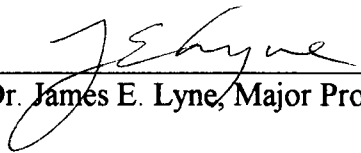
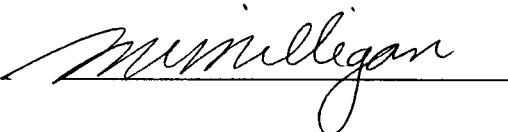


To the Graduate Council:

I am submitting herewith a thesis written by Richard Matthew Fought entitled "A Computer Model and Parametric Study of Earth-Atmospheric Entry of Meteors." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.


Dr. James E. Lyne, Major Professor

We have read this thesis and
recommend its acceptance:




Accepted for the Council:


Associate Vice Chancellor and
Dean of The Graduate School

**A COMPUTER MODEL AND
PARAMETRIC STUDY OF
EARTH-ATMOSPHERIC ENTRY
OF METEORS**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Richard Matthew Fought
December 1995

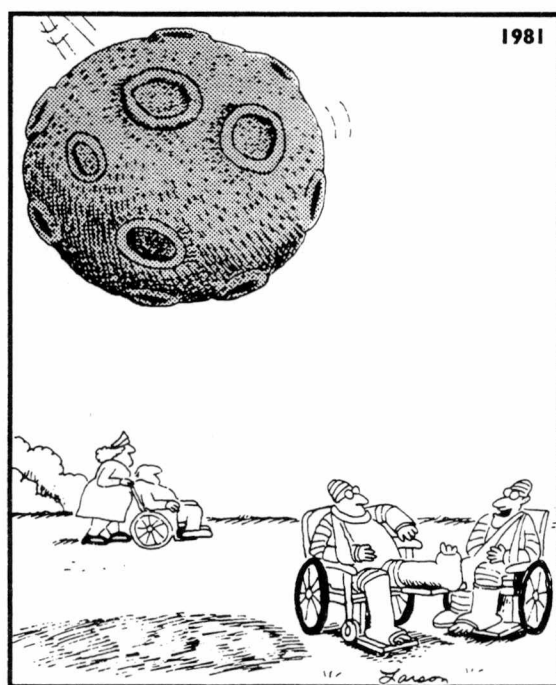
DEDICATION

I would like to dedicate this work to my parents

Wayne Earl Fought

and

Mary Donis Fought



"You're kidding! ... I was struck twice
by lightning too!"

The
FAR SIDE
July
20
THURSDAY

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ABSTRACT

This investigation involves the physics of meteors entering the Earth's atmosphere. A computer model coded in FORTRAN is developed that simulates the trajectory of such bodies through the atmosphere. Both new and old techniques are used to simulate the various aspects of the problem physics. An improvement is made over previous work primarily in the radiative heat transfer and ablation models. To this end a new, estimation technique for the thermodynamic properties of high-pressure, high-temperature equilibrium air is devised. This new radiative model produces energy fluxes and ablation rates much lower than previously calculated, and this significantly affects the predicted trajectory of the meteors. For a given bolide, the model predicts deeper penetration and lower airburst heights than calculated by previous models. As proven by the Tunguska event of 1908, catastrophic disruptions in the lower atmosphere can have devastating effects, and it is almost certain that the airburst altitude is of consequence. The code is used to conduct a parametric study involving a wide range of meteors of different materials, body sizes, entry speeds and entry angles; the main result of interest is the airburst height achieved by the various cases. The study shows that stronger, denser bodies penetrate deeper into the atmosphere and deliver the most destructive power. The lighter bodies tend to ablate away more and are slowed down more easily by the atmosphere.

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NOMENCLATURE

a	shock wave shape coefficient
a_{ell}	ellipse semi-major axis
A	enthalpy curve fit coefficient
A_1	radiating area
A_f	frontal area
A_{ref}	reference area
$A_{\text{seg,nose}}$	stagnation point shock segment area
b	shock wave shape coefficient, gravity profile constant
b_{ell}	ellipse semi-minor axis
B	enthalpy curve fit coefficient
c	shock wave shape coefficient
c_p	specific heat
C	enthalpy curve fit coefficient
C_B	ballistic coefficient
C_D	drag coefficient
C_H^0	ablation coefficient
C_P	pressure coefficient
d	distance to middle of shock layer from body center
$d\alpha$	differential angular body step
d_{shock}	distance to shock layer from body center

dF_{12}	differential radiative view factor
D	enthalpy curve fit coefficient; diameter
E	enthalpy curve fit coefficient
E_{tot}	total flow energy
F_{12}	radiative view factor
$F_{12,\text{nose}}$	radiative view factor at nose
$F_{12,\text{shoulder}}$	radiative view factor at shoulder
g	local acceleration of gravity
g_0	acceleration of gravity at Earth's surface = 9.81 m/s^2
h	enthalpy
$h _{x_{ip}}$	enthalpy at inflection point
$h' _{x_{ip}}$	slope of enthalpy at inflection point
H	altitude above Earth's surface
H_{ablation}	heat of ablation
L_z	thermal lapse rate
m	mass
m_{ablation}	mass of ablation products
$m_{\text{freestream}}$	mass of freestream air
M	Mach number, molecular weight
M_0	sea level molecular weight = 28.9664
P	pressure

P_{∞}	ambient air pressure
P_0	ambient pressure (1 atm) = 1.01325 E5 Pa
P_{avg}	average pressure on front face of meteor
P_{dyn}	dynamic pressure
Q	total heat transfer
Q_{abl}	heat of ablation
Q''_{ad}	adiabatic radiative flux
Q''_{body}	radiative flux into body
$Q''_{conv,stag}$	stagnation point convective heat flux
Q''_G	non-adiabatic radiative flux
Q_{total}	total heat transferred into body
r	radius
r_{avg}	distance to middle of shock layer from body center
r_{body}	body radius
r_{new}	new body radius calculated from mass loss
r_{nose}	nose radius
r_{shock}	shock radius from center of body
R^*	universal gas constant = 8314.32 J/(kg-mole-K)
R_{earth}	radius of Earth = 6.37 E6 m
S_F	shape factor
t	time

T	temperature
T_{∞}	ambient air temperature
T_M	molecular temperature
V	velocity
V_E, V_0	entry velocity
V_{∞}	freestream velocity
z	geometric altitude
α	angular body location
β	local shock angle
χ	dimensionless temperature term
χ_{ip}	dimensionless temperature at inflection point
Δ	shock standoff distance
$\Delta\alpha$	discrete body angular step
Δm	mass loss
Δt	time step
γ	flight path angle
γ_E	entry flight path angle
Γ	Goulard number
ρ	density
ρ_{∞}	ambient air density

ρ_{mS}	material density
σ	Stefan-Boltzmann constant
σ_{abl}	ablation coefficient
θ	local body angle
$\left. \frac{dy}{dx} \right _{shock}$	local shock wave slope

CHAPTER I

INTRODUCTION / LITERATURE REVIEW

The impact of comet Shoemaker-Levy 9 in the summer of 1994 generated great interest in both the scientific community and the public eye. The spectacular display provided by the impact included large gas plumes or "fireballs" and remnant dark patches on the Jovian surface (Watson, 1994). Collisions of such magnitude, although numerous throughout history, are few and far between when considered in a human's time frame. Scientists got the opportunity to witness a very rare event, and the media coverage drew in the attention of the public.

Earth Strike?

This event raises the question of what would happen if such a impact occurred with Earth. Studies suggest that we eventually will have a collision in the future with an object large enough to cause major devastation in the form of tidal waves and sky-filling crater dust which would block out the sun (Chapman and Morrison, 1994). A similar event is believed to have caused the extinction of the dinosaurs 65 million years ago (Allman, 1994). A more recent example of such a collision is the Tunguska Blast of 1908.

On the morning of June 30, 1908 a huge explosion rocked the Siberian countryside in the area of Tunguska. It is estimated that the blast contained 2000 times the force of the Hiroshima nuclear detonation. Because of the remote site of the event, no significant investigations into the blast were carried out until years after the fact. But the some 2100

square kilometers of felled trees lay testament to the immense devastation caused by the explosion. The trees lay in a radial pattern directed away from a central point which was marked by standing but scorched tree trunks, indicating that the blast had occurred some distance above the Earth's surface. Eyewitness accounts, recorded years after the event, described a fireball flying through the sky with a tail approximately 800 km long. About 6 kilometers above the surface the object quickly broke apart and vaporized, causing a shock wave which produced the surface destruction. Several people were injured, and hundreds of reindeer were incinerated. (Gallant, 1994) Proposed theories on what happened included such ideas as black holes and extraterrestrial vehicles, but the accepted explanation is that a meteor entered earth's atmosphere and exploded in mid-air. Sekanina (1983) points out that such sudden disintegrations of meteors are not uncommon, as shown by the fireball designated PN40503 (i.e., Prairie Network 40503).

Modeling Disaster

Recent studies, sparked by the Jupiter impact, have been conducted to determine the nature of the object which struck Earth in 1908, and to examine meteor entries in general. The physics involved in atmospheric entry are quite complex, as will be shown later. The atmosphere exerts a drag force on meteors just as it does on moving cars or airplanes. However, meteors travel in the hypersonic flight regime and their aerodynamics must be treated in a special way, with particular consideration being given to the aerodynamic heating of the body. Objects moving at hypersonic velocities produce shock waves behind

which the temperature can reach tens of thousands of degrees. Such high temperatures cause material to ablate away from the body, reducing the mass. Gravity also exerts a force on the object, directed towards the center of the Earth. Both this and the aerodynamic forces affect the body's trajectory through the atmosphere. At some point, the dynamic pressure may become high enough to actually break the body up. The characteristics of such a conglomerated mass of rubble are not easy to define. Since so many variables are involved, various methods have been employed to model the physics. However, no model really attempts to investigate in detail the physics involved in the shock layer radiation and body ablation. Most utilize overall approximations to these areas; a more thorough model of the shock layer heating, radiation and resulting ablation is put forth in this thesis. It is compared to previous work and used in a parametric study of meteor impacts in general.

The study done by Chyba, Thomas and Zahnle (1993) presents a physical model of the entry of an object into Earth's atmosphere and its resulting deceleration, ablation and disruption. Their method uses a finite difference approach to solve the equations of motion and ablation. The equations of motion, which include gravity effects and a lift coefficient, assume a cylindrical body, having a C_L of 10^{-3} and a C_D of 1.7. The ablation model used assumes a profile of the form

$$Q_{abl} \frac{dm}{dt} = -A \min(\frac{1}{2} C_H^0 \rho_{\infty} V_{\infty}^3, \sigma T^4) \quad (1.1)$$

where Q_{abl} is the heat of ablation, m is mass, t is time, A is cross-sectional area, C_H^0 is the heat transfer coefficient, ρ_∞ is the freestream density, V_∞ is the object velocity, σ is the Stefan-Boltzmann constant, and T is temperature. The $\min()$ is a minimum function; the A term on the right-hand side of Eq. (1.1) is multiplied by either $1/2 C_H^0 \rho_\infty V^3$ or σT^4 , depending on which one is smaller. This model assumes a constant C_H^0 of 0.1 and T of 25,000 K, assuming the temperature behind the shock layer to be constant regardless of the object velocity. They also contend that once the object disrupts, the high pressure on the front face coupled with low pressures on the sides of the body causes the body to spread out in a “pancake” fashion which dramatically increases the surface area and quickly decelerates it. Using data from the Tunguska event, Chyba, et al. determine that the object which struck the Siberian countryside was probably a stony asteroid. Only an entry angle of 45 degrees is studied for most cases, except for the stony object. This is due to the inexact data on the actual Tunguska object.

Sekanina (1983) uses a similar ablation method as Chyba, et al. in his quest to characterize objects that could have caused the Tunguska devastation. The model employs an ablation equation from meteor theory of the form

$$\dot{m} = -\sigma_{abl} A_f V P_{dyn} \quad (1.2)$$

where m is mass, A_f is the frontal area, V is velocity, and P_{dyn} is the aerodynamic pressure. σ_{abl} is an ablation coefficient taken from measurements of meteors that have entered Earth’s atmosphere in the past. Sekanina’s equations of motions are derived from the drag equation of single-body meteor theory and the exponential atmospheric model; these

are solved analytically. The drag and lift coefficients are assumed to be 1.2 and 0, respectively; gravity effects are neglected. The curvature of the earth is taken into account due to the Tunguska object's shallow trajectory. The objects are assumed to disrupt once the material's strength is exceeded by the dynamic pressure. From this model, Sekanina concludes that the Tunguska object could not have been a comet, as the entry velocity required is not characteristic of comets.

A broader study was conducted by Baldwin and Shaeffer (1971) as a test for a model developed for use on the Martian atmosphere. The equations of motion are of the same form as those used by Chyba, et al. and are derived from a simple summation of forces on the body. The atmosphere is simulated with tabulated planetary atmospheric densities. The ablation model is based on an assumed profile exactly like the first term of the $\min()$ function in Eq. (1.1), with coefficients coming from meteorite data. The area of the object is assumed from an equation of the form

$$A_{ref} = S_F (m / \rho_{ms})^{2/3} \quad (1.3)$$

where S_F is the shape factor, equal to A divided by the object volume^{2/3}, m is mass and ρ_{ms} is the meteoroid density. A hemispherical shape is assumed for the meteorites. The breakup model employed is quite detailed, and assumes that premature fragmentation due to odd object shapes will occur if the material's tensile stress is exceeded. Veining and brecciation are also given as explanations for premature splitting. A semi-statistical method is used to account for such fragmentation before the final disruption, which is due to the material's compressive strength being exceeded by the dynamic pressure.

Petrov and Stulov (1976) generated a model similar to those previously mentioned, especially in their use of the assumed first-order differential equation profile for the ablation. Like Sekanina the effect of gravity is neglected, along with the resulting change in flight path angle. In their model, an isothermal exponential atmosphere is assumed, and the equations of motion and ablation are solved analytically. This study determines that the Tunguska object most likely had a density on the order of 0.01g/cm^3 , and entered the atmosphere with an initial velocity of 40 km/s and entry angle of 20° .

The present study describes a model similar in many ways to those just cited, except that the actual processes going on in the shock layer are modeled. Instead of assuming one coefficient for the entire heating and ablation process, the temperature distribution in the shock layer is calculated from oblique shock relations and thermodynamic data. The shape of the shock wave must be assumed, and from this the state of the gases behind any section of the shock wave can be estimated. This is not trivial as the air the shock layer is usually dissociated. Once the temperature distribution behind the shock is determined, a radiation model is used to determine the heat transfer to the body and resulting ablation. The resulting mass loss is implemented into the equations of motion, and the trajectory of the object through the atmosphere is determined with a numerical integration scheme. The exact details of the problem physics are described in the following chapter.

CHAPTER II

QUALITATIVE PROBLEM PHYSICS

The physics involved in the atmospheric entry of a meteor are quite complex. The object follows a trajectory through the atmosphere defined by the equations of motion, derived from Newton's second law. The atmosphere must be defined as its properties directly affect the aerodynamics. The body is moving at hypersonic velocities, which results in a shock wave and large aerodynamic forces. Extreme radiative and convective heating also results from such velocities, which cause the material to ablate away. This in turn affects the trajectory. Moreover, the object is subject to fragmentation by the aerodynamic forces. This material failure must be modeled, as well as what happens to the object after it has disrupted. The goal of creating a simple yet effective model requires that approximations be made regarding many aspects of the problem. This chapter will discuss the various physical processes involved.

The Object Properties

To accurately calculate a meteor's entry trajectory, the body's physical characteristics must be defined. These include the shape, size, density, strength and heat of ablation. The shape strongly influences aerodynamic properties such as lift and drag and is impossible to accurately predict since most asteroids have probably collided with other bodies at some point in their existence, resulting in fragmentation and random shapes (Chapman and Morrison, 1989). The size of the object is of importance since it determines how much

mass the body carries into the atmosphere. The material density is required so that given the size of the object, the mass can be computed. It is also necessary when considering how much the object's size changes when mass is lost due to ablation. A much denser body will not lose as much size when subjected to the same heating load as a less dense body.

The material strength is required to determine the point of disruption. In theory, once the dynamic pressure exerted by the flow on the body reaches a certain value, the material will fail and disruption will ensue. The limiting value is most often taken as the material compressive yield stress, although the tensile stress may also play a role. The heat of ablation is the amount of energy required to heat, melt and vaporize a certain amount of material mass (i.e. J/kg). This is used to determine how much mass ablates away once the energy input into the body is determined. These properties may not be uniform throughout the body. Some typical values of these properties are given in Table 2.1 for different types of meteors.

Table 2.1. Common physical properties of different types of impactors. (Source: Chyba, Christopher F., Thomas, Paul J., Zahnle, Kevin J., "The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid," *Nature*, Vol. 361, No. 6407, Jan. 1993 pp. 40-44.)

Material	Density (kg/m ³)	Strength (N/m ²)	Heat of Ablation (J/kg)
Iron	7900	1.0E8	8.0E6
Stone	3500	1.0E7	8.0E6
Carbonaceous	2200	1.0E6	5.0E6
Comet	1000	1.0E5	2.5E6

The Earth's Atmosphere

The Earth's atmosphere is not static or uniform; variations in pressure and density occur with altitude due to the effects of gravity. In general, density and pressure decrease as altitude increases; however, this is not true for some thermal layers. Temperature is quite erratic due to dependence on a number of factors which include altitude, water vapor content, circulation speed, solar activity and insulating layers (Heintze, 1977). Density is of utmost importance, as it appears in many aerodynamic relations.

Meteor-Atmosphere Interaction

The atmosphere exerts a drag force on the object, slowing it down in its trajectory. The object's initial trajectory is defined by its entry velocity and entry angle. Velocities of meteors entering Earth's atmosphere are in excess of 11 km/s, the escape speed for Earth. Speeds of this magnitude fall in the hypersonic regime, usually defined as $M > 5$. Hypersonic flows are quite complex, and many analytical methods have been developed which yield good initial approximations. One of the best known of these is a technique developed by Sir Isaac Newton, termed Newtonian Theory. From a simple momentum analysis on a flat plate canted at an angle θ , Newton determined that the coefficient of pressure C_p defined as

$$C_P = \frac{P - P_\infty}{\frac{1}{2} \rho_\infty V_\infty^2} \quad (2.1)$$

is equal to twice the sine of the angle squared, or

$$C_P = 2 \sin^2 \theta \quad (2.2)$$

Thus for a plate normal to the flow, $C_P = 2$ and for a plate parallel to the flow, $C_P = 0$.

This theory gives poor results when applied to subsonic flows, but is reasonably accurate when applied to hypersonic flows. (Anderson, 1989) This theory is used in the present study which will be discussed later.

Also of importance is the entry angle γ_E ; this angle is defined with zero being parallel to the surface of the earth, and -90 being downwards and perpendicular to the surface (see Figure 2.1). The entry angle directly determines how much of the atmosphere the meteor must pass through before impacting the surface of the earth, and thus how much resistance the atmosphere can provide to slow down the impactor; it takes a column mass of air roughly greater or equal to the mass of the meteor to absorb the impactor's kinetic energy (Chapman and Morrison, 1994). The entry angle can vary anywhere from 0 to 90 degrees, depending on the trajectory of the impactor as it approaches Earth.

Once the object enters the atmosphere, drag begins to slow it down. Gravity is also playing a important role in the trajectory of the body, even out of the atmosphere. The equation which relates velocity to time is given by

$$\frac{dV}{dt} = -g \sin \gamma - \frac{\frac{1}{2} \rho_\infty V^2}{C_B} \quad (2.3)$$

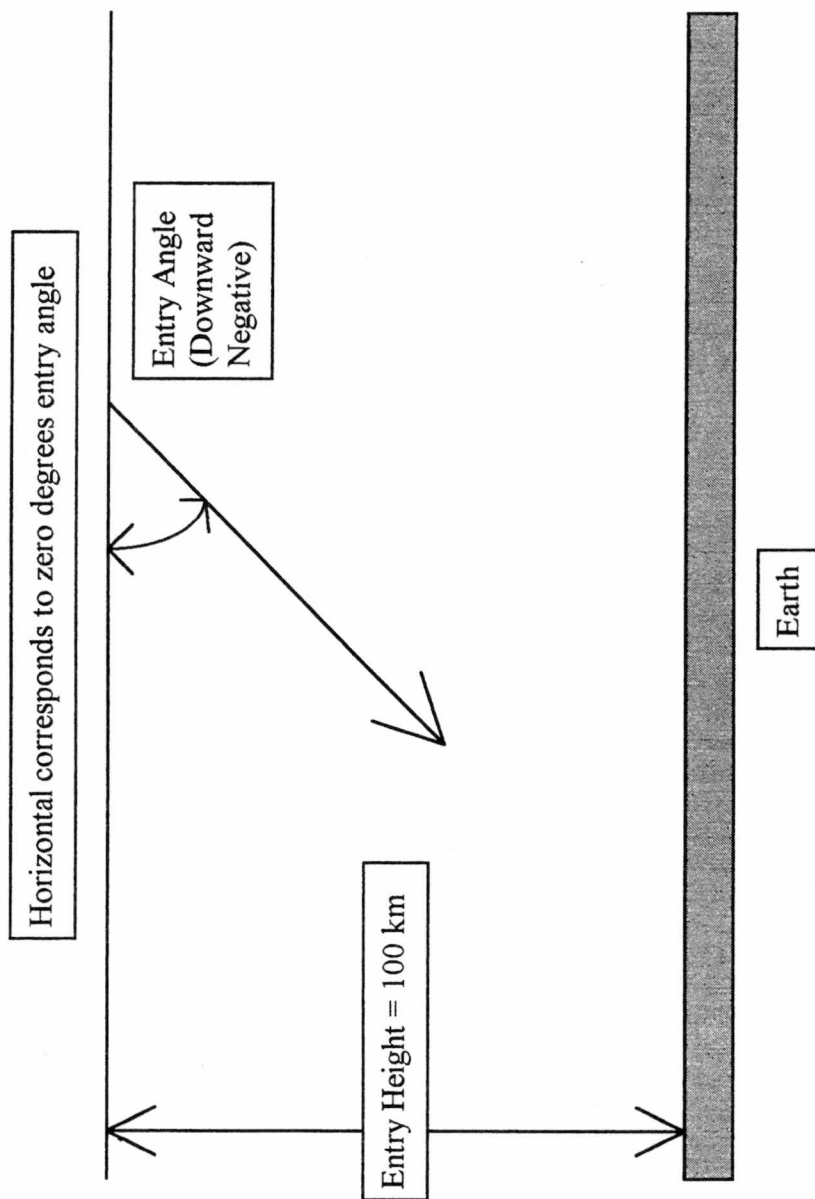


Figure 2.1 - Entry angle coordinate system definition.

where V is velocity, t is time, g is the local acceleration of gravity, γ is the flight path angle as defined previously, ρ_∞ is the freestream density, and C_B is the ballistic coefficient, defined as

$$C_B = \frac{m}{C_D A_{ref}} \quad (2.4)$$

Here m is the object mass, C_D is the drag coefficient and A_{ref} is the reference area.

Equation (2.3) is a first order non-linear differential equation, and applies for a ballistic entry, in which the object has zero lift.

The flight path angle, γ , varies as a function of time:

$$\frac{d\gamma}{dt} = -\left(\frac{g}{V} - \frac{V}{R_{earth} + H}\right) \cos \gamma \quad (2.5)$$

where R_{earth} is the radius of the earth and H is the altitude above the surface. Neglecting the Earth's curvature the variation of the meteor's altitude, H , is given by

$$\frac{dH}{dt} = V \sin \gamma \quad (2.6)$$

These three equations can be used to calculate the trajectory of the object as it passes through the atmosphere. (Lyne, 1994)

Any object moving through a medium faster than the speed of sound will have a shock wave in front of it. For sharp bodies like wedges, the shape of the shock in relation to the body is easily predictable through oblique shock theory. For blunt bodies however, the shock becomes detached and curved, with an essentially normal shock at the nose or stagnation region. The shape of this curved, oblique shock wave depends on the shape of

the body and its velocity. (Saad, 1993; John, 1984) Various methods have been developed to predict shock wave shapes, including simple correlations and complex iterative schemes such as Maslen's method (Saad, 1993). Lobb (1962) performed experimental measurements of the shock detachment distance from small spheres fired at hypersonic velocities. An exact analytical solution to a detached shock wave and the flow field behind it is not trivial, and often requires complex CFD codes.

The pressure on the body behind this shock wave is what determines the drag force that the body experiences. This can be found by integrating the pressure coefficient as defined by Eq. (2.1) over the surface of a body. If Newtonian theory is used as an approximation, and Eq. (2.2) is integrated over the surface of a sphere exposed to the oncoming flow (the front hemisphere), a drag coefficient of 1.0 is derived for hypersonic flows. The pressure also has importance in determining the flow conditions between the shock wave and the body, which has a direct impact on the heating to the body.

Aerodynamic and Radiative Heating

A body moving at high velocity through a gaseous medium such as air will experience aerodynamic heating due to convection. If the velocities are high enough to cause dissociation and/or ionization in the shock layer there will also be radiative heating which results from molecular recombination and electron-ion interactions. The resulting radiation can contribute significantly to the total heat transfer to the surface of the body. Heat loads due to convective and radiative heating necessitate special thermal protection systems on

re-entry vehicles, such as reusable ceramic tiles that radiate heat away from the vehicle and expendable heat shields which ablate away as they absorb energy. (Goldstein, et al., 1995)

The radiation heat transfer from a hot gas layer such as that behind a shock wave to a body is extremely complex, and involves many factors. Absorption, emission and scattering of energy occurs at all points within the shock layer. A detailed analysis requires that the temperature, radiation intensity and physical properties must also be known at all points within the layer. Spectral effects are very prominent in gases, and the mathematics involved are also inherently complex. (Siegel, 1981) Another complication is the fact that the air in a hypersonic shock layer is under real gas effects, and cannot be assumed to behave ideally. The thermodynamic properties are very non-linear, as are the diffusive properties and ratio of specific heats. The most prominent reason for this is chemical dissociation and ionization of the molecular species. At 2500 K, O_2 begins to dissociate into O; at about 4000 K, O_2 finishes dissociation and N_2 begins to dissociate into N. At about 9000 K, N_2 is almost fully dissociated and ionization of O and N into O^+ and N^+ begins. At higher temperatures double and even triple ionization can occur. These numbers are all for 1 atm pressure; the onset temperatures vary with the air pressure. An increased pressure will raise the temperatures, and a decreased pressure will reduce them. (Anderson, 1989)

Depending on the velocity involved, both radiative and convective heating can have different relative contributions to the overall heating to the body. At low velocities, convective dominates; as the velocity increases the temperature behind the shock increases

and radiation plays a greater role. At some point, radiation will dominate the heating. Care must be taken in determining how much heating the body experiences, for it determines how much ablation takes place.

Ablation

Heat transferred into the body by either of the above mechanisms causes the temperature of the material to rise. If enough energy is put in, the material will change phase from solid to liquid and even be vaporized. This ablation process is taken advantage of for most high speed re-entry problems where non-destructive means such as ceramic tiles are not sufficient. An example of this is the Apollo space capsule. Exact ablation theory is a heat and mass transfer problem; as the energy conducts through the body, the temperature profile changes and the surface eventually starts to burn away, changing the boundary conditions as it does. This type of problem can be complex and requires knowledge of the thermal transport properties of the material, which may not be uniform throughout the body. Computer codes have been developed to predict ablation rates for well characterized materials, a popular one being CMA or Charring Material Ablation. The ablation distribution on the body depends on the body shape, and as the body burns away it's shape will change. This causes a change in the shape of the shock wave, and thus a resulting change in the ablation distribution. Thus the problem is very dependent on previous conditions. In addition, the ablation products form a barrier in front of the body

which blocks radiation to the surface. Thus as radiation increases, ablation increases and so does the blocking effect. (Truitt, 1960)

Disruption

With the processes discussed above the body travels through the atmosphere, slowing down and burning away. At some point in its trajectory, the aerodynamic pressure forces experienced by the body will exceed the compressive yield strength of the material. This will cause the body to break apart into smaller pieces, increasing the surface area to volume ratio as it does so. The resulting pile of rubble is still traveling at high speeds but the actual aerodynamic characteristics of such a conglomeration are not easy to define, especially as the actual disruption mechanism is unknown and the mass is traveling at hypersonic velocities. As mentioned in the previous chapter, various methods have been used to model the behavior of such a process. There also exists the question of what exact stress condition causes the failure. Some authors have assumed that once the stagnation aerodynamic pressure exceeds the material compressive strength, the entire body crumbles simultaneously (Sekanina, 1983). A more sophisticated approach would account for pressure variations in the body and the disruption of material on the windward surface prior to the fragmentation of material in the interior or on the leeward surface.

It must also be noted that the point of body disruption does not necessarily correspond with the location of ground damage associated with such meteor explosions. It is thought that the point of maximum energy release rate defines the altitude at which the meteor's

destructive power is realized. Thus the predicted airburst altitude depends on the breakup model used.

All of these topics mentioned are of importance to the problem solution. Many are mathematically and physically well defined, while others have only approximate solutions. These however should give a good approximation, which is often how things are done in the area of hypersonics. The next chapter describes in detail the methods used to address the above areas, and how they are implemented into a complete whole to create a solution to the atmospheric entry problem of meteors.

CHAPTER III

PROBLEM SOLUTION

In creating a solution to the problem of atmospheric entry of meteors, some previously developed methods have been used as no better approximation is available. However, some new methods have been developed, particularly in the area of heat transfer and ablation. The following chapter discusses the specific methods used to account for the problem physics as described in the previous chapter. It also discusses how these methods are integrated into a computer model which simulates the entire re-entry process.

Equations of Motion

The core of the computer program, written in FORTRAN 77, is a stripped down version of a NASA trajectory code developed for re-entry of space vehicles. This code took into account L/D , pitch, yaw and roll maneuvers, and body shape and optimized roll angle for entry. The ballistic nature of meteors makes it possible to neglect such considerations. The part of interest in the NASA code is the differential equation solver which numerically integrates the equations of motion and computes next time step values. Also useful is the heat transfer subroutine, which serves as a shell to compute the radiative and convective fluxes. The equation solver is a subroutine from the IMSL library called IVPRK; it employs a sixth-order Runge-Kutte method. The code listing is included in Appendix A, along with a sample input and output file.

This solver is used to solve the system of three differential equations of motion (Eqs. 2.3, 2.5 and 2.6) with respect to time. The starting altitude is assumed to be 100 km. Eq. (2.3) assumes that the lift coefficient is zero, and that the entry angles evaluated are steep enough such that even if there was a small lifting force present it would not affect the trajectory. Referring back to Eq. (2.3), it can be seen that dV/dt depends on the local acceleration of gravity g , the freestream density ρ_∞ , and the ballistic coefficient $C_B = m/C_D A_{ref}$. The local acceleration of gravity, g , decreases from its surface value of $g_0 = 9.81 \text{ m/s}^2$ with the square of the distance from the surface, as given by

$$g(H) = \frac{g_0}{\left(1 + \frac{H}{R_{earth}}\right)^2} \quad (3.1)$$

where R_{earth} is the radius of the earth, equal to 6378135 m, and H is in meters.

The freestream density, ρ_∞ , is a function of the altitude, H , as are the ambient temperature and pressure. The atmospheric model used is that of Regan (1984); it is based upon measurements from the 1962 U.S. Standard Atmosphere. Compared to the 1962 atmosphere the results given by this model are quite acceptable, with maximum pressure errors on the order of 1%. The model yields density, pressure, temperature and molecular weight. It is assumed that the errors in density are of the same order as those for pressure. A detailed description of the model can be found in Appendix B.

The ballistic coefficient, C_B , depends on mass, drag coefficient and reference area. All of these are dependent on the shape of the meteor. The present model assumes that the meteor is spherical, as the actual shape is unknown. The hypersonic drag coefficient for a

sphere is theoretically 1.0 using Newtonian theory, but to account for non-spherical imperfections a value of 1.3 is assumed for all bodies. The reference area is taken to be the cross sectional area of the sphere or the disrupted body. The initial mass is calculated from the density and the volume of a sphere having the specified initial diameter. The mass and reference area are updated after the ablation is calculated for each time step. The shape is assumed to remain spherical until breakup, thus the mass loss due to ablation for each time step is assumed to take place in shells. This will be discussed further in the following sections.

The heating and ablation model is unique over previous methods as it physically models the actual processes taking place inside the shock layer. As described before, heating in the shock layer causes the gas to radiate energy to the body. The increase in temperature across the shock can be estimated provided that two other thermodynamic properties behind any section of the shock are known. The first requirement in the analysis is an estimate of the shock wave shape.

Shock Wave Shape

The shape of the shock wave is assumed using calculated data from Palmer (1995), obtained with an implicit flux-split algorithm. The standoff distance d_{shock} at the stagnation point is taken as 0.0707 times the sphere radius, and at the shoulder (90° from stagnation point) is taken as 0.35 times the radius. These figures were found using computational methods for a 4.694 m radius sphere traveling at Mach 30 with a velocity of 9.345 km/s.

As a check, the stagnation point standoff distance for a sphere can be calculated from the approximation

$$\Delta = 0.41 \frac{\rho_1}{\rho_2} D \quad (3.2)$$

where Δ is the detachment distance, ρ_1 and ρ_2 are the fore and aft density, respectively, and D is the sphere diameter (Lobb, 1962). Considering the 4.694 meter sphere at $M_1=30$ and assuming the ratio of specific heats c_p equal to 1.2 due to dissociation, from normal shock equations $M_2 = 0.29$ and $\rho_1/\rho_2 = 0.09192$. Using Eq. (3.2), $\Delta/D = 0.03742$ which corresponds to a shock standoff distance $d_{\text{shock}}/r_{\text{body}} = 0.0754$, close to the assumed value of 0.0707. It is assumed that speeds greater than this will cause little change in the standoff distance, as the experimental curves found by Lobb are fairly asymptotic at high speeds. The actual distance is not as important as the shape of the shock around the sphere, as this determines the temperature distribution.

Using the stagnation and shoulder values of $d_{\text{shock}}/r_{\text{body}}$ equal to 0.0707 and 0.35, respectively, a second order profile is assumed for the variation of the standoff distance around the body. This profile assumes an equation of the form

$$\frac{r_{\text{shock}}}{r_{\text{body}}} = a\alpha^2 + b\alpha + c \quad (3.3)$$

where r_{shock} is the distance of the shock from the sphere center, r_{body} the sphere radius, α the angular location on the body (the stagnation point being $\alpha = 0$, the shoulder being $\alpha = \pi/2$) and a , b and c the coefficients to be solved for. The boundary conditions imposed are

$$\frac{r_{shock}}{r_{body}}(0) = 1.0707 \quad (3.4)$$

$$\frac{r_{shock}}{r_{body}}\left(\frac{\pi}{2}\right) = 1.35 \quad (3.5)$$

$$\frac{r_{shock}}{r_{body}}\left(\frac{\pi}{4}\right) = 1.14053 \quad (3.6)$$

Eqs. (3.4) and (3.5) are simply the two previously mentioned data points, and Eq. (3.6) is derived by assuming that d_{shock}/r_{body} at the midpoint is equal to the value at the stagnation region plus 25% of the difference between the shoulder and stagnation values, biasing it towards the stagnation point. Several profiles were tried, but this one yielded the smoothest curve.

Using these conditions, the three constants in Eq. (3.3) are solved for, yielding the equation

$$\frac{r_{shock}}{r_{body}} = 0.113188\alpha^2 + 1.27097E - 5\alpha + 1.0707 \quad (3.7)$$

The resulting profile can be seen in Fig. 3.1, superimposed upon a unit sphere. From the above equation, the slope of the shock and thus the angle of the shock with respect to the freestream, β , can be calculated (see Appendix C). The shock angle β is found to be nearly linear with body location α , with a value of 90° at the stagnation point (the shock normal to the flow) and approximately 15° at the shoulder.

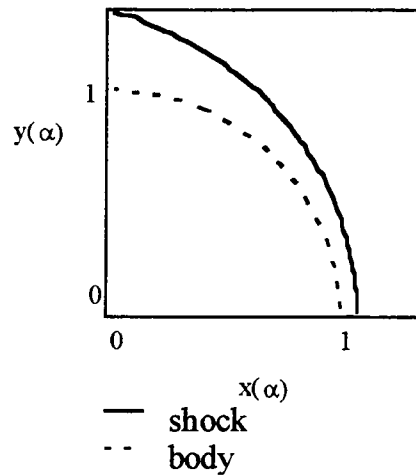


Figure 3.1 Shock wave shape (solid) superimposed upon a unit sphere (dashed).

Assuming a linear profile for β vs. α , the following equation is derived

$$\beta = -0.8333\alpha + 1.5708 \quad (3.8)$$

where β and α are in radians. From this, the shock wave angle can be calculated for any position from the stagnation point to the shoulder. This is important when determining the properties behind the shock wave. Fig. 3.2 shows a schematic for the nomenclature used to describe the shock wave and the body.

Shock Layer Thermodynamics

To determine the temperature behind the shock wave, the enthalpy and pressure are estimated, giving two thermodynamic properties with which to fix the thermodynamic state. The pressure as a function of body position can be approximated using Newtonian theory as discussed earlier. Combining Eqs. (2.1) and (2.2) from the previous chapter, the

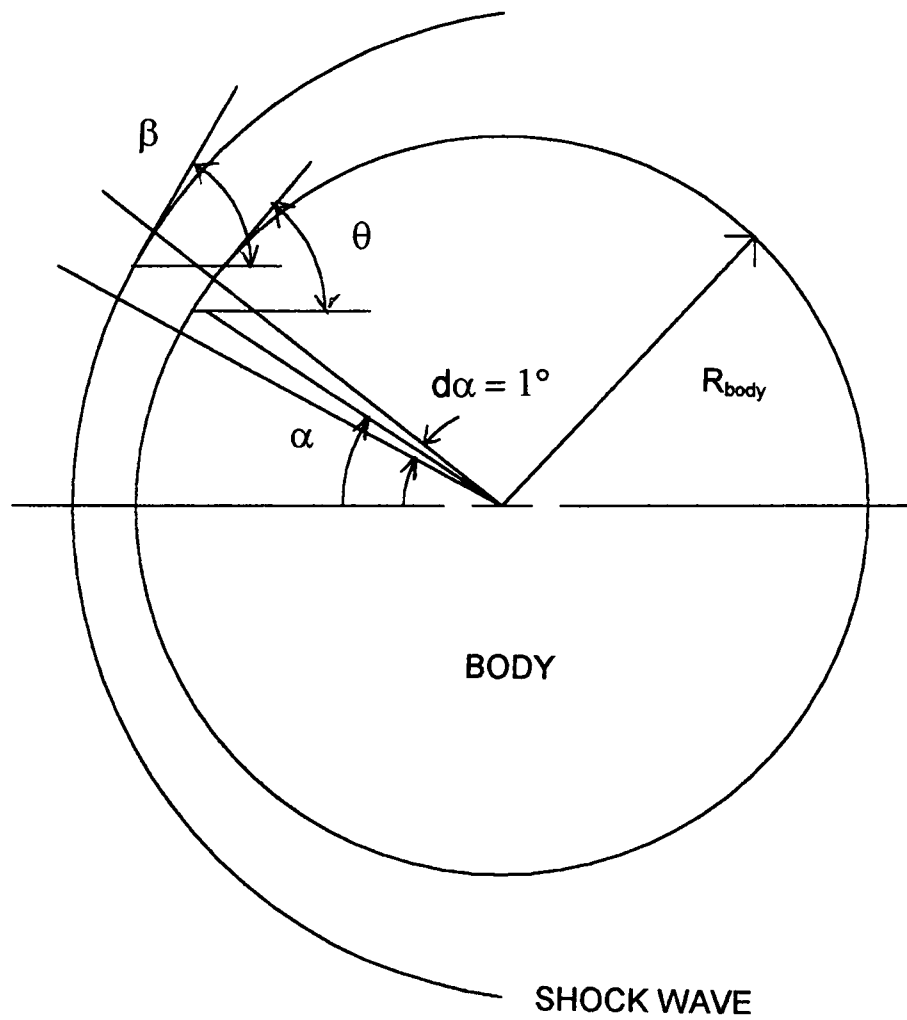


Figure 3.2. Nomenclature and coordinate system for body and shock wave.

pressure is given by

$$P(\theta) = \rho_{\infty} V_{\infty}^2 \sin^2 \theta + P_{\infty} \quad (3.9)$$

This, in combination with oblique shock theory, can be used to derive an expression relating enthalpy as a function of body position

$$h = c_p T_{\infty} + \frac{1}{2} V_{\infty}^2 \sin^2 \beta \left[1 - \left(1 - \frac{\sin^2 \theta}{\sin^2 \beta} \right)^2 \right] \quad (3.10)$$

as the local body angle θ for a sphere is a known function of body position α from geometry ($\theta = \pi/2 - \alpha$). The ambient enthalpy term $c_p T_{\infty}$ is generally not appreciable compared to the velocity term and is calculated using a c_p of 1000 J/kg·K. From Eqs. (3.9) and (3.10), both the pressure and enthalpy immediately downstream any point on the shock from the stagnation region to the shoulder can be estimated. From thermodynamics, these two properties can be used to determine the temperature.

