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Documentation of the Detailed Radiation Property Data for the Radiation-Ablation Code RASLE

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ABSTRACT

This report is a documentation of the necessary radiation property input data for the radiating shock layer simulation code RASLE. The data tabulated are required to simulate systems which are composed of oxygen, nitrogen, carbon, hydrogen and silicon. These data are needed to compute the flowfield effects of many practical ablative, hypersonic vehicle heat shield materials. A brief outline description is provided for the RASLE code. A more detailed discussion is provided for the RASLE code non-grey gas spectral radiation model. This model is related to the required radiation property data which are tabulated at the end of the report. Other correlations needed for the RASLE simulations are not discussed, since these are automatically included in the program and no input data are required.

NOMENCLATURE

C_H	surface heat transfer coefficient, g/cm^2-sec
B_ν	Plank black-body function, watts/cm^2-sr-ev
c	velocity of light, cm/sec
$f_{k(j)}$	oscillator strength (f-number), cm^2/sec
h	Plank's constant, (BTU-sec) or (joule-sec)
H_T	total enthalpy, cal/g
H_{T_w}	total enthalpy at wall or surface, cal/g
H_F	total enthalpy of formation of wall material, cal/g
I_ν	spectral intensity of radiant flux of frequency ν, watts/cm^2-ev
$\tilde{j}_k$	binary mass flux of species, k, g/cm^2-sec
$\tilde{K}_k$	mass fraction of species, k
$\dot{m}$	ablation mass loss rate, g/cm^2-sec
M_∞	freestream Mach number
N_{ij}	number density of absorbing level i for transitions from state j, cm^{-3}
P	local fluid pressure, Atm
Q^z	partition function for z-th charge state
q_a	local conduction heat flux, watts/cm^2
q_{r_ν}	local spectral radiative heat flux at frequency ν
q_r	local, total radiative heat flux
r	body symmetry axis normal local radius coordinate, m
R	local body radius of curvature, m
R_N	nose radius, m
s	streamline distance coordinate
T	local fluid temperature, K
u	tangential velocity component
u_e	tangential velocity component at or near shock
v	normal velocity component
V_∞	freestream velocity
α_{e_k}	elemental mass fraction of edge gas
α_{w_k}	elemental mass fraction of virgin wall material

ϵ_M	eddy viscosity
μ_e	viscosity of gas at or near the shock boundary
$\mu_\nu^{(i)}$	spectral absorption coefficient for radiative process (i)
ν	frequency or kinematic viscosity
$\xi(\nu)$	Biberman and Norman low frequency spectral coefficient
ϕ	azimuthal angle for tangent slab model
ρ	density, g/cm^3
θ	directional angle for tangent slab model

INTRODUCTION

A detailed analysis and design of forebody heat shields for hypersonic, planetary entry vehicles requires an in-depth knowledge of the bow shock layer heat transfer mechanisms. This includes the various molecular dissipation mechanisms as well as the radiative transfer processes. At the higher speeds encountered for re-entry from planetary transfer missions, forebody heatshield material surfaces experience very high temperatures. For example, a vehicle of the required type (typically, a blunt body having a nose radius of about 1 m) arriving at Earth from Mars at 14 km/sec will encounter very high peak stagnation point heating rates ($\approx 1.0 KW/cm^2$). This magnitude of heat flux would require a TPS material capable of withstanding operating temperatures in excess of 3590 °K if the only heat rejection mechanism was radiative cooling. There are, of course, presently no such materials. Additional dissipation mechanisms must therefore be included. One efficient means is through the use of ablative materials for the heat shield. Ablators can accept large amounts of surface energy input by endothermic, pyrolytic breakdown of the resident material. In addition, at the high operating temperatures of these TPS, the surface can undergo sublimation or vaporization with the associated vapor carrying a significant latent heat of vaporization and sensible pyrolytic vapor energy away from the surface. Finally, the ablation mechanism introduces a convective mass flux into the shock layer to actively block the incoming convective energy flux.

At the heat flux levels encountered in ablating systems, shock layer radiative heating processes become significant and eventually dominate as entry speeds approach hyperbolic values (approaching $M_\infty \approx 50$ for Earth entry). Any entry vehicle heating analysis which is to be definitive will have to therefore account for the combined dissipation mechanisms of flowfield shock generated radiation, mass addition at the surface, convection/conduction, and surface radiation absorption and emission in the presence of a reacting real gas flowfield. Computer simulation codes which do this are very few in number. There may be several in the developmental stage, but only two have been successfully applied to this type of problem. These include the HYVIS code from NASA Langely Research Center (ref. 1) and the RASLE code used at NASA Ames Research Center (ref. 2). Both codes were developed to simulate the radiation dominated ablating flowfields encountered in Jovian entry. The NASA Galileo Probe to Jupiter is protected by a carbon-phenolic forebody heat shield designed with the aid of these two computer codes. Each of these computer programs requires a comprehensive, thermodynamic and transport property input data set.

This report gives documentation for the required radiation property input data needed for simulating the behavior of ablating, radiating shock layers for systems which have either carbonaceous or silica

(SiO_2) as ablating heat shield materials. This data can be of general interest and can be used in the analysis of many different ablating materials which contain organic polymers which form chars and for materials composed primarily of SiO_2. Some materials contain both silica and polymeric constituents. From the standpoint of radiation properties these two systems can be divided into two generic types; i.e., C-H-O-N (hydrocarbon-air) and Si-O-N (silica- air) systems. The required data for each of these systems is presented in the context of the following description of the RASLE code and the associated detailed radiation model.

