that $Le = 1$ (i.e., $C_m = C_h$) and the net flux (excluding radiation) was represented as;

$$\frac{1}{\dot{q}_{w,o}} \left(k \frac{\partial T}{\partial y} \right)_w = \frac{C_h}{C_{h_o}} \left[\frac{h_T - h_w}{h_T - h_{w,air}} + B' \frac{h_c - h_w}{h_T - h_{w,air}} \right] \quad (16)$$

where the blowing relationship

$$\frac{C_h}{C_{h_o}} = \left[1 + 0.69 \left(\frac{\dot{m}_e}{\dot{m}_w} \right)^{1/3} \frac{B'}{(Pr)^{1/3}} \right]^{-1} \quad (17)$$

was employed and,

$$\dot{q}_{w,o} = \rho_e U_e C_{h_o} (h_T - h_{w,air}) \quad (18)$$

The correlations are based on suborbital speeds, i.e., $h_T \leq 12000$ Btu/lb, and given as;

$$C_{c,w}^* = 0.222 + 0.014 \log_{10} P_w$$

$$C_{c,w} = 0.15 \frac{\dot{m}_s}{\dot{m}_d}$$

$$\frac{\dot{m}_w}{\dot{m}_d} = 1 + 0.0667 e^{(.00297T^* - 500/T^*)}$$

$$T^* = (T_w - 5000) - 435 \log_{10} P_w$$

$$\text{For } C_{c,w} < C_{c,w}^*$$

$$\frac{1}{\dot{q}_{w,o}} \left(k \frac{\partial T}{\partial y} \right)_w = 1 - \left[\frac{0.18 + 0.14 \log_{10} P_w}{0.072 + 0.014 \log_{10} P_w} \right] (C_{c,w} - 0.15) \quad (19)$$

$$\text{for } C_{c,w} > C_{c,w}^*$$

$$\frac{1}{\dot{q}_{w,o}} \left(k \frac{\partial T}{\partial y} \right)_w = 0.82 - 0.014 \log_{10} P_w - S (C_{c,w} - C_{c,w}^*)$$

$$S = \left(0.873 + \frac{6673}{h_T - 2425} \right) \left(\frac{P_w}{100} \right)^{-0.0433}$$

with T_w in $^{\circ}\text{R}$, P_w in atm. and h_T in BTU/lb.

C. Comments on the Correlations

The reentry configurations of the nuclear heat sources currently under study (SNAP-19 and MHW) have a relatively low ballistic coefficient, $\beta = 40 \text{ lb/ft}^2$. These low β bodies result in decelerations and peak heat pulses which occur at high altitude and therefore low total pressures. In addition, the relatively high reentry speeds possible on current missions (PIONEER, $U_{\infty} = 44000 \text{ ft/sec}$ and LES-8/9, $U_{\infty} = 36,333 \text{ ft/sec}$) result in the heat pulse occurring at high total enthalpy levels, generally greater than 12000 Btu/lb, for the crucial safety evaluation trajectories. Both published correlation discussed above are restricted to $h_T \leq 12000 \text{ Btu/lb}$ and their use in an

aerothermal analysis of nuclear heat sources should be supported by an analysis attesting to the validity of any extrapolation. In addition, the Fogaroli and Brant correlation is restricted to $P_w \geq 1$ atm and, since the correlation equations exhibit a strong pressure effect, again extrapolations should be verified.

Critique can also be raised concerning the thermochemical assumptions employed in both correlations. The thermochemical data for the sublimating C_1 thru C_5 species have been modified¹⁹ since the Scala and Gilbert calculations and are currently still uncertain.²⁰ The Fogaroli and Brant correlations are based on the existence of equilibrium concentrations of C_1 thru C_{16} carbon vapor species for which the thermochemical information is based on theoretical calculations using estimated spectroscopic data. It has been shown^{16, 21} that this model grossly overpredicts the low pressure ($P_w < 4$ atm) sublimation experimental data of Lundell and Dickey^{12,22}, that includes a POCO-AXF-5Q graphite, the current MHW heat shield material.