It is assumed that the travel time for the molecules over such large bodies ($D > 1\text{m}$) is great enough such that the air in the shock layer is in thermodynamic equilibrium. Curve fits produced by Gupta, et al. (1991) for the enthalpy of equilibrium air as a function of temperature and pressure are employed. Curves are presented for pressures ranging from 10^{-4} to 10^2 atmospheres, with a maximum temperature limit of 30000 K for the higher pressures. The upper pressure limit of 100 atmospheres is inadequate, as values in the stagnation region can reach 1000 atmospheres in meteor entry hypersonic flows. No data is available for equilibrium air up to 30000 K at such high pressures. Thus a new method

was developed to extrapolate a 1000 atm curve from the lower pressure curves presented by Gupta, et al.

The curve fits presented by Gupta, et al. have an effective limit of 30000 K and 100 atmospheres for temperature and pressure, respectively. Although similar fits provided by Tannehill and Mugge (1974) have a higher pressure limit of 1000 atm, the temperature limit is only 25000 K. These fits are also older and less robust than those of Gupta, et al. The following overview demonstrates a scheme used to extrapolate data for enthalpy as a function of temperature to a pressure of 1000 atmospheres, using the existing fits of Gupta, et al.

The enthalpy curves of Gupta, et al. are presented in terms of $h(\text{kcal/g})$ vs. a non-dimensional temperature term χ defined as

$$\chi = \ln(T/10000) \quad (3.11)$$

where T is in Kelvin. The equations are of the general form

$$h = \exp(A\chi^4 + B\chi^3 + C\chi^2 + D\chi + E) \quad (3.12)$$

where A , B , C , D and E are constant coefficients. Curves are presented for pressures ranging from 10^{-4} to 10^2 atmospheres, in intervals of one order of magnitude (i.e. 10^{-3} atm, 10^{-2} atm, etc.). For any one pressure, the complete curve is made up of several pieces; each piece covers a temperature interval and has a unique set of coefficients. These curves have characteristic inflection points where the change in slope (or $d^2h/d\chi^2$) is zero. These correspond to points where different species begin and cease to dissociate.

Any one characteristic inflection point follows a reasonably smooth pattern in terms of h - χ location across the pressure spectrum. This pattern can be extrapolated to a higher pressure for which there is no curve available. From the extrapolated data, a curve consisting of equations like Eq. (3.12) can easily be reconstructed.

For each of the curves presented by Gupta, et al. Eq. (3.12) is differentiated to yield

$$\frac{dh}{d\chi} = (4A\chi^3 + 3B\chi^2 + 2C\chi + D)\exp(A\chi^4 + B\chi^3 + C\chi^2 + D\chi + E) \quad (3.13)$$

and

$$\frac{d^2h}{d\chi^2} = [(4A\chi^3 + 3B\chi^2 + 2C\chi + D)^2 + 12A\chi^2 + 6B\chi + 2C]\exp(A\chi^4 + B\chi^3 + C\chi^2 + D\chi + E) \quad (3.14)$$

Eq. (3.14) is used to find the inflection points for the curves by substituting in the appropriate coefficients, setting it equal to zero and solving for χ . With χ known, Eqs. (3.12) and (3.13) are used to find the enthalpy and slope at the inflection points, respectively. These three equations will be used later for evaluation of curve-fit coefficients in the extended pressure range.

Once the inflection points are found, it is observed that only three points exist for the 100 atmosphere curve. These three and their corresponding points on the other pressure curves are well behaved at the higher pressure ranges. These 3 point classes (termed class 3, 4, and 5 points) are used for the extrapolation. Lagrangian polynomials are used to fit the trend of each point class across the pressure range. These are of the form

$$f(x) = \sum_{k=0}^n \frac{l_k(x)}{l_k(x_k)} f_k \quad (3.15)$$

where

$$l_0(x) = (x - x_1)(x - x_2) \cdots (x - x_n) \quad (3.16)$$

$$l_k(x) = (x - x_0) \cdots (x - x_{k-1})(x - x_{k+1}) \cdots (x - x_n) \quad (3.17)$$

$$l_n(x) = (x - x_0)(x - x_1) \cdots (x - x_{n-1}) \quad (3.18)$$

Polynomials for the 3, 4 and 5 class inflection points are set up using $\log(P/P_0)$ as the independent variable x (not to be confused with χ , chi). Polynomials of the order $n=2$ are used for all three classes, using data from $\log(P/P_0) = 0, 1$, and 2 . The function $f(x)$ is used to represent χ , h and $dh/d\chi$. Once the polynomials are set up, an internal point different from the known points is solved for at $\log(P/P_0) = 0.5$. Then polynomials of one order higher are set up to include the unknown curve of 1000 atm. Using the derived data at $\log(P/P_0)=0.5$, the unknown function at 1000 atm can be calculated. This is required because if any of the original points are used, all other points go to zero leaving only an equality. Inflection points for 1000 atm which fall in the temperature range of the Tannehill and Mugge fits are compared to data from the same. The class 3 point shows an error of 2.1 %, while the class 4 point shows an error of less than 1 %. The class 5 point is out of the temperature range of the Tannehill and Mugge fits, and no comparison can be made.

Once χ , h and $dh/d\chi$ data are found for the class 3, 4 and 5 inflection points at 1000 atm, they are used to reconstruct the curves. This is done using Eqs. (3.12), (3.13) and (3.14)

containing the coefficients A, B, C, D and E. Since χ , h and dh/d χ are known for each inflection point, and $d^2h/d\chi^2$ is equal to zero, there are five equations and five unknowns. The logarithmic nature of Eq. (3.12) allows for easy substitution into the derivatives, such that a linear system of equations involving the coefficients can be easily derived and solved using matrix inversion. Using this method, three equations are used:

$$\ln(h|_{\chi_{ip}}) = A\chi_{ip}^4 + B\chi_{ip}^3 + C\chi_{ip}^2 + D\chi_{ip} + E \quad (3.19)$$

$$\frac{h'|_{\chi_{ip}}}{h|_{\chi_{ip}}} = 4A\chi_{ip}^3 + 3B\chi_{ip}^2 + 2C\chi_{ip} + D \quad (3.20)$$

$$-\left(\frac{h'|_{\chi_{ip}}}{h|_{\chi_{ip}}}\right)^2 = 12A\chi_{ip}^2 + 6B\chi_{ip} + 2C \quad (3.21)$$

In each equation, χ_{ip} denotes the location of the inflection point. Eqs. (3.19) and (3.20) are used twice, at the initial and final inflection points of the interval being solved for. Eq. (3.21) is used once, taken at the final point of the interval. For the initial point at T=500 K ($\chi = -2.99573$) on the first interval up to the class 3 inflection point, h and h' data are assumed from the approximation given by Gupta, et al. as $h(\text{kcal/g}) = 0.00024 T(\text{K})$. Thus $h=0.12$ kcal/g and $h'=0.12$ kcal/g at $\chi = -2.99573$. The curves and the inflection points, including the new 1000 atm data, can be seen in Appendix D.

The results from this method are best at the higher temperatures (above around 13000 K), as there are nuances at the lower temperatures which could not be picked up with the

inflection point technique. These nuances are present at low pressures, but quickly die out as pressure increases. Errors in the low temperature region as high as 40% are present when comparing the extrapolated data to that presented by Tannehill and Mugge for 1000 atm. Another contributor to this error at low temperatures is the use of the approximate relationship mentioned previously for the initial point. However, once the first inflection point is reached, agreement with the data of Tannehill and Mugge is remarkable, and shows an average error of only 2.25%. The comparison may be seen in Fig. 3.3. Since sufficient data already exist for enthalpy at low temperatures, this method gives a good approximation for high-temperature data at high pressures. To present curve fit coefficients for the entire temperature range at 1000 atm, data derived from Tannehill and Mugge are used to generate the enthalpy curve from 500 to 13050 K. These data are converted to a curve in the form of Eq. (3.12) with an average deviation of 1.5%, and a maximum of 5%. The curve from 13050 K to 32600 K is from the extrapolation method. The coefficients for the curves, in the form of Eq. (3.12), are provided in Table 3.1.

Table 3.1 Curve-fit coefficients for enthalpy of equilibrium air at 1000 atm.

A	B	C	D	E	Temp Range (K)	χ Range
0.036917	0.277409	0.79532	2.171407	1.741407	500 to 13050	-2.99573 to 0.267452
-59.90844	99.522322	-62.13573	18.320807	0.3166938	13050 to 15650	0.267452 to 0.448138
0.4887346	-3.011417	5.5598576	-2.320909	2.7638445	15650 to 32600	0.448138 to 1.18187

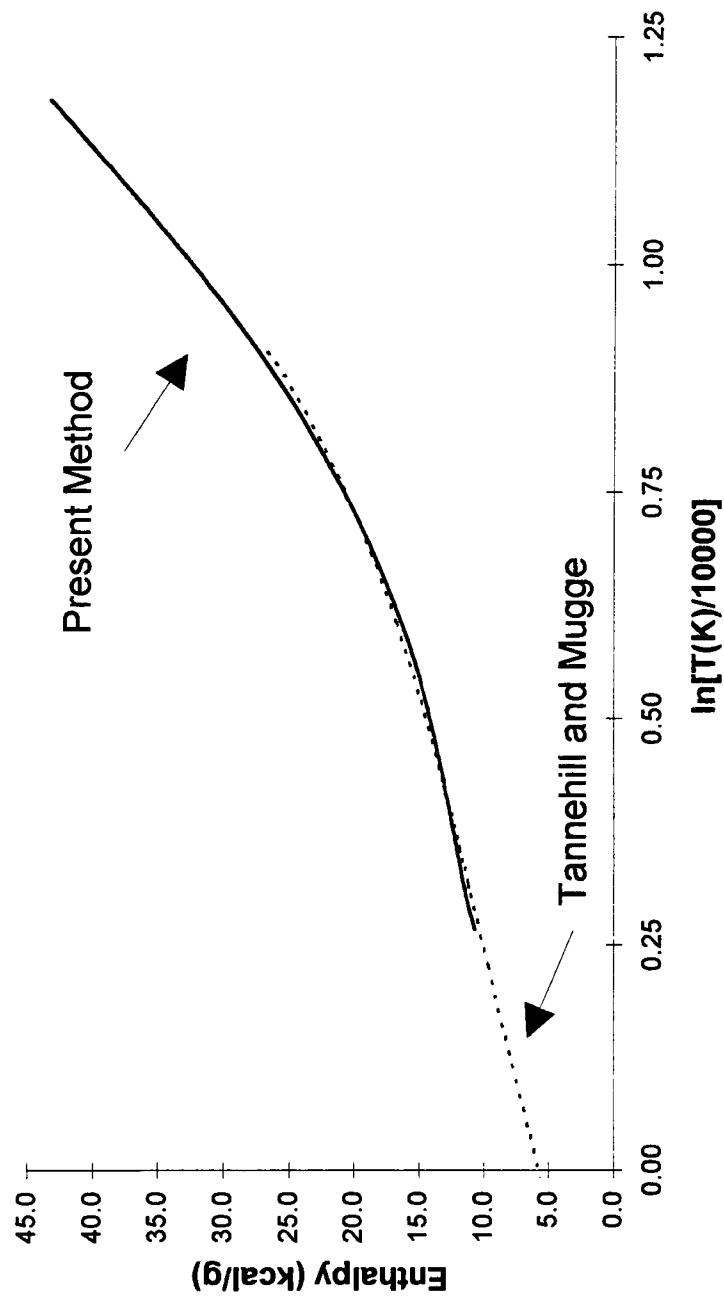


Figure 3.3. Comparison of enthalpy curves for 1000 atm pressure.
 (Adapted from Tannehill, J.C., and Mugge, P.H., "Improved Curve Fits for the Thermodynamic Properties of
 Equilibrium Air Suitable for Numerical Computation Using Time-Dependent or Shock-Capturing Methods," NASA
 CR-2470, Iowa State University for the National Aeronautics and Space Administration, October 1974.)

Once the 1000 atm curve was constructed, all of the curves for each pressure were converted over to temperature as a function of enthalpy and pressure using a curve-fitting package (see Appendix E). A subroutine called TEMPNEW employs these curves such that given enthalpy and pressure, temperature is returned.

An example of the temperature distribution behind the shock wave produced by this method can be observed in Fig. 3.4, for a 67 meter diameter stony asteroid entering at 15 km/s and -45° entry angle. The body is stepped around in one degree increments from the stagnation point to the shoulder. The temperatures are used to estimate the radiative energy given off by the hot gas.

Radiative Transfer

The radiative energy flux given off by any section of the shock layer is estimated with the black body equation

$$Q_{ad}'' = \sigma T^4 \quad (3.22)$$

where Q_{ad}'' is the adiabatic radiative flux in W/m^2 , σ is the Stefan-Boltzmann constant (equal to $5.67\text{E-}8 \text{ W/m}^2\text{K}^4$) and T is the temperature in Kelvin. The gas loses some of its energy between the shock and the body as it cools due to radiation to the surroundings. To account for these radiative losses, the reduction in the radiative flux due to non-adiabatic behavior can be estimated using a method developed by Goulard (1964). The

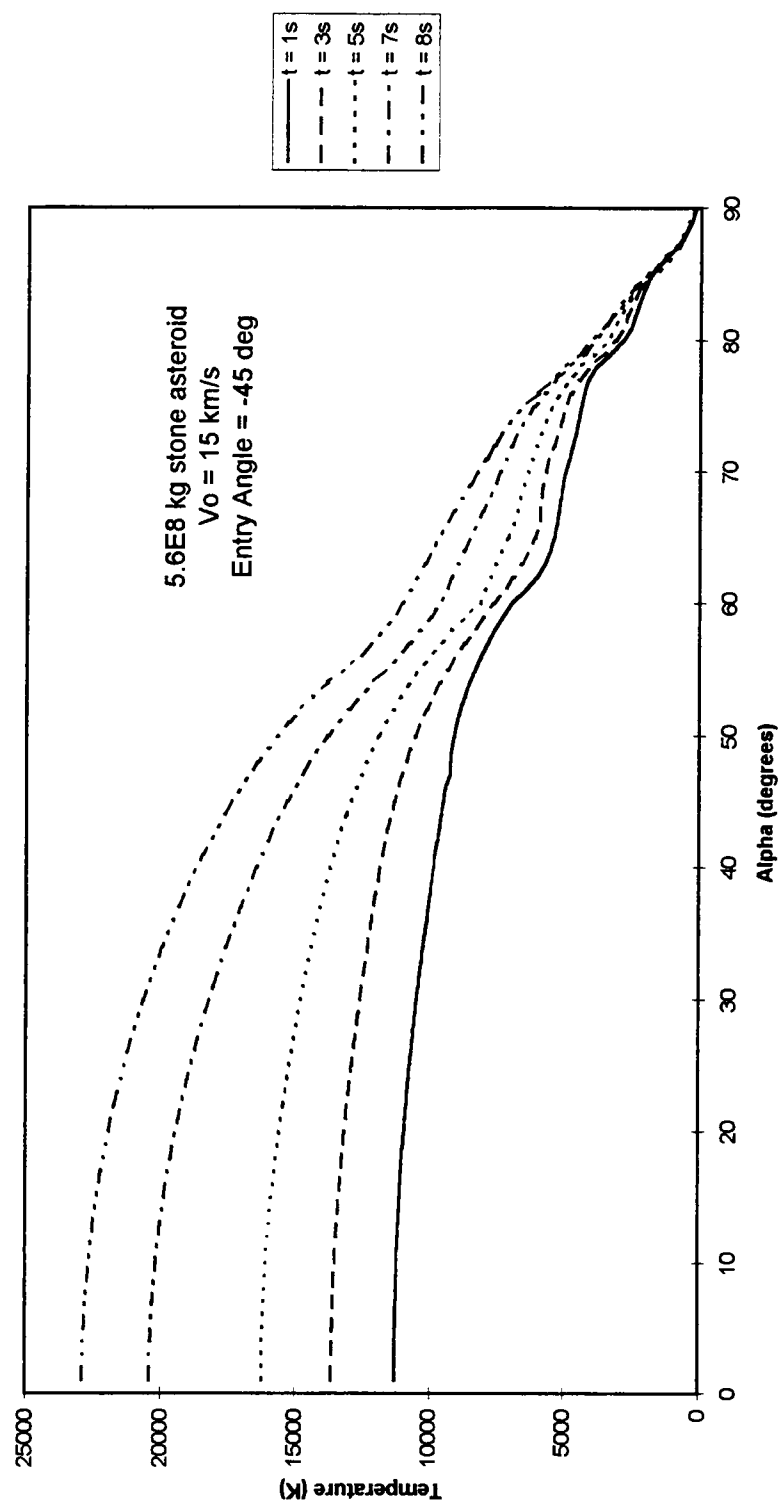


Figure 3.4 - Temperature distribution behind shock wave for various times.

Goulard number, Γ , is defined as

$$\Gamma = \frac{Q''_{ad}}{4\rho_{\infty}V_{\infty}^3} \quad (3.23)$$

Using a technique developed by Tauber(1969), The non-adiabatic flux Q''_G can then be approximated with

$$Q''_G = \frac{Q''_{ad}}{1 + 3.33\Gamma^{0.7}} \quad (3.24)$$

This non-adiabatic flux is used to compute the heat transfer from the shock layer to the body. Since the shock and body are stepped around in increments of one degree, each step will cut out a axisymmetric ring of the shock layer. Each ring is treated as a black body surface radiating energy out towards the spherical body and to the surroundings. A view factor between the shock ring and the sphere is needed to compute the heat transfer according to the equation

$$Q = F_{12} A_1 Q''_G \quad (3.25)$$

where Q is the energy input, F_{12} is the view factor from the ring to the body, and A_1 is the area of the shock ring radiating to the body. The view factor F_{12} can be modeled using the geometry of a sphere and a differential area whose normal vector is directed towards the sphere's center. The view factor from the differential area to the sphere is given by

$$dF_{12} = \left(\frac{r}{d}\right)^2 \quad (3.26)$$

where r is the sphere radius and d is the distance from the sphere center to the differential area (Siegel, 1982). This is for a differential area; if the shock ring is considered as a

summation of such differential areas, Eq. (3.26) can be applied to the shock ring as a whole. The divergence of the normal vector from the center of the sphere encountered at the shoulder is negligible, producing only a 3.4% difference in terms of area projected towards the sphere center.

The area A_1 of a shock ring can be estimated by the equation

$$A_1 = 2\pi r_{avg}^2 \sin \alpha \cos \beta \Delta \alpha \left(1 + \frac{dy^2}{dx_{shock}} \right)^{\frac{1}{2}} \quad (3.27)$$

Here r_{avg} is distance from the sphere center to the middle of the shock layer (halfway between the shock wave and the body), $\Delta \alpha$ is the discrete step angle equal to one degree ($\pi/180$ radians), and dy/dx_{shock} is the local slope of the shock wave taken at the midpoint of the discrete angle. This can be computed easily as a function of α from Eq. (3.7), trigonometry ($y = r \sin \alpha$, $x = r \cos \alpha$) and the chain rule

$$\frac{dy}{dx} = \frac{dy}{d\alpha} \frac{d\alpha}{dx} \quad (3.28)$$

Only the nose section is different, being approximated as a circle with the equation

$$A_{seg,nose} = \pi r_{avg}^2 \Delta \alpha^2 \quad (3.29)$$

Thus each shock layer segment is approximated as a flat plate ring located midway between the shock wave and the body, radiating the non-adiabatic flux Q''_G . Fig. 3.5 shows the radiative flux into the body for each discrete shock ring, for the 67-m stony asteroid. This is not the body flux at each point along the body, but rather the flux

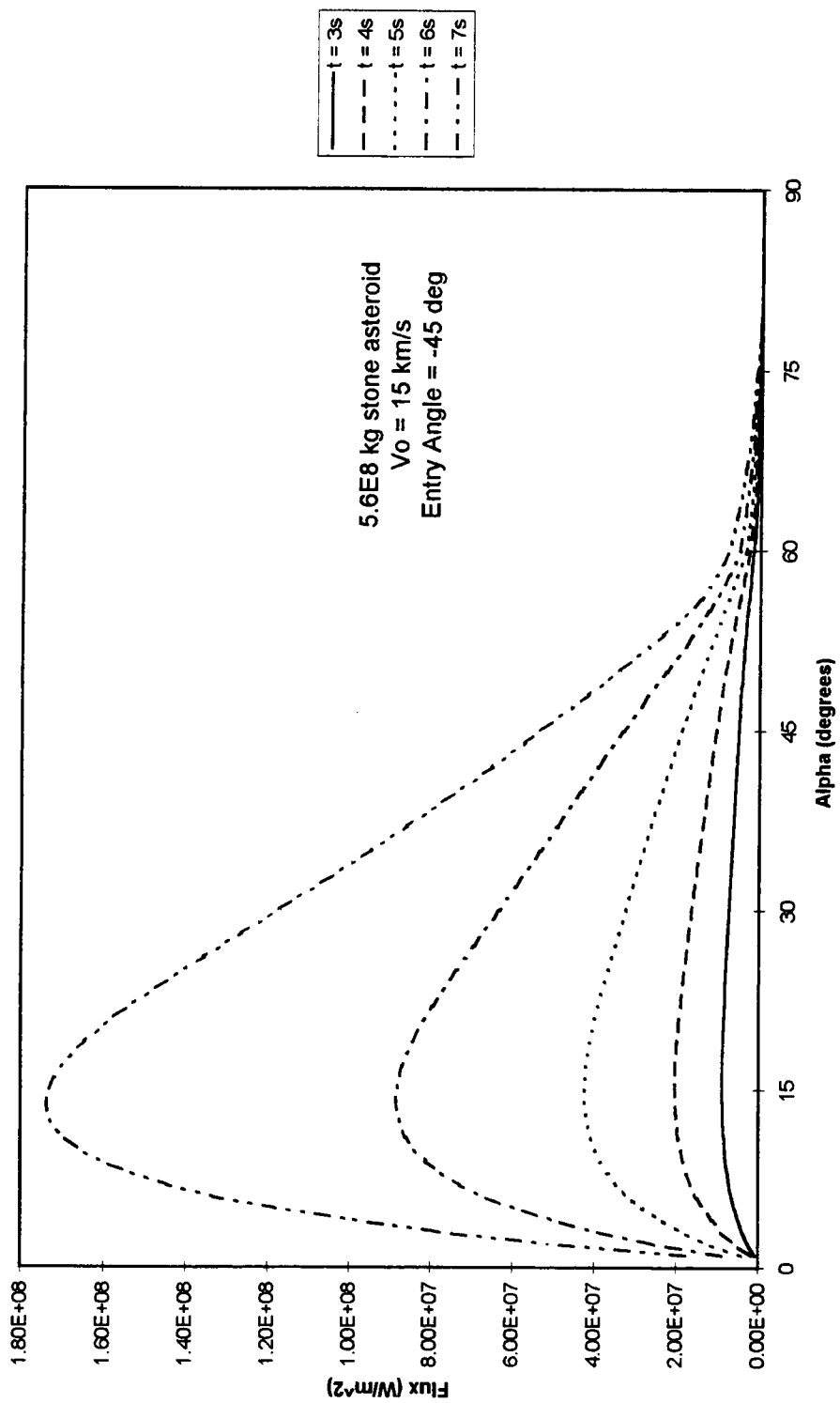


Figure 3.5 - Radiation flux into body from shock layer for various times.

into the body caused by each shock segment from $\alpha = 1$ to 90 degrees. These values are not corrected for blockage by ablation products.

Special considerations must be made when analyzing the heat transfer to the body after it has broken apart. Once disruption has occurred, it is assumed that the body flattens out like a pancake. A significant amount of mass can be vaporized during this phase as the shock wave in front of the pancake will have a significantly larger stagnation region due to the flat shape. The area irradiated by the radiation is also much larger due to the deforming shape. Since the exact shape of a deforming pile of rubble is unknown, for heat transfer purposes it is assumed to be ellipsoid. The semi-major axis a is set equal to the radius of the body (as found by the model of Chyba, et al., described later) for each time step. The density of the deforming object is assumed to remain constant, thus from the volume of the ellipse the semi-minor axis can be found from

$$b_{ell} = \left(\frac{3m}{4\pi \rho_{mS} r_{body}} \right)^{\frac{1}{2}} \quad (3.30)$$

where m is the current mass of the body, ρ_{mS} is the density of the body and r_{body} is the current radius. With the body thus defined, the shock wave is assumed to be an ellipse of the same aspect ratio b_{ell}/a_{ell} , the dimensions of which are increased by a factor of 1.21. This is the average of the standoff distances at the nose and shoulder of a sphere as defined in Eqs. (3.4) and (3.5). This elliptical estimation is used for lack of a better knowledge of the shock wave shape around a disintegrating body. Fig. 3.6 shows the geometry of the body and shock wave after disruption. The procedure for calculating the

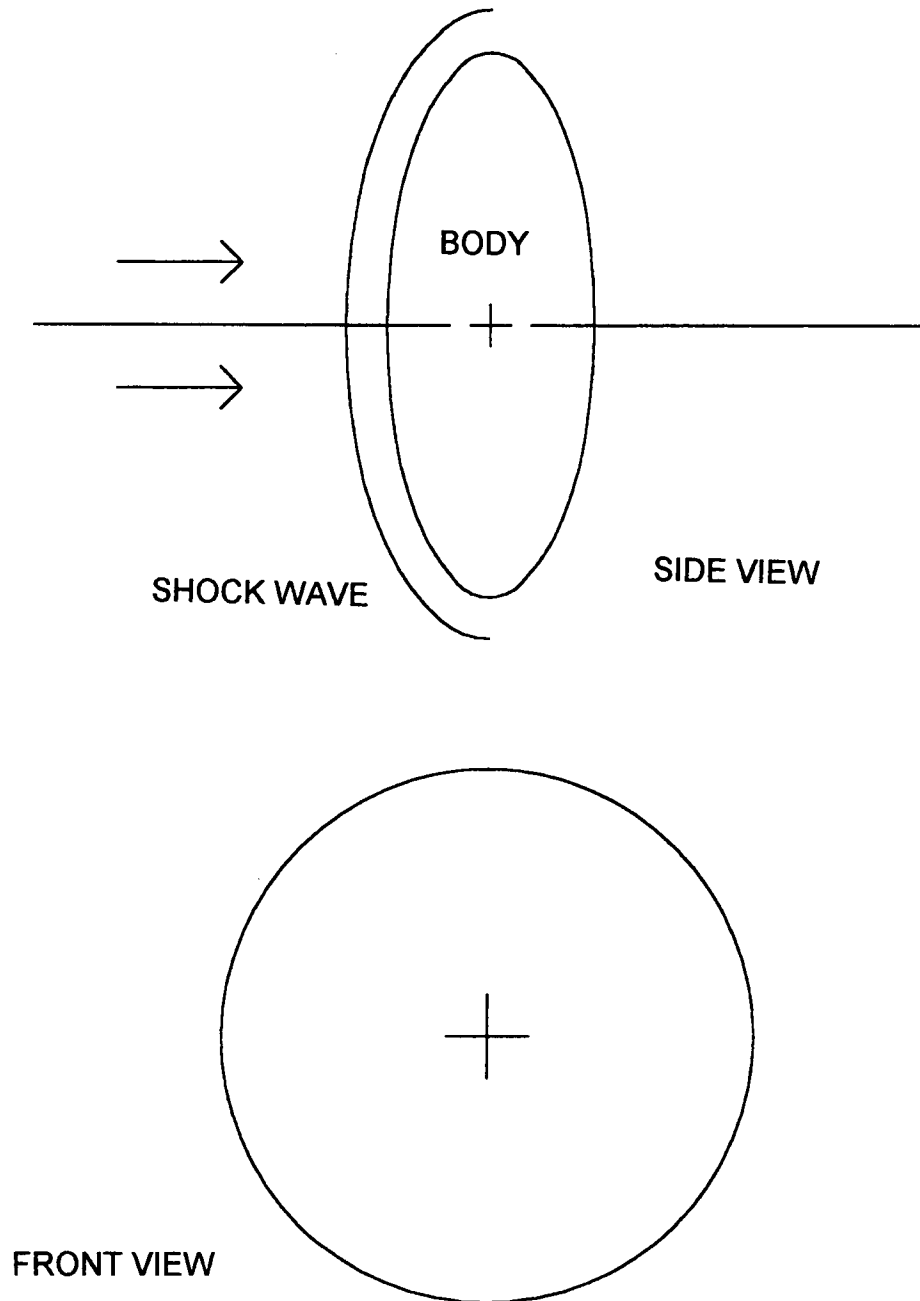


Figure 3.6. Ellipsoidal body and shock wave geometry after disruption.

heat transfer is much the same as for the spherical body.

One difference is in the view factors from the shock wave to the body. The view factor from the nose of the shock wave to the ellipsoid is approximated assuming that the ellipsoid can be approximated as a circular plate some distance from the centroid of the ellipse. The stagnation view factor is estimated using the derived relation

$$F_{12,nose} = \frac{a_{ell}^2}{r_{avg}^2 + a_{ell}^2 - b_{ell}^2} \quad (3.31)$$

where a_{ell} and b_{ell} are the semi-major and semi-minor axes of the ellipsoid, respectively, and r_{avg} is the local distance from the middle of the shock layer to the body centroid.

Similarly, the view factor at the shoulder of the ellipse is approximated with the derived relation

$$F_{12,shoulder} = \frac{a_{ell}b_{ell}}{r_{avg}(r_{avg}^2 - a_{ell}^2 + b_{ell}^2)^{\frac{1}{2}}} \quad (3.32)$$

Once the values of the view factors at the nose and shoulder are found for a time step, a linear profile is assumed as a function of body position α , yielding the view factors for the rest of the shock locations.

Another difference is in the calculation of the blockage of radiation by ablation products. Instead of doing a calculation for each angular increment, an overall calculation is made for the whole body. This is done since the areas on the elliptical body viewed by each section of the elliptical shock wave are difficult to calculate.

Radiation Blockage

The energy that goes into the body causes the material to ablate away. This vaporized mass has the effect of blocking some of the radiation going into the body. The effect depends primarily on the ratio of the freestream mass flow rate to the ablation product mass flow rate. This ratio can be computed for each shock section using the equation

$$\frac{\dot{m}_{ablation}}{\dot{m}_{freestream}} = \frac{Q''_{body}}{H_{ablation} \rho_{\infty} V_{\infty}} \quad (3.33)$$

where $H_{ablation}$ is the heat of ablation and Q''_{body} is the radiative flux into the body for the particular body step. The blocking effect is accounted for using a curve adapted from a study done by Gupta, et al (1994). The curve, shown in Fig. 3.7, plots a scale factor versus the ratio of freestream mass flow rate to ablation product mass flow rate. This scale factor is the ratio of the reduced radiative flux over the unblocked flux.

Fig. 3.8 shows the scale factor profile for the 67-m stony asteroid at various times in the trajectory before breakup. Fig. 3.9 shows the reduction in radiative flux into the body caused by the ablation products for the stony asteroid at $t = 5$ seconds. Once the new flux is found, the ablation rate is reduced and thus a new mass flow ratio must be found which will yield a new scale factor. Thus the solution is iterative. The body flux for each section is found by dividing the total energy found by Eq. (3.25) for each shock section by the body area visible to the shock section. This area is found from the geometry between the shock location and the sphere. Once the new flux is found, the total energy input for the section can be found by simply multiplying by the body area.

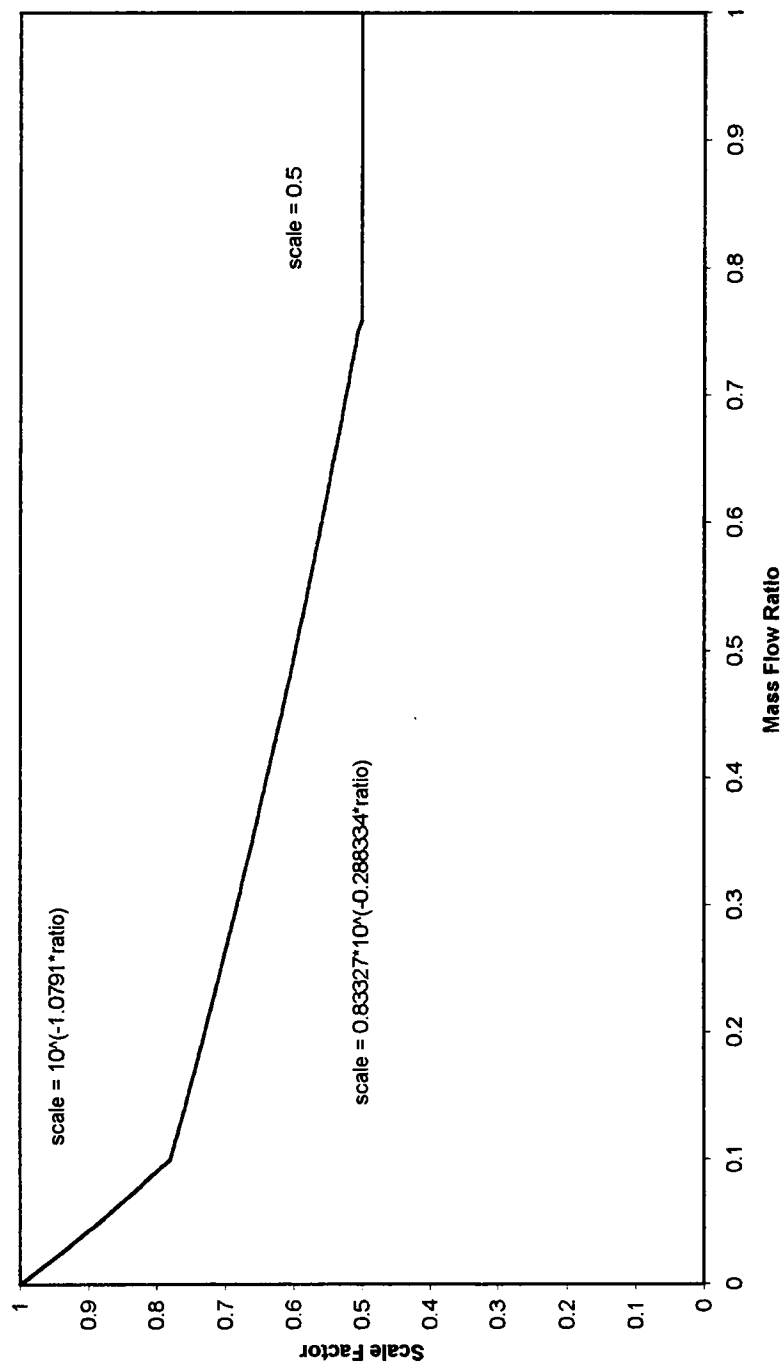


Figure 3.7. Radiation blockage scale factor as a function of mass flow ratio.

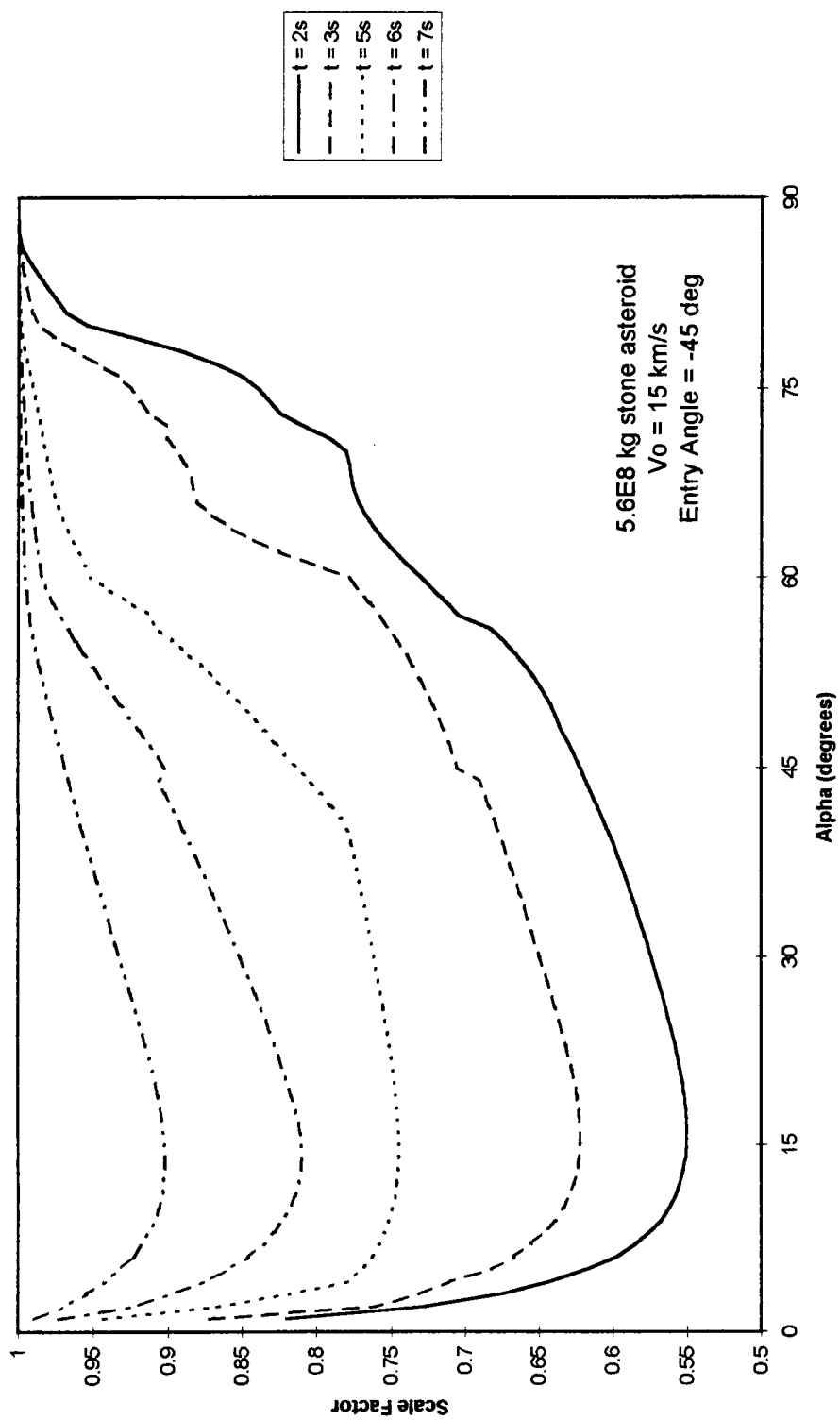


Figure 3.8. Radiation blockage scale factor distribution for various times.