THE RADIATIVELY COUPLED VISCOUS SHOCK LAYER CODE RASLE

The VSL code, RASLE (Radiating Shock Layer Environment) was developed for NASA Ames Research Center (ref. 2) for research and development efforts in the Galileo Probe project. This program is designed to solve the coupled problem of a non-grey radiating gas and the hypersonic, thin-layer viscous shock external body flow. The flowfield is, in turn, coupled with a general radiation-ablating surface mass and energy balance boundary condition. Flight conditions are presumed to occur in the continuum flow region, and pressures (and total enthalpy) are assumed to be high enough that the shock layer is in thermochemical equilibrium. Both laminar and turbulent flow conditions can be modelled. Flowfield governing equations written in a body fixed coordinate system. All field variables are time averaged.

Governing Equations

Continuity

$$\frac{\partial(\rho u r)}{\partial s} + \frac{\partial(\rho v r)}{\partial y} = 0 \tag{1}$$

s-Momentum

$$\rho u \frac{\partial u}{\partial s} + \rho v \frac{\partial u}{\partial y} + \frac{\rho u v}{R} = \frac{1}{r}\frac{\partial}{\partial y}\left[\rho r(\nu + \epsilon_M)\frac{\partial u}{\partial y}\right] - \frac{\partial P}{\partial s} \tag{2}$$

y-Momentum

$$\frac{\partial P}{\partial y} = 0 \tag{3}$$

Energy

$$\rho u \frac{\partial H_T}{\partial s} + \rho v \frac{\partial H_T}{\partial y} = -\frac{1}{r}\frac{\partial}{\partial y}\left[\rho r(q_a + q_r)\right] \tag{4}$$

The equilibrium real gas thermochemical model assumed here employs a simplified binary diffusion model due to Lees (ref. 3). Conservation of elemental species in the thin shock layer is then given as:

Species Continuity

$$\rho u \frac{\partial \tilde{\kappa}}{\partial s} + \rho v \frac{\partial \tilde{\kappa}}{\partial y} = \frac{1}{r}\frac{\partial}{\partial y}(r\tilde{j}) \tag{5}$$

Mass fractions of individual elements are related functionally to the variable $\tilde{\kappa}$ as

$$\tilde{K_k} = \alpha_{w_k}\tilde{\kappa} + \alpha_{e_k}(1 - \tilde{\kappa}) \tag{6}$$

Here α_{w_k} and α_{e_k} are the elemental species mass fractions of virgin wall material and pure edge gas respectively.

As mentioned above, equations (1–6) must be solved subject to the appropriate boundary conditions at the bow shock and at the body surface. In this case, boundary conditions at the shock are the usual hypersonic, equilibrium Rankine-Hugoniot (no-slip) adiabatic shock relations. At the surface, mass, momentum, and energy are conserved by the following boundary conditions. All variables are evaluated at local surface conditions.

Wall Normal Velocity

$$(\rho v)_w = -\alpha^* \left[f + 2\xi \frac{\partial f}{\partial \xi}|_y \right] \tag{7}$$

Wall Elemental Mass Balance

$$\dot{m}(\tilde{K}_k - 1) + \tilde{j}_{k_w} = 0 \tag{8}$$

Total Wall Energy Balance

$$\dot{m}(H_{T_w} - H_F) = -q_{a_w} + q_{r_w} \tag{9}$$

f is the Levy-Lees stream function, defined as

$$f = \frac{u}{u_e} \tag{10}$$

and

$$\xi = \int_0^s \rho_e u_e \mu_e r^2 ds \tag{11}$$

The variable α^* is the flux normalization factor given as

$$\alpha^* = \rho_e u_e \mu_e r / (2\xi)^{1/2} \tag{12}$$

Solution of these governing equations is effected by means of a finite difference method. As described in reference 2, the shock layer is divided into two zones between the shock and body surface. Forward difference relations are used in the zone adjacent to the body, while the outer region near the shock employs backward difference relations. The two regions are joined by matching adjacent interior nodes with higher order splines. The overall ellipic type Cauchy problem is approximately solved through the use of a hypersonic bow shock correlation. The bow shock is approximated by means of the Falanga and Olstad shock correlation (ref. 4), and together with the equilibrium normal shock stand-off (determined by the code) a stagnation streamline and downstream solution can be obtained. This solution procedure is globally iterated from the shock correlation ultimately to yield the desired body shape. It is, in a sense, a classical blunt-body inverse solution procedure. The primary mathematical difficulty in solving this equation set is the evaluation and coupling of the local radiative flux , q_r, with the total energy equation (4). To do this the RASLE code was developed to include a very extensive non-grey radiative transfer model. An abbreviated discussion of this model is given here.

RASLE DETAILED RADIATION MODEL

The radiative transport model included in RASLE was developed by Nicolet and Wilson (refs. 5 and 6). It is extensive and is designed to be essentially complete with perhaps two exceptions. When considering hypersonic flows over planetary entry vehicles, it is assumed that flight regimes of interest (specifically where high heating rates occur) will be in the near transitional and continuum flow region. If this is not true, two radiation limiting processes will occur: namely, collision limiting and general nonequilibrium radiation. The RASLE radiation model is therefore not capable of representing these latter two low density (high altitude) related phenomena. In the future these limitations can perhaps be removed without giving up generality of the radiation-shock layer physics or ease of flowfield/radiation computations. The present model is a detailed spectral representation of the dominant radiative processes in a general multicomponent radiating gas. It is assumed that the gas is locally in radiative equilibrium and is allowed to both absorb and emit, but scattering is neglected. Radiation at the body surface can be emitted spectrally, reflected diffusely, but cannot be transmitted in-depth. To account for the non-zero view factor with respect to more intense stagnation region radiation, radiation at the shock can have an angular dependence.