Another source of uneasiness in using these correlations is that no quantitative results were presented as to the accuracy of the final correlation compared to the numerical results of the boundary layer analyses upon which they are based. Based on the above considerations the above correlations are not recommended as a realistic model for the sublimation region of current nuclear heat source re-entry configurations. The approach recommended and employed by APL has been outlined in Section II above. However, in recognition of the advantages in terms of simplicity and cost of a correlation scheme, we have developed another correlation, similar in form to the Scala and Gilbert correlation equations, based on the thermochemical data and heat and mass transfer coefficients discussed in Section II. The correlations extend into

the superorbital regime and a discussion of the errors is given. Application of a mechanical erosion correlation previously developed brings the correlations in agreement with low pressure experimental mass loss data.²²

IV. CORRELATION OF CURRENT RESULTS

A. FOGAROLI AND BRANT FORM OF CORRELATION.

Initially an attempt was made to correlate the APL calculations of net flux in the same form as that employed by Fogaroli and Brant, i.e.,

$$\frac{1}{\dot{q}_{w,o}} \left(k \frac{\partial T}{\partial y} \right)_w = \psi \frac{h_T - h_w}{h_T - h_{w,air}} + \phi B' \frac{h_c - h_w}{h_T - h_{w,air}} \quad (20)$$

The correlation was attempted by using the APL techniques described in Section II to evaluate the terms in Equation 20. The scheme involved employing Eqs. (6), (7) and (8) for ψ and ϕ , h_w and B' from Figs. 4 and 5 and the air enthalpy evaluated at T_w and P_w from Ref. 23. On this basis, Eq. 20 was evaluated as a function of T_w , P_w and h_T . However, as noted from Eq. 20 the form of the correlation introduces anomalies in the resulting curves. At $h_T = h_{w,air}$ a singularity is introduced and at $h_w = h_{w,air}$ the ratio is independent of h_T .

Both of these effects can be illustrated in Fig. 10, where we have shown the Fogaroli and Brant correlation curves (dotted lines) and the data points evaluated from the thermochemistry employed by Fogaroli and Brant and Eq. (16) at a typical pressure condition (1 atm). The region to the left of the point $h_w = h_{w,air}$ (the point where the curves converge was evidently approximated by a straight line to the point $\frac{1}{\dot{q}_{w,o}} \left(k \frac{\partial T}{\partial y} \right)_w = 1$, $C_{c,w} = 0.15$).

At the point $C_{c,w} = 0.15$, the beginning of the diffusion controlled

regime, the wall temperature is $\approx 5500^{\circ}\text{R}$ and $h_{w_{\text{air}}} \approx 1900 \text{ Btu/lb}$. As h_T approaches $h_{w_{\text{air}}}$ it is noted that the net flux is increasing. At $h_T = h_{w_{\text{air}}}$ the value of the net flux would become indeterminant. The anomalies are a direct result of the definition of the normalizing heat transfer rate, Eq. (18), and results in an unsatisfactory correlation.

B. IMPROVED CORRELATION FORM

In order to bypass this difficulty it was decided that it would be more appropriate to normalize by the diffusion limited value of heat flux. Accordingly, the net flux given by Eq. (5) was evaluated in the diffusion controlled regime where $B'_d = 0.175$, $\Psi_d = 0.90$ and we have assumed that $\phi \approx \Psi_d$. The enthalpies are independent of pressure (see Fig. 4) and a linear variation with T_w was found to be adequate in the diffusion controlled regime,

$$(h_w)_d \approx 0.3 T_w - 800, \text{ Btu/lb} \quad (21)$$

$$(h_c)_d \approx 0.41 T_w - 221, \text{ Btu/lb} \quad (22)$$

with T_w in $^{\circ}\text{R}$. Equation (5) then reduces to

$$\dot{q}_d = \left(k \frac{\partial T}{\partial y} \right)_{w,d} = \rho_e U_e C_{h_o} [0.9 h_T - 0.253 T_w + 808] \quad (23)$$