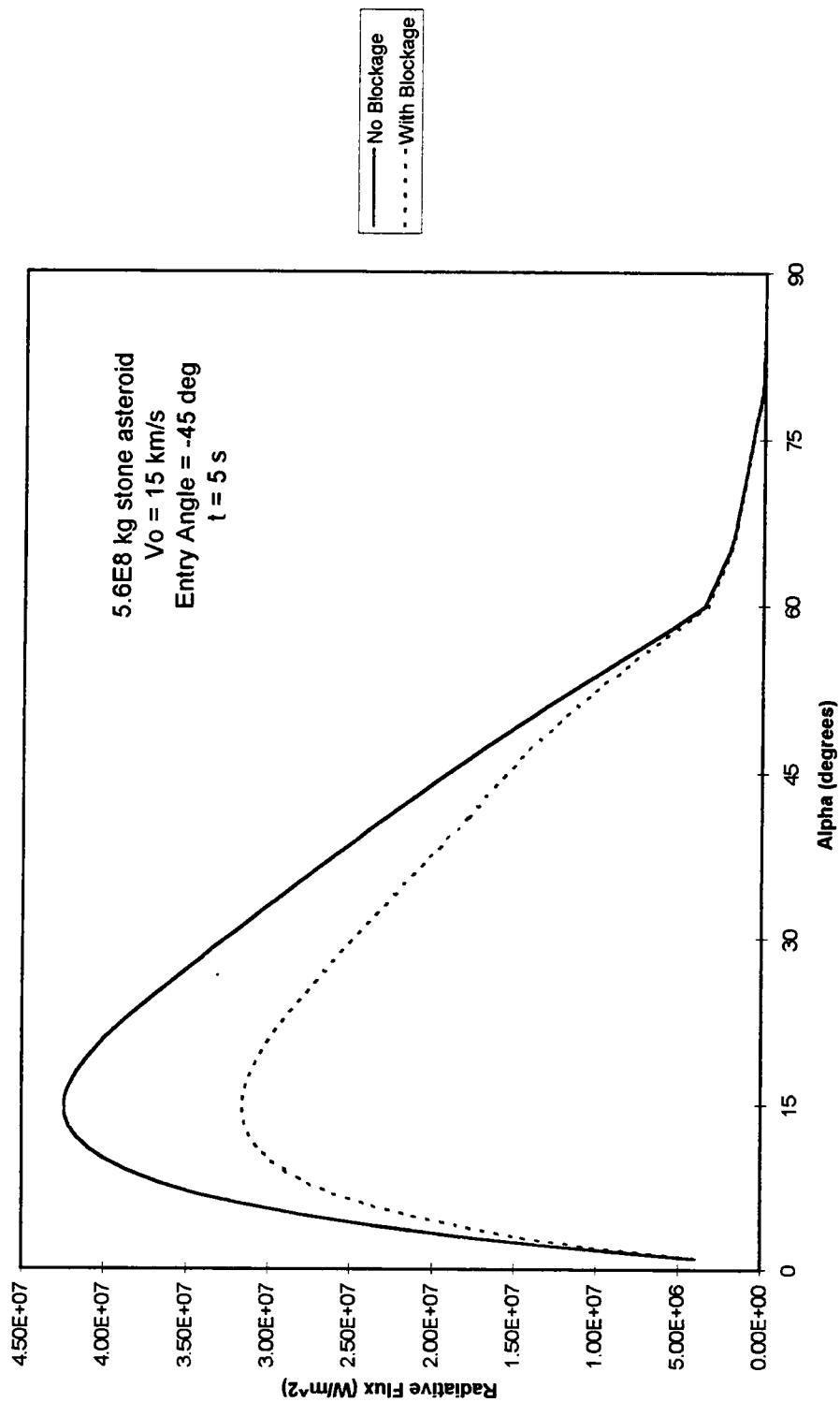


Figure 3.9. Radiative flux distribution for $t = 5 \text{ s}$ before and after correcting for ablation product blockage.

Observations have shown that most of the flow energy goes into heating the atmosphere rather than the body undergoing atmospheric entry (Lyne and Tauber, 1994). For this reason, the overall flux into the body is limited to 15% of the total energy in the flow, given by

$$E_{tot} = \frac{1}{2} \rho_{\infty} V_{\infty}^3 \quad (3.34)$$

This limit is most important at high altitudes, where the shock temperatures can cause excessive radiation despite low flow energy due to low ambient density.

Once the final radiative energy input to the body is determined by summing up the individual inputs from all the sections and checking for the flow energy limit of Eq. (3.34), the final mass loss due to ablation can be calculated from

$$\Delta m = \frac{Q_{total} \Delta t}{H_{ablation}} \quad (3.35)$$

where Δt is the discrete time step. Assuming the body has not yet disrupted and that the material ablates away evenly from the whole sphere, the new body radius can be calculated from the volume of a sphere:

$$r_{new} = \left(\frac{3m}{4\pi \rho_{mS}} \right)^{\frac{1}{3}} \quad (3.36)$$

The overall radiative flux into the body is calculated by simply dividing the total energy transferred by the total surface area of the sphere exposed to the radiation. From the assumed shock wave shape and geometry, this area is $10.504 r_{body}^2$ for the spherical shape before disruption. This amounts to approximately 84% of the total sphere surface area.

The shock wave is assumed to effectively stop at the shoulder, thus the other 16% of the sphere surface area is physically blocked from seeing the shock. After disruption the area is taken to be that of the front face of the ellipsoid, the rear face being neglected for the same geometric considerations.

Convective Heat Transfer

There is also some heat transfer due to convection, but this is generally regarded as negligible compared to the immense radiative transfer involved in entry mechanics. As a check, the stagnation point convective heat transfer is calculated using the empirical approximation (Tauber, 1994)

$$Q''_{conv,stag} = 0.000183 \left(\frac{\rho_{\infty}}{r_{nose}} \right)^{\frac{1}{2}} V_{\infty}^3 \quad (3.37)$$

where r_{nose} is the body nose radius in meters and $Q''_{conv,stag}$ is the convective flux in W/m^2 . The convective heating is maximum at the stagnation point, thus the actual average over the entire body will be less than this value. This maximum figure is used as a gauge against the stagnation point radiative flux to ensure convection is negligible. As an example, the maximum ratio of convective to radiative flux for the 67-m stone meteor is 0.0167, or less than 2 percent.

Disruption

The disruption model is based upon that described by Chyba, et al. (1993). Once the pressure in the center of the body reaches the material yield strength, disruption is assumed to occur. The average pressure over the front face of the body is

$$P_{avg} = \frac{1}{2} C_D \rho_{\infty} V_{\infty}^2 \quad (3.38)$$

The average pressure in the interior is one half of this assuming zero pressure on the back side, and determines when the body disrupts. The body is assumed to deform as a cylinder, becoming shorter as the radius expands. Assuming the density of the mass remains constant, a second order equation is derived (Chyba, et al., 1993) that relates radius as a function of time:

$$r \frac{d^2 r}{dt^2} = \frac{C_D \rho_{\infty} V_{\infty}^2}{2 \rho_{ms}} \quad (3.39)$$

This is solved using trapezoidal approximation on the integrands, yielding a new body radius based on current conditions.

Provided the body has not completely ablated away, the body decelerates rapidly due to the increased surface area once disruption has occurred. This is where most of the meteor's energy is deposited, and the airburst height is defined as the point of maximum energy release rate measured in MT/km. This is accomplished easily by keeping track of body altitude and kinetic energy.

This model is used to carry out a parametric study of various types of meteors entering earth's atmosphere under various entry conditions. Certain results are also used as a comparison with previous models. The comparison is described in the next chapter.

CHAPTER IV

CODE EVALUATION

The main difference between the present method and previous methods is in the heat transfer and ablation computations. The resulting differences in the trajectory of the body are quite significant. Various cases put forth by Chyba, et al. and Baldwin and Shaeffer are duplicated using the present code, and the results are compared. The variation in the present method as a result of changing the drag coefficient, shock wave profile and time step is also investigated.

Comparison With Previous Methods

Chyba, et al. present results for eight various cases, two of which (short-period and long-period comets) cannot be analyzed using the present method due to the high entry velocities producing shock layer temperatures above the limits of the present model. The six cases that are analyzed are summarized in Table 4.1. For each case the mass is $5.6E8$ kg and the entry velocity is 15 km/s; this corresponds to an initial kinetic energy of 15 Mtons of TNT equivalent (1 ton TNT = 1 billion calories). When running these cases using the present code, the object diameter is set according to the density and mass. The values of Table 4.1 are used for density, heat of ablation, strength and entry angle.

Figure 4.1 shows energy deposition curves for the iron meteorite case. Figure 4.1(a) shows energy deposition in MT/km vs. altitude in km, while 4.1(b) shows cumulative energy deposition in MT. The data for Chyba, et al. were read from plots, and the

Table 4.1 Meteorites considered by Chyba, et al. (Source: Chyba, Christopher F., Thomas, Paul J., Zahnle, Kevin J., "The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid," Nature, Vol. 361, No. 6407, Jan. 1993 pp. 40-44.)

Object Type	Density (kg/m ³)	Heat of Ablation (J/kg)	Yield Strength (N/m ²)	Entry Angle (degrees)	Airburst Height (km)
Iron	7900	8.0E6	1.0E8	-45	0
Stone	3500	8.0E6	1.0E7	-45	9
Stone	3500	8.0E6	1.0E7	-15	15
Stone	3500	8.0E6	1.0E7	-30	11
Stone	3500	8.0E6	1.0E7	-90	6
Carbonaceous	2200	5.0E8	1.0E6	-45	14

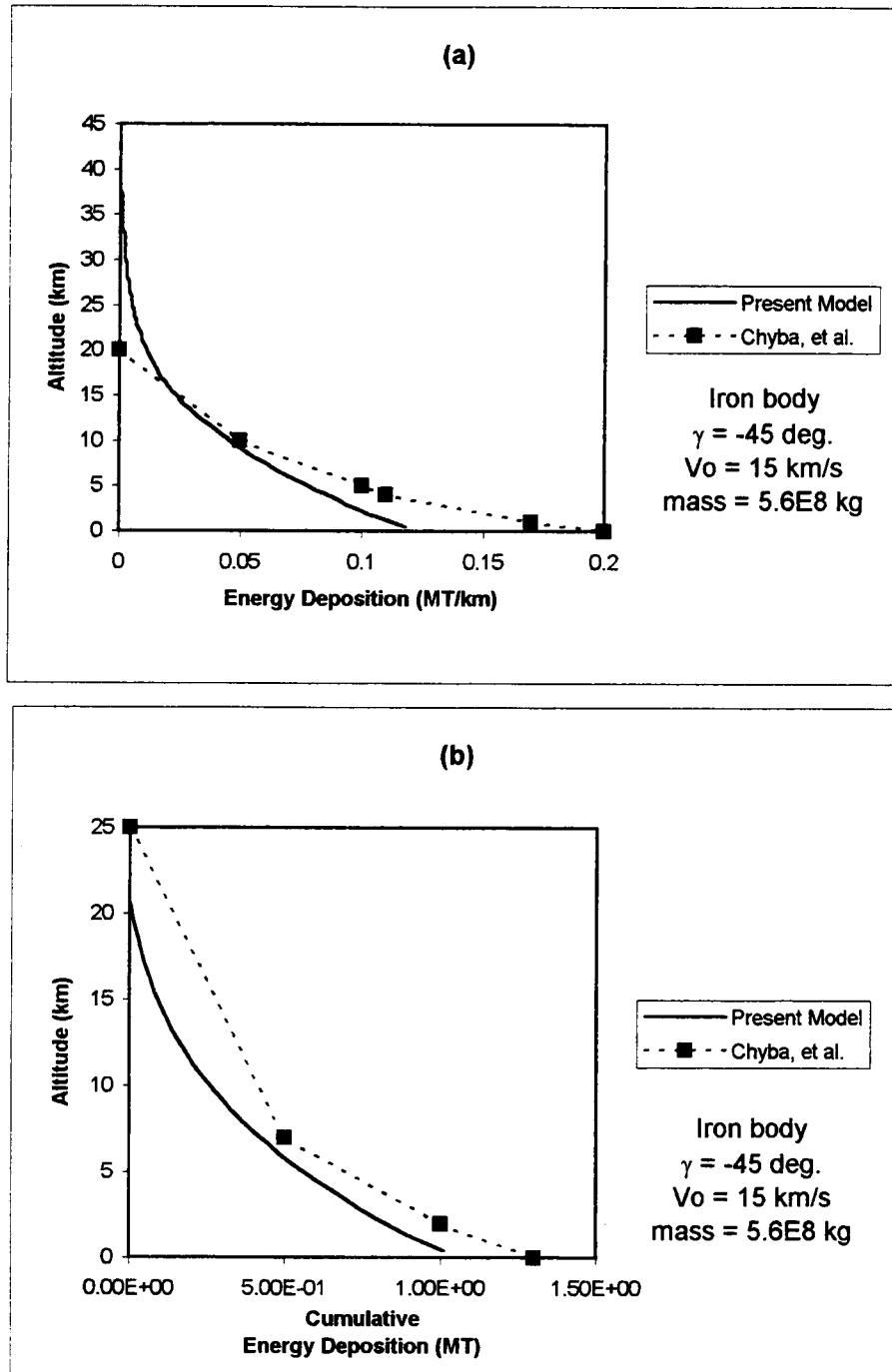


Figure 4.1. Local (a) and cumulative (b) energy deposition curves for iron.
 (Adapted from Chyba, Christopher F., Thomas, Paul J., Zahnle, Kevin J., "The 1908
 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid," Nature, Vol. 361,
 No. 6407, Jan. 1993, pp. 40-44.)

resolution is questionable. However, it can be seen that the present method predicts that the body loses its energy later in the trajectory, and thus lower in the atmosphere than that of Chyba, et al. for pre-breakup flight since this particular body is strong enough such that disruption does not occur. The difference lies in the ablation rate caused by the heat transfer into the body.

Figure 4.2 compares the ablation rate on the iron meteorite as computed using the present method and the method of Chyba, et al. The present model predicts an earlier onset of significant ablation; however at 30 km the model of Chyba, et al. quickly surpasses the present model. It can also be seen to peak at over twice the value of the present model. The sharp leveling off in the ablation rate is caused by the limiting of the radiative flux to $\sigma(25000K)^4$ where σ is the Stefan-Boltzmann constant. If one considers the difference in the areas under the two curves, it is realized that much more mass is lost using the model of Chyba, et al. In this case, the present model yields a total mass loss that is 42% of that predicted using the method of Chyba, et al.

This is even more pronounced when considering a body which does disrupt such as the stony asteroid at a -45° entry angle, shown in Figure 4.3. The peak ablation rate computed with the method of Chyba, et al. can be seen to be approximately one order of magnitude greater than that of the present method. This enormous ablation rate can be partly attributed to the vast increase in cross-sectional area after disruption occurs. Eq. (1.1) shows that the ablation rate predicted by Chyba, et al. is directly proportional to this area. The present model predicts lower temperatures and thus lower radiative fluxes, and also takes into account radiation blockage by ablation products. The overall result is a

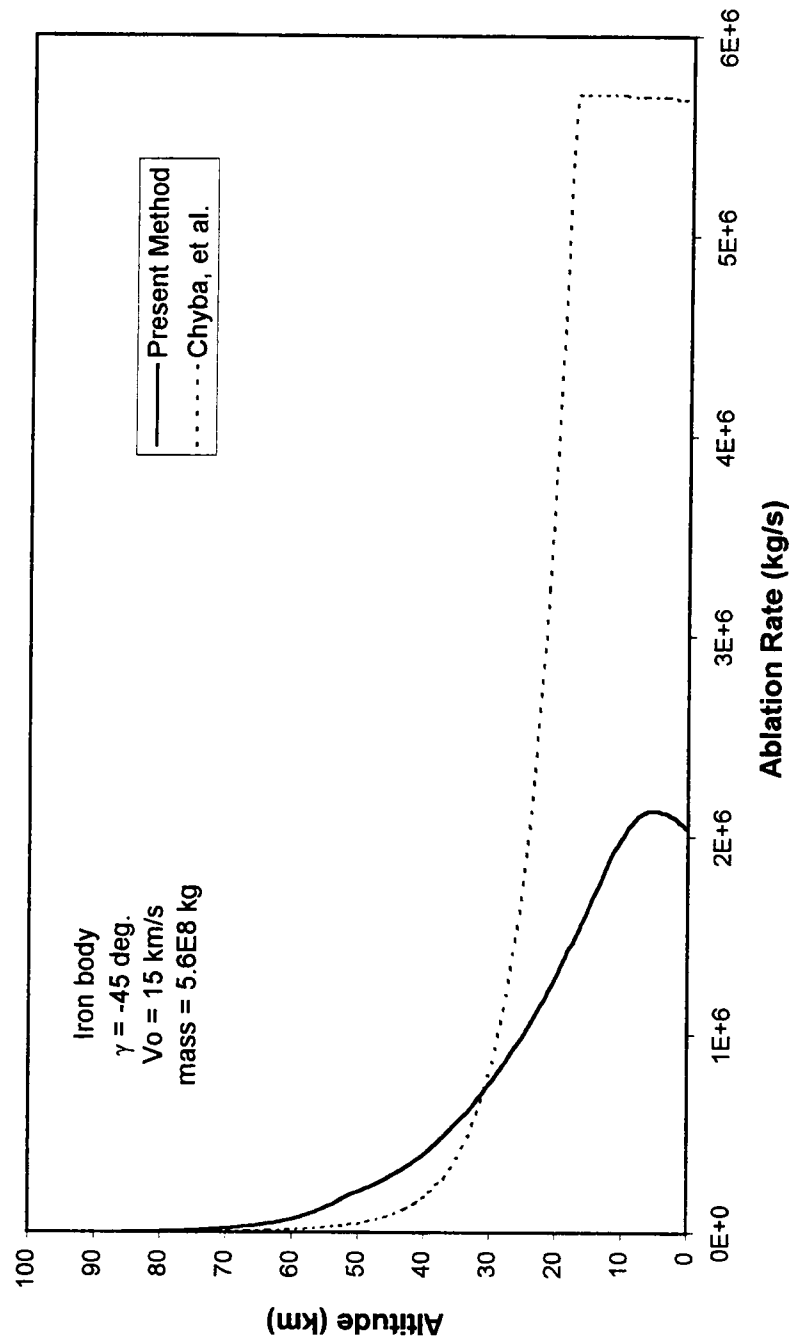


Figure 4.2. Ablation rate curves for iron.

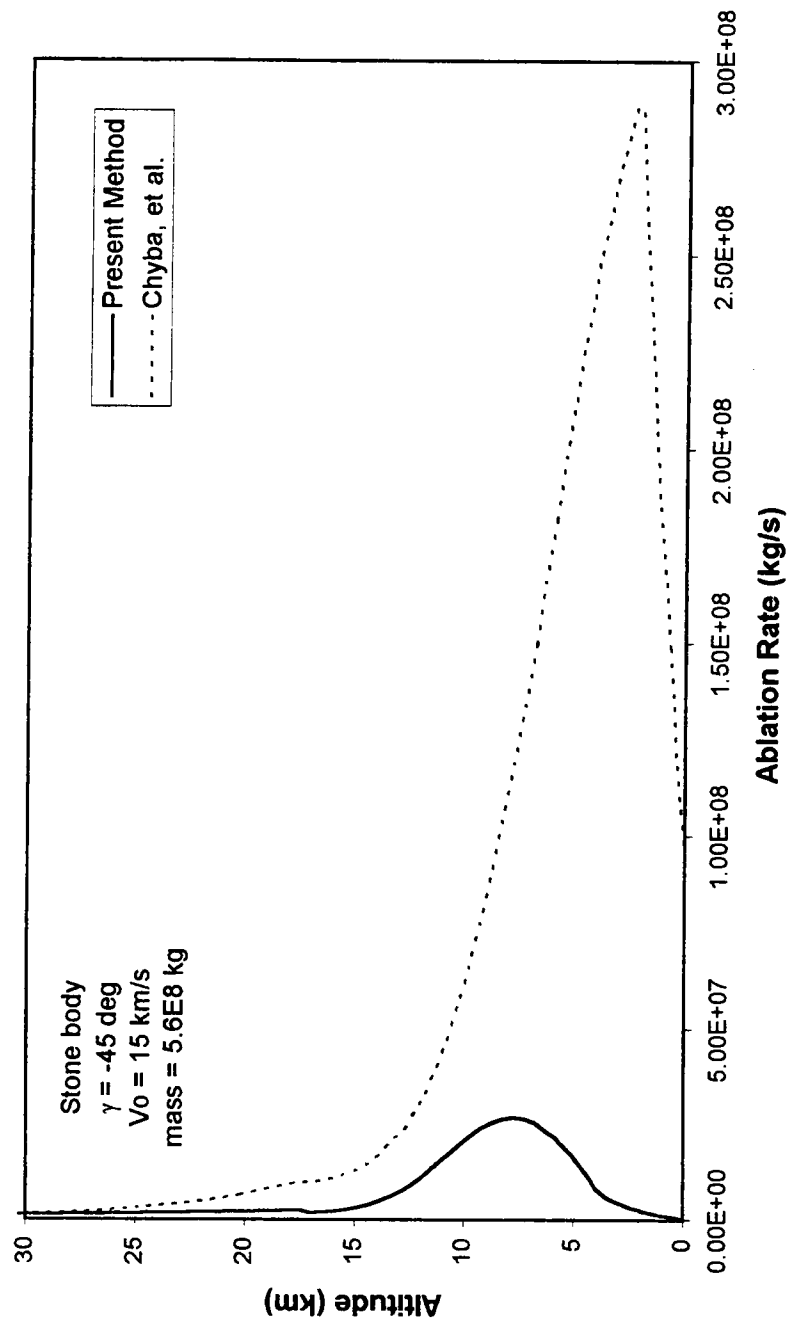


Figure 4.3. Ablation rate curves for stone @ 45 degrees.

much lower ablation rate than that predicted by Chyba, et al. For the stony asteroid case, the method of Chyba, et al. predicts a total mass loss almost 12 times that predicted by the present model. The effect that this reduced mass loss has on the body trajectory is quite pronounced.

Figure 4.4 shows the energy deposition curves for the stony asteroid at -45° . Figure 4.4(a) shows the energy deposition rate for both methods; the peak of Chyba, et al. is 5 MT/km, while the present method yields a peak of 1.7 MT/km, less than half as much. To make up for the difference the peak is broader, occurring over a wider altitude band. This is expected since the area under each curve should total up to the same initial kinetic energy, 15 MT (provided the object does not impact the earth before being slowed to a free-fall, which happens in this case). The present method's peak occurs at an altitude of 4.3 km, whereas the peak of Chyba, et al. occurs at 9 km. Naturally as a result of this, the total energy deposition curve of the present method is lower on the altitude scale as well, as shown in Figure 4.4(b). This vast decrease in airburst altitude is due to the body having more mass as a result of the smaller ablation. This mass carries the body farther into the atmosphere, resisting the decelerative forces.

This pattern of reduced airburst altitude and peak deposition is consistently repeated for each of the cases in Table 4.1. The results of the remaining comparisons are given in Table 4.2. The variance of airburst height and peak energy deposition as a function of entry angle for the stony asteroid is shown in Figure 4.5. Figure 4.5(a) shows that the

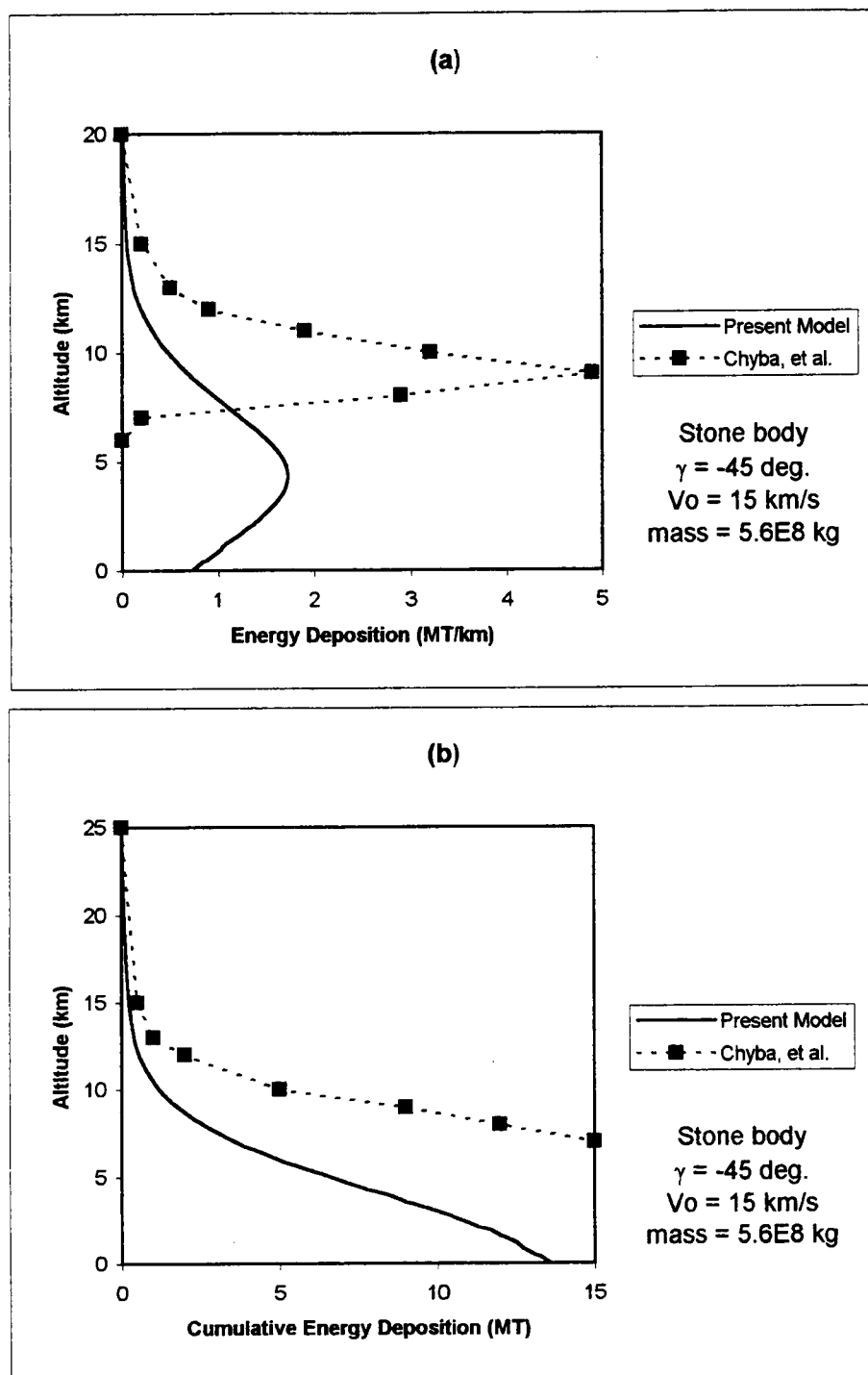


Figure 4.4. Local (a) and cumulative (b) energy deposition curves for stone @ 45 deg. (Adapted from Chyba, Christopher F., Thomas, Paul J., Zahnle, Kevin J., "The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid," Nature, Vol. 361, No. 6407, Jan. 1993, pp. 40-44.)

Table 4.2 - Summary of comparison with Chyba, et al. (Source: Chyba, Christopher F., Thomas, Paul J., Zahnle, Kevin J., "The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid," Nature, Vol. 361, No. 6407, Jan. 1993 pp. 40-44.)

Object (entry angle deg)	Chyba, et al. Airburst Alt. (km)	Present Airburst Alt. (km)	% Difference	Chyba, et al. Peak Dep. (MT/km)	Present Peak Dep. (MT/km)	% Difference
Iron (-45)	0	0	0	-	-	-
Stone (-45)	9	4	55	5	1.7	66
Stone (-15)	15	12	20	10.5	2.6	75
Stone (-30)	11	8	36	6	1.9	68
Stone (-90)	6	1	83	4	1.6	60
Carbon. (-45)	14	8	43	3	1.4	53

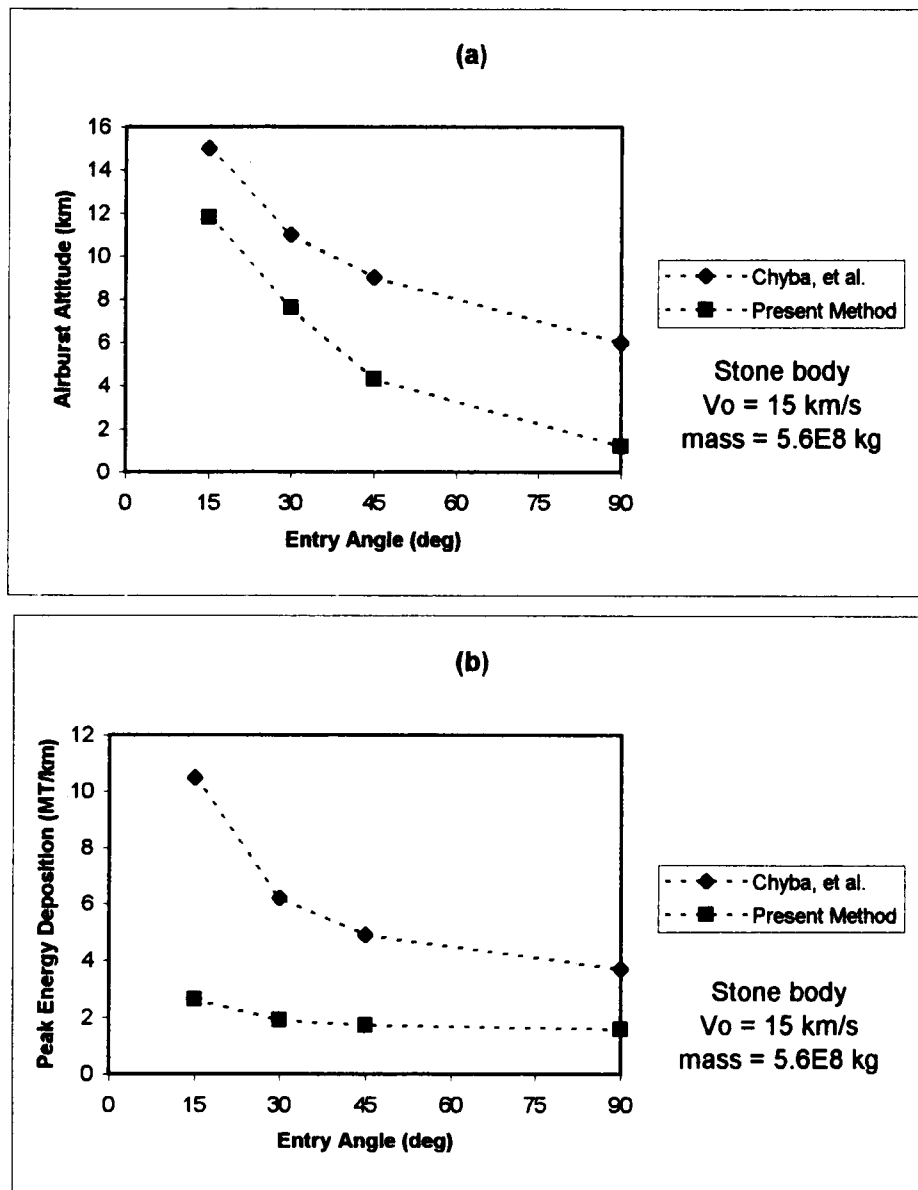


Figure 4.5. Airburst altitude (a) and peak deposition (b) vs. entry angle for stone. (Adapted from Chyba, Christopher F., Thomas, Paul J., Zahnle, Kevin J., "The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid," Nature, Vol. 361, No. 6407, Jan. 1993 pp. 40-44.)

airburst altitude difference between the two methods is greatest at steeper entry angles. This is due to the excessive heating associated with such angles; the body has no time to slow down before it reaches the denser lower atmosphere. Thus the differences in ablation are equally excessive. Figure 4.5(b) shows the opposite to be true for peak energy deposition. The present method approaches that of Chyba et al. as entry angle increases, the greatest differences being at shallower angles.

The method of Baldwin and Shaeffer (1971) predicts higher ablation rates, as well as breakup much higher in the atmosphere than the present method. They present velocity and ablation curves for a carbonaceous and olivine bronzite body, both with a mass of 500 kg, entry velocity of 14.2 km/s and entry angle of -38.4° . The data for the Baldwin and Shaeffer curves are taken from plots presented in their paper, so the resolution is not exact. Figure 4.6(a) shows the normalized velocity curves for a carbonaceous body. It can be seen that Baldwin and Shaeffer predict breakup at about 45 km altitude, after which the body decelerates to zero velocity at 25 km. The present method predicts a steeper profile; breakup occurs at about 28 km altitude where the object is quickly decelerated within a couple of kilometers. Figure 4.6(b) shows the ablation curves for the carbonaceous body. The high ablation rate of Baldwin and Shaeffer compared to the present method shows again the effects of such an early breakup. At 40 km it peaks at around 250 kg/s, the entire curve being quite broad and depleting much mass. The present model yields a narrow spike of about 350 kg/s upon breakup. Before disruption occurs

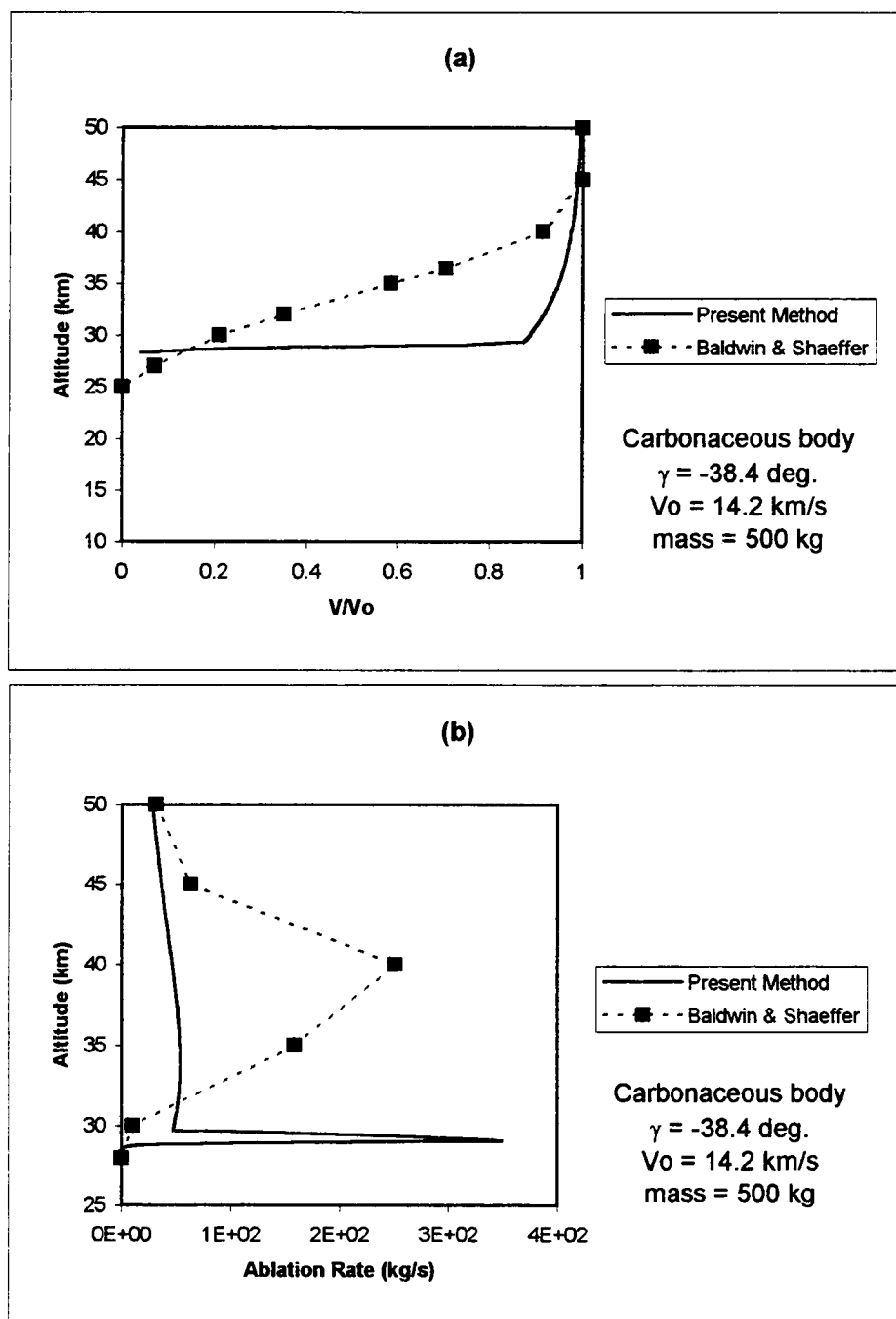


Figure 4.6. Velocity (a) and ablation rate (b) curves for 500 kg carbonaceous body. (Adapted from Baldwin, Barrett, and Shaeffer, Yvonne, "Ablation and Breakup of Large Meteoroids During Atmospheric Entry," Journal of Geophysical Research, Vol. 76, No. 19, July 1, 1971.)

the ablation rate is mild compared to Baldwin and Shaeffer, with a maximum value of around 50 kg/s.

Figure 4.7 shows the same velocity and ablation curves for the olivine bronzite body, which is strong enough not to disrupt. Figure 4.7(a) shows that the present method predicts only a slightly deeper penetration into the atmosphere. This shows that the main difference between the two methods occurs because of the differing breakup models. Fig. 4.7(b) shows that the ablation rate of Baldwin and Shaeffer has a higher peak, but is lower at the high altitudes. Inspecting the areas under the curves, it appears that roughly the same amount of mass is lost using both methods. Thus the velocity curves of Fig. 4.7(a) are nearly the same; the slight difference could be brought on by the differing ablation profiles and the different drag coefficients used in the models. Baldwin and Shaeffer use a variable drag coefficient which is a function of the local atmospheric density and the radius of the reference area for the body. The material properties used by Baldwin and Shaeffer for carbon and bronzite, respectively, are: density, 2800 and 3621 kg/m³; compressive strength, 10⁶ and 1.736E8 Pa; and heat of ablation, 8.51E6 J/kg for both.

No direct comparison with Sekanina (1983) could be made; however, since the ablation model used is the same as that of Baldwin and Shaeffer, the mass loss profiles would compare much the same before the point of disruption. It is unclear how Sekanina defines and models the disruption process, thus no useful comparison can be made.

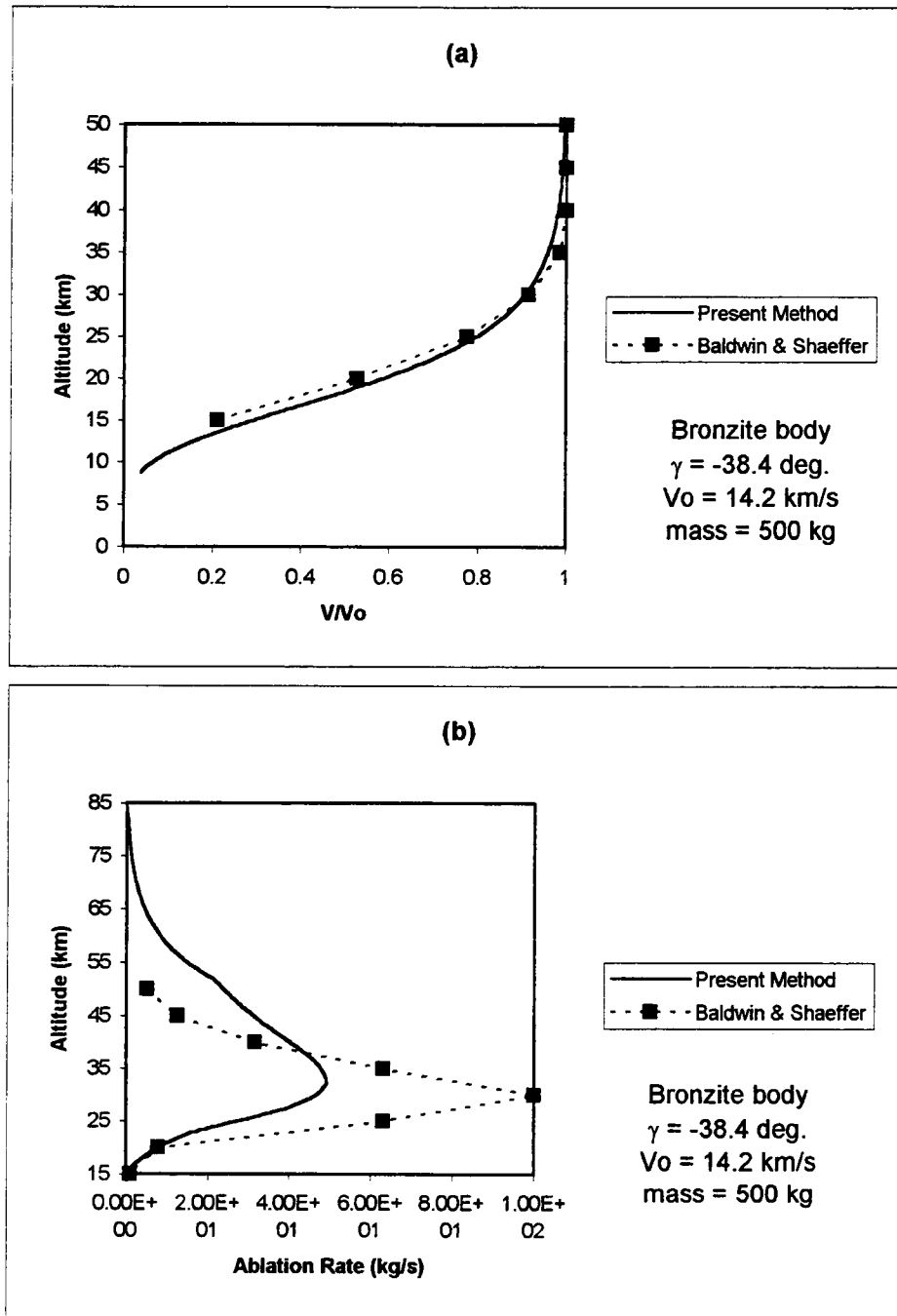


Figure 4.7. Velocity (a) and ablation rate (b) curves for 500 kg bronzite body. (Adapted from Baldwin, Barrett, and Shaeffer, Yvonne, "Ablation and Breakup of Large Meteoroids During Atmospheric Entry," Journal of Geophysical Research, Vol. 76, No. 19, July 1, 1971.)