This equilibrium, radiating gas model is implemented in RASLE through use of the tangent slab approximation. In this one-dimensional approximation, it is assumed that the flowfield (with respect to the radiation field) extends uniformly to infinity along planes parallel to the plane tangent to the body station of interest. On any given plane, radiation properties are constant, but there are variations from plane to plane from the surface to the shock boundary. The radiation governing equations representing this approximate transport model are expressed as follows. For a radiating gas in local thermodynamic equilibrium at a point, the radiative heat flux (cf. eq. (4)) is given as

$$q_r = \int_o^\infty q_{r_\nu} d\nu \tag{13}$$

The spectral components, q_{r_ν}, are given by

$$q_{r_\nu} = \int_o^\pi \int_o^{2\pi} I_\nu(\theta, \phi) \cos\theta \, \sin\theta d\phi d\theta \tag{14}$$

where the spectral intensity, I_ν, is given by the well known radiative equation of transfer,

$$-\frac{1}{\rho \mu_\nu} \frac{dI_\nu}{dl} = I_\nu - B_\nu(T) \tag{15}$$

μ_ν is the local gas spectral absorption coefficient (containing all processes), and $B_\nu(T)$ is the Planck black-body function given by

$$B_\nu(T) = \frac{2h}{c^2} \frac{\nu^3}{(e^{h\nu/kT} - 1)} \tag{16}$$

θ and ϕ are the directional angles between the surface normal vector, $\hat{n}$, and the local ray, $\hat{l}$, emanating from the flowfield point of interest along the surface normal direction.

Integration of equations (14) and (15) has been performed (among others) by Kendall (ref. 7) for an axisymmetric entry body for the tangent slab model. The results are simply presented here for reference and familiarization. For the frequency dependent radiative heat flux, the following relation is obtained:

$$q_{r_\nu} = q^+_{r_\nu} - q^-_{r_\nu} - 2\pi \int_{\tau_\nu}^{\tau_{\nu S}} B_\nu(T) E_2(t-\tau_\nu)dt - 2\pi \int_o^{\tau_\nu} B_\nu(T) E_2(\tau_\nu - t)dt$$
$$-2\pi e_{\nu_w} B_\nu(T_w) E_3(\tau_\nu) - 4\pi(1-e_{\nu_w})E_3(\tau_\nu) \int_o^{\tau_\nu} B_\nu(T)E_2(t)dt$$
$$+\int_o^{\pi/2} q^+_{r_\nu,\theta_S} e^{-(\tau_{\nu S}-\tau_\nu)/cos\theta} d\theta - 2(1-e_{\nu_w})E_3(\tau_\nu)\int_o^{\pi/2} q^+_{r_\nu,\theta_S} e^{-\tau_{\nu S}/cos\theta} d\theta \quad (17)$$

The quantities E_2 and E_3 are defined as the exponential integrals

$$E_n(t) = \int_o^1 \chi^{n-2} e^{-t/\chi} d\chi \quad (18)$$

and τ_ν is the frequency dependent optical thickness, defined as

$$\tau_\nu = \int_o^y \rho\mu_\nu dy' \quad (19)$$

$q^+_{r_\nu,\theta_S}$ is the partial derivative of the spectral flux toward the surface (defined as positive) with respect to the angle θ evaluated at the shock boundary. It is essentially a function of the local radiation intensity at the shock (at a point located along the surface normal) which is a known function of the shock state variables. Furthermore, detailed expressions for these quantities and the method of implementing them are available from reference 7.

Final integration of the energy equation (4) and the radiative flux integral, equation (17), requires knowledge of the optical thickness, τ_ν, as a function of position in the shock layer. Herein lies most of the radiation physics in that optical depth is a function of the spectral gas absorption coefficient, μ_ν. The absorption coefficient of a radiating plasma is dependent on all of the various radiating processes. In particular, μ_ν can be expressed as the linear combinant sum

$$\mu_\nu = \sum_{i=1}^{N_c} \mu_i^C(\nu) + \sum_{k=1}^{N_L} \mu_k^L \quad (20)$$

The first summation represents the contribution from continuum radiation and is taken over all N_c continuum transitions, and the second term is the contribution from line radiation summed over all N_L line transitions. Individual terms in the μ_ν summation which are significant for the high enthalpy re-entry flow are outlined briefly below. The radiation model which these specific functional forms represent is due to Nicolet (ref. 5), and reference should be made to that work for an in-depth discussion of the theory.

Continuum Contributions

Contributions to μ_ν^C are included from both atomic continua and molecular processes. Among the atomic continua, contributions are included to account for free-free and bound-free processes. The bound-free events include photoionization and photodetachment. These phenomena are described statistically in terms of quantum mechanical cross-sections pertinent to each process. Namely, these continua are usually written as, for the i-th absorbing level,

$$\mu_i^C(\nu) = \sum_j N_{ij}\sigma_{ij}^C(\nu) \quad (21)$$

N_{ij} is the number density of the absorbing level, usually obtained from the equilibrium chemistry calculation, and σ_{ij}^{C} is the cross-section (effective probability) for the event. For purely hydrogenic systems, cross-sections for the free-free and bound-free transitions are well understood and can be written in direct analytical form. These expressions can be found in reference 5. For the more practical heavy-ion systems, the most reliable results have been obtained from the so-called "quantum defect" method. In RASLE this method is implemented as follows. In the low frequency regime, Biberman and Norman's (ref. 8) approximation is applied to the photoionization and free-free transitions in the form

$$\mu_i^{PI,FF}(\nu) = \left(\frac{2Q^{(z+1)}}{Q^z}\right) \xi(h\nu, T)[\mu_i^{PI,FF}(\nu)]_{\text{hydrogenic}} \tag{22}$$

where Q is the partition function for the $z-$th charge state. Based on this theory, tabulated values for $\xi(h\nu, T)$ are available from reference 6. The remaining portion of the spectrum must be represented explicitly through knowledge of actual event cross-sections. These are tabulated for many atomic and ion systems in the extensive work by Peach (ref. 9). A synopsis of the necessary cross sections used in this work are given for each species in table 1. For air systems, the O_2 Schumann-Runge photodissociation continuum is the most important contributor to this process. Cross-section information for this contribution is available from Evans and Schexnayder (ref. 10). Additional contributions due to photodetachment for O^-, C^-, and H^- have been included from various investigators (cf. refs. 11–13).