The net flux to be correlated is then

$$\frac{1}{\dot{q}_d} \left(k \frac{\partial T}{\partial y} \right)_w = \frac{\Psi (h_T - h_w) + \phi B' (h_c - h_w)}{0.9 h_T - 0.253 T_w + 808} \quad (24)$$

Using data that encompass the range $0.00001 \leq P_w \leq 100$ atm and $2000 \leq h_T \leq 28,000$ Btu/lb new correlations have been developed as described below. The carbon concentration mass fraction can be represented by

$$C_{c,w} = 0.148 + a P_w^z e^{-\frac{n}{T_w}} \quad (25)$$

where

$$a = 3.5715 \times 10^7, z = -1.2952 \text{ for } P_w \geq 0.43 \text{ atm}$$

$$a = 4.2768 \times 10^7, z = -1.0802 \text{ for } P_w < 0.43 \text{ atm}$$

$$n = 107,343 + 5,963 \left| \ln \frac{P_w}{100} \right|^{0.83056} \text{ for } P_w \geq 1.0 \text{ atm}$$

$$n = 128,543 + 3,071 \left| \ln P_w \right|^{0.72410} \text{ for } P_w < 1.0 \text{ atm}$$

The thermochemical mass flux is then given by

$$\dot{m}_w = B' \phi (\rho_e U_e C_{h_o}) \quad (26)$$

$$B' = C_{c,w} / (1 - C_{c,w}) \quad (27)$$

$$\phi = \frac{1}{1.6 B'} \ln (1 + 1.6 B') \quad (28)$$

Equation (28) is shown plotted in Fig. 3 and represents a close approximation to the Putz and Bartlett correlation for $\dot{m}_w/\dot{m}_e \geq 1.55$ and $B' \leq 3$. For $h_T \geq 10,000$ Btu/lb, $\dot{m}_w/\dot{m}_e > 1.55$ for all pressures and therefore Eq. (28) is a

valid representation in this region. At the lower enthalpy levels, $0.95 < m_w/m_e < 1.55$, and Eq. (28) represents at most a 10% overprediction, the greatest error occurring at the lowest enthalpy level, (i.e., at $h_T = 2000$ Btu/lb, $1.0 < m_w/m_e < 1.1$). However, in this region, the B' 's are low (< 0.50) and the errors are expected to be less than 10%. The net flux is given by

$$\frac{1}{\dot{q}_d} \left(k \frac{\partial T}{\partial y} \right)_w = 1 - (C_{c,w} - C_{c,d}) \left[a + b (C_{c,w} - C_{c,d}) \right] \quad (29)$$

where

$$\left. \begin{aligned} a &= \left[1.0 - 0.0024 \ln 100 P_w \left| \ln 100 P_w \right| \right] \left[0.714 + \frac{13660}{h_T - c} \right] \\ b &= \frac{d}{h_T - 1450 - 125 \ln P_w} + 0.54 \left\{ 1 + \left| \ln \frac{P_w}{.00316} \right| \left[-0.005 + 0.00642 \right. \right. \\ &\quad \left. \left. \left| \ln \frac{P_w}{.00316} \right| \right] \right\} \\ c &= 900 + 70 \ln P_w + 2.5 (\ln P_w)^2 \\ d &= 9820 \left\{ 1 + \left| \ln 100 P_w \right| \max \left[.002, -0.015 + .00706 \left| \ln 100 P_w \right| \right] \right\} \\ C_{c,d} &= 0.148 \end{aligned} \right\} \quad (30)$$

$$\dot{q}_d = (0.90 h_T - 0.253 T_w + 808) \rho_e U_e C_{h_o}$$

where T_w in $^{\circ}R$, P_w in atm. and h_T in Btu/lb. It is recommended that the value of $\rho_e U_e C_{h_o}$ be found from the Detra, Kemp and Riddell²⁴