Self-Comparison

The present model assumes a constant value of drag coefficient throughout the whole flight regime of 1.3. This is assumed since the actual shape of the body is unknown. For a perfect sphere the hypersonic drag coefficient is 1.0, while for a flat plate normal to the oncoming flow the value is 2.0. To account for the almost certainly odd shape of the meteor and the unknown shape after disruption, it was decided to pick a value in between 1.0 and 2.0. The dependence of the airburst height and peak energy deposition can be seen in Fig. 4.8 for the stony asteroid of Table 4.1 at -45° . Fig. 4.8(a) shows an airburst altitude of 2.5 km at a C_D of 1.0, increasing to over 7 km for a C_D of 2.0. This is quite a disparity, and displays the importance of the C_D chosen. Fig. 4.8(b) shows the variation in peak energy deposition; the extreme values are 1.64 and 1.86 for drag coefficients of 1.0 and 2.0, respectively. The used C_D of 1.3 was chosen as a safe, middle of the road estimate biased more towards the perfect sphere end of the spectrum.

The dependence of the results on the assumed shock angle was also investigated for the -45° stony asteroid case. The shock wave profile as described in Ch. 3 was changed such that the angle β at the shoulder was 10 and 21 degrees (the normal value used being 15°). Both cases produced a negligible difference in airburst height of about 1 meter. The 10° case produced slightly less heating around the shoulder as would be expected, but this region contributes so little to the total heating that no major effects occur. The same is true for the 21° case; the increase in heating was present but very slight and of no significance.

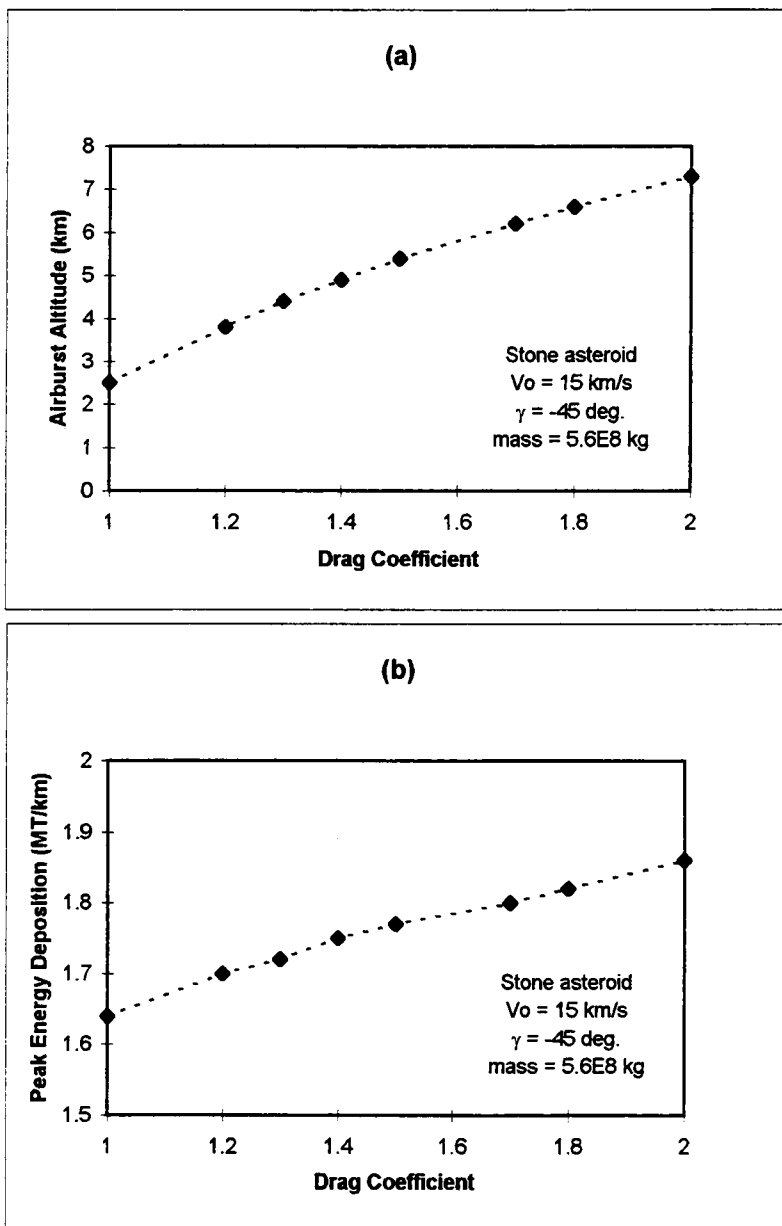


Figure 4.8. Airburst altitude (a) and peak deposition (b) vs. drag coefficient.

In the analysis of the code, it was noticed that the time step chosen has a direct impact on the computed trajectory, especially the airburst height. Fig. 4.9 shows the variance in the airburst height for the stony asteroid of Table 4.1 at -45° with differing time steps. There is a narrow range for which the code 'converges'; above or below this the airburst height is appreciably underestimated. This range is around 3-5 milliseconds; the time step used for the test runs is 0.005 seconds. The errors associated with the larger time steps can be attributed to the immense velocities associated with the objects. Apparently the smaller time steps produce a stability problem; the Δt value is used in the ablation calculation, and this may be the cause of such a problem.

These comparisons validate the heat transfer model in general, and show the differences in ablation profiles between the present model and the overall-coefficient type approach. The differences brought on by differing breakup models is also obvious. The next chapter discusses the results of a parametric study carried out using the present model on various bodies and entry conditions.

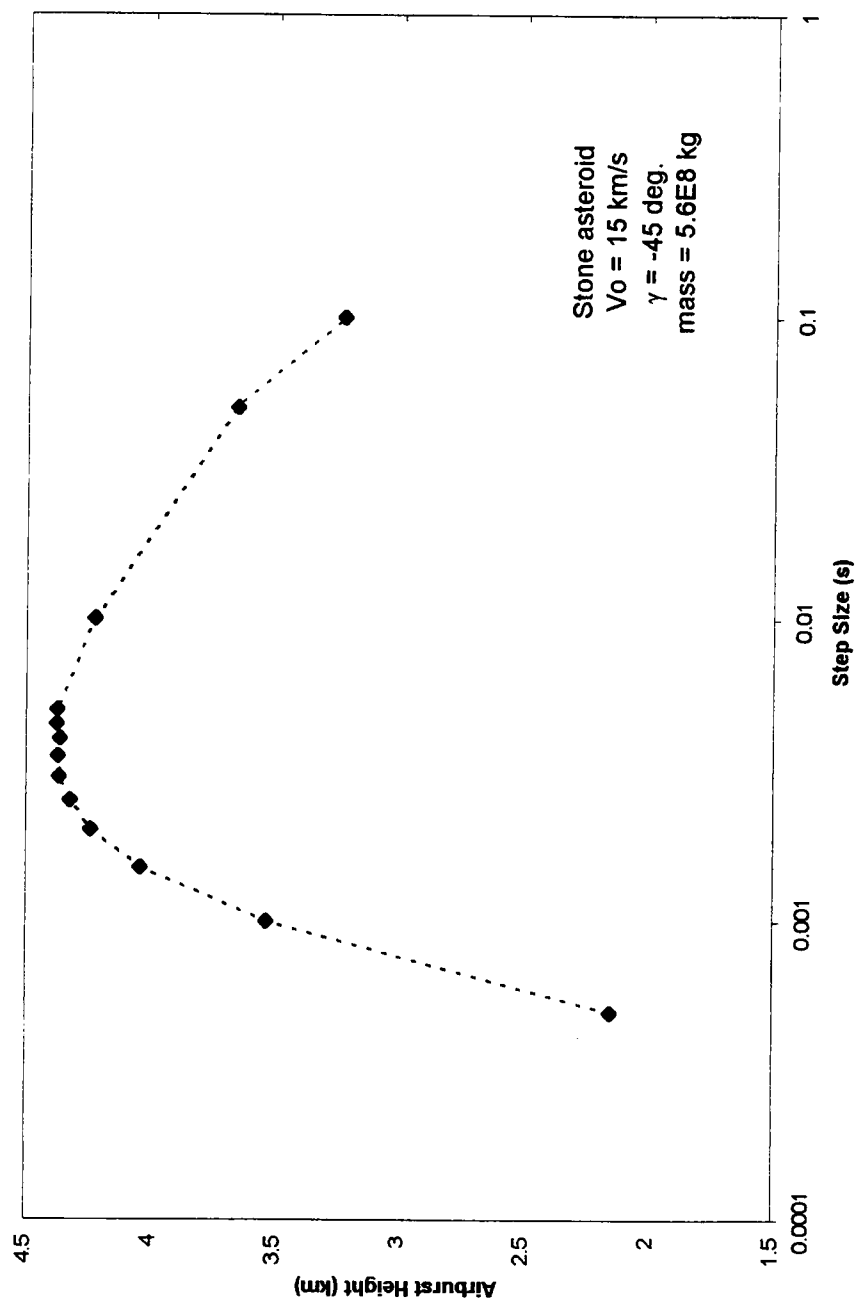


Figure 4.9. Variance in airburst height with time step.

CHAPTER V

PARAMETRIC STUDY RESULTS

Using the present method, a parametric study is carried out covering a variety of materials and entry conditions. This is done to gauge the potential threat presented by various possible impactors. The materials and conditions considered are summarized in Table 5.1.

Table 5.1 Parametric study test matrix.

Material Type	Body Diameter (m)	Entry Velocity (km/s)	Entry Angle (degrees)
Iron	10	12	15
Stone	50	15	30
Carbonaceous	100	17	45
Comet	500	18.5 - 19	90

The properties for all the materials are taken to be the same as those used by Chyba, et al. (1993), and are given in Table 2.1. Runs are performed for each material at each diameter, each entry velocity and each entry angle for a total of 256 test cases. The higher end velocity is limited by the temperature-enthalpy curve fits used to calculate the radiative flux. 19 km/s was used when achievable, otherwise a speed of 18.5 km/s was employed.

Five parameters are investigated once the test runs are made. These are 1) final mass ratio, 2) maximum radiative flux, 3) breakup height, 4) maximum energy deposition and 5) airburst height. Rather than tediously cover every single case, each of these five categories will be discussed and commented upon. Examples of common trends will be shown, and peculiarities will be pointed out. The actual test data are included in Appendix F. The plots of each parameter for each test run are also available in Appendix G.

Final Mass Ratio

The final mass ratio describes how much of the original body is left at the end of the trajectory (when the body either is depleted of 99.9% of its initial kinetic energy, or hits the ground). One would expect that less dense bodies with lower heats of ablation would lose the largest fraction of their mass due to heating, and this is the case. The cometary bodies lost the most mass; as much as 80% of the original mass was vaporized for the 10 meter body at $\gamma = -15^\circ$ and $V_E = 19$ km/s. At the other end of the spectrum, the 500 meter iron body, with a heat of ablation 3 times greater and a density 8 times greater than that of cometary material, loses only about 0.5% of its initial mass under similar entry conditions (the only difference being a V_E of 18.5 k/s). The lower the final mass ratio, the more initial kinetic energy is lost due to ablation. High final mass ratios correspond to kinetic energy losses resulting primarily from deceleration rather than mass loss.

The general trend for all cases is for the mass loss to increase as entry speed is increased, and as entry angle is decreased. The temperature in the shock layer is a

function of the velocity; thus an increase in velocity would be expected to increase the mass loss. The shallower entry angles provide a longer flight time than the steeper ones, thus a longer duration heat pulse. The mass loss curves for the 50 meter carbonaceous body shown in Figure 5.1 display the general trends. The ratio tends to increase as body diameter increases, as initial mass increases faster than surface area available for radiation exposure. Also, as diameter increases the variance with entry angle shows up mainly at the shallower angles, between -15 and -30 degrees.

Maximum Radiative Flux

The maximum radiative flux is the maximum averaged overall energy flux into the body (the total energy input for a time step divided by the total body area irradiated) due to radiation, measured in W/cm^2 . The highest value obtained in this study is approximately 2.5 million W/cm^2 for the larger stone bodies. The value increases with entry speed as would be expected, since the temperature is a function of velocity. It decreases with decreasing density and heat of ablation. The maximum value for a given material tends to occur at the intermediate body diameters, as they penetrate deeper into the atmosphere than the smaller bodies, and spread out laterally (the implications of which will soon be discussed) quicker than the larger bodies. The trend has an unexpected twist, however. The profiles start off with the steeper entry angles yielding the highest fluxes. However, as the body size increases a transition occurs where the peak fluxes for the shallower entry angles actually catch up and surpass fluxes for the steeper entries.

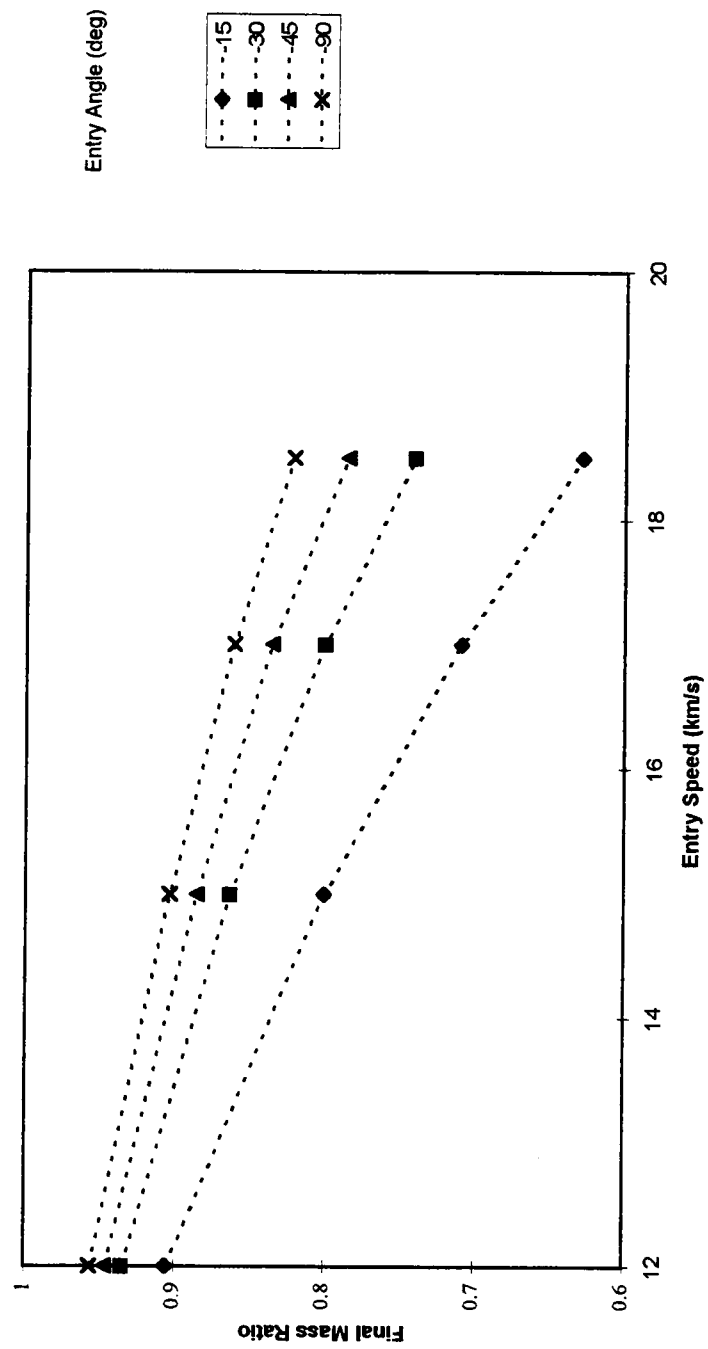


Figure 5.1. Final mass ratio curves for the 50 meter carbonaceous body.

This effect is illustrated in Figure 5.2. Fig 5.2(a) shows the curves for the 10 meter stone body, with fluxes increasing with steeper entry angles. As the body increases in size through 50 and 100 meters (Fig. 5.2(b) and 5.2 (c), respectively) the curves get closer to one another and even overlap, until at 500 meters the -15° entry angle produces the highest flux and the values decrease with increasing entry angle (Fig. 5.2(d)). This effect is delayed for the weaker, less dense bodies: for the carbonaceous and cometary bodies, the transition is not yet complete at a diameter of 500 meters. The iron body, however, shows complete reversal at 100 m diameter. This effect can be explained as follows.

Due to the nature of Eq. (3.39) smaller body radii produce quicker lateral expansions after breakup occurs. The larger the body radius, the slower the expansion. The more the body has flattened into an ellipsoid, the higher the flux will be due to the flattened shock wave in front of it (since the shock wave is assumed to have the same shape as the ellipsoidal body). A shallower entry angle provides more time during which the body can laterally expand thus producing greater fluxes than a body that, having not expanded nearly as flat, undergoes less radiative heating. Figure 5.3 shows the lateral expansions for a 10 meter and a 500 meter stone body, for two different entry angles, in terms of body radius divided by initial body radius vs. altitude. The 10 meter body expands quickly, while the 500 meter body is much more slower. The 10-m body expands more for a steeper entry angle, though it takes longer. The 500-m body expands so slowly that a -15 degree entry angle produces a greater expansion than for a $\gamma = -90$ because of the time difference in the two trajectories.

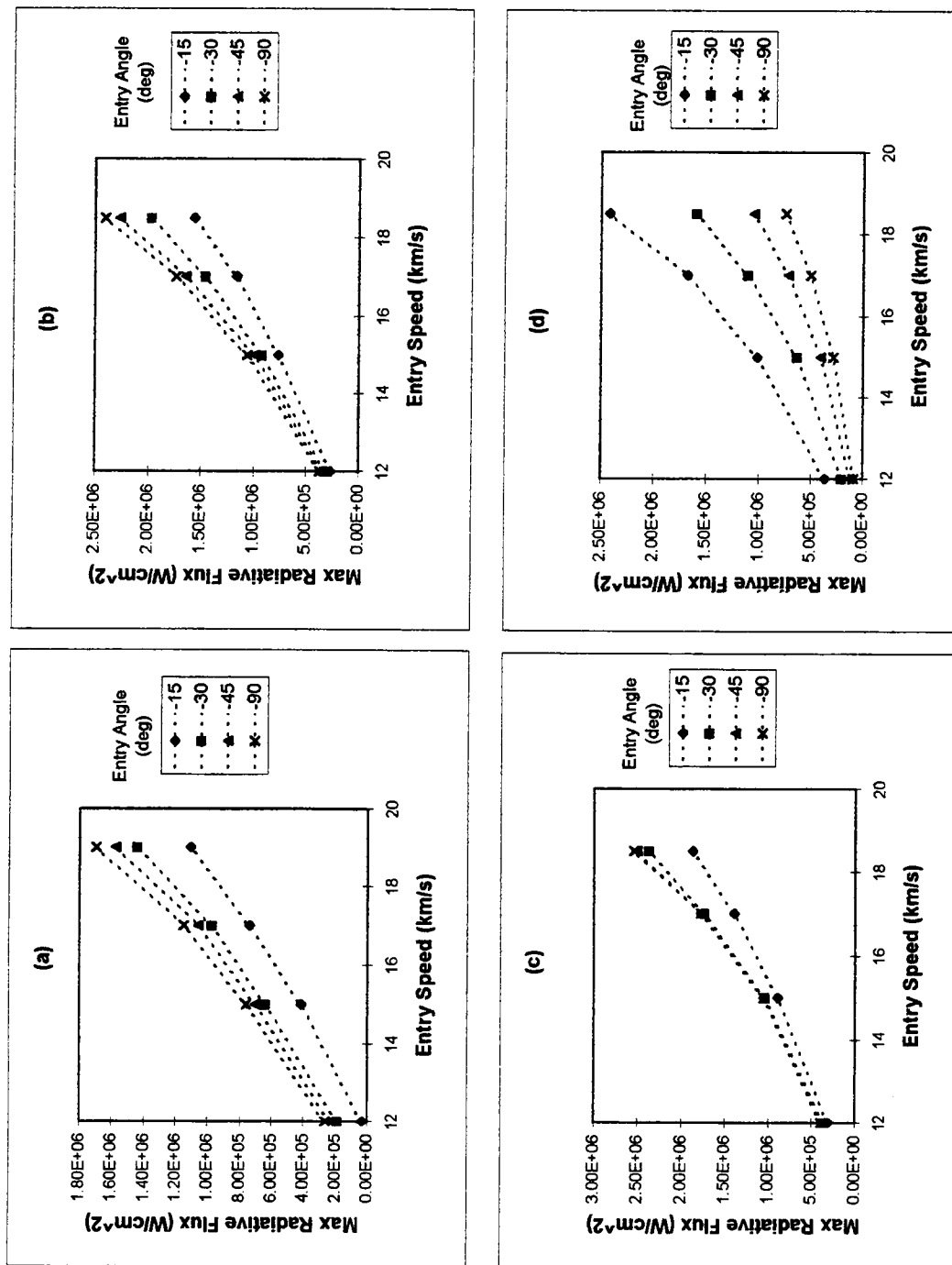


Figure 5.2. Max. radiative flux curves for 10 (a), 50 (b), 100 (c) and 500 (d) meter stone body.

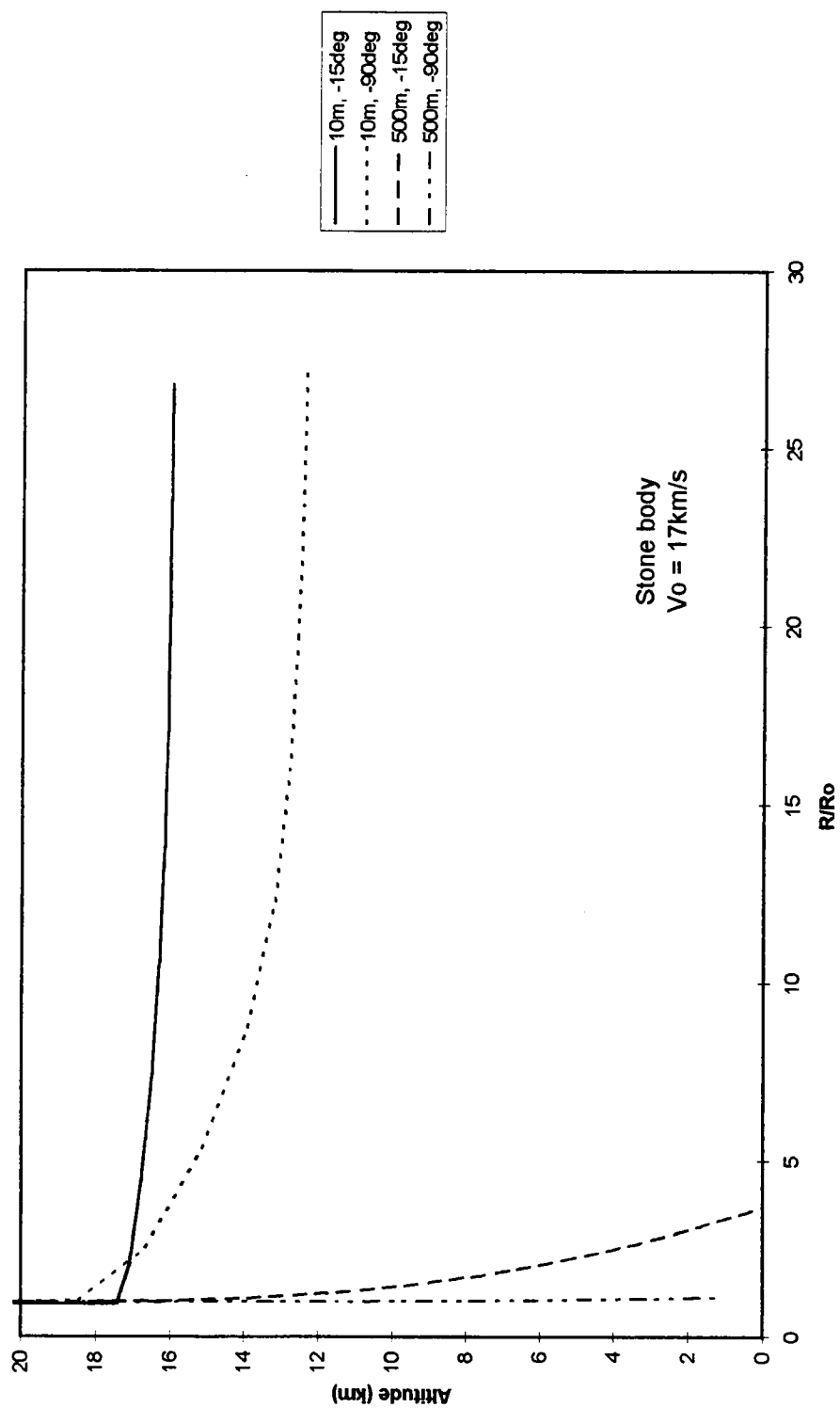


Figure 5.3. Body radius ratio vs. altitude for stone body.

The convective heating is important to mention; it was found that for most cases considered the ratio of convective heating to radiative heating at the stagnation point is negligible, being no greater than 4-5 percent. The only situation where this is not true is for bodies which do not disrupt. In these cases the ratio reaches as high as 60%; however this is near the end of the trajectory where velocity was very low. This may seem important, but when the absolute maximums of convective and radiative are compared (which are not going to occur at the same time) in no case does the convective peak reach greater than 5% of the radiative peak. Thus overall, convection is negligible.

Fig. 5.4 shows the time-variance of the stagnation point radiative and convective heat flux for a 10 meter stone body. It can be seen from Fig. 5.4(a) that the radiative peak is much larger than the convective. Fig. 5.4(b) is the same plots on a logarithmic y-axis, showing the time-delay between the two peaks. The point mentioned where the convective heating is 60% of the radiative occurs at the end of the trajectory, where both are negligible compared to the radiative peak. This displays how predominant the radiative heating is at such high entry velocities, here 12 km/s.

The differences in the radiative fluxes between a body that has disrupted and one that remains intact can be seen in Figure 5.5, for the 10-m iron body. Only one case experiences disruption, the one corresponding to -90° entry angle and 18.5 km/s entry speed. The sudden jump in the radiative flux to the body can easily be seen from the plot. This is due to the increased surface area exposed to the high radiative heating forces,

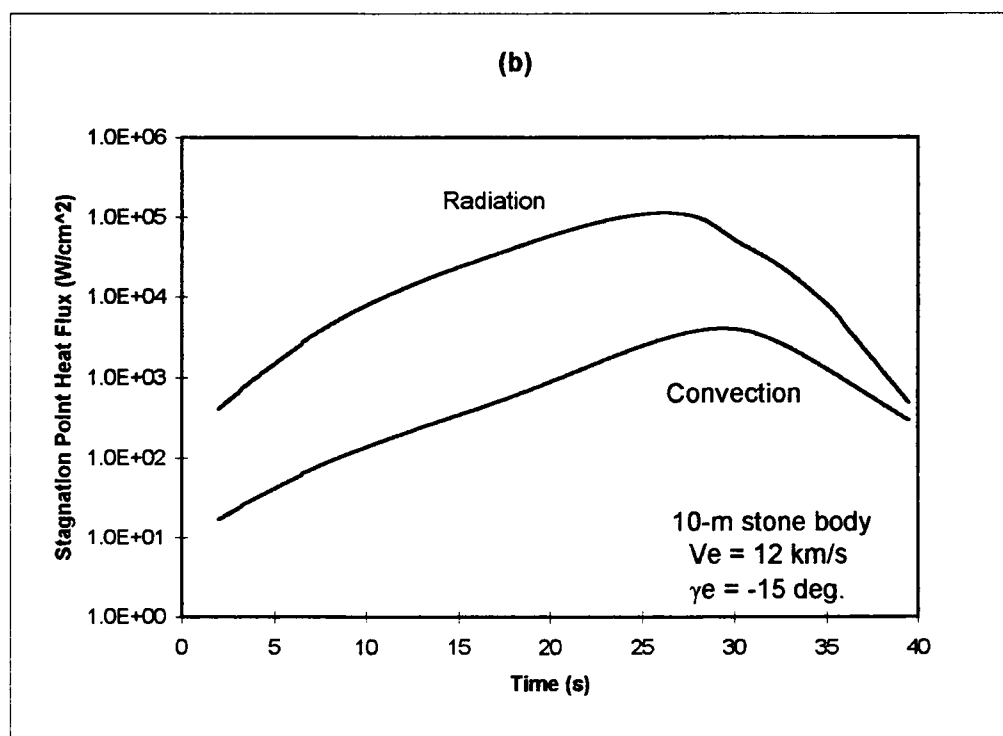
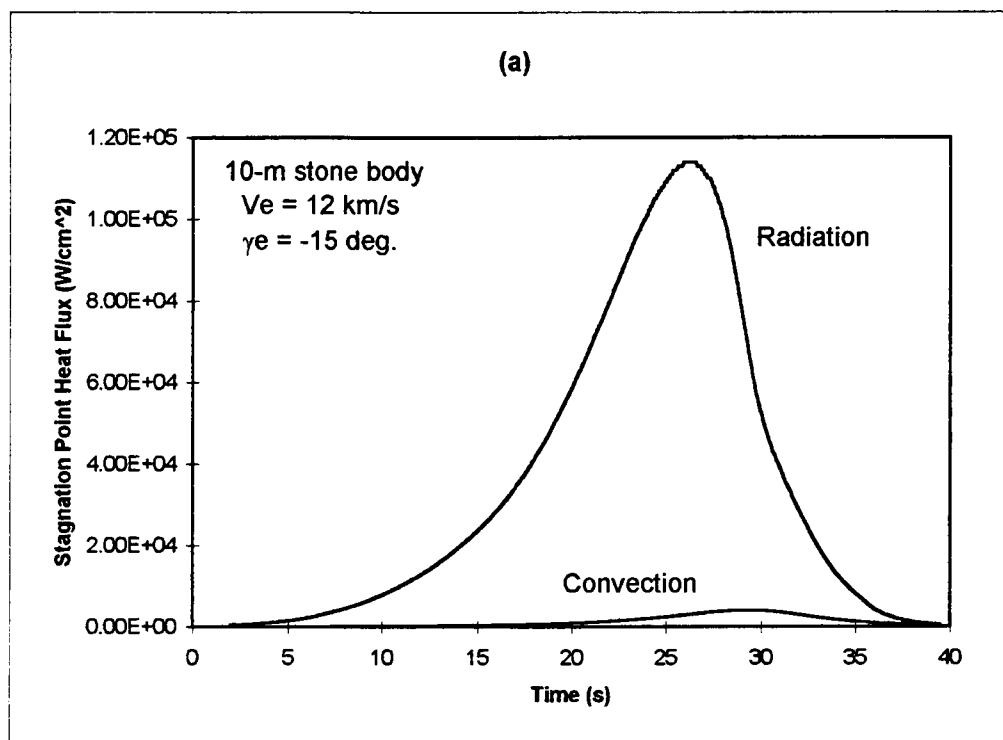


Figure 5.4. Radiative and convective stagnation point heat flux for 10-m stone body.

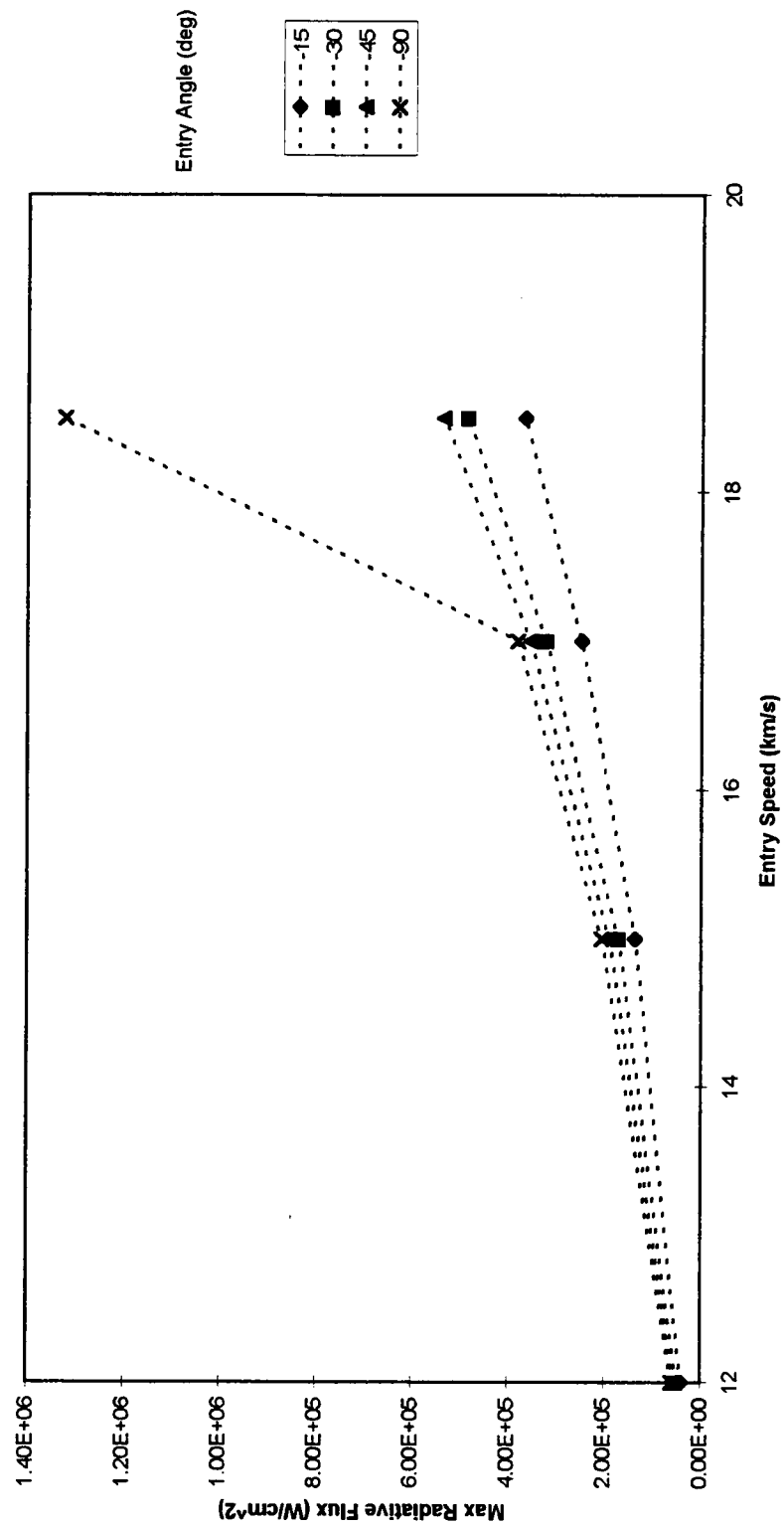


Figure 5.5. Max. radiative flux curves for the 10 meter iron body.

which have been boosted by the flattened shock wave shape. The altitude at which such breakup occurs will be explored next.

Breakup Height

The breakup height is the altitude at which the body mechanically fails and begins to spread apart and rapidly decelerate. The values increase with entry speed, usually by 6-8 km over the interval from 12 to 19 km/s. The differences in breakup height caused by the different entry angles are slight, with a maximum of around 1 km at the lower body sizes. Figure 5.6 shows the breakup heights for the 50-m iron body; at the two lower speeds no breakup at all occurred, while at the two higher speeds breakup occurred 7 out of 8 times (save for the -15° entry angle at 17 km/s). For the larger diameter iron bodies, breakups occur at all entry angles for the two higher entry velocities. Iron meteors consistently break up below 3 km, while the cometary bodies fragment anywhere from 44 to 52 km altitude, regardless of diameter. Since breakup is determined by object strength, the weaker bodies naturally breakup earlier in the trajectory. Besides increasing the maximum radiative flux, the breakup can also cause an extreme increase in energy loss due to drag.

Peak Energy Deposition

The peak energy deposition is the maximum rate of energy release into the atmosphere, measured in MT/km (MT=megaton of TNT equivalent). This peak is associated with the point of maximum deceleration, as this is the point at which the body's kinetic energy loss

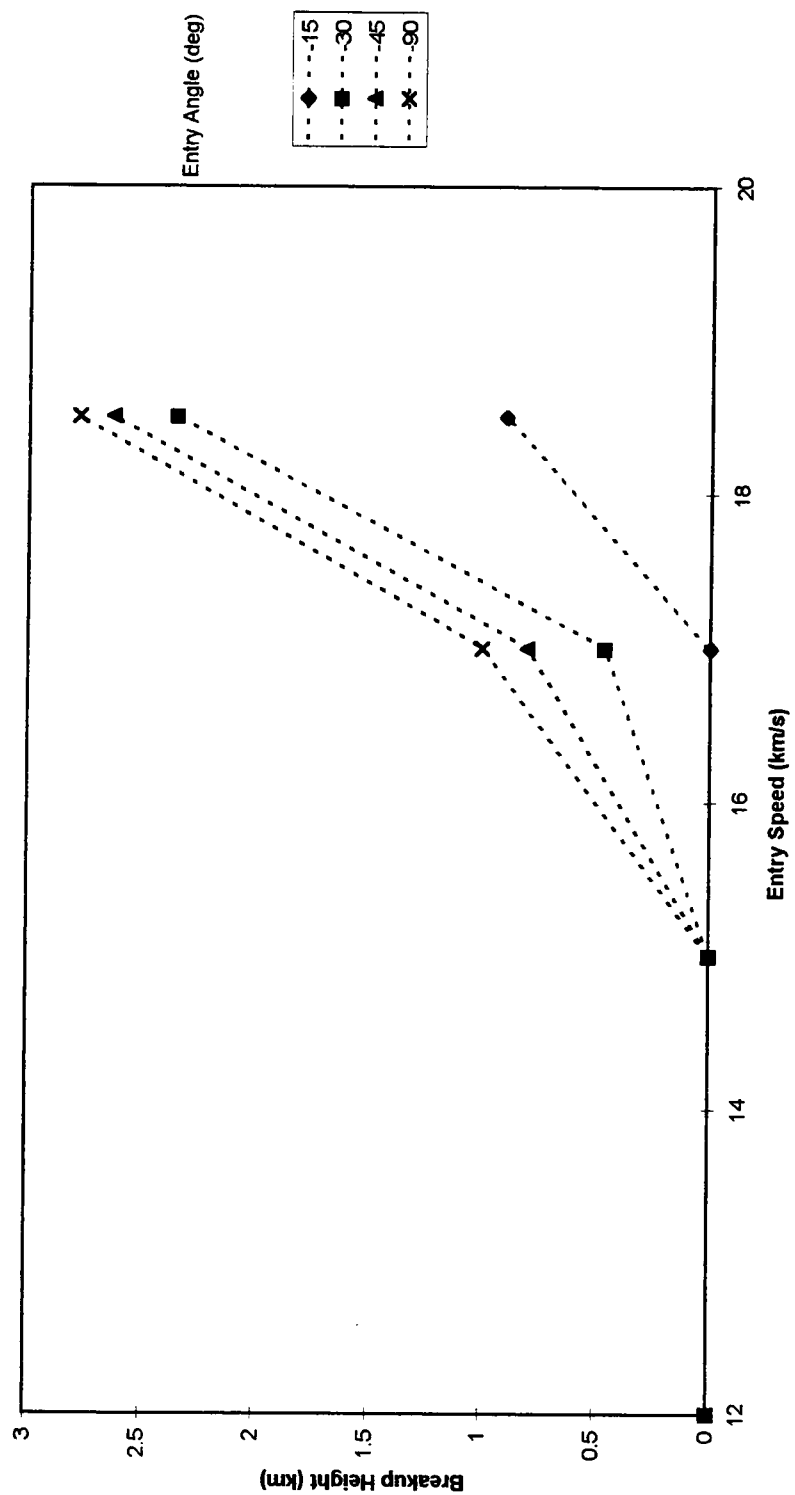


Figure 5.6. Breakup height curves for the 50 meter iron body.

is maximum. This is further complicated by the mass loss of the body due to ablation as this factors into the kinetic energy loss. The breakup process amplifies this decelerative process through a rapid increase in surface area, boosting the aerodynamic drag and resulting atmospheric energy deposition. The largest values of the peak energy deposition are close to 500 MT/km, produced by the 500 meter stone body at -15° entry angle, no doubt caused by the more gradual decrease in the body's vertical altitude. This is not always the case though; for the less dense, weaker materials it is observed that for intermediate sizes (50 and 100 m diameters) the shallowest entry angle does not always produce the highest peak energy deposition rate. The exact reason for this is unclear, but may depend on the interaction between percent mass lost and flight time.