Molecular continuum processes include the pseudo-continua of molecular rotational and vibrational lines and are modelled by the bandless approximation represented as

$$\overline{\mu_\nu} = \left(\int_{\delta^o\nu} \mu_\nu^o d\nu\right) / (\delta^o\nu) \tag{23}$$

Individual data and correlations for the various μ_ν^o have been obtained from various resources (cf. ref. 2) and are included in the RASLE code. Specifically, correlations are available for N_2^+, NO, O_2, N_2, CO, CN, $C3$, and SiO molecular systems.

Atomic and Ionic Line Transitions

Radiation due to spectral line transitions is evaluated in a statistical manner similar to the atomic continua. In addition, however, a configurational parameter is required to represent the functional form (shape) of the individual lines. For the $j-$th series or lumped (if so configured) group of lines, the absorption coefficient for the $k-$th line is

$$\mu_{k(j)}^L(\nu) = \frac{\pi e^2}{mc} f_{k(j)} N_{ij} b_{k(j)}(\nu, T, P, \cdots) \tag{24}$$

where $f_{k(j)}$ is the oscillator strength or "f number" of the $k-$th line in the $j-$th series of lines. $b_{k(j)}$ is the individual line shape function which accounts for the various "broadening" mechanisms. The RASLE radiation model accounts for Stark, resonance, and Doppler broadening effects. The code allows for up to 20 line groupings. Within each frequency group the total line group contribution is obtained by summing the individual contributions within that group. Specific details of the actual implementation of this group model are given in references 5 and 6. Oscillator strengths for individual lines due to the various atom and ion systems of interest can be obtained from Moore (ref. 14).

RADIATION PROPERTY DATA

Obtaining radiation property and cross-section data is a difficult task, and for this reason the values obtained for two more common ablating systems are tabularized in this document for reference. Tables 2 and 3 list the atomic and ionic line transition properties and oscillator strengths ($f - numbers$) for the carbon- hydrogen-air and silicon-air systems, respectively. The frequency line centers are listed for all of the appropriate line transitions included in the calculation, but not all of the associated energy levels are actually used. A maximum of eight (8), lumped levels are allowed. Those used by the author are listed in table 4 together with the associated energy level degeneracy (rotational quantum number). In addition to line centers and $f - numbers$, tables 2 and 3 also give species line parameters needed to implement the RASLE line averaging model. These include the index of the absorbing level for the species line listed ($Level$), Stark broadening exponent (ref. 2) ($EXPN(k)$), Stark broadening $\frac{1}{2}$−half width/free electron for non-hydrogen lines, and the number of lines (for each species) considered as identical for averaging purposes. For continuum radiation properties, table 4 lists the low frequency photoionization, Biberman and Norman (ref. 8) parameters, $\xi(\nu)$ and E_{th}. E_{th} is the maximum energy for the low energy model. Above this, the higher energy discrete photoionization cross sections must be considered. (The species cross sections needed for this study are given in table 1.) Also shown are the transition energies, $E_{th}^{ex}(1, 2, \cdots)$ and the principal quantum numbers, $N_{(1,2,\cdots)}^{ex}$, associated with each of the explicit photoionization transitions. These have been obtained from Nicolet and Wilson (ref. 6) and Peach (ref. 9) by linear interpolation of tabular data. The author has been unable to obtain actual values for the Biberman and Norman parameter, ξ, for Si and Si^+. However, since there is not a great variation in the known values (ref. 6) the values for N and N^+ were used as an approximation. For actual implementation of this data in the RASLE code, the reader is urged to consult reference 1. This input data is similar to that needed for the Langely Research Center HYVIS code, and documentation for that program should be consulted for specific use in that code.

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Table 1. RASLE species discrete photoionization cross sections (e.g., ref. 12)

Energy increment, ev	0	1	2	4	6	8	10	20
Species	C							
Cross section, $cm^2 \times 10^{18}$								
Ground state	11.0	11.0	11.0	10.4	9.55	8.7	7.85	4.5
1st excited state	8.5	8.5	8.5	8.3	8.0	7.0	2.0	0.1
2nd excited state	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
$E_{th}^{ex}(1)$	11.26 ev							
$N_{(1)}^{ex}$	1.0							
$E_{th}^{ex}(2)$	10.0 ev							
$N_{(2)}^{ex}$	2.0							
$E_{th}^{ex}(3)$	8.51 ev							
$N_{(3)}^{ex}$	3.0							
Species	O							
Cross section, $cm^2 \times 10^{18}$								
Ground state	3.0	3.2	3.1	3.0	3.0	5.3	5.0	2.5
1st excited state	10.12	7.933	6.435	4.869	4.29	4.46	0.187	0.110
$E_{th}^{ex}(1)$	13.6 ev							
$N_{(1)}^{ex}$	1.0							
$E_{th}^{ex}(2)$	4.33							
$N_{(2)}^{ex}$	4.0							