correlation equation for the hypersonic ($6 \leq M_o \leq 57$), laminar, continuum, stagnation point cold wall heat transfer coefficient, i.e.,

$$\rho_e U_e C_{h_o} = \frac{17,600}{h_T \sqrt{R_N}} \left(\frac{\rho_\infty}{\rho_{SL}} \right)^{\frac{1}{2}} \left(\frac{U_\infty}{U_s} \right)^{3.15} \left(\frac{\beta}{\beta_s} \right)^{\frac{1}{2}} 2^{\frac{k-1}{2}} \quad (31)$$

This equation has been verified based upon a compilation of experimental shock tube data,²⁵ where $\rho_{SL} = 0.0765 \text{ lb/ft}^3$, $U_s = 26,000 \text{ ft/sec}$, β_s is the stagnation point velocity gradient for a sphere and β is the corresponding value for the geometry under consideration. For a planar geometry $k = 0$ and for an axisymmetric geometry $k = 1$. A comparison of Eq. (31) to experimental shock tube data is shown in Fig. 11.

Shown in Figs. 12 to 15 are the numerical results evaluated from Eq. (24) (circles) for $P_w = 0.00001, 0.01, 1.0$ and 100.0 atm compared to the correlation equations (solid lines) as given by Eq. (29). The numerical results shown in the four figures represent $\sim 25\%$ of the total number of points employed in developing the correlation. Except for $P_w = 100 \text{ atm}$ the correlation equations are within $\pm 10\%$ of the numerical results for

$\frac{1}{\dot{q}_d} \left(k \frac{\partial T}{\partial y} \right)_w > 0.05$ with the higher errors (10%) occurring at the lower values of the net flux. At $P_w \sim 100 \text{ atm}$ (Fig. 15) the region where the errors are $> 10\%$ is indicated by the cross-hatched line.

The mass loss due to erosion was previously correlated¹⁶ from the Lundell and Dicky experimental data for $P_w < 4 \text{ atm}$ and given by

$$\frac{\dot{m}_e - \dot{m}_w}{\dot{m}_w} = \frac{314}{7520 - T_w} - 0.155 \quad (32)$$

for $4500 \leq T_w \leq 7290^\circ\text{R}$. For $T_w \geq 7290^\circ\text{R}$, $(\dot{m}_e - \dot{m}_w) / \dot{m}_w = 1.78$. Figure 16 shows a comparison of Eq. (32) to the experimental data.

V. CONCLUSIONS

Based on the discussion in Section III it is concluded that previous correlations for the sublimation of graphite are inapplicable for use in an aerothermal analysis of nuclear heat source reentry bodies, primarily because the correlations are restricted to the suborbital flight regime and require extensive extrapolation. Employing current thermochemical data and correlations of the heat and mass transfer coefficients resulting from a numerical boundary layer analysis, a new set of correlation equations has been developed. The new correlations are felt to be an improvement over previous correlations, with respect to the nuclear safety program, in that a) the range of the correlations has been extended to cover the superorbital regime, b) current thermochemistry is employed, c) mass loss rates, when the erosion model is included, agree with experimental data and d) the correlations extend into the diffusion limited regime, and it is not assumed that blowing off-sets exothermic heat release. The correlation is accurate to $\pm 10\%$ over the majority of the region except at the high pressure point of $P_w = 100$ atm where the correlation equations yield errors $>10\%$ over a substantial region, i.e., see Fig. 15. Based on the graphite ablation review in Ref. 16 kinetic effects become pre-dominant below $T_w = 2400^\circ\text{R}$. No attempt has been made to model this region and in light of this it is suggested that the correlations not be employed below $T_w = 2400^\circ\text{R}$. Rarefied flow effects, although not considered herein, can be approximated by appropriately modifying $\rho_e U_e C_{h_o}$. This aspect of the analysis is currently under review and the results will be reported in a forthcoming memo.