Figure 5.7 shows the peak energy deposition curves for the 50-m iron body. It can be noticed that at an entry speed of 18.5 km/s, the values take a sharp upswing. Looking back at Fig. 5.6, this corresponds to a breakup at about 2.5 km (1 km for $\gamma = -15^\circ$). There is also a breakup at < 1 km for the 17 km/s case, but it is so close to the ground that the body impacts the earth before any appreciable increase in peak energy deposition can appear. In cases such as this when the body impacts the ground before aerodynamic forces can cause a true peak, the peak is the maximum energy release value encountered before impact.

The nature of each peak can be deduced from the airburst height curves, discussed in the next section. Bodies which have disrupted but for which the airburst value is zero, have impacted earth before a peak could be reached. If the body does have an airburst value, this corresponds to the point of peak energy deposition. There are a very few

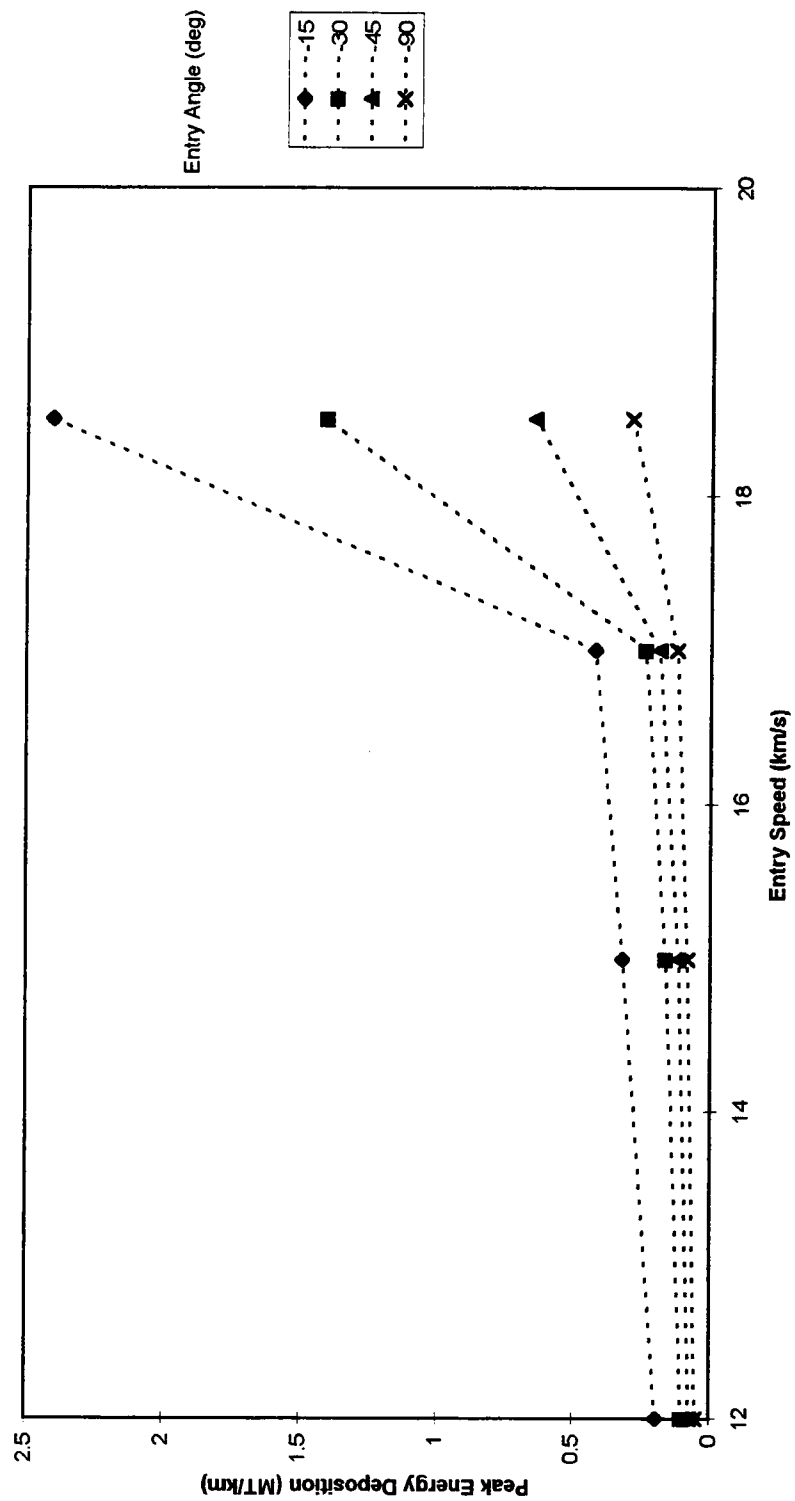


Figure 5.7. Peak energy deposition curves for the 50 meter iron body.

cases where the body does not rupture, but does in fact reach a peak energy deposition rate due to aerodynamic deceleration. The cases where this occurs are the 10 meter iron body at $\gamma = -15^\circ$, all entry velocities and the 10 meter stone body at 12 km/s, -15° . All other cases which do not disrupt do not reach a peak energy deposition rate prior to ground impact.

Airburst Height

The final parameter investigated is airburst height, defined as the altitude at which the peak energy deposition occurs after disruption. Thus only bodies which break up will have an airburst height, provided they do not impact the ground before the peak can be reached as discussed previously. The airburst height is taken to be the 'point' of catastrophic energy release, which causes the devastation associated with large meteors. The energy release actually takes place over a wide altitude band, but there is an altitude of peak energy release, and this point is convenient to take as the 'explosion' point.

The airburst altitude increases with entry velocity, and decreases with entry angle (-15 degrees producing the highest values, and -90 degrees the lowest). Also, as the body diameter increases, the airburst altitudes decrease. The iron body never experienced airburst, the smaller bodies never breaking up and the larger ones breaking up too close to the ground. All other bodies experience airbursts to some degree, save for the 500 meter stone and carbonaceous bodies. The 500 meter cometary body experiences airbursts only

at a $\gamma = -15^\circ$. A typical set of airburst curves is shown in Figure 5.8, for the 50-m stone body.

This study gives an insight into how certain types of impactors would behave under various entry conditions. For all of the cases covered above, none completely ablated away, meaning that at least some catastrophic energy will get through the atmosphere for these types of impactors. The study of the actual damage and catastrophic effects of such impacts is a science in itself and is outside the scope of this work. The altitude at which the body 'explodes' is of prime importance in such investigations, as is the peak value of the body's energy deposition rate.

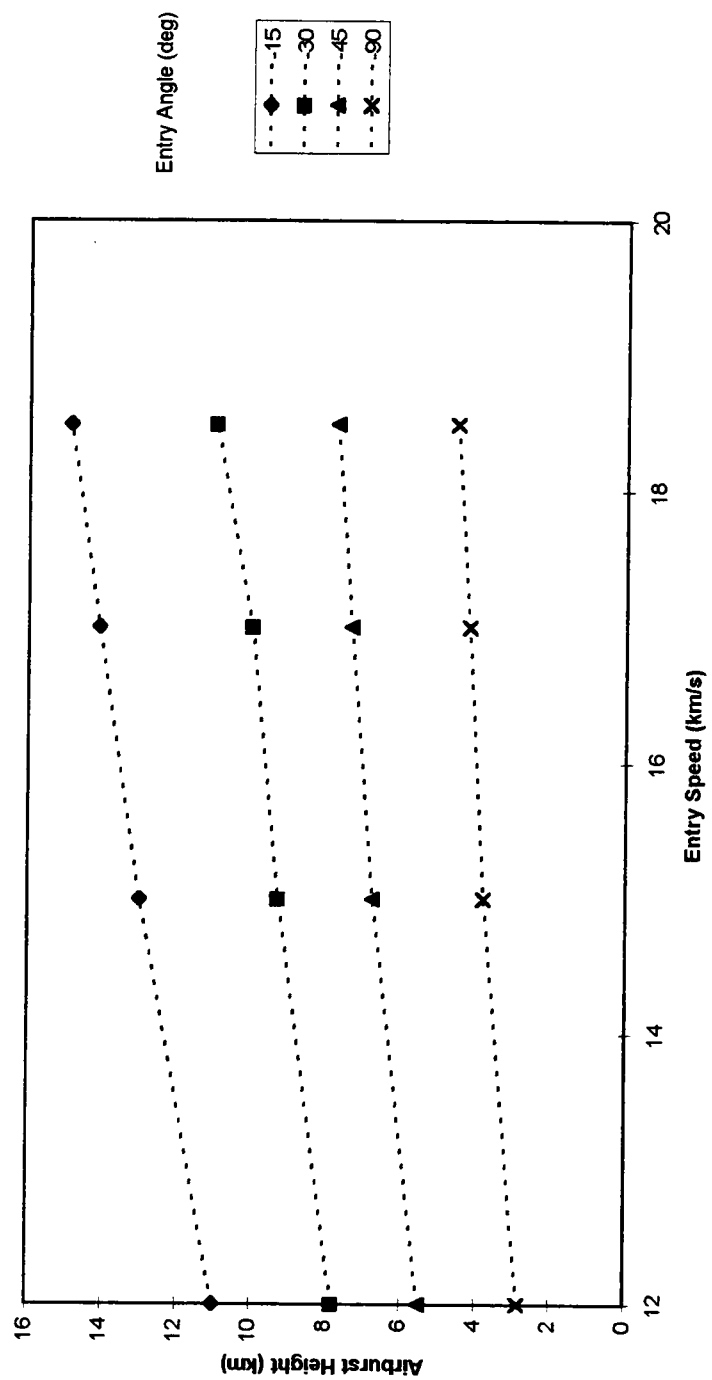


Figure 5.8. Airburst height curves for the 50 meter stone body.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Compared to previous studies, the present model yields a more detailed estimate of the trajectory of a meteor traveling through Earth's atmosphere. The heat transfer model represents a significant improvement over previous attempts to account for ablation with global approximations based on ablation coefficients. While predicting radiative fluxes and ablation rates substantially lower than those determined by other previous works, they are not unreasonable. It is clear that this lower flux and ablation rate has a substantial effect on the trajectories of meteors which collide with Earth and its atmosphere. *The airburst heights found are consistently lower than those previously determined, and the profile of the energy release associated with breakup is much more drawn out and less sharp.*

Although this model has an advantage in the detailed radiation analysis, this is also its limiting point. In the present study the nature of the method does not allow shock layer temperatures exceeding 30000 K, corresponding to an entry speed of approximately 19 km/s. The method of using an ablation parameter in an equation such as (1.1) has the advantage of being unrestricted in terms of velocities considered. However, if the ablation coefficient is inaccurate or dependent on velocity, then that method may not be reliable. It is recommended that even higher temperature limits be devised for the thermodynamic properties of high-temperature, high-pressure air, perhaps through approximate methods such as that used in this study. Indeed, the method developed to extend the curve fits of

Gupta, et al. (1991) could be carried out even further, extending the temperature and thus velocity range of the present method. With this would come some uncertainty and error due to the basic method, but it would still provide a better estimate than methods previously used. The errors associated with this method are quite acceptable in the range investigated and prove the usefulness of such an approach. It can also be applied to other properties besides enthalpy.

The present study, as well as most previous works, could benefit greatly from a more accurate disruption model. The actual physics behind a mechanically failing chunk of rock half a kilometer in diameter are so complex, that any simple model such as the one commonly used cannot accurately model the process. It would also be an improvement to model the true radiation physics of the shock layer including emissivity, absorption, scattering, etc., although this may be out of the scope of a 'simple analysis'. The present model, although yielding reasonable estimates for a hypersonic shock layer, is still crude compared to state-of-the-art computational methods.

It is also recommended that more test runs be carried out for smaller and larger bodies. Certainly at some point the meteor will completely ablate away; this data may be of interest to those wanting to know which particular bodies may be stopped by Earth's atmosphere without surface damage.

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APPENDICES

APPENDIX A
COMPUTER CODE LISTING

richtest.f

```

C   This version uses the NASA CR-2470 Curve Fits
C   of Tannehill and Mugge for density behind shock and modified
C   Gupta Curves for temperature behind shock.
C   Uses spherical body throughout regime.
C
COMMON/STAND/RAIR,M0,P0,RHO0,B,R0,G0
COMMON/PROPS/RHO,PR,TEMP,M
COMMON/CONS2/HDATANEW,THETAMAX
COMMON/BLOCK2/V,T,DT,RT,SREF,HCOMET,COMDEN,DALPHA,BOLTZ,PFLAG
COMMON/BAL/CB,GLOAD
COMMON/HEAT/QDFCS,QDFRS,QDOTR,RADALT,QSUMS,MLOSS,MASS
DIMENSION PARAM(50),Y(3)
DIMENSION HDATANEW(36,6),THETAMAX(8)
REAL COMDEN, DIAM, CDI, CDP, CSIGMA, SREF, MASSI, PI,
1 PDYN, HBP, TBP, MASS, CD, HCOMET, MRAT, ERAT, MACH,QSUMS,
2 MDOT,EDTOT,DT,MLOSS,MDOTCHYB,EKIN,EKINLAS,T,TNEXT,
3 MRATBP, QSRATMAX,QMAXRAT, QRAT, QRSMAX, PDYNMAX
REAL DALPHA, VEXP, D2, D20, D1, D10, RB, RB0
PARAMETER (PI = 3.14159265)
CHARACTER*150 DUMMY
INTEGER EFLAG, GFLAG, PFLAG, COUNT, SKIP, ITERS
C
C
EXTERNAL FCN1
OPEN(UNIT=8,FILE='trajec.out',STATUS='old')
OPEN(UNIT=16,FILE='startmu.dat',STATUS='old')
OPEN(UNIT=29,FILE='tempdist.dat',STATUS='old')
OPEN(UNIT=30,FILE='raddist.dat',STATUS='old')
OPEN(UNIT=10,FILE='gupdist.dat',STATUS='old')
C
READ(16,*)DUMMY,VE,HE,GAMMAE,CDI,CDP,DIAM,COMDEN,CSIGMA,HCOMET,
2 DUMMY,DT,IWR,SKIP
CLOSE (16)
C
C Read in Curve fit constants for temperature finder

OPEN(UNIT=22,FILE='hdatanew.dat',STATUS='old')
DO 346 I=1,36
READ(22,*) (HDATANEW(I,J),J=1,6)
346 CONTINUE

DO 347 I=1,8
READ(22,*) THETAMAX(I)
347 CONTINUE
CLOSE(22)

C   Compute Initial Mass (assuming sphere)

RB=DIAM/2.
MASSI = COMDEN*4./3.*PI*RB**3.
C
MASS = MASSI
CD=CDI

```

```

SREF = PI*RB*RB
CB = MASS/(CD*SREF)
DALPHA=PI/180.
BOLTZ=5.67E-8
C
C Set altitude below which radiation model is good
C
RADALT=80000.
C
C Set standard air properties
C
R0=6378135.
G0=9.81
RAIR=287.
M0=28.964
P0=1.01325E5
RHO0=1.225
B=3.139E-7

ECON=238.846E-15
EBARMAX=0.
EDTOT=0.

ID0=0
GMAX=0.

COUNT=0
GFLAG = 0
PFLAG = 0
tend=1000.
C
C Initialize output files
C
WRITE(8,*) 'Diam ',DIAM,' m'
WRITE(8,*) 'Object Rho ',COMDEN,' kg/m^3'
WRITE(8,*) 'Drag Coeff. ',CDI
WRITE(8,*) 'Initial Mass ',MASSI,' kg'
WRITE(8,*) 'Ball. Coeff. ',CB
WRITE(8,*) 'Object Strength ',CSIGMA,' Pa'
WRITE(8,*) 'Heat of Ablat. ',HCOMET,' J/kg'
WRITE(8,*)
WRITE(8,*) 'ENTRY CONDITIONS'
WRITE(8,*) '_____'
WRITE(8,*) 'ENTRY ANGLE ', GAMMAE
WRITE(8,*) 'ENTRY VELOCITY ', VE,' m/s'
WRITE(8,*)
WRITE(8,*) 'time step ',DT
WRITE(8,*)

IF(IWR.EQ.8) THEN
WRITE(8,*) 't(s) Alt(km) V/VE GAM(d) GL(g) M/Mi KER
1EBAR(MT/km) Etot(MT) QSRAT QDR(W/cms) QSUMS(W) Rb Mdot MdotC'
WRITE(8,*) '_____'
1_____
END IF

```


C Compute ballistic coefficient

$$CB = \text{MASS}/(\text{CD}*\text{SREF})$$

C Compute freestream Mach number...

$$\text{MACH} = V/(1.4*8314./M*\text{TEMP})^{.5}$$

C Update maximum G-loading...

```
IF (ABS(GLOAD).GT.ABS(GMAX)) THEN
  GMAX=GLOAD
END IF
```

C Compute Kinetic Energy Ratio...

$$\begin{aligned} \text{EKIN} &= .5*\text{MASS}*V*V \\ \text{ERAT} &= \text{MASS}*V*V/(\text{MASSI}*V_E*V_E) \end{aligned}$$

C Compute Mass Ratio...

$$\text{MRAT} = \text{MASS}/\text{MASSI}$$

C Compute energy deposition in MT/km...

```
EBAR=ECON*(EKINLAS-EKIN)/(HLAST-H)
IF (EBAR.GT.EBARMAX) THEN
  EBARMAX=EBAR
  HBURST=H
END IF
```

C Write current time step data...

```
IF (T.EQ.0.0.OR.COUNT.EQ.SKIP) THEN
  IF (IWR.EQ.8) THEN
    WRITE(8,90) T,H/1000.,V/VE,GAMMA,GLOAD,MRAT,ERAT,EBAR,EDTOT,
    IQSRAT,QDOTR,QSUMS,RB,MDOT,MDOTCHYB
  END IF
  IF (IWR.EQ.6) THEN
    WRITE(6,90) T,H/1000.,V/VE,GAMMA,GLOAD,MRAT,ERAT,EBAR,EDTOT,
    IQSRAT,QDOTR,QSUMS,RB,MDOT,MDOTCHYB
  END IF
  COUNT=0
END IF
```

C Check for free-fall conditions...

```
IF (ABS(GLOAD).LT.0.1.AND.V/VE.LT.0.3) THEN
  WRITE(6,*) 'Body free-falls to surface'
  GOTO 200
END IF
```

C Check for Kinetic Energy dissipation...

```

IF(EFLAG.EQ.1)GO TO 17
IF(ERAT.LT.0.001) THEN
  WRITE(6,*)'99.9% of kinetic energy dissapated at t=',t
  TKD=t
  EFLAG=1
  GO TO 200
END IF
17 CONTINUE

```

C Check for material failure using dynamic pressure...

```

PDYN=CD/4.*RHO*V**2

IF(PDYN.GT.PDYNMAX) THEN
  PDYNMAX=PDYN
  VPEAK=V
END IF

IF(PFLAG.EQ.1)GO TO 18
IF(PDYN.GT.CSIGMA) THEN
  WRITE(6,*) 'Object ruptured at time',t,' altitude',h
  VEXP=V
  HBP=h
  TBP=t
  EKINBP=EKIN
  MRATBP=MASS/MASSI
  PFLAG = 1
END IF
18 CONTINUE

```

C Calculate radius increase according to Zahnle's 'pancake' model
C if dynamic pressure failure has occurred,,

```

IF(PFLAG.EQ.1) THEN
  RB0=RB
  D2=CD*RHO*V/(COMDEN*RB*2.)*V
  D1=D10+.5*(D2+D20)*DT
  RB=RB0+.5*(D1+D10)*DT
  D20=D2
  D10=D1
  CD=CDP
  SREF=PI*RB*RB
END IF

```

C Check for material failure using ablation...

```

IF (MASS.LT.0.)THEN
  WRITE(6,*) 'Object ablates away @ altitude ',h,' time ',t
  HABL = H
  TABL = t
  GO TO 200
END IF

```

C Check for altitude ...

```

IF (H.LE.0.) GO TO 200

EDTOT=EDTOT+(EKINLAS-EKIN)*ECON/1000.
HLAST=H
EKINLAS=EKIN

C Solve for next time step using IMSL routine IVPRK first order
C differential equation solver...

T=ITERS*DT

TNEXT=(ITERS+1)*DT

CALL IVPRK(IDO,N,FCN1,T,TNEXT,TOL,PARAM,Y)

V=Y(1)
GAMMA=180./(ACOS(-1.))*Y(2)
H=Y(3)

C Calculate new local atmospheric properties...

CALL ATMOS(H)
G=G0/(1.+H/R0)**2.

C Calculate heating to the body...

IF(V.LT.1000.OR.RHO.LT.1.5E-6)THEN
  QDFCS=0.
  QDOTR=0.
  MLOSS=0.
  GO TO 228
END IF

C IF((T-AINT(T)).LT.0.5*DT) THEN
C   WRITE(29,*)
C   WRITE(29,*)T
C   WRITE(29,*)
C   WRITE(10,*)
C   WRITE(10,*)T
C   WRITE(10,*)
C   WRITE(30,*)
C   WRITE(30,*)T
C   WRITE(30,*)
C   END IF

CALL QDOTMS

QSRAT=QDFCS/QDFRS

IF(PFLAG.EQ.1) THEN
  QSRAT=0.
  END IF

MASS=MASS-MLOSS

```

```
MDOT=MLOSS/DT*1.
MDOTCHYB=PI*RB*RB/HCOMET*MIN(.05*RHO*V*V*V,BOLTZ*25000.**4.)
```

C Calculate new body radius...

```
IF(PFLAG.EQ.0) THEN
  RB=(3.*MASS/4./PI/COMDEN)**.33333
END IF
```

```
228  if(qdotr.gt.qrmax)qrmax=qdotr
    if(qdfcs.gt.qcmax)qcmax=qdfcs
    if(qdfsr.gt.qrsmax)qrsmax=qdfsr
    IF (QSRAT.GT.QSRATMAX) QSRATMAX=QSRAT
    QRAT=QCMAK/QRSMAX
    IF(QRAT.GT.QMAXRAT) QMAXRAT=QRAT
```

```
ITERS=ITERS+1
```

```
GO TO 100
```

C Output run summary...

```
200  CONTINUE
```

```
IF(PFLAG.EQ.1) THEN
  ERTOT=EKINBP*ECON/1000.
  WRITE(6,*)'Airburst altitude =',HBURST/1000.,' km'
ELSE
  ERTOT=(.5*MASSI*VE*VE-EKINLAS)*ECON/1000.
  WRITE(6,*)'Max Deposition altitude =',HBURST/1000.,' km'
  MRATBP=0.
END IF
```

```
WRITE(8,*)
WRITE(8,*) 'PRESSURE FAILURE CONDITIONS'
WRITE(8,*) '-----'
WRITE(8,*) 'FAILURE ALTITUDE ',HBP/1000.,' km'
WRITE(8,*) 'FAILURE TIME    ',TBP,' s'
WRITE(8,*) 'VPEAK =          ',VPEAK/1000.,' km/s'
WRITE(8,*) 'VEXP =           ',VEXP/1000.,' km/s'
WRITE(8,*)
WRITE(8,*) 'AIRBURST CONDITIONS'
WRITE(8,*) '-----'
WRITE(8,*) 'AIRBURST ALTITUDE ', HBURST/1000.,' km'
WRITE(8,*) 'AIRBURST EBAR    ', EBARMAX,' MT/km'
WRITE(8,*) 'TOT ENERGY RELEASE ', ERTOT,' MT'
WRITE(8,*) '99.9% Diss. Alt.  ', H/1000.,' km'
WRITE(8,*)
WRITE(8,*) 'HEATING SUMMARY'
WRITE(8,*) '-----'
WRITE(8,*) 'Qcon MAXIMUM    ', QCMAK,' W/cm^2'
WRITE(8,*) 'Qrad MAXIMUM    ', QRMAY,' W/cm^2'
WRITE(8,*) 'Max Stag Ratio  ', QSRATMAX
WRITE(8,*) 'MaxC/MaxR      ', QMAXRAT
```

```

WRITE(8,*)
WRITE(8,*) 'ABLATION SUMMARY'
WRITE(8,*) '-----'
WRITE(8,*) 'Breakup Mass Ratio', MRATBP
WRITE(8,*) 'Final Mass Ratio ', MRAT
WRITE(8,*) 'DISINT. ALT. ', HABL/1000., ' km'
WRITE(8,*) 'DISINT. TIME ', TABL, ' s'

ID0=3
TNEXT=T+DT
CALL IVPRK(ID0,N,FCN1,T,TNEXT,TOL,PARAM,Y)
ID0=1

208 WRITE(8,205)
205 FORMAT(' ')

stop
END
*****
SUBROUTINE FCN1 (N,T,Y,YPRIME)
C
C...ROUTINE TO EVALUATE THE RIGHT HAND SIDE OF THE DIFFERENTIAL EQUATION
C
COMMON/STAND/RAIR,M0,P0,RHO0,B,R0,G0
COMMON/PROPS/RHO,PR,TEMP,M
COMMON/BAL/CB,GLOAD
REAL Y(N),YPRIME(N),A1,T
PARAMETER(PI=3.14159)
C
R=R0+Y(3)
A1=1.+Y(3)/R0
G=G0/(A1*A1)
C
YPRIME(1)=1.*G*SIN(Y(2)) - 0.5*RHO*Y(1)*Y(1)/CB
YPRIME(2)=(Y(1)/R - G/Y(1))*COS(Y(2))
YPRIME(3)=Y(1)*SIN(Y(2))

GLOAD = YPRIME(1)/G
RETURN
END
*****
SUBROUTINE QDOTMS
C
COMMON/PROPS/RHO,PR,TEMP,M
COMMON/BLOCK2/V,T,DT,RB,SREF,HCOMET,COMDEN,DALPHA,BOLTZ,PFLAG
COMMON/HEAT/QDFCS,QDFRS,QDOTR,RADALT,QSUMS,MLOSS,MASS
PARAMETER (PI = 3.14159265)
REAL T,AS,BS,CS,DALPHA,DT,ALPHA,THETA,MASS,MLOSS,AE,BE,RBL,RB
REAL BETA, COF, ASH
INTEGER PFLAG

C Alpha is the local position angle, beta is the local shock angle,
C theta is the local body angle

C Shock shape parameters...
```

C Normal parameters..

AS=0.113188

BS=0.0000127097

CS=1.0707

C Closer parameters..

C AS=0.061

C BS=0.0070944967

C CS=1.0707

C Further parameters..

C AS=0.184

C BS=0.0213547917

C CS=1.0707

C Calculate stagnation point convective heat transfer...

QDFCS=0.000183*(RHO/RB)**0.5*V*V*V/10000.

C Calculate limiting qdot from 15% of flow K.E. ...

QALIM=0.15*0.5*RHO*V*V*V

C Calculate the radiative heating on the body...

MLOSS=0.

QDFRS=0.

QDRSUM=0.

IF(PFLAG.EQ.0) THEN

DO 901 I=1,90

ALPHA=I*DALPHA-0.5*DALPHA

THETA=PI/2.-ALPHA

C Calculate temperature behind each shock section...

BETA=0.

BETA=-0.833333*ALPHA+1.5708

C BETA=-0.88888*ALPHA+1.5708

C BETA=-0.76666*ALPHA+1.5708

PAFT=0.

PAFT=RHO*V*V*SIN(THETA)**2.+PR

HAFT=0.

COF=0.

COF=1.-(1.-SIN(THETA)**2./SIN(BETA)**2.))**2.

HAFT=1000.*TEMP+.5*V*V*SIN(BETA)**2.*COF

CALL TEMPNEW(HAFT,PAFT,TCF)

TAFT=0.

TAFT=TCF

IF((T-AINT(T)).LT.0.5*DT) THEN

C WRITE(29,*)TAFT

END IF

C Calculate local shock radius and slope...

```
RS=RB*(AS*ALPHA**2.+BS*ALPHA+CS)
DAVG=(RB+RS)/2.
X1=2.*AS*ALPHA+BS
X2=X1*SIN(ALPHA)+RS/RB*COS(ALPHA)
X3=X1*COS(ALPHA)-RS/RB*SIN(ALPHA)
DYDXS=X2/X3
X4=(1+DYDXS**2. )**0.5
```

C Calculate local shock area...

```
IF(LEQ.1) THEN
  ASH=PI*DAVG**2.*DALPHA**2.
ELSE
  ASH=2*PI*DAVG**2.*SIN(ALPHA)*COS(BETA)*DALPHA*X4
END IF
```

C Calculate local heat transfer to body from shock ring...

```
QDAR=BOLTZ*TAFT**4.
GOUL=QDAR/(4.*RHO*V*V*V)
QDGR=QDAR/(1.+3.33*GOUL**0.7)
QRAT=QDGR/QDAR
F12=(RB/DAVG)**2.

QDR=F12*ASH*QDGR
```

C Calculate A2 on the body for each step, and body heat flux...

```
ZETA=ACOS(RB/RS)
IF(ALPHA.LT.0.408407) THEN
  A2=2.*PI*RB*RB*(1-COS(ZETA+ALPHA))
END IF
IF(ALPHA.GE.0.408407.AND.ALPHA.LT.1.00444) THEN
  A2=2.*PI*RB*RB*(COS(ALPHA-ZETA)-COS(ALPHA+ZETA))
END IF
IF(ALPHA.GT.1.00444) THEN
  A2=2.*PI*RB*RB*(COS(ALPHA-ZETA)+COS(PI-ALPHA-ZETA))
END IF

QDRB=QDR/A2
```

C Calculate stagnation point total radiative flux into body

C in W/cm^2...

```
IF(ALPHA.LT.0.408407) THEN
  QDFRS=QDFRS+QDRB/10000.
END IF
```

C Correct using Gupta's wall blowing...

```
QDRG=QDRB
CALL GUPTA(QDRG)

IF((T-AINT(T)).LT.0.5*DT) THEN
```

```

C      WRITE(10,*)QDRG/QDRB
      END IF

      IF((T-AINT(T)).LT.0.5*DT) THEN
C      WRITE(30,*)QDRB
      END IF

      QDRSUM=QDRSUM+QDRG*A2

901  CONTINUE

      ABHEAT=10.504*RB*RB

      ELSE

C This is for heat calculations after body has disrupted...

      AE=RB
      BE=(3.*MASS/4./COMDEN/PI/RB)**0.5
      IF(BE.GE.AE)THEN
        BE=.95*AE
      END IF

      IF(BE.LT.0.01*AE) THEN
        HAFT=1000.*TEMP+.5*V*V*SIN(PI/2.)**2.
        PAFT=RHO*V*V*SIN(PI/2.)**2.+PR
        CALL TEMPNEW(HAFT,PAFT,TCF)
        TAFT=TCF
        IF((T-AINT(T)).LT.0.5*DT) THEN
C      WRITE(29,*)TAFT
        END IF
        QDAR=BOLTZ*TAFT**4.
        GOUL=QDAR/(4.*RHO*V*V*V)
        QDGR=QDAR/(1.+3.33*GOUL**0.7)
        QDRG=QDGR
        CALL GUPTA(QDRG)
        WRITE(10,*)QDRG/QDRAVG
        QDRSUM=QDRG*PI*AE*AE
        ABHEAT=PI*AE*AE
        GO TO 903
      END IF

      DO 902 I=1,90

        ALPHA=I*DALPHA-0.5*DALPHA
        RBL=(COS(ALPHA)**2./BE/BE+SIN(ALPHA)**2./AE/AE)**(-0.5)
        RS=1.21*RBL

        XS=RS*COS(ALPHA)

        DYDX=0.
        DYDX=.8265*AE/(1.-XS*XS/1.4641/BE/BE)**(1/2)*(-XS)/BE/BE

```

```

BETA=ABS(ATAN(DYDX))
IF(1.EQ.1) BETA=PI/2.

HAFT=1000.*TEMP+.5*V*V*SIN(BETA)**2.
PAFT=RHO*V*V*SIN(BETA)**2.+PR
CALL TEMPNEW(HAFT,PAFT,TCF)
TAFT=TCF
IF((T-AINT(T)).LT.0.5*DT) THEN
C   WRITE(29,*)TAFT
END IF

DAVG=1.105*RBL

C Calculate local shock area...

IF(1.EQ.1) THEN
  ASH=PI*DAVG**2.*DALPHA**2.
ELSE
  COF=COS(BETA)/COS(BETA+ALPHA-PI/2.)
  ASH=2*PI*DAVG**2.*SIN(ALPHA)*(1+DYDX**2.)**.5*COF*DALPHA
END IF

C Calculate local heat transfer to body from shock ring...

F12STAG=AE*AE/((1.105*BE)**2.+AE**2.-BE**2.)
F12SHOL=AE*BE/((1.105*AE)**2.*(1.105*AE**2.-AE**2.+BE**2.))**.5

F12=(F12SHOL-F12STAG)/PI*2.*ALPHA+F12STAG

QDAR=BOLTZ*TAFT**4.
GOUL=QDAR/(4.*RHO*V*V*V)
QDGR=QDAR/(1.+3.33*GOUL**0.7)

QDR=F12*ASH*QDGR

QDRSUM=QDRSUM+QDR

902 CONTINUE

C Do overall Gupta wall blowing for body...

CE=(AE**2.-BE**2.))**.5
ABHEAT=2.*PI*AE*BE*(BE/AE+AE/CE*ASIN(CE/AE))

QDRG=QDRSUM/ABHEAT
CALL GUPTA(QDRG)
QDRSUM=QDRG*ABHEAT
C   WRITE(10,*)QDRG/QDRSUM*ABHEAT

END IF

903 CONTINUE

C Check for limiting case...