Table 1. Continued

Energy increment, ev	0	1	2	4	6	8	10	20
Species	N							
Cross section, $cm^2 \times 10^{18}$								
Ground state	7.86	8.16	9.16	15.16	16.8	16.1	16.1	8.0
1st excited state	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
$E_{th}^{ex}(1)$	14.5 ev							
$N_{(1)}^{ex}$	1.0							
$E_{th}^{ex}(2)$	12.0							
$N_{(2)}^{ex}$	2.0							
Species	N^+							
Cross section, $cm^2 \times 10^{18}$								
Ground state	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
$E_{th}^{ex}(1)$	29.6 ev							
$N_{(1)}^{ex}$	1.0							
Species	H							
Cross section, $cm^2 \times 10^{18}$								
Ground state	8.3078	6.6923	5.4699	3.7906	2.7339	2.0362	1.557	0.535
1st excited state	15.822	7.3	3.9493	1.5346	0.7487	0.4197	0.2584	0.0485
2nd excited state	19.938	4.646	1.75	0.465	0.186	0.0923	0.0523	0.0081
$E_{th}^{ex}(1)$	13.38 ev							
$N_{(1)}^{ex}$	1.0							
$E_{th}^{ex}(2)$	3.4 ev							
$N_{(2)}^{ex}$	2.0							
$E_{th}^{ex}(3)$	1.6 ev							
$N_{(3)}^{ex}$	3.0							

Table 1. Concluded

Energy increment, ev	0	1	2	4	6	8	10	20
Species	Si							
Cross section, $cm^2 \times 10^{18}$								
Ground state	34.78	30.94	27.79	15.24	5.0	5.0	5.0	5.0
1st excited state	4.73	4.05	4.05	4.05	4.05	4.05	4.05	4.05
$E_{th}^{ex}(1)$	8.15 ev							
$N_{(1)}^{ex}$	1.0							
$E_{th}^{ex}(2)$	7.397							
$N_{(2)}^{ex}$	4.0							
Species	Si^+							
Cross section, $cm^2 \times 10^{18}$								
Ground state	2.32	1.89	1.82	0.45	0.008	0.008	0.10	0.19
$E_{th}^{ex}(1)$	16.33 ev							
$N_{(1)}^{ex}$	1.0							

Table 2. Carbon-hydrogen-air system atomic line transition data

Species	Level	EXPN(k)	hν(i)	f–number	γ_P	No. lines
H	3	16.0000	0.66110	0.84210	0.1267+04	1
O	8	0.46	0.685	0.1960	0.1100-20	6
C	6	0.3930	0.68590	0.04400	0.3210-20	3
N	6	0.25	1.689	1.1597	0.1870-19	6
C	7	0.1340	0.71000	0.20800	0.6390-17	4
N	5	0.25	1.7525	1.0149	0.4460-20	1
C	6	0.3540	0.84400	0.08080	0.4120-20	3
C	5	0.4570	0.85200	0.06870	0.1080-20	1
N	5	0.25	1.875	1.0366	0.3800-20	4
O	7	0.46	0.884	0.1570	0.3670-20	1
N	4	0.25	1.9158	1.00847	0.7390-21	1
N	6	0.25	1.9304	1.0253	0.3870-19	2
N	6	0.25	1.965	1.0262	0.3870-19	4
O	8	0.46	0.991	0.0805	0.3090-19	2
C	7	0.6120	1.01900	0.03290	0.2050-18	4
N	5	0.25	1.0355	1.0735	0.3310-20	7
C	6	0.3540	1.08280	0.10080	0.3200-20	8
O	7	0.46	1.098	0.7490	0.3440-20	1
O	6	0.46	1.132	0.2010	0.3670-20	1
C	5	0.4020	1.16300	0.47400	0.1080-20	1
C	6	0.3610	1.22400	0.02850	0.2620-20	1
N	5	0.25	1.2610	1.118	0.3120-20	3
N	4	0.25	1.3190	1.1833	0.9840-21	1
C	5	0.3470	1.32600	0.20600	0.1380-20	3
O	6	0.46	1.338	0.9130	0.3420-20	1
N	5	0.25	1.3677	1.0387	0.2920-20	1
N	4	0.25	1.4380	1.256	0.8240-21	3
O	5	0.46	1.467	0.9500	0.8650-21	1
C	5	0.2910	1.48700	0.04050	0.2180-20	1
N	5	0.25	1.5527	1.0030	0.2930-19	1
O	4	0.46	1.594	1.0300	0.7090-21	1
N	4	0.25	1.6630	1.0923	0.9580-21	1
O	7	0.46	1.767	0.0226	0.2750-19	3
C	6	0.3780	1.8140	0.00390	0.3500-19	5
N	5	0.25	1.8357	0.00566	0.2930-19	5
H	2	0.0000	1.8880	0.64070	0.0000	1
O	6	0.46	2.015	0.0258	0.2750-19	3
H	2	0.0000	2.5490	0.11930	0.0000	1
N	4	0.25	2.925	1.0070	0.1060-19	3
O	5	0.46	3.000	0.0100	0.8100-20	2
O	4	0.46	3.167	0.00826	0.5200-20	1
N	4	0.25	3.4724	0.00861	0.4520-19	3