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NOMENCLATURE

A	=	Reference area
B'	=	Mass transfer parameter = $\dot{m}_w / (\rho_e U_e C_m)$
B'_o	=	No blowing mass transfer parameter = $\dot{m}_w / (\rho_e U_e C_{h_o})$
$C_{c,d}$	=	Carbon mass fraction at the wall in the diffusion limited regime
$C_{c,w}$	=	Carbon mass fraction at the wall
$C_{c,w}^*$	=	See Eq. (19)
C_D	=	Drag coefficient
C_h	=	Heat transfer coefficient
C_{h_o}	=	Non-ablating (i.e., no blowing) heat transfer coefficient
C_m	=	Mass transfer coefficient
C_p	=	Specific heat at constant pressure
$C(c)$	=	Solid carbon specie
D	=	Diameter
h_c	=	Solid carbon enthalpy
$h_{e,w}$	=	Enthalpy evaluated with the boundary layer edge composition at T_w and P_w
h_i	=	Enthalpy of i^{th} species
$h_i^{T_w}$	=	Enthalpy of i^{th} species evaluated at T_w
h_T	=	Free stream total enthalpy
h_w	=	Wall static enthalpy
$h_{w,air}$	=	Air enthalpy, static, evaluated at T_w and P_w

H_f^{298}	=	Heat of formation at 298.16 °K
K_i	=	Mass fraction of i^{th} species
$K_{i,e}$	=	Mass fraction of i^{th} species at the edge of the boundary layer
$K_{i,w}$	=	Mass fraction of i^{th} species at the wall
K_p	=	Equilibrium constant in terms of partial pressure
k	=	Thermal conductivity
Le	=	Lewis number, $= \rho C_p D_{12}/k$, where D_{12} is the diffusion coefficient
$\dot{m}_e$	=	Experimental mass flux data
$\dot{m}_d$	=	Mass flux in diffusion limited regime
$\dot{m}_w$	=	Mass flux at the wall
P_R	=	Prandtl number $= C_p \mu / k$
P_w	=	Wall pressure
$\dot{q}_d$	=	Heat transfer in diffusion limited regime, Btu/ (ft ² -sec)
$\dot{q}_{w,o}$	=	Heat transfer used to normalize net flux in correlations
R_N	=	Reynolds number $= \rho DU / \mu$
T	=	Temperature
T_w	=	Wall temperature
T^*	=	See Eq. (19)
U_e	=	Velocity at edge of the boundary layer
U_s	=	Satellite speed (26000 ft/sec)
U_∞	=	Free stream velocity
W	=	Weight
y	=	Distance normal to the surface

Z_i^*	=	Modified diffusion forces
θ	=	Velocity gradient = $D/U_\infty (dU_e/dS)_{s=0}$, also ballistic coefficient = $W/C_D A$
θ_s	=	Velocity gradient for a sphere
λ_m	=	Empirical coefficient, see Eqs. (7) and (9)
μ	=	Viscosity
ρ_e	=	Density at edge of boundary layer
ρ_∞	=	Free stream density
ρ_{SL}	=	Density at sea level
ϕ	=	Mass transfer correlation parameter = C_m/C_{h_o}
ψ	=	Heat transfer correlation parameter = C_h/C_{h_o}
m_w	=	Molecular weight at the wall
m_e	=	Molecular weight at the edge of the boundary layer
$a, b, c, d, e, f, F_1, F_2, n, z$	=	Empirical coefficients employed in the various correlations
Subscripts		
$()_d$	=	Value in diffusion limited regime