```

```

QFLUXRT=QDRSUM/ABHEAT

IF(QFLUXRT.GT.QALIM) THEN
  QFLUXRT=QALIM
END IF

C Calculate overall radiative flux to body in W/cm^2...

QDOTR=QFLUXRT/10000.

C Calculate mass loss from ablation...

MLOSS=QFLUXRT*ABHEAT*DT/HCOMET

C Sum up total energy input...

QSUMS=QSUMS+QFLUXRT*ABHEAT*DT

RETURN
END

C*****
SUBROUTINE ATMOS(Z)
C
COMMON/STAND/RAIR,M0,P0,RHO0,B,R0,G0
COMMON/PROPS/RHO,PR,TEMP,M
C
DIMENSION XM(22),ZM(22),TM(22),PM(22),P(22),MM(22),D(22),AM(21)
C
REAL Q1,Q2,Q3,Q4,Q5,Q6,Q7,Q8
INTEGER I,J
RHO=0.
C
DATA XM/0.,11.019,20.063,32.162,47.35,52.43,61.59,80.0,90.0,
1 100.,110.,120.,150.,160.,170.,190.,230.,300.,400.,
2 500.,600.,700./
C
DATA TM/288.1,216.65,216.65,228.65,270.65,270.65,252.65,
1 188.65,180.65,210.65,260.65,360.65,960.65,1110.6,
2 1210.65,1350.65,1550.65,1830.65,2160.65,2420.65,
3 2590.65,2700.65/
C
DATA PM/1.,2.284E-1,5.462E-2,8.567E-3,1.095E-3,5.823E-4,1.797E-4,
1 1.024E-5,1.622E-6,2.98E-7,7.22E-8,2.488E-8,5.0E-9,3.64E-9,
2 2.756E-9,1.66E-9,6.869E-10,1.86E-10,3.977E-11,1.08E-11,
3 3.4E-12,1.176E-12/
C
DATA MM/28.964,28.964,28.964,28.964,28.964,28.964,28.964,28.964,
1 28.964,28.88,28.56,28.07,26.92,26.66,26.5,25.85,24.69,
2 22.66,19.94,17.94,16.84,16.17/
C
DO 1111 I=1,22
  ZM(I)=XM(I)*1000.
  P(I)=PM(I)*P0
  D(I)=P(I)/(RAIR*TM(I))
1111 CONTINUE

```



```

ELSE
  BP(2)=AINT(BPS)
  BP(1)=AINT(BPS)-1
  IF (THETAS.GT.THETAMAX(BP(2)+5)) THEN
    BP(2)=BP(1)
    BP(1)=BP(1)-1
  END IF
  IF (BPS.LT.-4) THEN
    BP(1)=-3
    BP(2)=-4
  END IF
END IF

DO 3 I=1,2

  IF (BP(I).EQ.-4) THEN
    IF (THETAS.LE.-2.085) THEN
      CHI(I)=THETAS-0.87547
      GO TO 4
    END IF
    IF (THETAS.GT.-2.085.AND.THETAS.LE.-0.0846) ZN=1
    IF (THETAS.GT.-0.0846.AND.THETAS.LE.1.284) ZN=2
    IF (THETAS.GT.1.284.AND.THETAS.LE.2.227) ZN=3
    IF (THETAS.GT.2.227.AND.THETAS.LE.2.3065) ZN=4
    IF (THETAS.GT.2.3065.AND.THETAS.LE.3.607) ZN=5
    IF (THETAS.GT.3.607.AND.THETAS.LE.4.172) ZN=6
    IF (THETAS.GT.4.172.AND.THETAS.LE.4.652) ZN=7
    IF (THETAS.GT.4.652) THEN
      WRITE(6,*)'Enthalpy out of range'
      GO TO 4
    END IF
  END IF

  IF (BP(I).EQ.-3) THEN
    IF (THETAS.LE.-2.087) THEN
      CHI(I)=THETAS-0.87547
      GO TO 4
    END IF
    IF (THETAS.GT.-2.087.AND.THETAS.LE.-0.2788) ZN=8
    IF (THETAS.GT.-0.2788.AND.THETAS.LE.0.9678) ZN=9
    IF (THETAS.GT.0.9678.AND.THETAS.LE.2.247) ZN=10
    IF (THETAS.GT.2.247.AND.THETAS.LE.3.607) ZN=11
    IF (THETAS.GT.3.607.AND.THETAS.LE.4.005) ZN=12
    IF (THETAS.GT.4.005.AND.THETAS.LE.4.686) ZN=13
    IF (THETAS.GT.4.686) THEN
      WRITE(6,*)'Enthalpy out of range'
      GO TO 4
    END IF
  END IF

  IF (BP(I).EQ.-2) THEN
    IF (THETAS.LE.-2.086) THEN
      CHI(I)=THETAS-0.87547
      GO TO 4
    END IF
    IF (THETAS.GT.-2.086.AND.THETAS.LE.0.1125) ZN=14

```

```

IF (THETAS.GT.0.1125.AND.THETAS.LE.1.498) ZN=15
IF (THETAS.GT.1.498.AND.THETAS.LE.2.748) ZN=16
IF (THETAS.GT.2.748.AND.THETAS.LE.3.779) ZN=17
IF (THETAS.GT.3.779.AND.THETAS.LE.4.689) ZN=18
IF (THETAS.GT.4.689) THEN
  WRITE(6,*)'Enthalpy out of range'
  GO TO 4
END IF
END IF

IF (BP(I).EQ.-1) THEN
  IF (THETAS.LE.-2.093) THEN
    CHI(I)=THETAS-0.87547
    GO TO 4
  END IF
  IF (THETAS.GT.-2.093.AND.THETAS.LE.0.352) ZN=19
  IF (THETAS.GT.0.352.AND.THETAS.LE.1.837) ZN=20
  IF (THETAS.GT.1.837.AND.THETAS.LE.3.644) ZN=21
  IF (THETAS.GT.3.644.AND.THETAS.LE.4.648) ZN=22
  IF (THETAS.GT.4.648) THEN
    WRITE(6,*)'Enthalpy out of range'
    GO TO 4
  END IF
END IF

IF (BP(I).EQ.0) THEN
  IF (THETAS.LE.-2.096) THEN
    CHI(I)=THETAS-0.87547
    GO TO 4
  END IF
  IF (THETAS.GT.-2.096.AND.THETAS.LE.0.485) ZN=23
  IF (THETAS.GT.0.485.AND.THETAS.LE.2.269) ZN=24
  IF (THETAS.GT.2.269.AND.THETAS.LE.3.659) ZN=25
  IF (THETAS.GT.3.659.AND.THETAS.LE.4.365) ZN=26
  IF (THETAS.GT.4.365) THEN
    WRITE(6,*)'Enthalpy out of range'
    GO TO 4
  END IF
END IF

IF (BP(I).EQ.1) THEN
  IF (THETAS.LE.-2.097) THEN
    CHI(I)=THETAS-0.87547
    GO TO 4
  END IF
  IF (THETAS.GT.-2.097.AND.THETAS.LE.0.555) ZN=27
  IF (THETAS.GT.0.555.AND.THETAS.LE.2.265) ZN=28
  IF (THETAS.GT.2.265.AND.THETAS.LE.3.468) ZN=29
  IF (THETAS.GT.3.468.AND.THETAS.LE.4.043) ZN=30
  IF (THETAS.GT.4.043) THEN
    WRITE(6,*)'Enthalpy out of range'
    GO TO 4
  END IF
END IF

IF (BP(I).EQ.2) THEN

```



```

QDRNEW=QDR
IDIFF=0
DIFF=0.

369  CONTINUE

MDOTRATIO=QDRNEW/HCOMET/(RHO*V)

IF(MDOTRATIO.LE.0.1) SCALE=10.**(-1.0791*MDOTRATIO)

IF(MDOTRATIO.GT.0.1.AND.MDOTRATIO.LE.0.75) THEN
  SCALE=0.83327*10.**(-0.288334*MDOTRATIO)
END IF

IF(MDOTRATIO.GT.0.75) SCALE=0.5

QDROLD=QDRNEW
QDRNEW=SCALE*QDR
DIFF=ABS(QDROLD-QDRNEW)/QDROLD
IDIFF=IDIFF+1

IF(DIFF.GT.0.1.AND.IDIFF.LT.50) GO TO 369

QDR=QDRNEW

RETURN
END

```

hdatanew.dat

0.36792, 1.9855, 3.69152, 2.4947, 0.94984, -1.42273,
3.32252, -10.039, 9.44106, -2.45916, 0.27423, -1.44495,
5.85465, -50.41259, 172.44859, -292.69416, 246.49644, -83.26526,
0., 0., 1212.4691, -8280.53891, 18850.34011, -14304.25034,
1.15994, -17.07733, 100.2556, -293.36459, 428.12011, -249.75083,
-7.38864, 114.37491, -651.68812, 1569.97133, -1100.87773, -721.47555,
177.10525, -3878.33092, 33963.9926, -148682.80326, 325363.69346,
-284728.90962,

0.40021, 2.16399, 4.09553, 3.02192, 1.37606, -1.26614,
-3.14298, 3.95424, -0.14963, -0.47247, 0.32279, -1.39588,
2.51128, -19.28722, 58.3013, -86.61811, 63.4113, -19.16074,
0.94446, -13.95871, 82.33669, -242.33227, 356.2089, -209.63757,
0., 96.72156, -1462.4591, 8283.69276, -20830.59287, 19620.58431,
32.77847, -702.40676, 6017.74894, -25765.0275, 55128.57161, -47158.18267,

0.18306, 0.87172, 1.28508, 0.3471, 0.37305, -1.33829,
1.00783, -3.37166, 3.20782, -0.36742, 0.04574, -1.29487,
1.01771, -12.56824, 59.72415, -136.87702, 152.07869, -66.46436,
3.92273, -60.75236, 375.55033, -1158.22831, 1782.35659, -1095.11491,
8.04456, -169.13342, 1421.21484, -5966.23528, 12512.9908, -10488.70302,

0.07548, 0.3274, 0.36126, -0.19019, 0.40128, -1.26111,
-1.12528, 6.72767, -15.239, 15.883, -6.83461, -0.11916,
-0.54424, 7.99288, -46.21328, 131.19935, -182.00997, 97.98977,
-0.61676, 10.87787, -72.66004, 221.23786, -277.00271, 66.11603,

0.04262, 0.1683, 0.12631, -0.24238, 0.52093, -1.19969,
-0.3306, 2.42029, -6.58383, 8.03395, -3.7383, -0.44064,
0.15540, -2.44985, 15.74501, -51.48847, 85.80067, -58.14484,
-36.7164, 740.94297, -5974.17918, 24056.26101, -48373.36264, 38857.89427,

0.02717, 0.09355, 0.02857, -0.21844, 0.63204, -1.15356,
-0.29894, 2.23927, -6.29789, 8.07059, -4.06617, -0.21108,
-1.51875, 22.11342, -127.8385, 366.41568, -519.62395, 291.07944,
2.74721, -64.46691, 578.2605, -2513.04164, 5335.58147, -4450.8672,

-0.00255, 0.00509, 0.01103, -0.09746, 0.72365, -1.13289,
0.5683, -4.98262, 17.33445, -29.91522, 25.98863, -9.49988,
0.69442, -10.96021, 69.17530, -218.33441, 345.266, -218.90481,

0.00078, 0.00034, -0.0148, -0.07009, 0.79671, -1.10889,
60.85771, -764.47928, 3835.91917, -9609.53722, 12018.80013, -6003.93011,
0.23722, -3.88917, 25.58596, -84.39968, 140.10571, -93.4311,

4.652, 4.686, 4.689, 4.648, 4.365, 4.043, 3.861, 3.764,

sample input file

Ve_He_Gamma_Cdi_Cdp_DIAM_DENS_SIGMA_HABLA_,
 18500., 100000., -90., 1.3, 1.3, 500., 7900., 1.E8, 8.E6,
 dt_iwr_skip,
 0.005, 6, 20

sample output file

Diam 500.000 m
 Object Rho 7900.00 kg/m^3
 Drag Coeff. 1.30000
 Initial Mass 5.17054E+11 kg
 Ball. Coeff. 2.02564E+06
 Object Strength 1.00000E+08 Pa
 Heat of Ablat. 8.00000E+06 J/kg

ENTRY CONDITIONS

ENTRY ANGLE -90.0000
 ENTRY VELOCITY 18500.0 m/s

time step 5.00000E-03

t(s)	Alt(km)	V/VE	GAM(d)	GL(g)	M/Mi	KER	EBAR(MT/km)	Etot(MT)	QSRAT	QDR(W/cms)	QSUMS(W)	Rb	Mdot	MdotC
0.000	100.000	1.000	-90.0	0.00	1.000	1.000	0.000	0.000E+00	0.000E+00	0.000E+00	0.000E+00	250.00	0.000E+00	0.000E+00
0.200	96.300	1.000	-90.0	1.00	1.000	1.000	*****	-418E+01	0.000E+00	0.000E+00	0.000E+00	250.00	0.000E+00	0.000E+00
0.400	92.599	1.000	-90.0	1.00	1.000	1.000	*****	-846E+01	0.504E-02	0.905E+02	0.372E+11	249.99	0.742E+05	0.148E+05
0.600	88.898	1.000	-90.0	1.00	1.000	1.001	*****	-127E+02	0.426E-02	0.191E+03	0.215E+12	249.99	0.157E+06	0.313E+05
0.800	85.197	1.000	-90.0	1.00	1.000	1.001	*****	-170E+02	0.367E-02	0.369E+03	0.573E+12	249.99	0.302E+06	0.603E+05
1.000	81.495	1.001	-90.0	1.00	1.000	1.001	*****	-213E+02	0.320E-02	0.704E+03	0.126E+13	249.99	0.577E+06	0.115E+06
1.200	77.793	1.001	-90.0	1.00	1.000	1.001	*****	-256E+02	0.280E-02	0.136E+04	0.260E+13	249.99	0.112E+07	0.222E+06
1.400	74.091	1.001	-90.0	1.00	1.000	1.001	*****	-301E+02	0.250E-02	0.235E+04	0.499E+13	249.99	0.193E+07	0.384E+06
1.600	70.388	1.001	-90.0	1.00	1.000	1.002	*****	-346E+02	0.226E-02	0.393E+04	0.906E+13	249.99	0.322E+07	0.642E+06
1.800	66.685	1.001	-90.0	1.00	1.000	1.002	*****	-390E+02	0.207E-02	0.638E+04	0.158E+14	249.99	0.524E+07	0.104E+07
2.000	62.981	1.001	-90.0	1.00	1.000	1.002	*****	-434E+02	0.193E-02	0.101E+05	0.265E+14	249.99	0.831E+07	0.166E+07
2.200	59.277	1.001	-90.0	1.00	1.000	1.002	*****	-478E+02	0.182E-02	0.159E+05	0.434E+14	249.99	0.131E+08	0.261E+07
2.400	55.573	1.001	-90.0	1.00	1.000	1.002	*****	-521E+02	0.171E-02	0.250E+05	0.700E+14	249.98	0.205E+08	0.408E+07
2.600	51.868	1.001	-90.0	0.99	1.000	1.003	*****	-564E+02	0.163E-02	0.388E+05	0.111E+15	249.98	0.319E+08	0.635E+07
2.800	48.163	1.001	-90.0	0.99	1.000	1.003	*****	-604E+02	0.160E-02	0.550E+05	0.174E+15	249.98	0.452E+08	0.101E+08
3.000	44.457	1.002	-90.0	0.98	1.000	1.003	*****	-643E+02	0.156E-02	0.717E+05	0.257E+15	249.98	0.588E+08	0.165E+08
3.200	40.751	1.002	-90.0	0.97	1.000	1.003	-952	-681E+02	0.155E-02	0.932E+05	0.365E+15	249.98	0.765E+08	0.280E+08
3.400	37.045	1.002	-90.0	0.95	1.000	1.003	-930	-716E+02	0.154E-02	0.122E+06	0.506E+15	249.98	0.999E+08	0.484E+08
3.600	33.338	1.002	-90.0	0.91	1.000	1.004	-816	-748E+02	0.156E-02	0.159E+06	0.690E+15	249.97	0.131E+09	0.857E+08
3.800	29.631	1.002	-90.0	0.83	1.000	1.004	-635	-774E+02	0.161E-02	0.208E+06	0.931E+15	249.97	0.171E+09	0.154E+09
4.000	25.924	1.002	-90.0	0.70	1.000	1.004	-340	-793E+02	0.168E-02	0.267E+06	0.124E+16	249.96	0.219E+09	0.274E+09
4.200	22.216	1.002	-90.0	0.46	1.000	1.004	0.091	-799E+02	0.174E-02	0.341E+06	0.164E+16	249.95	0.280E+09	0.492E+09
4.400	18.508	1.002	-90.0	0.02	0.999	1.004	0.771	-785E+02	0.183E-02	0.433E+06	0.215E+16	249.94	0.355E+09	0.543E+09
4.600	14.801	1.002	-90.0	-0.76	0.999	1.003	1.904	-738E+02	0.194E-02	0.541E+06	0.279E+16	249.93	0.444E+09	0.543E+09
4.800	11.093	1.002	-90.0	-2.15	0.999	1.003	3.786	-636E+02	0.217E-02	0.660E+06	0.358E+16	249.91	0.542E+09	0.543E+09
5.000	7.387	1.002	-90.0	-3.84	0.999	1.002	5.873	-461E+02	0.264E-02	0.705E+06	0.448E+16	249.90	0.578E+09	0.543E+09
5.200	3.682	1.001	-90.0	-6.26	0.999	1.001	8.893	-191E+02	0.319E-02	0.726E+06	0.542E+16	249.88	0.595E+09	0.543E+09
5.400	-0.021	1.000	-90.0	-9.62	0.999	0.999	*****	0.196E+02	0.000E+00	0.455E+06	0.616E+16	251.54	0.446E+09	0.550E+09

PRESSURE FAILURE CONDITIONS

FAILURE ALTITUDE 3.12598 km
 FAILURE TIME 5.23000 s
 VPEAK = 18.5047 km/s
 VEXP = 18.5182 km/s

AIRBURST CONDITIONS

AIRBURST ALTITUDE -2.10338E-02 km
 AIRBURST EBAR 12.6245 MT/km
 TOT ENERGY RELEASE 21146.4 MT
 99.9% Diss. Alt. -2.10338E-02 km

HEATING SUMMARY

Qcon MAXIMUM 8101.64 W/cm²
Qrad MAXIMUM 727688. W/cm²
Max Stag Ratio 5.30962E-03
MaxC/MaxR 5.30962E-03

ABLATION SUMMARY

Breakup Mass Ratio 0.998657
Final Mass Ratio 0.998514
DISINT. ALT. 0. km
DISINT. TIME 0. s

APPENDIX B
ATMOSPHERIC MODEL DESCRIPTION

Regan's atmospheric model is based on the 1962 U.S. Standard Atmosphere's measurements of temperature, pressure and molecular weight for various altitudes. His developed equations yield temperature, pressure, density and molecular weight for any altitude; the particular subroutine he presents is valid to 300 km geometric altitude. The temperature is in terms of molecular temperature, defined by

$$T_M = T(M_0/M) \quad (B.1)$$

thus both the variation of temperature and molecular weight are lumped into one variable. Here M_0 is the surface molecular weight, and M is the local molecular weight. Gravity is assumed to vary with altitude above the Earth's surface as

$$g = g_0(1 - b_g z) \quad (B.2)$$

where z is altitude, g_0 is the surface value of gravity (taken to be 9.806 m/s^2) and $b_g = 2/R_E$ or $3.139\text{E-}7 \text{ (1/m)}$.

To determine properties between designated measured points (chosen at points where the temperature variation showed a discontinuity - the space between any two consecutive points is termed a *layer*; see Table B.1), the model integrates the following equation, which is a combination of hydrostatic and thermal state equations:

$$\int_{P_i}^P \frac{dP}{P} = - \int_{z_i}^z \frac{Mgdz}{R^* T(z)} \quad (B.3)$$

The subscript i denotes the values at the beginning of the i th layer.

Table B.1. Measured values of the 1962 U.S. Standard Atmosphere at break points used by Regan. Thermal lapse rates shown are between present and following break point. Zero lapse rate indicates an isothermal layer. (Source: Regan, Frank J., "Re-Entry Vehicle Dynamics," American Institute of Aeronautics and Astronautics, Inc., New York, 1984, p.6).

Altitude (km)	Molecular Temperature (K)	Pressure Ratio P/P_0	Lapse Rate (K/km)
0.000	288.10	1.000	-6.50
11.019	216.65	2.284 E-1	0.00
20.063	216.65	5.462 E-2	+1.00
32.162	228.65	8.567 E-3	+2.80
47.350	270.65	1.095 E-5	0.00
52.430	270.65	5.823 E-4	-2.00
61.590	252.65	1.797 E-4	-4.00
80.000	180.65	1.024 E-5	0.00
90.000	180.65	1.622 E-6	+3.00
100.000	210.65	2.980 E-7	+5.00
110.000	260.65	7.228 E-8	+10.00
120.000	360.65	2.488 E-8	+20.00
150.000	960.65	5.000 E-9	+15.00
160.000	1110.60	3.640 E-9	+10.00
170.000	1210.65	2.756 E-9	+7.00
190.000	1350.65	1.660 E-9	+5.00
230.000	1550.65	6.869 E-10	+4.00
300.000	1830.65	1.860 E-10	-

Temperature varies with altitude linearly for any one layer, but with different gradients depending on which layer is considered. The thermal lapse rate L_z is defined via the equation

$$T_M = T_{M_i} + L_z(z - z_i) \quad (\text{B.4})$$

Molecular weight is defined similarly as a linear function. Equations (B.2) - (B.4) are combined to yield the following equations for density and pressure. For the isothermal layers (no change in temperature with altitude),

$$\frac{P}{P_i} = \exp \left\langle - \left\{ \left[\frac{g_0(z - z_i)}{RT_{M_i}} \right] \left[1 - \frac{b}{2}(z + z_i) \right] \right\} \right\rangle \quad (\text{B.5})$$

$$\frac{\rho}{\rho_i} = \exp \left\langle - \left\{ \left[\frac{g_0(z - z_i)}{RT_{M_i}} \right] \left[1 - \frac{b}{2}(z + z_i) \right] \right\} \right\rangle \quad (\text{B.6})$$

For the layers where temperature varies with altitude:

$$\frac{P}{P_i} = \left[\frac{L_z}{T_{M_i}}(z - z_i) + 1 \right]^{- \left\{ \frac{g_0}{RL_z} \left[1 + b \left(\frac{T_{M_i}}{L_z} - z_i \right) \right] \right\}} \exp \left[\frac{g_0 b}{RL_z}(z - z_i) \right] \quad (\text{B.7})$$

$$\frac{\rho}{\rho_i} = \left[\frac{L_z}{T_{M_i}}(z - z_i) + 1 \right]^{- \left\{ \frac{g_0}{RL_z} \left[\frac{RL_z}{g_0} + 1 + b \left(\frac{T_{M_i}}{L_z} - z_i \right) \right] \right\}} \exp \left[\frac{g_0 b}{RL_z}(z - z_i) \right] \quad (\text{B.8})$$

Regan implements these principles into a subroutine which can be seen in Appendix A on pages 102-103 as subroutine ATMOS. Further information can be obtained from Regan's book "Re-entry Vehicle Dynamics", cited in the references.

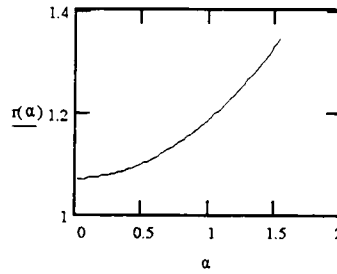
APPENDIX C
SHOCK PROFILE MATHCAD DOCUMENT

$$\alpha := 0.025, 0.05, 1.571$$

$$a := .113188 \quad b := .0000127097 \quad c := 1.0707$$

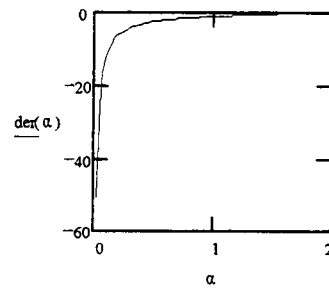
$$r(\alpha) := a \cdot \alpha^2 + b \cdot \alpha + c$$

r/R vs. Alpha



$$\text{der}(\alpha) := \frac{(2 \cdot a \cdot \alpha + b) \cdot \sin(\alpha) + (a \cdot \alpha^2 + b \cdot \alpha + c) \cdot \cos(\alpha)}{(2 \cdot a \cdot \alpha + b) \cdot \cos(\alpha) - (a \cdot \alpha^2 + b \cdot \alpha + c) \cdot \sin(\alpha)}$$

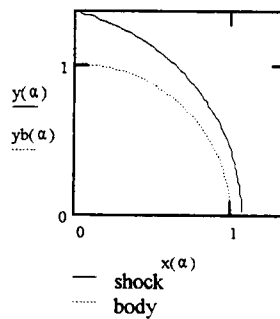
Shock dy/dx vs. Alpha



$$y(\alpha) := (a \cdot \alpha^2 + b \cdot \alpha + c) \cdot \sin(\alpha)$$

$$x(\alpha) := (a \cdot \alpha^2 + b \cdot \alpha + c) \cdot \cos(\alpha)$$

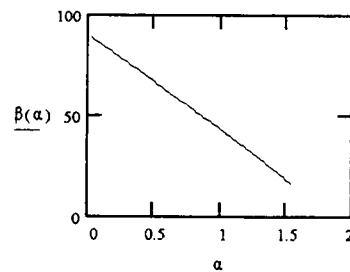
$$yb(\alpha) := (1 - x(\alpha))^2)^{.5}$$



second order close shock shape

$$\beta(\alpha) := \text{atan}(\text{der}(\alpha)) \cdot \frac{180}{3.14159(-1)}$$

Beta vs. Alpha



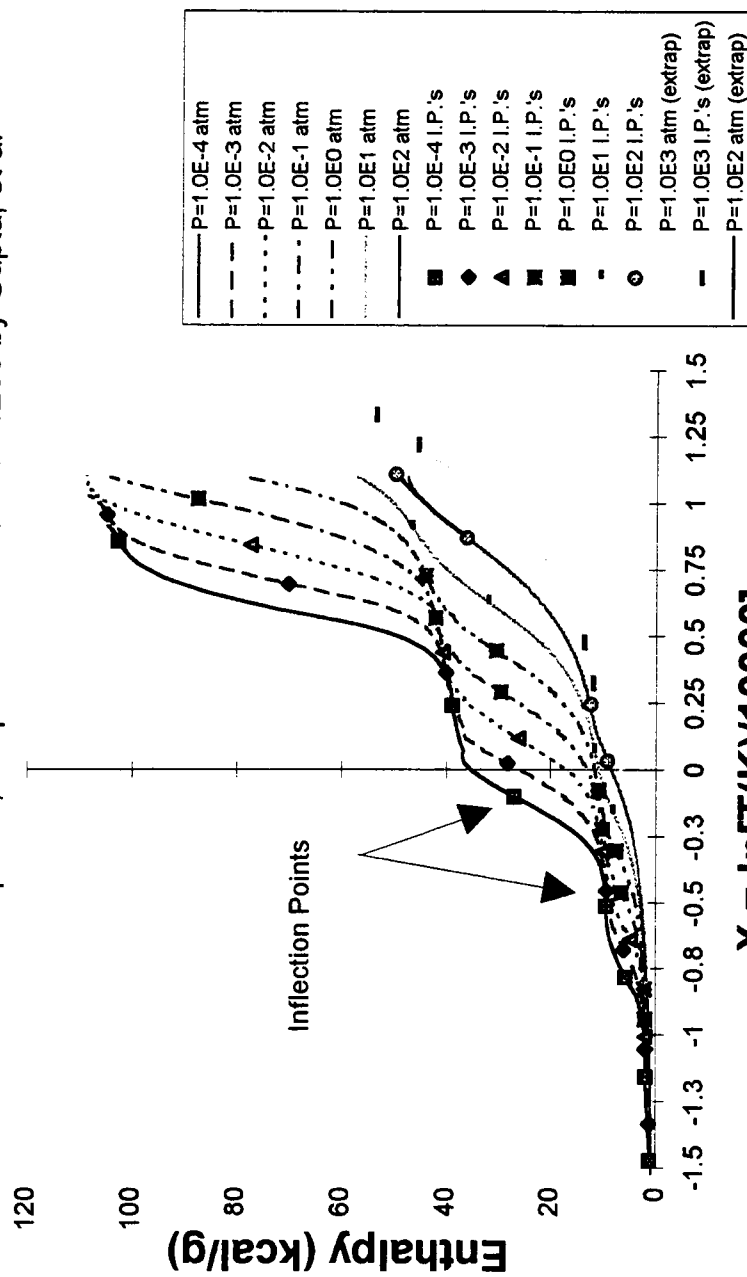
Shock deflection angle Beta as a function of Body position Alpha appears to be linear with the second order shock shape approximation.

APPENDIX D

ENTHALPY-TEMPERATURE CURVE FIT INFLECTION POINTS

Enthalpy vs. X, Equilibrium Air

and inflection points, adapted from NASA RP-1260 by Gupta, et al



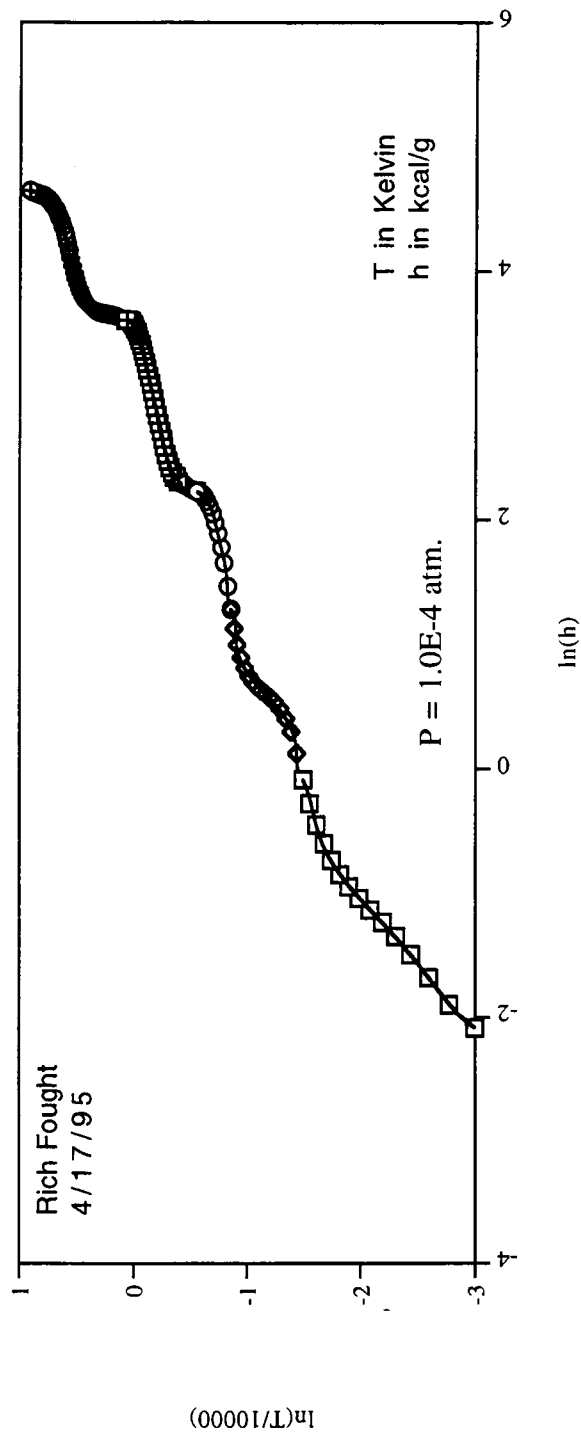
$$X = \ln[T(K)/10000]$$

Rich Fought 3/17/95

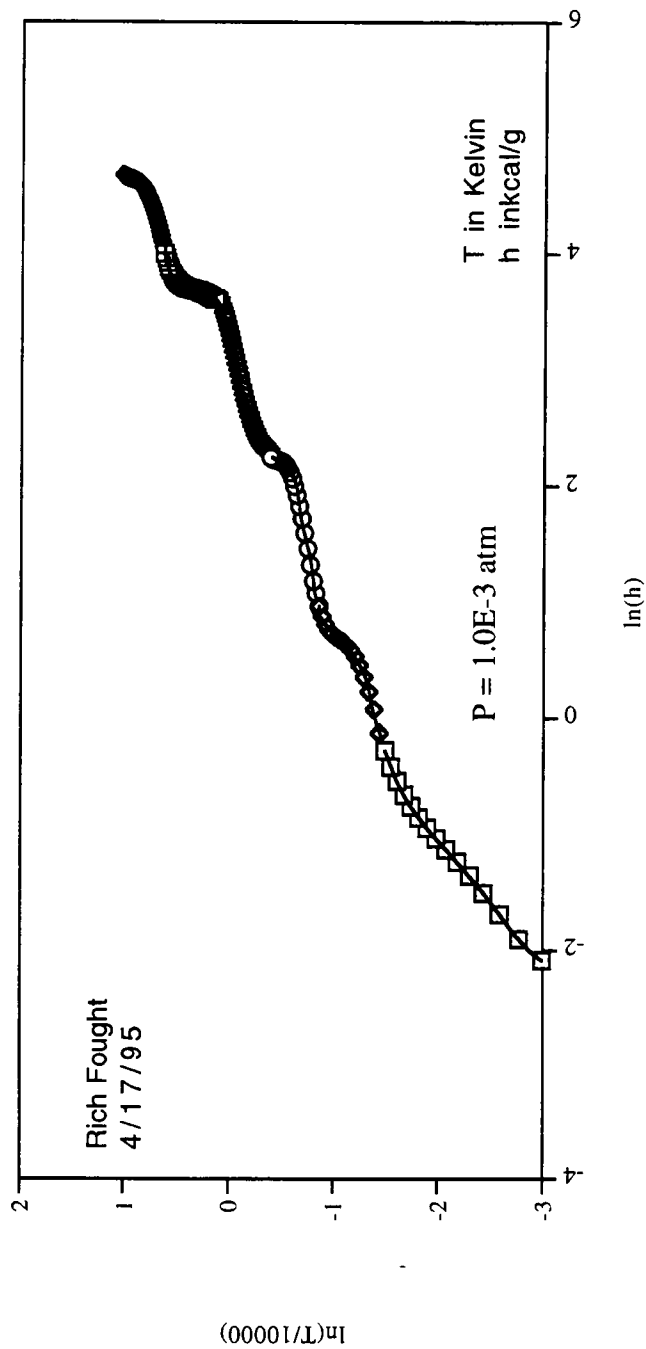
APPENDIX E

TEMPERATURE-ENTHALPY CURVE FITS FOR AIR

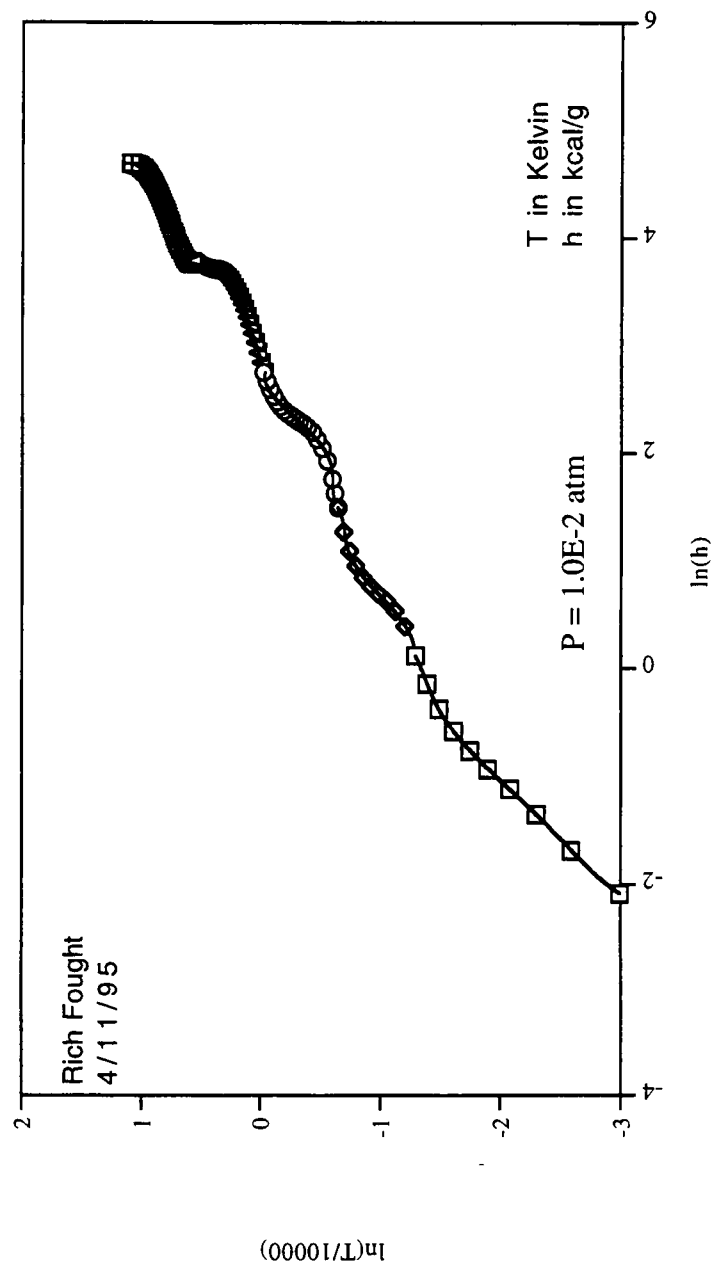
$y = 0.36792x^5 + 1.98550x^4 + 3.69152x^3 + 2.49470x^2 + 0.94984x - 1.42273$	□	-2.085 < ln(h) < -0.0846
$y = 3.32252x^5 - 10.03900x^4 + 9.44106x^3 - 2.45916x^2 + 0.27423x - 1.44495$	◇	-0.0846 < ln(h) < 1.284
$y = 5.85465x^5 - 50.41259x^4 + 172.44859x^3 - 292.69416x^2 + 246.49644x - 83.26526$	○	1.284 < ln(h) < 2.227
$y = 1212.46910x^3 - 8280.53891x^2 + 18850.34011x - 14304.25034$	△	2.227 < ln(h) < 2.3065
$y = 1.15994x^5 - 17.07733x^4 + 100.25560x^3 - 293.36459x^2 + 428.12011x - 249.75083$	⊞	2.3065 < ln(h) < 3.607
$y = -7.38864x^5 + 114.37491x^4 - 651.68812x^3 + 1569.97133x^2 - 1100.87773x - 721.47555$	◆	3.607 < ln(h) < 4.172
$y = 177.10525x^5 - 3878.33092x^4 + 33963.99260x^3 - 148682.80326x^2 + 325363.69346x - 284728.90962$	⊕	4.172 < ln(h) < 4.652



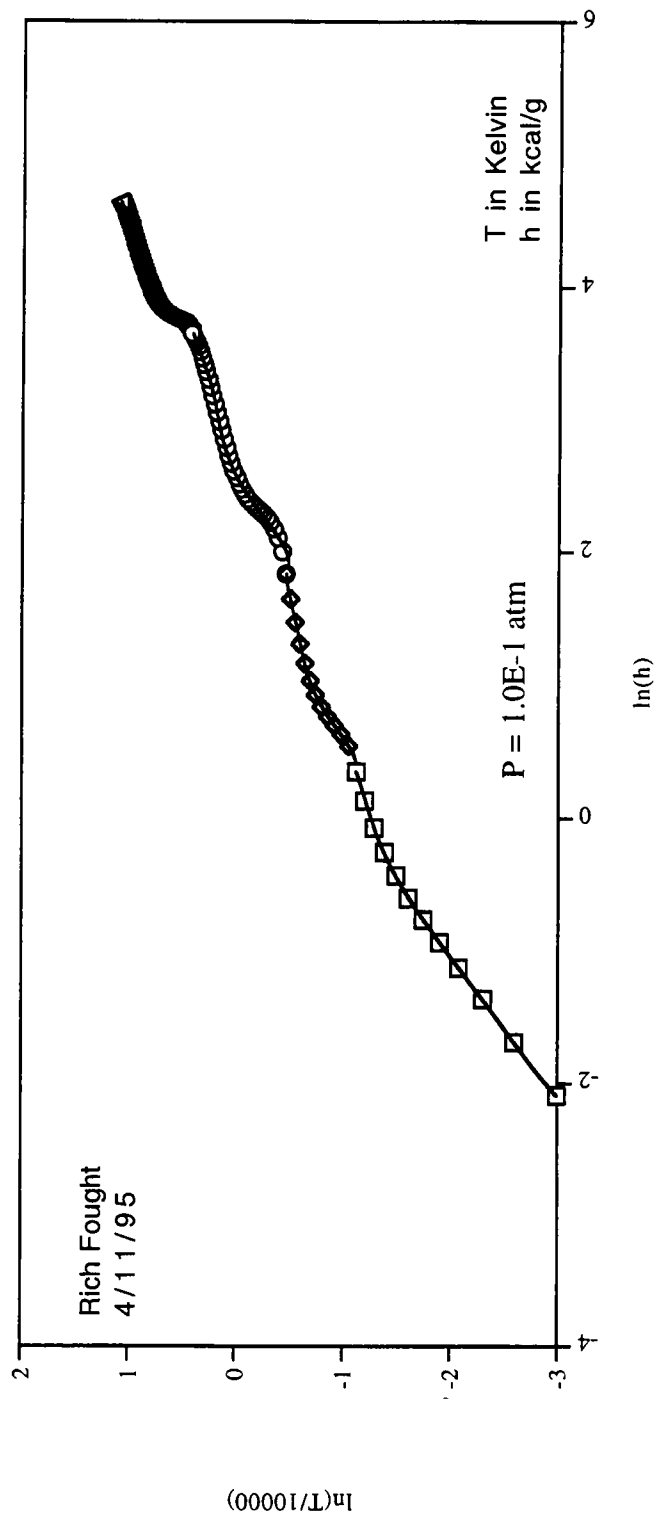
$y = 0.40021x^5 + 2.16399x^4 + 4.09553x^3 + 3.02192x^2 + 1.37606x - 1.26614$	□	-2.087 < ln(h) < -0.2788
$y = -3.14298x^5 + 3.95424x^4 - 0.14963x^3 - 0.47247x^2 + 0.32279x - 1.39588$	◇	-0.2788 < ln(h) < 0.9678
$y = 2.51128x^5 - 19.28722x^4 + 58.30130x^3 - 86.61811x^2 + 63.41130x - 19.16074$	○	0.9678 < ln(h) < 2.247
$y = 0.94446x^5 - 13.95871x^4 + 82.33669x^3 - 242.33227x^2 + 356.20890x - 209.63757$	△	2.247 < ln(h) < 3.607
$y = 96.72156x^4 - 1462.45910x^3 + 8283.69276x^2 - 20830.59287x + 19620.58431$	▣	3.607 < ln(h) < 4.005
$y = 32.77847x^5 - 702.40676x^4 + 6017.74894x^3 - 25765.02750x^2 + 55128.57161x - 47158.18267$	◆	4.005 < ln(h) < 4.686