Table 2. Continued

Species	Level	EXPN(k)	hν(i)	f–number	γ_P	No. lines
O	4	0.46	3.711	0.0143	0.1100-19	1
C	3	0.3150	5.00200	0.06760	0.1130-20	1
C	2	0.3150	6.42400	0.07290	0.1130-20	1
C	3	0.3390	7.01300	0.01410	0.5000-20	1
C	3	0.3610	7.07800	0.07480	0.2620-20	1
N	3	0.25	7.111	1.0634	0.9120-21	1
C	1	0.3230	7.48100	0.10500	0.8730-21	1
C	3	0.3260	7.71700	0.00534	0.2200-19	1
C	3	0.6260	7.72100	0.03670	0.1090-18	1
C	1	0.9570	7.94700	0.28300	0.2080-21	1
C	3	0.8400	8.03000	0.00457	0.6900-18	1
C	3	0.7520	8.19100	0.01160	0.1300-17	1
C	3	0.3300	8.20300	0.00147	0.1190-18	1
C	3	0.2890	8.30200	0.00831	0.5380-17	1
N	2	0.25	8.3021	1.0740	0.9120-21	1
C	2	0.4770	8.36800	0.01100	0.2140-20	1
C	3	0.8480	8.37700	0.00501	0.6770-17	1
C	2	0.3390	8.43300	0.01420	0.5000-20	1
C	2	0.3790	8.47400	0.06250	0.2480-20	1
N	3	0.25	8.781	1.0435	0.6610-21	1
C	2	0.3260	9.13700	0.00526	0.2200-19	1
C	2	0.6350	9.14100	0.03620	0.1090-18	1
N	3	0.25	9.301	1.0166	0.4460-20	1
C	1	1.0650	9.33200	0.20300	0.5570-22	1
N	3	0.25	9.394	1.0119	0.2290-20	1
C	2	0.8190	9.45000	0.02180	0.6900-18	1
N	3	0.25	9.460	1.0360	0.3360-20	1
O	1	0.46	9.501	0.0471	0.5480-21	1
C	2	0.7640	9.6110	0.01140	0.1300-17	1
C	2	0.3420	9.62300	0.00143	0.1190-18	1
C	1	0.342	9.697	0.0233	0.4568-20	1
C	1	0.3490	9.69800	0.00380	0.2350-20	1
C	1	0.3720	9.70900	0.07670	0.2350-20	1
C	2	0.2890	9.72200	0.00810	0.5380-17	1
C	2	0.8480	9.79700	0.00488	0.6770-17	1
C	1	0.3200	9.83400	0.02600	0.2930-20	1
N	2	0.25	9.973	1.0890	0.6610-21	1
N	3	0.25	10.102	0.0374	0.2930-19	1
O	3	0.46	10.182	0.1510	0.6530-21	1
H	1	0.0000	10.19600	0.41620	0.0000	1
N	1	0.25	10.332	0.1840	0.6210-21	1
C	1	0.3260	10.40100	0.00719	0.2200-19	1
C	1	0.6260	10.40500	0.04950	0.1090-18	1

Table 2. Continued

Species	Level	EXPN(k)	$h\nu(i)$	f–number	γ_P	No. lines
N	3	0.25	10.418	0.0225	0.5320-19	1
N	2	0.25	10.493	0.0187	0.4460-19	1
N	3	0.25	10.585	0.0131	0.7960-19	1
N	2	0.25	10.619	0.0533	0.3120-20	1
N	3	0.25	10.682	0.00819	0.2680-18	1
C	1	0.8190	10.71400	0.02980	0.6900-18	1
N	3	0.25	10.757	0.00518	0.4370-18	1
O	2	0.46	10.761	0.1200	0.6530-21	1
C	2	–0.6480	10.87300	0.70500	0.6300-20	1
C	1	0.7530	10.87500	0.01550	0.1300-17	1
C	1	0.3310	10.88700	0.00195	0.1190-18	1
N	1	0.25	10.927	0.4540	0.1610-22	1
C	1	0.3280	10.98600	0.01100	0.2530-18	1
O	3	0.46	11.007	0.0185	0.3670-20	1
C	1	0.8480	11.06100	0.00659	0.6770-17	1
N	3	0.25	11.200	1.0200	0.4460-20	1
N	2	0.25	11.293	1.0418	0.2930-19	1
N	3	0.25	11.310	1.0254	0.3230-20	1
N	7	0.25	11.424	1.2260	0.1430-22	1
N	2	0.25	11.609	1.0250	0.5320-19	1
N	2	0.25	11.776	1.0220	0.7960-19	1
O	3	0.46	11.806	0.0049	0.1450-19	1
O	1	0.46	11.852	0.0199	0.3670-20	1
N	2	0.25	11.874	1.0091	0.2680-18	1
N	2	0.25	11.948	0.00575	0.4370-19	1
N	3	0.25	12.000	1.0269	0.2990-19	1
O	1	0.46	12.067	0.0218	0.3440-20	1
H	1	0.0000	12.08400	0.07910	0.0000	1
O	3	0.46	12.160	0.0019	0.1280-19	1
C	3	0.1610	12.18100	1.05000	0.1590-21	1
N	3	0.25	12.316	1.0156	0.6960-19	1
O	2	0.46	12.404	0.0461	0.6530-21	1
N	2	0.25	12.414	1.0574	0.3900-20	1
N	2	0.25	12.511	1.0279	0.3370-20	1
O	1	0.46	12.521	0.0775	0.6330-21	1
O	1	0.46	12.651	0.00524	0.1450-19	1
H	1	16.0000	12.74600	0.02899	0.1025+04	1
N	1	0.25	12.877	1.0230	0.4460-20	1
N	1	0.25	13.004	1.1320	0.2940-20	1
C	1	–0.4220	13.11900	0.37900	0.1010-20	1
N	2	0.25	13.190	1.0489	0.2990-19	1
N	2	0.25	13.508	1.0291	0.6960-18	1
N	7	0.2	13.543	1.1610	0.9500-23	1
C	2	0.1610	13.60100	0.29500	0.1590-21	1

Table 2. Concluded

Species	Level	EXPN(k)	$h\nu(i)$	f–number	γ_P	No. lines
N	1	0.25	13.677	1.0957	0.2930-19	1
N	1	0.25	13.993	1.0584	0.5320-19	1
N	1	0.25	14.160	1.0342	0.7960-19	1
N	1	0.25	14.257	1.0212	0.2680-18	1
N	1	0.25	14.332	1.0138	0.4370-18	1