TABLE I. SUMMARY COMPARISONS OF SCALA AND JANAF
THERMOCHEMICAL PROPERTIES

	ΔH_f^{298} Kcal/mole		$h_i = \int_{540^{\circ}\text{R}}^{7000^{\circ}\text{R}} C_{P_i} dT$ Kcal/mole		$\log_{10} K_p$ at 7000°R		C_p $\frac{\text{cal}}{\text{mole } ^{\circ}\text{K}}$
SPECIES	SCALA	JANAF	SCALA	JANAF	SCALA	JANAF	SCALA
O	59.147	59.559	21.150	18.001	+0.06	-0.074	5.89
O ₂	0.0	0.0	31.60	32.100	0.0	0.0	8.80
N	112.988	113.000	17.470	17.955	-2.93	-2.934	4.865
N ₂	0.0	0.0	31.148	30.095	0.0	0.0	8.674
CO	-26.413	-26.420	31.400	30.317	5.89	5.891	8.744
CO ₂	-94.063	-93.965	51.272	49.861	4.52	5.299	14.278
C	171.696	170.890	19.168	18.216	-1.43	-1.440	5.338
C ₃	190.339	196.000	53.043	42.583	-0.75	-0.559	14.771
CN	111.064	104.000	37.411	32.500	-0.15	-0.675	10.418
C(s)	0.0	0.0	21.187	19.858	0.0	0.0	5.900

$$\dot{q}_{DIFF} = \underbrace{\rho_e U_e C_h (h_T - h_{e, w})}_I + \underbrace{\rho_e U_e C_m \sum (Z_{I, a}^* - Z_{I, w}^*) h_I T_w}_{II}$$

I = CONVECTIVE SENSIBLE ENERGY TRANSFER

II = CHEMICAL ENERGY TRANSFER

NO INTERNAL GAS PRODUCTION VIA PYROLYSIS

NO MECHANICAL EROSION

Fig. 1 SURFACE ENERGY BALANCE

Fig. 2 BLOWING - NONBLOWING HEAT TRANSFER RATIO (ψ) AS A FUNCTION OF B'

Fig. 3 MASS TRANSFER - NON BLOWING HEAT TRANSFER RATIO (ϕ) AS A FUNCTION OF B'

Fig. 4 WALL ENTHALPIES FOR CARBON-AIR — BASED ON 1971 JANAF THERMOCHEMICAL DATA

Fig. 5 MASS TRANSFER PARAMETER, B' , FOR CARBON-AIR BASED ON 1971 JANAF THERMOCHEMICAL DATA

Fig. 6 CARBON ENTHALPY AS A FUNCTION OF TEMPERATURE

Fig. 7 CHEMICAL COMPOSITION AT A GRAPHITE SURFACE, BASED ON EQUILIBRIUM SURFACE REACTION

Fig. 8 COMPARISONS OF SUBLIMATION REGION $B' - T_w$ RELATIONSHIPS,
 $P_w = 1$ ATM

Fig. 9 COMPARISONS OF SUBLIMATION REGION $h_w - T_w$ RELATIONSHIPS
 $P_w = 1$ ATM

Fig. 10 EVALUATION OF FOGAROLI AND BRANT⁽¹⁷⁾ GRAPHITE HEAT TRANSFER CORRELATION, $P_w = 1$ ATM

Fig. 11 COMPOSITE PLOT COMPARING EXPERIMENTAL DATA WITH THE DETRA, KEMP AND RIDDELL CORRELATION

Fig. 12 COMPARISON OF CORRELATION TO NUMERICAL RESULTS' $P_w = 0.00001 \text{ ATM}$

Fig. 13 COMPARISON OF CORRELATION TO NUMERICAL RESULTS, $P_w = 0.01$ ATM

Fig. 14 COMPARISON OF CORRELATION TO NUMERICAL RESULTS, $P_w = 1.0 \text{ ATM}$

Fig. 15 COMPARISON OF CORRELATION TO NUMERICAL RESULTS, $P_w = 100.0$ ATM

Fig. 16 INCREMENTAL EXPERIMENTAL MASS LOSS RATE ABOVE JANAF (71) RATES

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