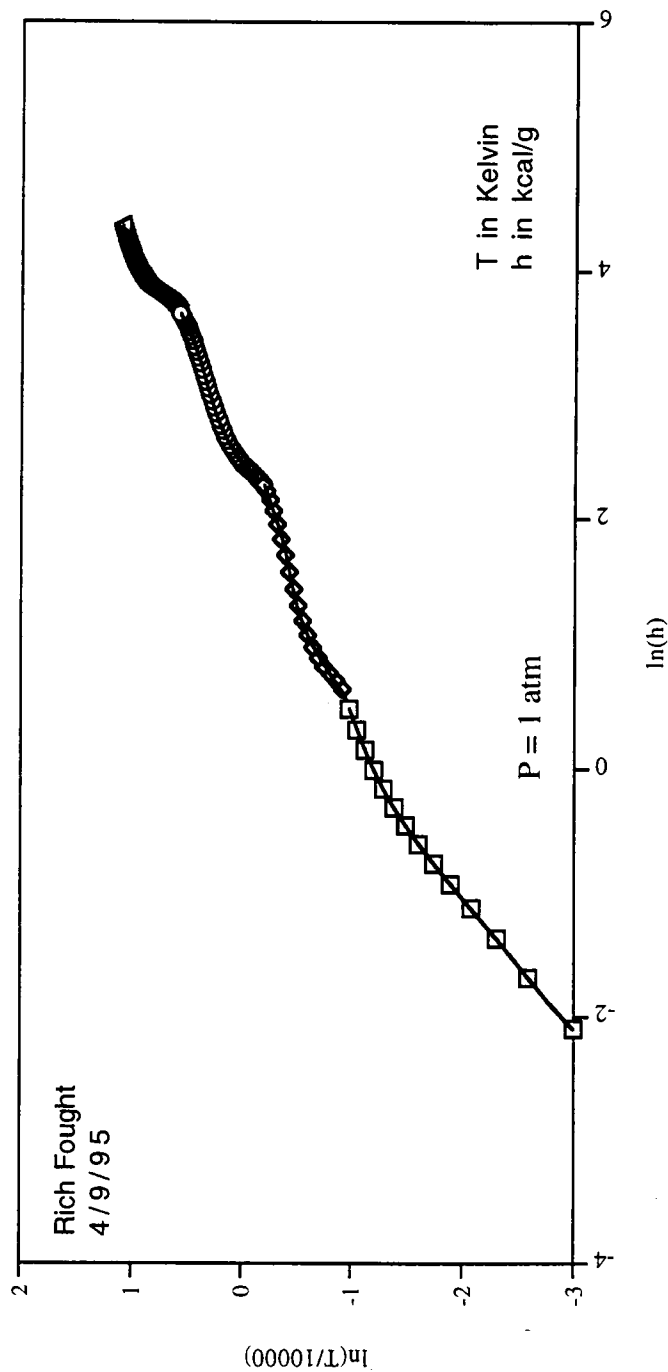
$y = 0.18306x^5 + 0.87172x^4 + 1.28508x^3 + 0.34710x^2 + 0.37305x - 1.33829$	□	$-2.086 < \ln(h) < 0.1125$
$y = 1.00783x^5 - 3.37166x^4 + 3.20782x^3 - 0.36742x^2 + 0.04574x - 1.29487$	◇	$0.1125 < \ln(h) < 1.498$
$y = 1.01771x^5 - 12.56824x^4 + 59.72415x^3 - 136.87702x^2 + 152.07869x - 66.46436$	○	$1.498 < \ln(h) < 2.748$
$y = 3.92273x^5 - 60.75236x^4 + 375.55033x^3 - 1158.22831x^2 + 1782.35659x - 1095.11491$	△	$2.748 < \ln(h) < 3.779$
$y = 8.04456x^5 - 169.13342x^4 + 1421.21484x^3 - 5966.23528x^2 + 12512.99080x - 10488.70302$	■	$3.779 < \ln(h) < 4.689$



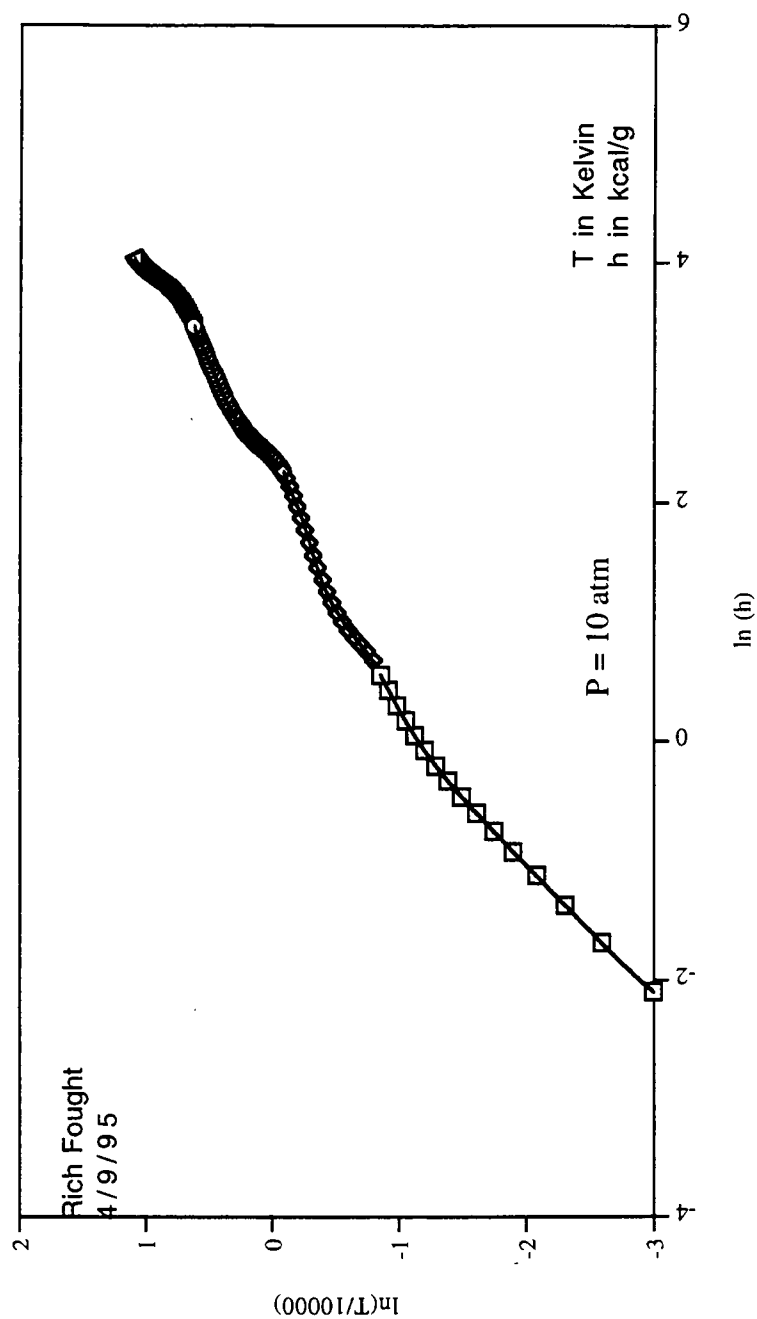
$y = 0.07548x^5 + 0.32740x^4 + 0.36126x^3 - 0.19019x^2 + 0.40128x - 1.26111$	□	-2.093 < ln(h) < 0.352
$y = -1.12528x^5 + 6.72767x^4 - 15.23900x^3 + 15.88300x^2 - 6.83461x - 0.11916$	◇	0.352 < ln(h) < 1.837
$y = -0.54424x^5 + 7.99288x^4 - 46.21328x^3 + 131.19935x^2 - 182.00997x + 97.98977$	○	1.837 < ln(h) < 3.644
$y = -0.61676x^5 + 10.87787x^4 - 72.66004x^3 + 221.23786x^2 - 277.00271x + 66.11603$	△	3.644 < ln(h) < 4.648



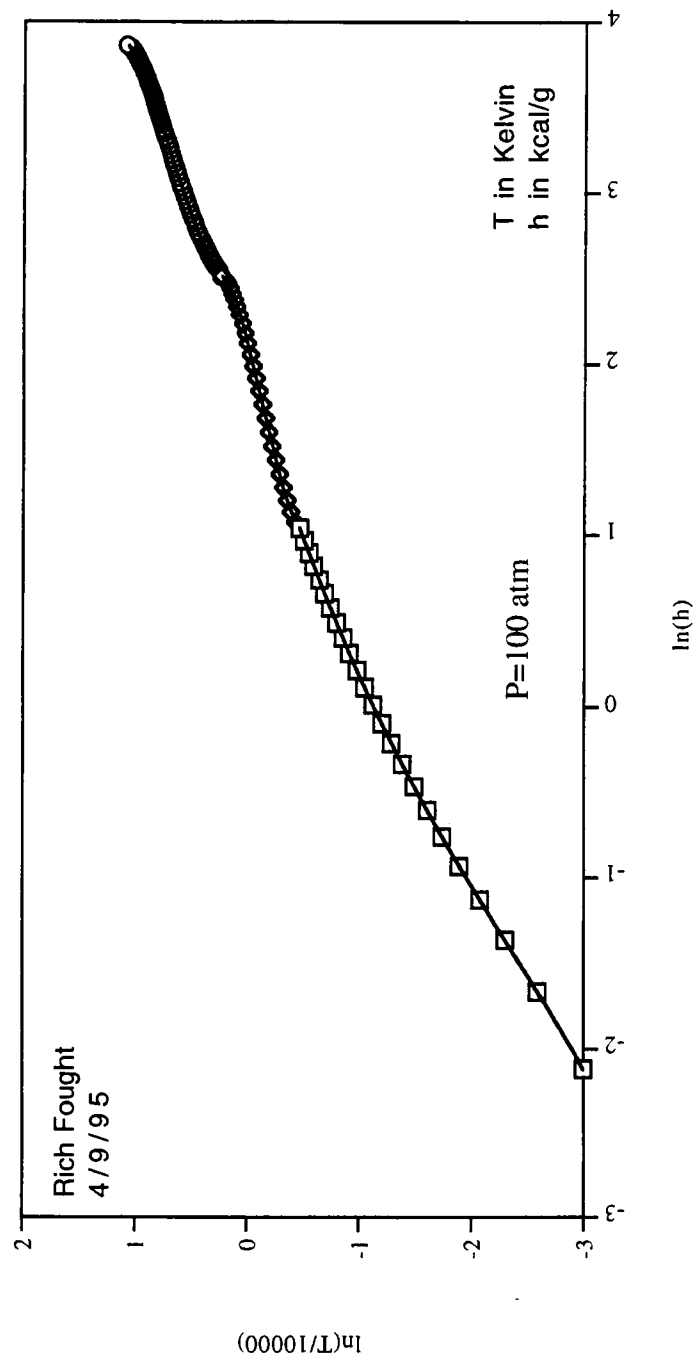
$y = 0.04262x^5 + 0.16830x^4 + 0.12631x^3 - 0.24238x^2 + 0.52093x - 1.19969$	□	-2.096 < ln(h) < 0.485
$y = -0.33060x^5 + 2.42029x^4 - 6.58383x^3 + 8.03395x^2 - 3.73830x - 0.44064$	◇	0.485 < ln(h) < 2.269
$y = 0.15540x^5 - 2.44985x^4 + 15.74501x^3 - 51.48847x^2 + 85.80067x - 58.14484$	○	2.269 < ln(h) < 3.659
$y = -36.71640x^5 + 740.94297x^4 - 5974.17918x^3 + 24056.26101x^2 - 48373.36264x + 38857.89427$	△	3.659 < ln(h) < 4.365



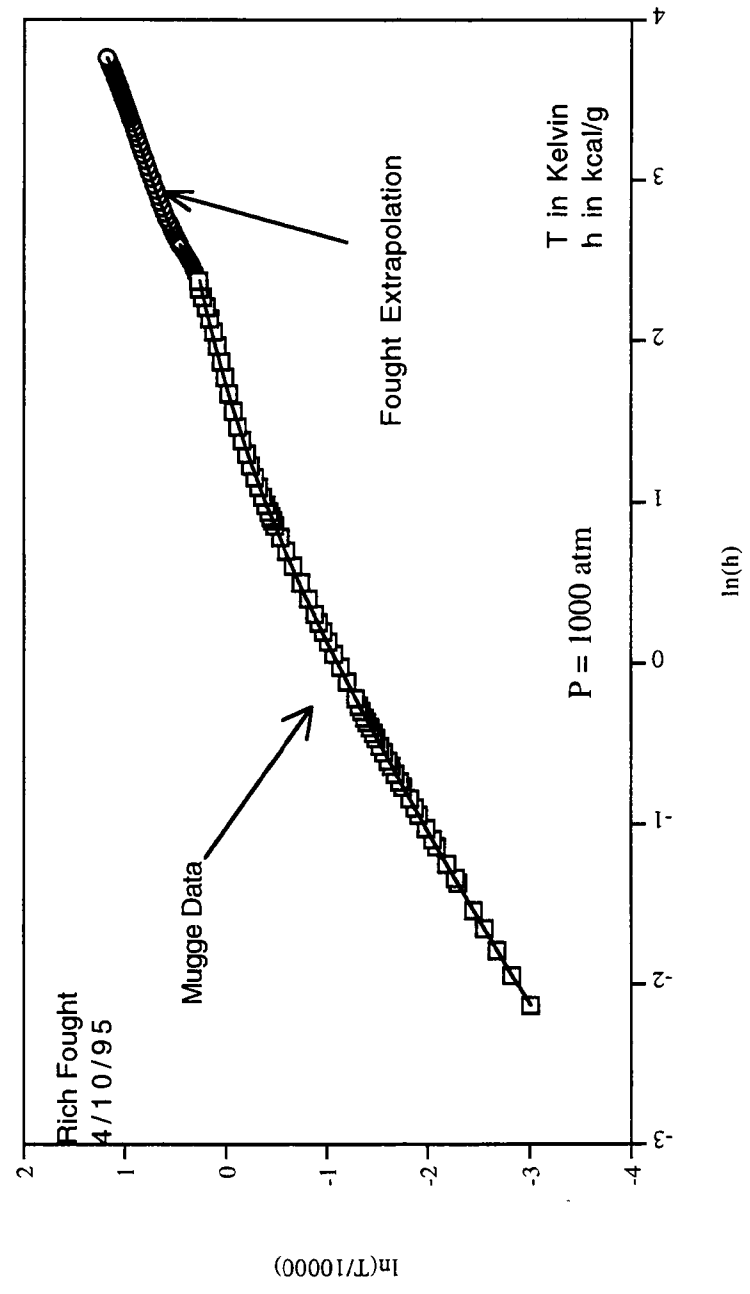
$y = 0.02717x^5 + 0.09355x^4 + 0.02857x^3 - 0.21844x^2 + 0.63204x - 1.15356$	□	-2.097 < ln(h) < 0.555
$y = -0.29894x^5 + 2.23927x^4 - 6.29789x^3 + 8.07059x^2 - 4.06617x - 0.21108$	◆	0.555 < ln(h) < 2.265
$y = -1.51875x^5 + 22.11342x^4 - 127.83850x^3 + 366.41568x^2 - 519.62395x + 291.07944$	○	2.265 < ln(h) < 3.468
$y = 2.74721x^5 - 64.46691x^4 + 578.26050x^3 - 2513.04164x^2 + 5335.58147x - 4450.86720$	Δ	3.468 < ln(h) < 4.043



$y = -0.00255x^5 + 0.00509x^4 + 0.01103x^3 - 0.09746x^2 + 0.72365x - 1.13289$	□	-2.117 < ln(h) < 1.041
$y = 0.56830x^5 - 4.98262x^4 + 17.33445x^3 - 29.91522x^2 + 25.98863x - 9.49988$	◇	1.041 < ln(h) < 2.515
$y = 0.69442x^5 - 10.96021x^4 + 69.17530x^3 - 218.33441x^2 + 345.26600x - 218.90481$	○	2.515 < ln(h) < 3.861



$y = 0.00078x^5 + 0.00034x^4 - 0.01480x^3 - 0.07009x^2 + 0.79671x - 1.10889$	□	$-2.137 < \ln(h) < 2.369$
$y = 60.85771x^5 - 764.47928x^4 + 3835.91917x^3 - 9609.53722x^2 + 12018.80013x - 6003.93011$	◇	$2.369 < \ln(h) < 2.596$
$y = 0.23722x^5 - 3.88917x^4 + 25.58596x^3 - 84.39968x^2 + 140.10571x - 93.43110$	○	$2.596 < \ln(h) < 3.764$



APPENDIX F
DATA FOR PARAMETRIC TEST RUNS

Iron 10

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	0	0	0	12	0.9584	0.9762	0.9822	0.9868
15	0	0	0	0	15	0.90215	0.9421	0.9565	0.9677
17	0	0	0	0	17	0.85086	0.9106	0.9328	0.9502
18.5	0	0	0	0.695	18.5	0.80481	0.88159	0.9107	0.9317
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	3	0	0	0	12	0.0032	0.0026	0.00215	0.00169
15	3.9	0	0	0	15	0.00486	0.00407	0.00338	0.00266
17	4.75	0	0	0	17	0.00611	0.00521	0.00436	0.00347
18.5	5.5	0	0	0	18.5	0.0071	0.00612	0.00518	0.0138
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0.15	0.11735	0.102	0.081	12	0.0425	0.0462	0.04875	0.05235
15	0.131	0.0623	0.051	0.0461	15	0.0438	0.0438	0.0438	0.0438
17	0.125	0.04895	0.04389	0.04385	17	0.04396	0.04396	0.04389	0.04385
18.5	0.123	0.04375	0.03782	0.0375	18.5	0.0376	0.03755	0.03753	0.0375
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	40979	50195	55295	59668					
15	136215	171664	189244	205033					
17	247586	320442	354157	381042					
18.5	366354	485625	536228	1323180					

Iron 50

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	0	0	0	12	0.9884	0.9941	0.9958	0.997
15	0	0	0	0	15	0.9707	0.9856	0.9898	0.9928
17	0	0.46	0.8	1	17	0.9541	0.9778	0.9843	0.9889
18.5	0.9	2.35	2.63	2.78	18.5	0.9358	0.9662	0.9771	0.9845
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	0	0	0	12	0.194	0.101	0.0722	0.0514
15	0	0	0	0	15	0.3189	0.1625	0.1159	0.0828
17	0	0	0	0	17	0.421	0.2382	0.1849	0.122
18.5	0	0	0	0	18.5	2.406	1.407	0.6447	0.2889
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0.03383	0.0273	0.02616	0.02547	12	0.02378	0.0244	0.02436	0.02434
15	0.02026	0.01958	0.0196	0.0196	15	0.0196	0.01958	0.0196	0.0196
17	0.01966	0.01966	0.01963	0.01961	17	0.01966	0.01966	0.01963	0.01961
18.5	0.01682	0.01679	0.01678	0.01679	18.5	0.01682	0.01679	0.01678	0.01679
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	61522	72310	76741	80146					
15	209433	237537	247014	254404					
17	386816	431027	445701	457393					
18.5	1515260	2187310	1774160	1258560					

Iron 100

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	0	0	0	12	0.9938	0.9969	0.9979	0.9985
15	0	0	0	0	15	0.9844	0.9926	0.9948	0.9963
17	0.3	1	1.15	1.235	17	0.9755	0.9886	0.9921	0.9944
18.5	2.24	2.78	2.86	2.9	18.5	0.9619	0.9841	0.9892	0.9925
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	0	0	0	12	0.8708	0.4223	0.2944	0.206
15	0	0	0	0	15	1.45	0.6847	0.4792	0.3345
17	0	0	0	0	17	2.034	1.0326	0.6836	0.4593
18.5	0	0	0	0	18.5	15.269	2.52	1.222	0.687
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0.0195	0.018	0.01766	0.01746	12	0.0172	0.01719	0.01717	0.01717
15	0.01386	0.01384	0.01386	0.01386	15	0.01386	0.01384	0.01386	0.01386
17	0.0139	0.0139	0.01388	0.01387	17	0.0139	0.0139	0.01388	0.01387
18.5	0.0199	0.01188	0.01187	0.01187	18.5	0.0199	0.01188	0.01187	0.01187
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	71437	79963	82961	85278					
15	234754	253767	260112	265158					
17	426039	456392	466433	474429					
18.5	2248110	1288520	880662	703736					

Iron 500

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	0	0	0	12	0.9987	0.9994	0.9996	0.9997
15	0	0	0	0	15	0.9967	0.9985	0.9989	0.9993
17	1.3	1.39	1.42	1.425	17	0.9949	0.9977	0.9984	0.9989
18.5	3	3.1	3.1	3.12	18.5	0.9931	0.9969	0.9978	0.9985
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	0	0	0	12	23.02	10.1	6.652	4.307
15	0	0	0	0	15	39.29	16.97	11.354	7.592
17	0	0	0	0	17	55.266	22.703	15.08	10.15
18.5	0	0	0	0	18.5	82.176	28.82	18.99	12.625
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0.00777	0.00768	0.00766	0.00764	12	0.00767	0.00767	0.00766	0.00764
15	0.0062	0.00619	0.0062	0.0062	15	0.0062	0.00619	0.0062	0.0062
17	0.00622	0.00622	0.00621	0.0062	17	0.00622	0.00622	0.00621	0.0062
18.5	0.00532	0.00531	0.00531	0.00531	18.5	0.00532	0.00531	0.00531	0.00531
Max Rad. Flux (W/cm^2)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	86075	88840	89699	90224					
15	266111	273684	275827	277216					
17	475841	487996	491031	493251					
18.5	705453	721249	725023	727688					

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	13.4	13.8	14.1	12	0.9283	0.953	0.9605	0.9663
15	15.3	16.7	16.9	17.1	15	0.8389	0.8888	0.9051	0.9178
17	17.4	18.5	18.6	18.8	17	0.7677	0.8383	0.8606	0.8779
19	19.2	20	20	20.1	19	0.6929	0.7802	0.8082	0.8304
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	11.93	11.62	11	12	0.0016	0.02035	0.01567	0.0123
15	14.5	14.75	14.1	13.14	15	0.04212	0.02426	0.01897	0.0152
17	16.5	16.2	15.4	14.27	17	0.04612	0.0269	0.02125	0.0173
19	18.1	17.5	16.44	15.16	19	0.0493	0.0293	0.0236	0.01945
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0.612	0.0445	0.04256	0.0425	12	0.0425	0.0425	0.04256	0.0425
15	0.04382	0.04378	0.04384	0.04384	15	0.04382	0.04378	0.04384	0.04384
17	0.04396	0.04396	0.0439	0.04385	17	0.04396	0.04396	0.0439	0.04385
19	0.0333	0.0333	0.0333	0.0333	19	0.0333	0.0333	0.0333	0.0333
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	33224	186445	232037	264387					
15	414559	638764	703114	761113					
17	740165	975879	1061850	1152090					
19	1109170	1443910	1574890	1696960					

Stone 50

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	14.2	14.4	14.5	14.5	12	0.9671	0.9758	0.9792	0.9824
15	17.1	17.3	17.35	17.3	15	0.9178	0.9394	0.948	0.9559
17	18.8	18.9	18.9	18.9	17	0.8759	0.9072	0.9193	0.9318
18.5	19.9	20	20	20	18.5	0.8387	0.8786	0.8937	0.9103
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	11	7.8	5.5	2.85	12	1.0299	0.6704	0.5724	0.5019
15	13	9.3	6.76	3.8	15	1.3265	0.9259	0.8133	0.732
17	14.1	10	7.36	4.2	17	1.5273	1.1204	0.997	0.908
18.5	14.9	11	7.75	4.55	18.5	1.6807	1.28167	1.145	1.0498
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0.01903	0.01901	0.01903	0.019	12	0.01903	0.01901	0.01903	0.019
15	0.0196	0.0196	0.0196	0.0196	15	0.0196	0.0196	0.0196	0.0196
17	0.01966	0.01966	0.01963	0.01961	17	0.01966	0.01966	0.01963	0.01961
18.5	0.01682	0.01697	0.01678	0.01679	18.5	0.01682	0.01697	0.01678	0.01679
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	269532	319747	343710	366466					
15	762896	919961	985649	1058410					
17	1159110	1457260	1641430	1736600					
18.5	1563930	1967800	2267070	2407650					

Stone 100

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	14.4	14.5	14.55	14.5	12	0.9744	0.982	0.9865	0.9915
15	17.3	17.3	17.4	17.4	15	0.9352	0.9546	0.9655	0.9758
17	18.9	19	19	19	17	0.9002	0.9294	0.9461	0.96647
18.5	20	20	20	20	18.5	0.8693	0.9072	0.9284	0.9545
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	8.15	3.08	0	0	12	4.667	3.5229	3.188	1.9534
15	9.87	4.13	0.66	0	15	6.553	5.19073	4.789	3.34963
17	11	4.58	0.98	0	17	8.123	6.474	6.046	4.465
18.5	11.1	4.9	1.18	0	18.5	9.337	7.5263	7.062	5.404
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12					12				
15					15				
17					17				
18.5					18.5				
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	311309	360079	383452	390505					
15	888910	1040210	1056130	1052420					
17	1393870	1736330	1774990	1773830					
18.5	1872400	2372330	2509440	2540330					

Stone 500

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	14.6	14.6	14.6	14.6	12	0.9936	0.9983	0.999	0.9993
15	17.4	17.4	17.4	17.4	15	0.9826	0.9958	0.9976	0.9985
17	19	19	19	19	17	0.9721	0.9935	0.9963	0.9977
18.5	20	20	20	20	18.5	0.9615	0.9914	0.9952	0.9969
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	0	0	0	12	152.79	25.503	12.08	6.524
15	0	0	0	0	15	287.235	45.924	20.953	11.216
17	0	0	0	0	17	398.41	63.46	28.56	15.141
18.5	0	0	0	0	18.5	494.012	78.9	35.186	18.607
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12					12				
15					15				
17					17				
18.5					18.5				
Max Rad. Flux (W/cm^2)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	362114	199194	125646	89653					
15	1013370	631703	400812	283706					
17	1681950	1105780	716501	503981					
18.5	2423400	1598500	1048730	745765					

Carbon 10

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	28.8	29	29	29	12	0.8351	0.8763	0.8927	0.9076
15	31.8	31.9	32	32	15	0.6711	0.7448	0.7772	0.8069
17	33.3	33.5	33.5	33.5	17	0.5484	0.6382	0.6801	0.7199
19	34.8	34.9	34.9	34.9	19	0.4453	0.5211	0.5649	0.6138
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	26.6	24.5	22.9	20.9	12	0.0059	0.00386	0.00333	0.00302
15	29.3	26.7	24.75	22.34	15	0.00755	0.00499	0.00437	0.00406
17	30.75	27.9	25.75	23.26	17	0.00906	0.00599	0.00524	0.00484
19	31.9	29.2	26.9	24.2	19	0.0104	0.00717	0.00618	0.00567
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12					12				
15					15				
17					17				
19					19				
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	121141	141369	156361	164470					
15	302200	342394	367943	399179					
17	469425	540386	588923	648969					
19	543639	779579	919959	1023290					

Carbon 50

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	29.1	29.1	29.1	29.1	12	0.9058	0.9347	0.9463	0.9564
15	32	32	32	32	15	0.8003	0.8629	0.8853	0.9036
17	33.5	33.5	33.5	33.5	17	0.7089	0.7999	0.8351	0.861
18.5	34.6	34.6	34.6	34.6	18.5	0.6285	0.7402	0.7851	0.8214
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	18.8	13.8	11	8.2	12	0.2543	0.2533	0.2636	0.2538
15	20	14.9	11.8	8.8	15	0.3596	0.3718	0.3912	0.3846
17	21.8	15.4	12.2	9	17	0.4339	0.4633	0.4938	0.4896
18.5	22.9	15.8	12.5	9.25	18.5	0.5034	0.5296	0.5684	0.573
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12					12				
15					15				
17					17				
18.5					18.5				
Max Rad. Flux (W/cm^2)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	167732	217578	250032	276318					
15	399348	527281	611449	737101					
17	654008	850469	972599	1171680					
18.5	916960	1238060	1423810	1651470					

Carbon 100

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	29.1	29.1	29.1	29.1	12	0.9308	0.955	0.9645	0.9734
15	32	32	32	32	15	0.8523	0.9001	0.9177	0.9359
17	33.5	33.5	33.5	33.5	17	0.7836	0.8557	0.8796	0.9059
18.5	34.6	34.6	34.6	34.6	18.5	0.7194	0.8145	0.8463	0.88
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	13.2	8.1	4.7	0.9	12	1.798	1.783	1.769	1.742
15	14.7	8.9	5.3	1.3	15	2.635	2.739	2.73	2.695
17	15.3	9.3	5.6	1.4	17	3.288	3.517	3.501	3.45
18.5	15.9	9.6	5.7	1.7	18.5	3.754	4.133	4.23	4.064
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12					12				
15					15				
17					17				
18.5					18.5				
Max Rad. Flux (W/cm^2)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	209404	269772	294348	313015					
15	504624	720701	842155	942115					
17	808088	1144970	1383940	1514750					
18.5	1170950	1614120	1924130	2074890					

Carbon 500

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	29.1	29.1	29.1	29.1	12	0.9782	0.9938	0.9969	0.9983
15	32	32	32	32	15	0.9447	0.9861	0.993	0.996
17	33.5	33.5	33.5	33.5	17	0.9166	0.9788	0.9896	0.9941
18.5	34.6	34.6	34.6	34.6	18.5	0.8921	0.9719	0.9863	0.9924
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0	0	0	0	12	156.91	45.4	19.15	9.11
15	0	0	0	0	15	257.9	76.37	31.93	15.08
17	0	0	0	0	17	336.4	103.4	42.92	20.23
18.5	0.4	0	0	0	18.5	400.217	126.7	52.77	24.8345
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12					12				
15					15				
17					17				
18.5					18.5				
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	307892	302188	206192	133285					
15	893141	824197	585963	388870					
17	1478840	1393810	972479	661748					
18.5	2028810	2013420	1400070	944811					

Comet 10

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	44.3	44.4	44.4	44.4	12	0.5258	0.597	0.6316	0.6739
15	47.6	47.7	47.7	47.7	15	0.3478	0.4028	0.4276	0.4555
17	49.7	49.7	49.7	49.7	17	0.2612	0.3038	0.3225	0.343
19	51.5	51.5	51.5	51.5	19	0.1935	0.2255	0.2391	0.253
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	39.4	36	33.8	30.3	12	0.00106	0.00088	0.00078	0.00074
15	41.8	37.1	34.4	32	15	0.00144	0.00128	0.00128	0.00128
17	43.2	38.2	35.4	32.1	17	0.00173	0.00158	0.00159	0.00165
19	44.5	39.2	36.4	33.4	19	0.00205	0.00192	0.00194	0.00201
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	0.0425				12				
15	0.0438				15				
17	0.044				17				
19	0.0333				19				
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	40683	66354	88588	103136					
15	57752	103173	147891	219423					
17	70851	132362	192681	291285					
19	85723	165812	243985	372410					

Comet 50

Breakup height (km)					Final Mass Ratio				
Velocity	Entry Angle (deg)				Velocity	Entry Angle (deg)			
(km/s)	-15	-30	-45	-90	(km/s)	-15	-30	-45	-90
12	44.4	44.4	44.4	44.4	12	0.6803	0.7944	0.8397	0.8733
15	47.7	47.7	47.7	47.7	15	0.4243	0.5913	0.6694	0.736
17	49.7	49.7	49.7	49.7	17	0.2934	0.4469	0.5392	0.6225
19	51.5	51.5	51.5	51.5	19	0.1941	0.3011	0.3969	0.4896
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity	Entry Angle (deg)				Velocity	Entry Angle (deg)			
(km/s)	-15	-30	-45	-90	(km/s)	-15	-30	-45	-90
12	24.9	19.7	16.8	13.7	12	0.0761	0.09	0.099	0.109
15	30.8	22.6	18.7	14.8	15	0.1219	0.1252	0.1407	0.157
17	32	24.4	20	15.4	17	0.1778	0.1614	0.1732	0.1902
19	32.1	26.4	21.8	17.2	19	0.2277	0.2061	0.2102	0.2213
Max Stagnation Ratio					Max Peak Ratio				
Velocity	Entry Angle (deg)				Velocity	Entry Angle (deg)			
(km/s)	-15	-30	-45	-90	(km/s)	-15	-30	-45	-90
12	0.019				12				
15	0.0196				15				
17	0.0197				17				
19	0.0149				19				
Max Rad. Flux (W/cm^2)									
Velocity	Entry Angle (deg)								
(km/s)	-15	-30	-45	-90					
12	103357	126271	137168	162098					
15	249632	344130	397620	450220					
17	392753	570230	675769	787544					
19	538504	899750	1093070	1309010					

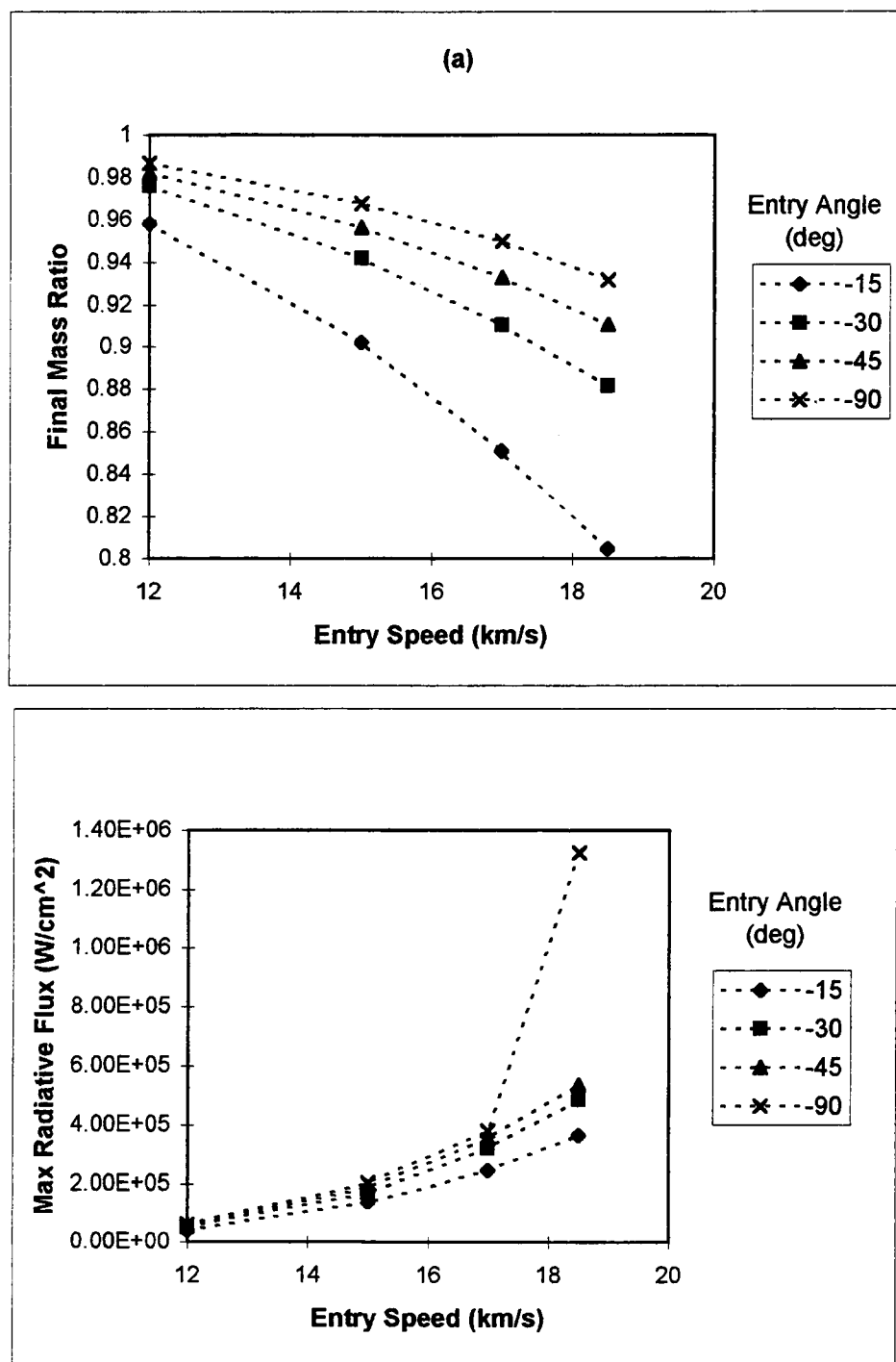
Comet 100

Breakup height (km)					Final Mass Ratio				
Velocity	Entry Angle (deg)				Velocity	Entry Angle (deg)			
(km/s)	-15	-30	-45	-90	(km/s)	-15	-30	-45	-90
12	44.4	44.4	44.4	44.4	12	0.7857	0.8693	0.8953	0.916
15	47.7	47.7	47.7	47.7	15	0.5698	0.726	0.7859	0.8272
17	49.7	49.7	49.7	49.7	17	0.4184	0.6109	0.6888	0.75
18.5	51	51	51	51	18.5	0.3079	0.5123	0.6015	0.6755
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity	Entry Angle (deg)				Velocity	Entry Angle (deg)			
(km/s)	-15	-30	-45	-90	(km/s)	-15	-30	-45	-90
12	18.7	13.3	11	7.1	12	0.6678	0.7823	0.8437	0.8395
15	22.5	14.8	11.3	7.8	15	0.9092	1.136	1.2722	1.268
17	25	15.4	11.7	8.2	17	1.193	1.383	1.567	1.599
18.5	26.5	17.1	12.4	8.7	18.5	1.463	1.5876	1.7598	1.824
Max Stagnation Ratio					Max Peak Ratio				
Velocity	Entry Angle (deg)				Velocity	Entry Angle (deg)			
(km/s)	-15	-30	-45	-90	(km/s)	-15	-30	-45	-90
12	0.0134	0.0134	0.0134	0.0134	12	0.0134	0.0145	0.0192	0.0254
15	0.0138	0.0138	0.0138	0.0138	15	0.0138	0.0161	0.0215	0.0287
17	0.0139	0.0139	0.0139	0.0139	17	0.0139	0.017	0.0229	0.0309
18.5	0.0119	0.0119	0.0119	0.0119	18.5	0.0119	0.0165	0.0224	0.03
Max Rad. Flux (W/cm ²)									
Velocity	Entry Angle (deg)								
(km/s)	-15	-30	-45	-90					
12	120511	158745	191186	225242					
15	329002	439089	490419	591155					
17	545376	768701	874765	974857					
18.5	763668	1125410	1308660	1485400					

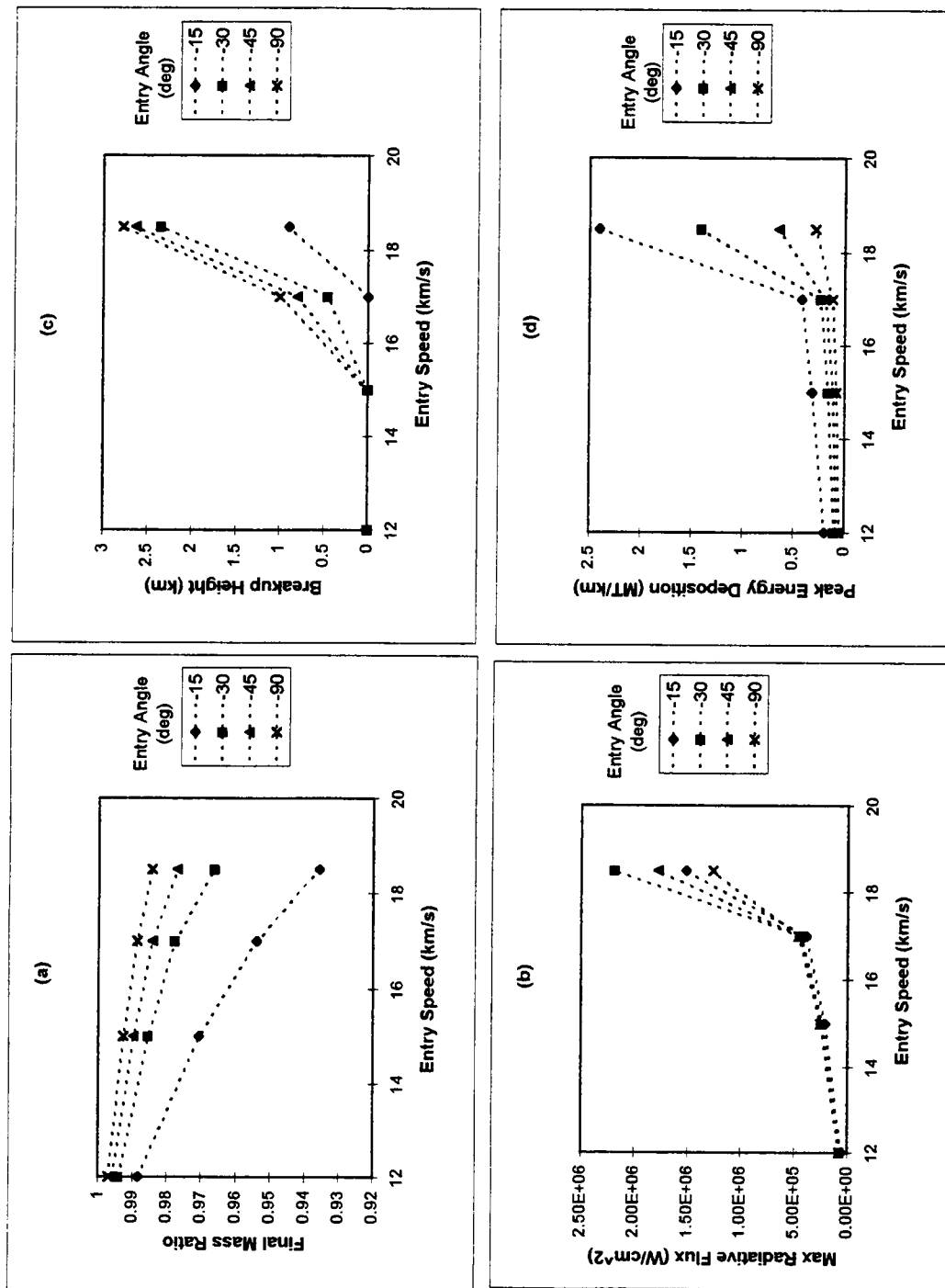
Comet 500

Breakup height (km)					Final Mass Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	44.4	44.4	44.4	44.4	12	0.923	0.966	0.9819	0.9908
15	47.7	47.7	47.7	47.7	15	0.8333	0.92	0.9592	0.9798
17	49.7	49.7	49.7	49.7	17	0.7585	0.885	0.94	0.9697
18.5	51.1	51.1	51.1	51.1	18.5	0.6859	0.8549	0.923	0.9606
Airburst Height (km)					Peak Energy Deposition (MT/km)				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	4.7	0	0	0	12	82.29	67.19	33.5	14.87
15	6.33	0	0	0	15	128.48	111.27	56.9	25.11
17	7	0	0	0	17	166.24	147.575	77.13	34.47
18.5	7.6	0	0	0	18.5	193.6	177.95	95.35	42.67
Max Stagnation Ratio					Max Peak Ratio				
Velocity (km/s)	Entry Angle (deg)				Velocity (km/s)	Entry Angle (deg)			
	-15	-30	-45	-90		-15	-30	-45	-90
12	221969	252181	254609	200764	12	0.0136	0.0221	0.0277	0.0343
15	608691	741950	721760	546979	15	0.0149	0.0251	0.0316	0.0392
17	1015890	1192260	1215550	937374	17	0.0157	0.0269	0.0339	0.0424
18.5	1460480	1628890	1682820	1341960	18.5	0.0153	0.0264	0.0332	0.0414
Max Rad. Flux (W/cm ²)									
Velocity (km/s)	Entry Angle (deg)								
	-15	-30	-45	-90					
12	221969	252181	254609	200764					
15	608691	741950	721760	546979					
17	1015890	1192260	1215550	937374					
18.5	1460480	1628890	1682820	1341960					