Table 3. Silicon-air system atomic line transition data

Species	Level	EXPN(k)	$h\nu(i)$	f–number	γ_P	No. lines
HO	8	0.46	0.685	0.1960	0.1100-20	6
HN	6	0.25	0.689	0.1597	0.1870-19	6
HN	5	0.25	0.7525	0.0149	0.4460-20	1
HN	5	0.25	0.875	0.0366	0.3800-20	4
HO	7	0.46	0.884	0.1570	0.3670-20	1
HN	4	0.25	0.9158	0.00847	0.7390-21	1
HN	6	0.25	0.9304	0.0253	0.3870-19	2
HN	6	0.25	0.965	0.0262	0.3870-19	4
HO	8	0.46	0.991	0.0805	0.3090-19	2
HSI	4	0.214	1.035	0.1533	0.2970-20	1
HN	5	0.25	1.0355	0.0735	0.3310-20	7
HO	7	0.46	1.098	0.7490	0.3440-20	1
HO	6	0.46	1.132	0.2010	0.3670-20	1
HSI	4	0.236	1.163	0.043	0.4710-20	1
HSI	4	0.147	1.205	0.014	0.4710-20	1
HN	5	0.25	1.2610	0.118	0.3120-20	3
HSI	5	0.282	1.317	0.06	0.5250-20	1
HN	4	0.25	1.3190	0.1833	0.9840-21	1
HO	6	0.46	1.338	0.9130	0.3420-20	1
HN	5	0.25	1.3677	0.0387	0.2920-20	1
HN	4	0.25	1.4380	0.256	0.8240-21	3
HO	5	0.46	1.467	0.9500	0.8650-21	1
HN	5	0.25	1.5527	0.0030	0.2930-19	1
HO	4	0.46	1.594	1.0300	0.7090-21	1
HN	4	0.25	1.6630	0.0923	0.9580-21	1
HO	7	0.46	1.767	0.0226	0.2750-19	3
HN	5	0.25	1.8357	0.00566	0.2930-19	5
HO	6	0.46	2.015	0.0258	0.2750-19	3
HSI	5	0.315	2.085	0.0095	0.1700-19	1
HSI	4	0.00624	2.145	0.0017	0.2590-19	1
HSI	4	0.379	2.197	0.0026	0.1210-19	1
HSI	4	0.366	2.205	0.0026	0.1380-19	1
HN	4	0.25	2.925	0.0070	0.1060-19	3
HO	5	0.46	3.000	0.0100	0.8100-20	2
HO	4	0.46	3.167	0.00826	0.5200-20	1
HSI	3	0.351	3.175	0.10	0.9190-21	1
HN	4	0.25	3.4724	0.00861	0.4520-19	3
HO	4	0.46	3.711	0.0143	0.1100-19	1
HSI	2	0.337	4.175	0.00019	0.1400-20	1
HSI	2	0.359	4.946	0.0243	0.1010-20	1
HSI	1	0.352	5.086	0.002	0.9230-21	1
HSI	1	0.126	5.616	0.068	0.5040-21	1
HN	3	0.25	7.111	0.0634	0.9120-21	1

Table 3. Continued

Species	Level	EXPN(k)	hν(i)	f–number	γ_P	No. lines
HN	2	0.25	8.3021	0.0740	0.9120-21	1
HN	3	0.25	8.781	0.0435	0.6610-21	1
HN	3	0.25	9.301	0.0166	0.4460-20	1
HN	3	0.25	9.394	0.0119	0.2290-20	1
HN	3	0.25	9.460	0.0360	0.3360-20	1
HO	1	0.46	9.501	0.0471	0.5480-21	1
HN	2	0.25	9.973	0.0890	0.6610-21	1
HN	3	0.25	10.102	0.0374	0.2930-19	1
HO	3	0.46	10.182	0.1510	0.6530-21	1
HN	1	0.25	10.332	0.1840	0.6210-21	1
HN	3	0.25	10.418	0.0225	0.5320-19	1
HN	2	0.25	10.493	0.0187	0.4460-19	1
HN	3	0.25	10.585	0.0131	0.7960-19	1
HN	2	0.25	10.619	0.0533	0.3120-20	1
HN	3	0.25	10.682	0.00819	0.2680-18	1
HN	3	0.25	10.757	0.00518	0.4370-18	1
HO	2	0.46	10.761	0.1200	0.6530-21	1
HN	1	0.25	10.927	0.4540	0.1610-22	1
HO	3	0.46	11.007	0.0185	0.3670-20	1
HN	3	0.25	11.200	0.0200	0.4460-20	1
HN	2	0.25	11.293	0.0418	0.2930-19	1
HN	3	0.25	11.310	0.0254	0.3230-20	1
HN	7	0.25	11.424	0.2260	0.1430-22	1
HN	2	0.25	11.609	0.0250	0.5320-19	1
HN	2	0.25	11.776	0.0220	0.7960-19	1
HO	3	0.46	11.806	0.0049	0.1450-19	1
HO	1	0.46	11.852	0.0199	0.3670-20	1
HN	2	0.25	11.874	0.0091	0.2680-18	1
HN	2	0.25	11.948	0.00575	0.4370-19	1
HN	3	0.25	12.000	0.0269	0.2990-19	1
HO	1	0.46	12.067	0.0218	0.3440-20	1
HO	3	0.46	12.160	0.0019	0.1280-19	1
HN	3	0.25	12.316	0.0156	0.6960-19	1
HO	2	0.46	12.404	0.0461	0.6530-21	1
HN	2	0.25	12.414	0.0574	0.3900-20	1
HN	2	0.25	12.511	0.0279	0.3370-20	1
HO	1	0.46	12.521	0.0775	0.6330-21	1
HO	1	0.46	12.651	0.00524	0.1450-19	1
HN	1	0.25	12.877	0.0230	0.4460-20	1
HN	1	0.25	13.004	0.1320	0.2940-20	1
HN	2	0.25	13.190	0.0489	0.2990-19	1

Table 3. Concluded

Species	Level	EXPN(k)	$h\nu(i)$	f–number	γ_P	No. lines
HN	2	0.25	13.508	0.0291	0.6960-18	1
HN	7	0.25	13.543	0.1610	0.9500-23	1
HN	1	0.25	13.677	0.0957	0.2930-19	1
HN	1	0.25	13.993	0.0584	0.5320-19	1
HN	1	0.25	14.160	0.0342	0.7960-19	1
HN	1	0.25	14.257	0.0212	0.2680-18	1
HN	1	0.25	14.332	0.0138	0.4370-18	1

Table 4. RASLE species energy level and low frequency photoionization data

Energy increment, ev	0	1	2	4	6	8	10	20
Species	C							
Ionization potential	11.26 ev							
Energy level	0.0	1.2639	2.6839	4.1825	7.5351	7.9461	8.6442	
Degeneracy	9.0	5.0	1.0	5.0	12.0	15.0	36.0	
$\xi(\nu)$	1.0	0.64	0.42	0.3	0.33	0.68	1.17	1.6
(EV)	0.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
E_{th}	3.78 ev							
Species	C^+							
Ionization potential	24.376 ev							
Energy level	0.0	5.32	9.28	11.95	13.7			
Degeneracy	6.0	12.0	10.0	2.0	6.0			
$\xi(\nu)$	1.0	0.76	0.62	0.55	0.55	0.85	1.42	2.0
(EV)	0.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
E_{th}	12.47 ev							
Species	O							
Ionization potential	13.614 ev							
Energy level	0.0096	1.967	4.189	9.144	9.519	10.74	10.99	12.08
Degeneracy	9.0	5.0	10.0	5.0	3.0	15.0	9.0	40.0
$\xi(\nu)$	1.0	0.71	0.51	0.34	0.21	0.30	0.71	1.38
(EV)	0.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
E_{th}	4.4 ev							
T_{th} = 8000 °R								
μ_A = 0.1415								
μ_B = 0.0001073								

Table 4. Continued

Energy increment, ev	0	1	2	4	6	8	10	20
Species	O^+							
Ionization potential	35.146 ev							
Energy level	0.0	3.325	5.0171	14.8694	20.5797	23.135	25.938	28.833
Degeneracy	4.0	10.0	6.0	12.0	10.0	18.0	54.0	90.0
$\xi(\nu)$	1.0	0.76	0.62	0.55	0.55	0.85	1.42	2.0
(EV)	0.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
E_{th}	20.ev							
Species	N							
Ionization potential	14.54 ev							
Energy level	0.0	2.384	3.576	10.45	11.88	13.0	14.0	
Degeneracy	4.0	10.0	6.0	18.0	54.0	90.0	1.0	
$\xi(\nu)$	1.0	0.67	0.45	0.26	0.22	0.50	1.18	2.3
(EV)	0.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
E_{th}	4.0 ev							
T_{th} = 8000 °R								
$\mu_A = 0.867$								
$\mu_B = 2.8 \times 10^{-5}$								
Species	N^+							
Ionization potential	29.605 ev							
Energy level	0.011	1.8989	4.0528	5.8005	11.4366	18.48014	20.9555	23.2704
Degeneracy	9.0	5.0	1.0	5.0	15.0	12.0	36.0	60.0
$\xi(\nu)$	1.0	0.76	0.62	0.55	0.55	0.85	1.42	2.0
(EV)	0.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
E_{th}	18.0 ev							

Table 4. Concluded

Energy increment, ev	0	1	2	4	6	8	10	20
Species	H							
Ionization potential	13.595 ev							
Energy level	0.	10.19189	12.07926	12.7399	13.04568			
Degeneracy	2.0	8.0	18.0	32.0	50.0			
$\xi(\nu)$	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
(EV)	0.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
E_{th}	0.855 ev							
Species	Si							
Ionization potential	8.152 ev							
Energy level	0.0	0.0491	1.9088	4.9422	5.0786	6.0092	6.2562	7.1291
Degeneracy	1.0	8.0	1.0	9.0	6.0	8.0	7.0	16.0
$\xi(\nu)$	1.0	0.67	0.45	0.26	0.22	0.5	1.18	2.3
(EV)	0.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
E_{th}	3.78 ev							
Species	Si^{+}							
Ionization potential	16.345 ev							
Energy level	0.0	5.488	6.858	8.121	9.506	9.839	10.072	10.408
Degeneracy	6.0	12.0	10.0	2.0	2.0	10.0	6.0	6.0
$\xi(\nu)$	1.0	0.76	0.62	0.55	0.55	0.85	1.42	2.0
(EV)	0.0	1.0	2.0	3.0	4.0	6.0	8.0	10.0
E_{th}	12.0 ev							

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16. Abstract

This report is a documentation of the necessary radiation property input data for the radiating shock layer simulation code RASLE. The data tabulated are required to simulate systems which are composed of oxygen, nitrogen, carbon, hydrogen and silicon. These data are needed to compute the flowfield effects of many practical ablative, hypersonic vehicle heat shield materials. A brief outline description is provided for the RASLE code. A more detailed discussion is provided for the RASLE code non-grey gas spectral radiation model. This model is related to the required radiation property data which are tabulated at the end of the report. Other correlations needed for the RASLE simulations are not discussed, since these are automatically included in the program and no input data are required.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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