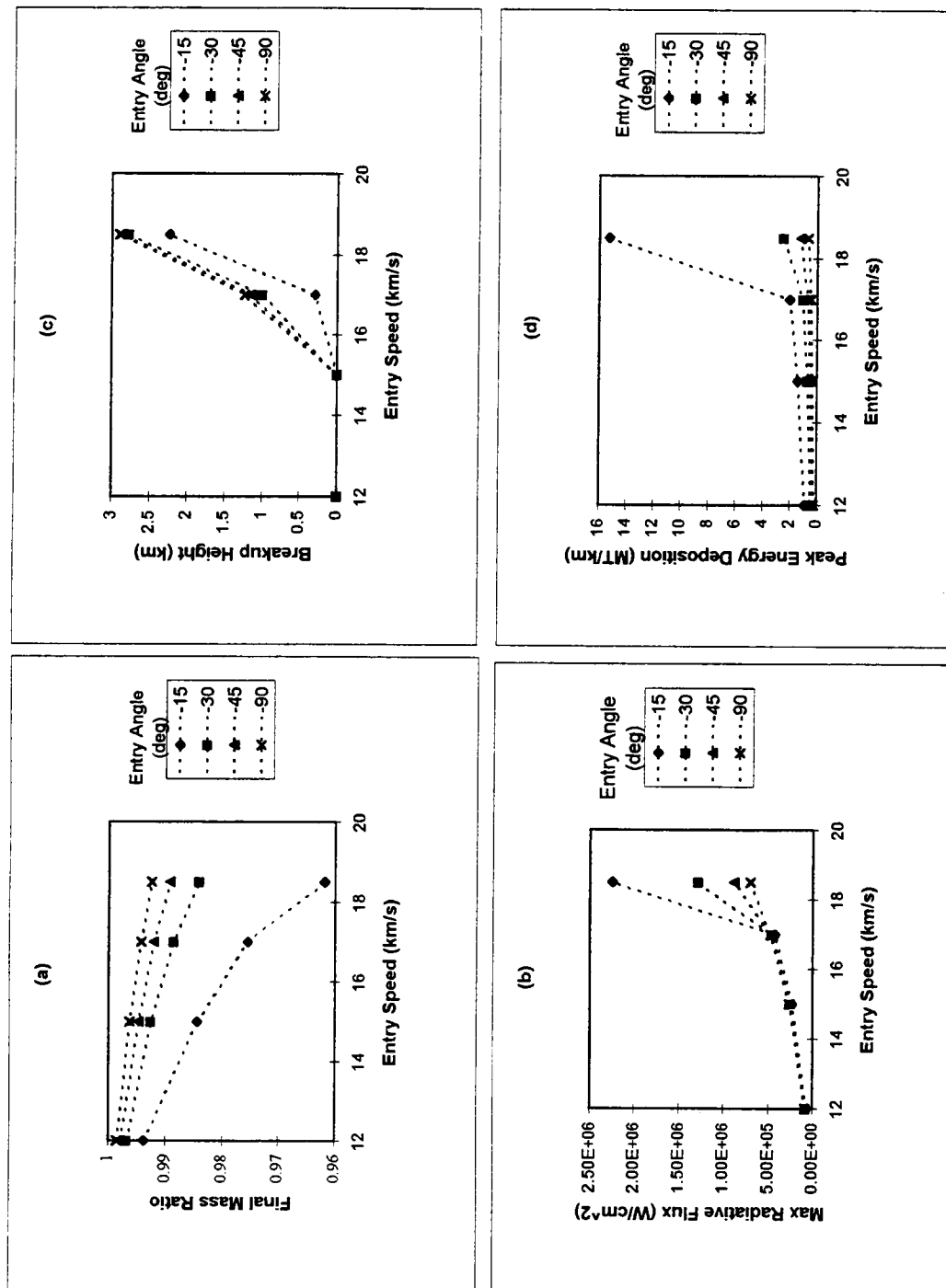
APPENDIX G
PLOTS FOR PARAMETRIC TEST RUNS



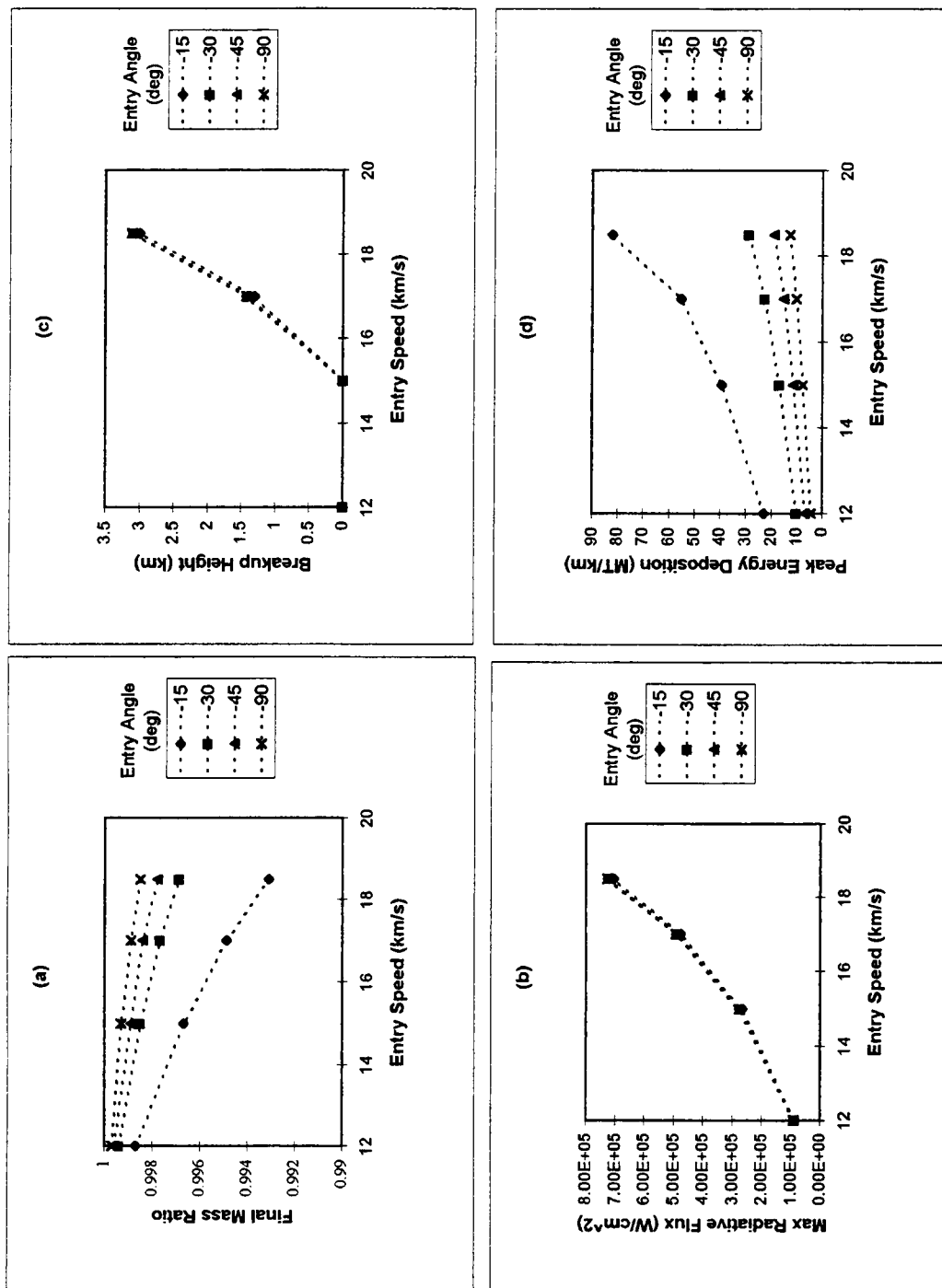
G. 1. Final mass ratio (a) and max. radiative flux (b) for 10-m iron body.



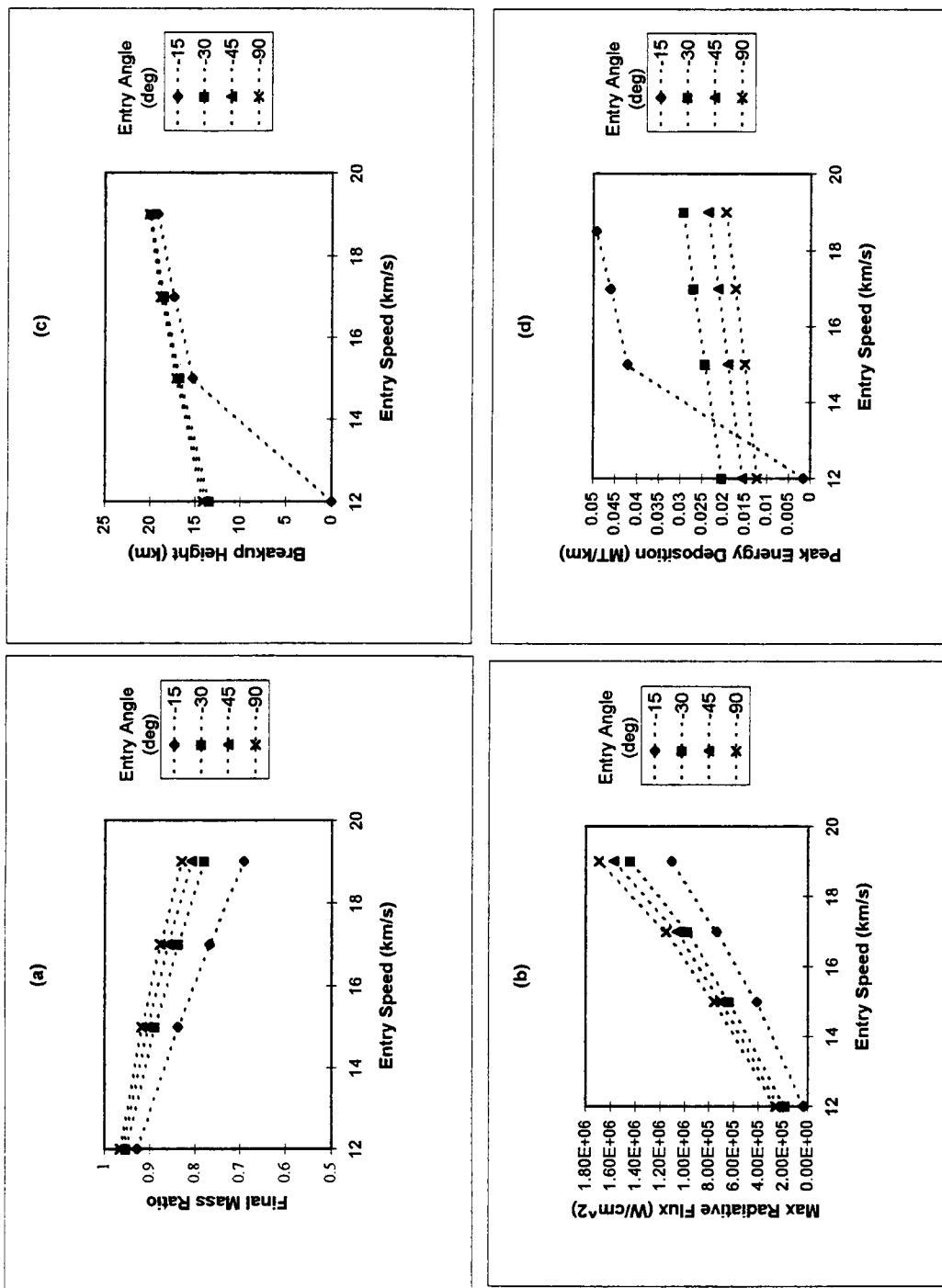
G. 2. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 50-m iron body.



G. 3. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 100-m iron body.

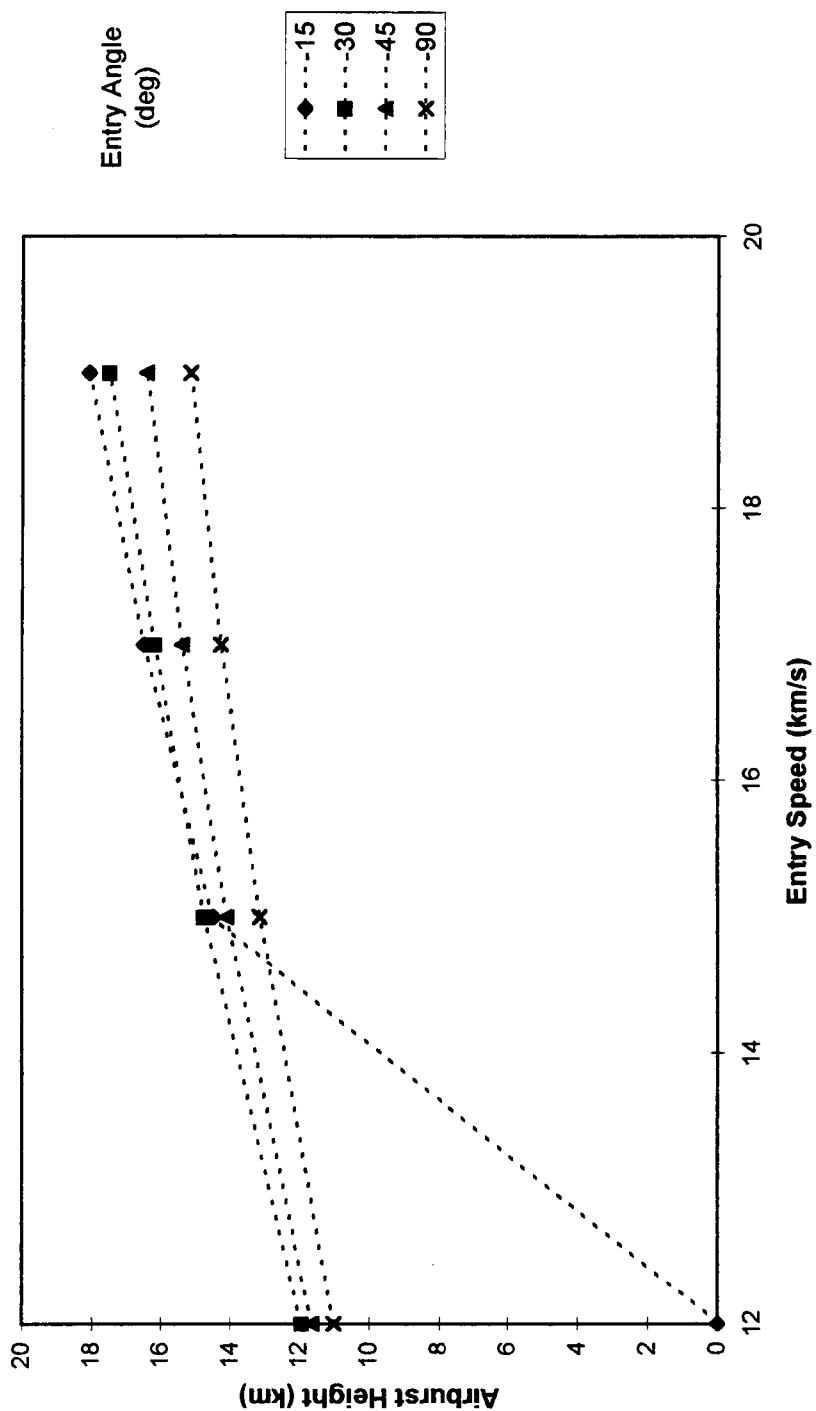


G. 4. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 500-m iron body.

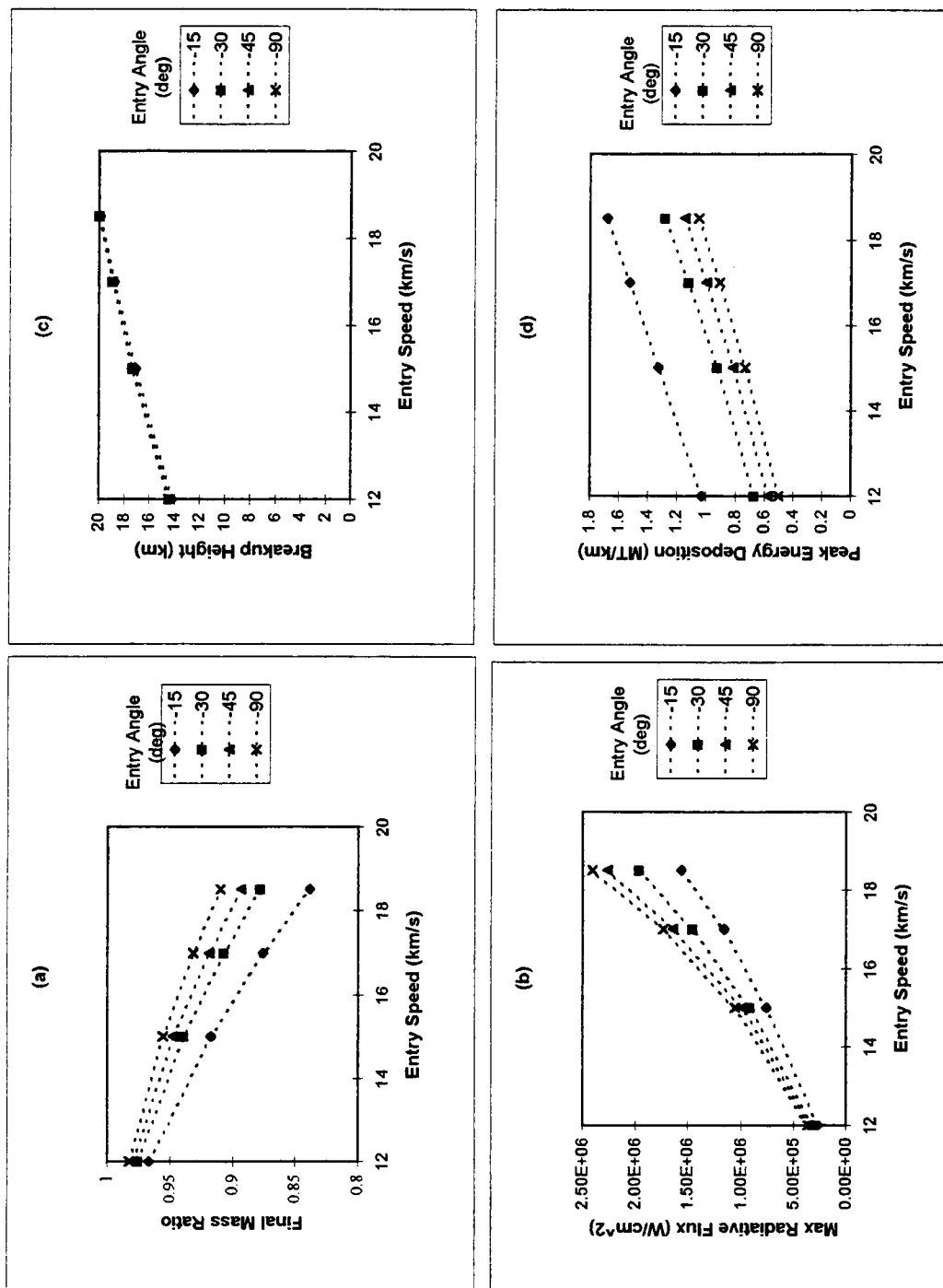


G. 5. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 10-m stone body.

(e)

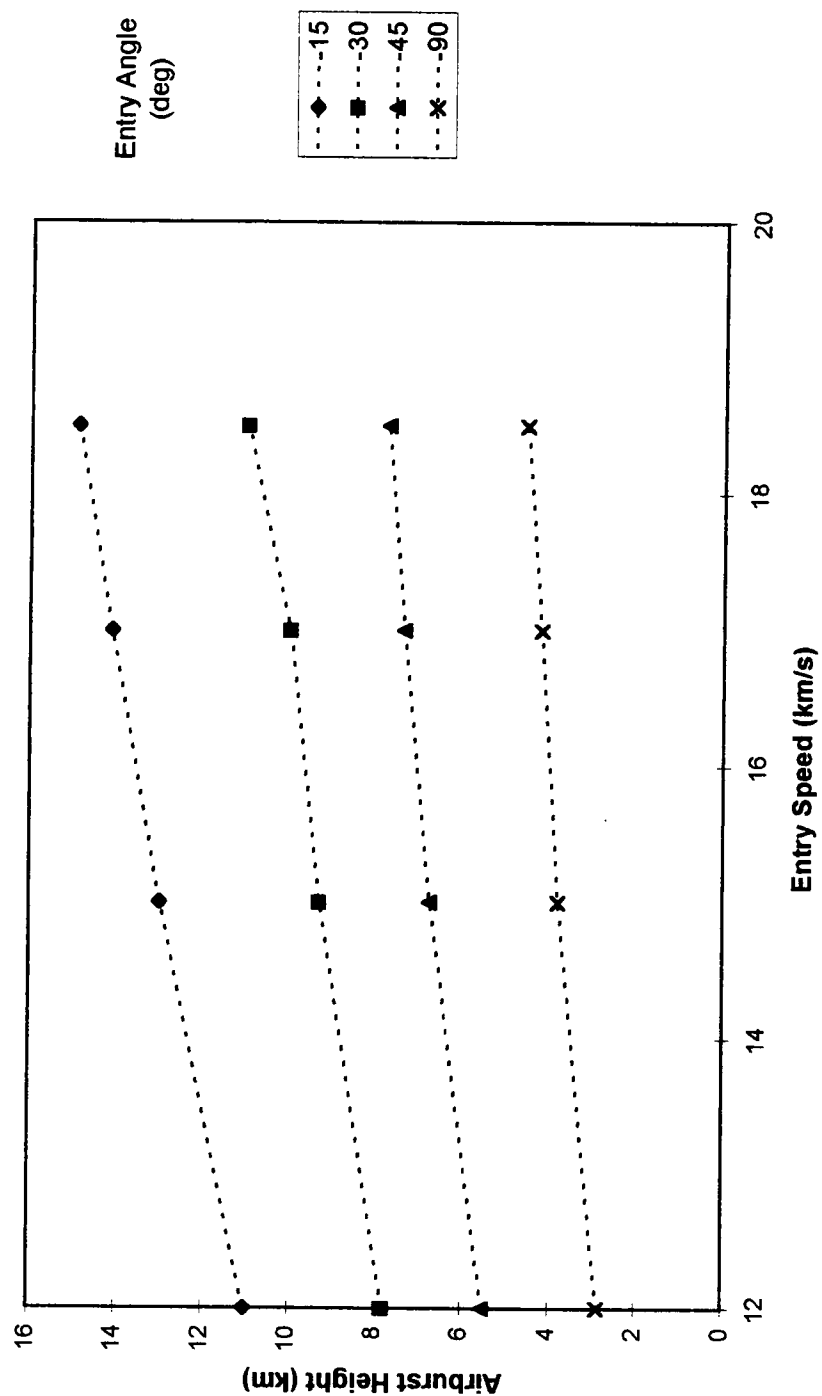


G. 5. (continued) Airburst height (e) for 10-m stone body.

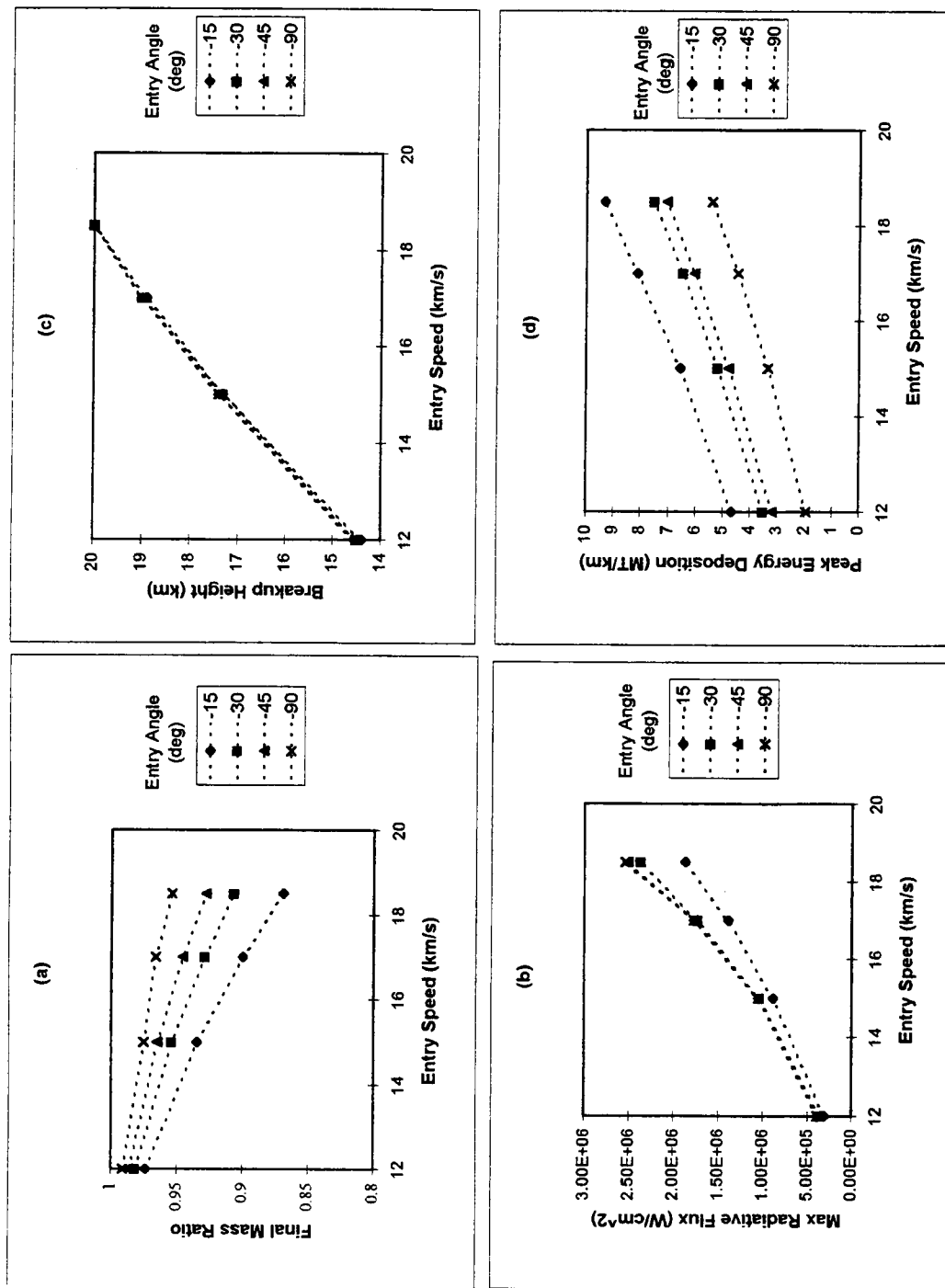


G. 6. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 50-m stone body.

(e)

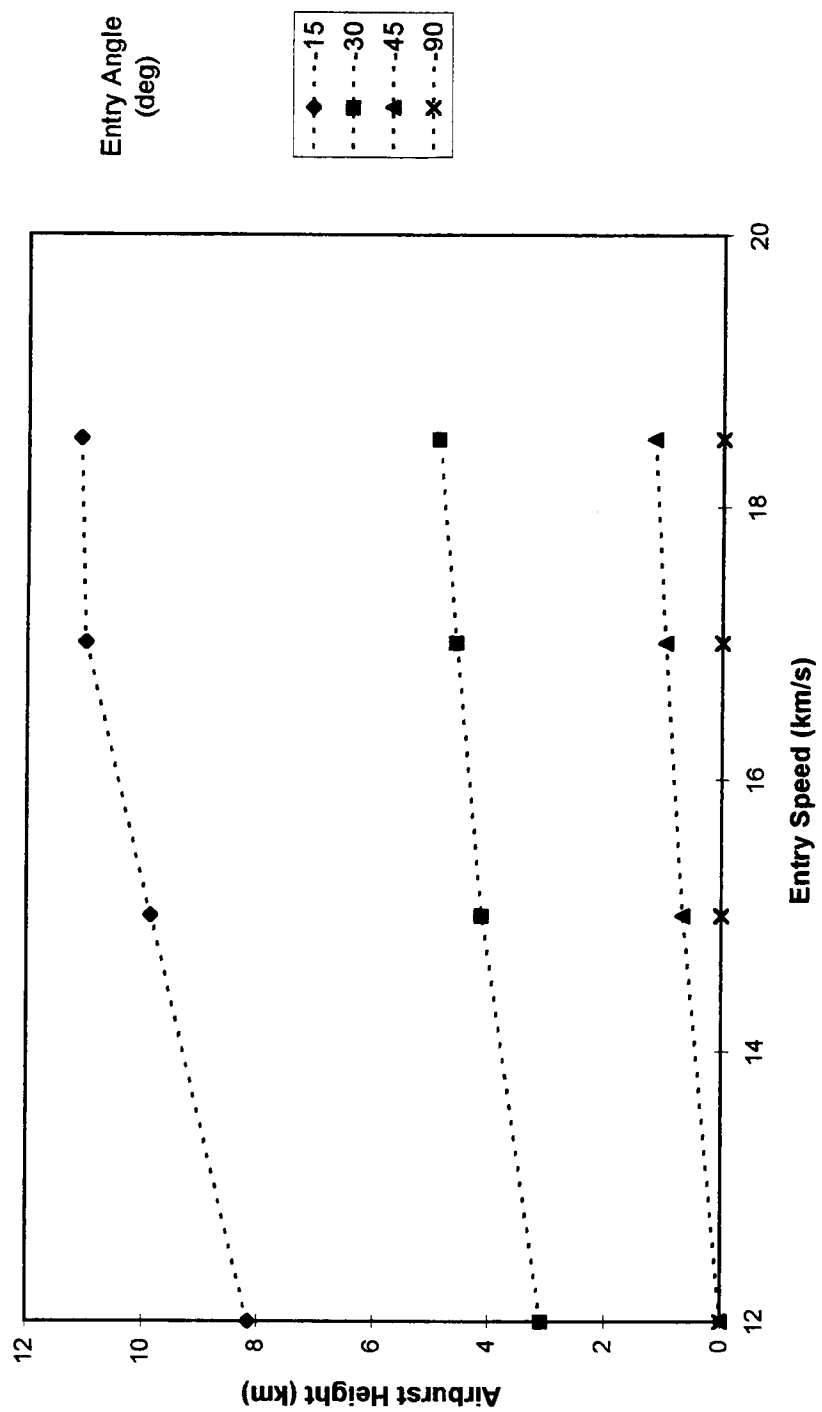


G. 6. (continued) Airburst height (e) for the 50 meter stone body.

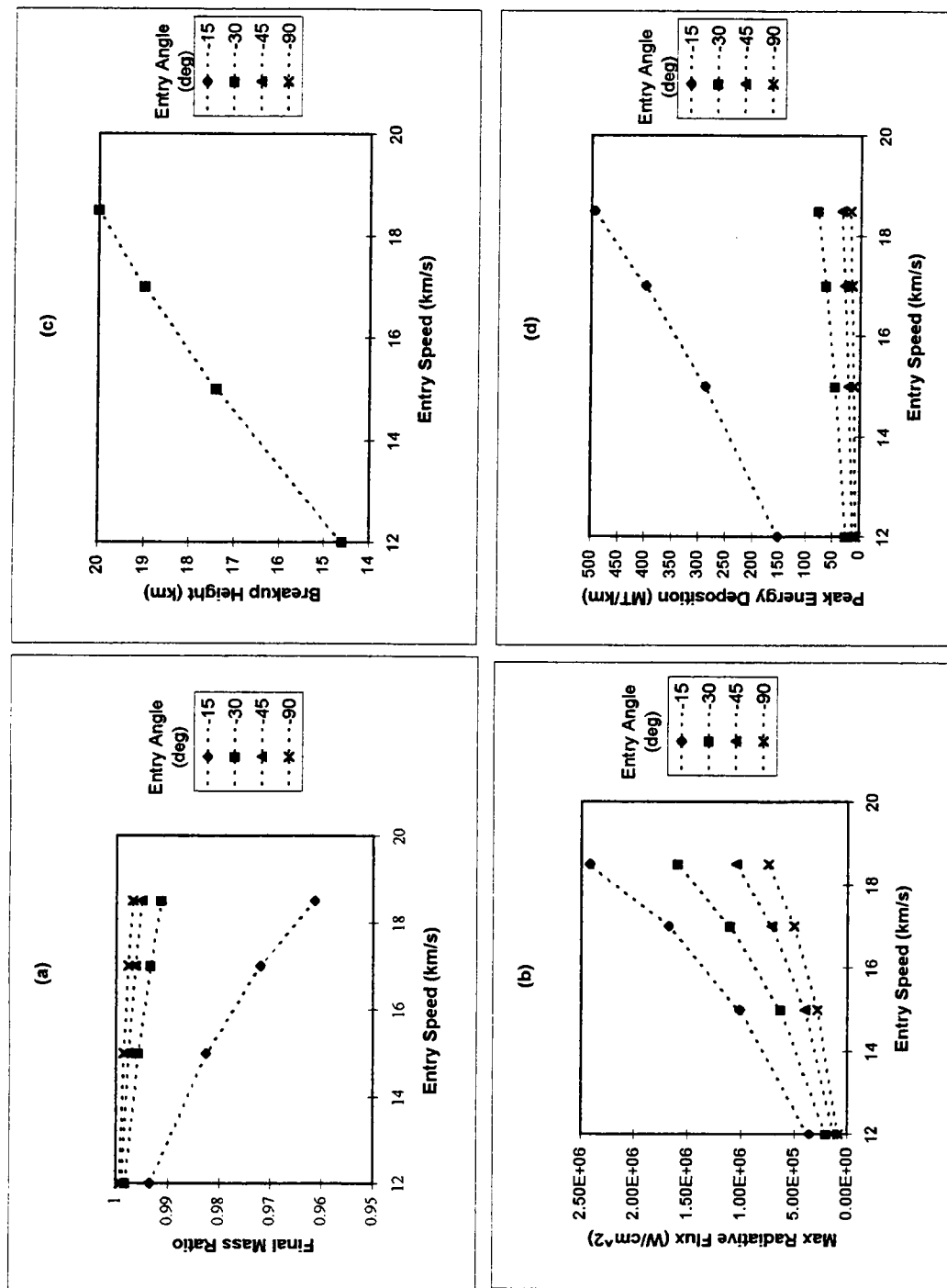


G. 7. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 100-m stone body.

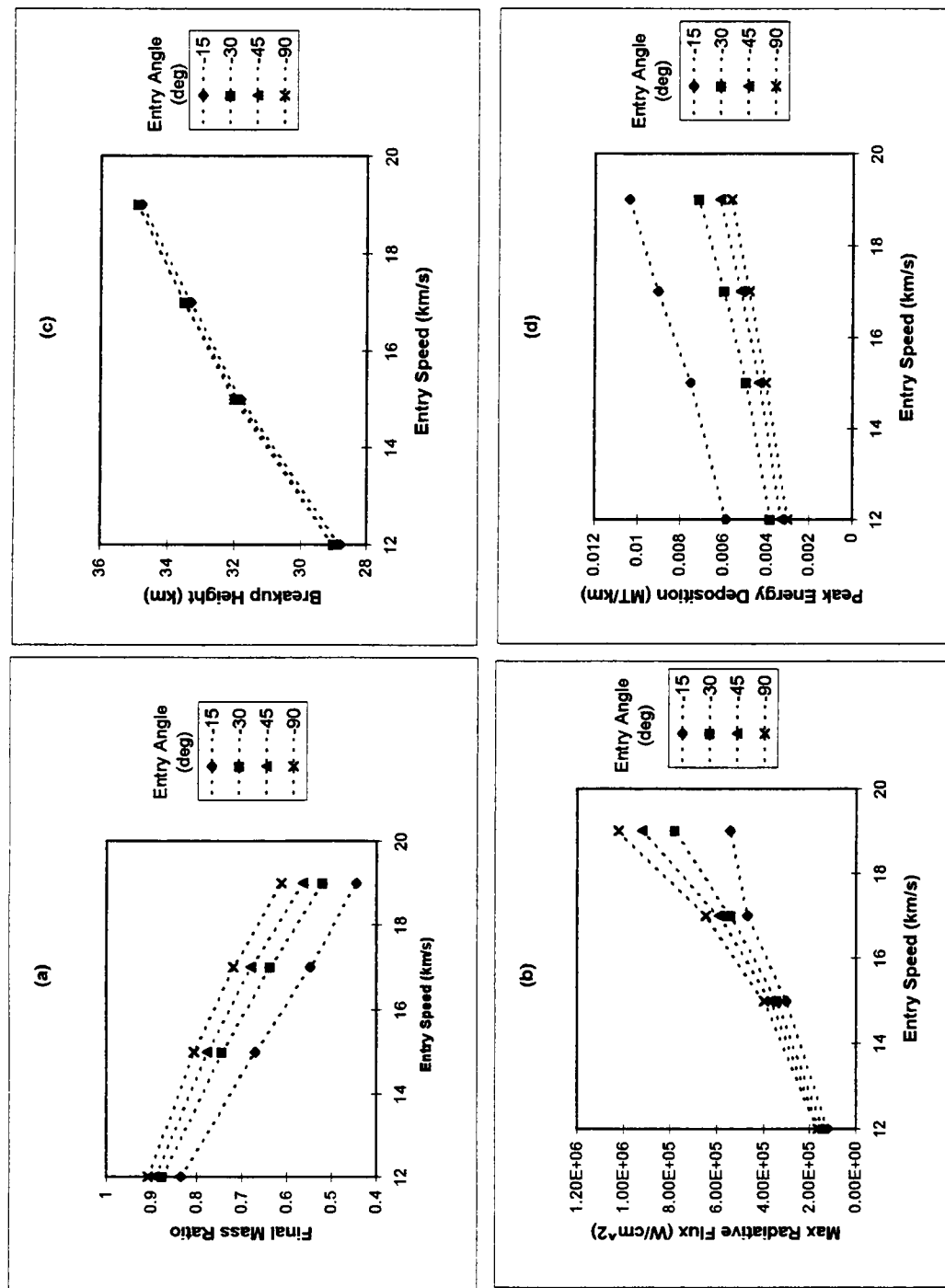
(e)



G. 7 (continued) Airburst height (e) for 100-m stone body.

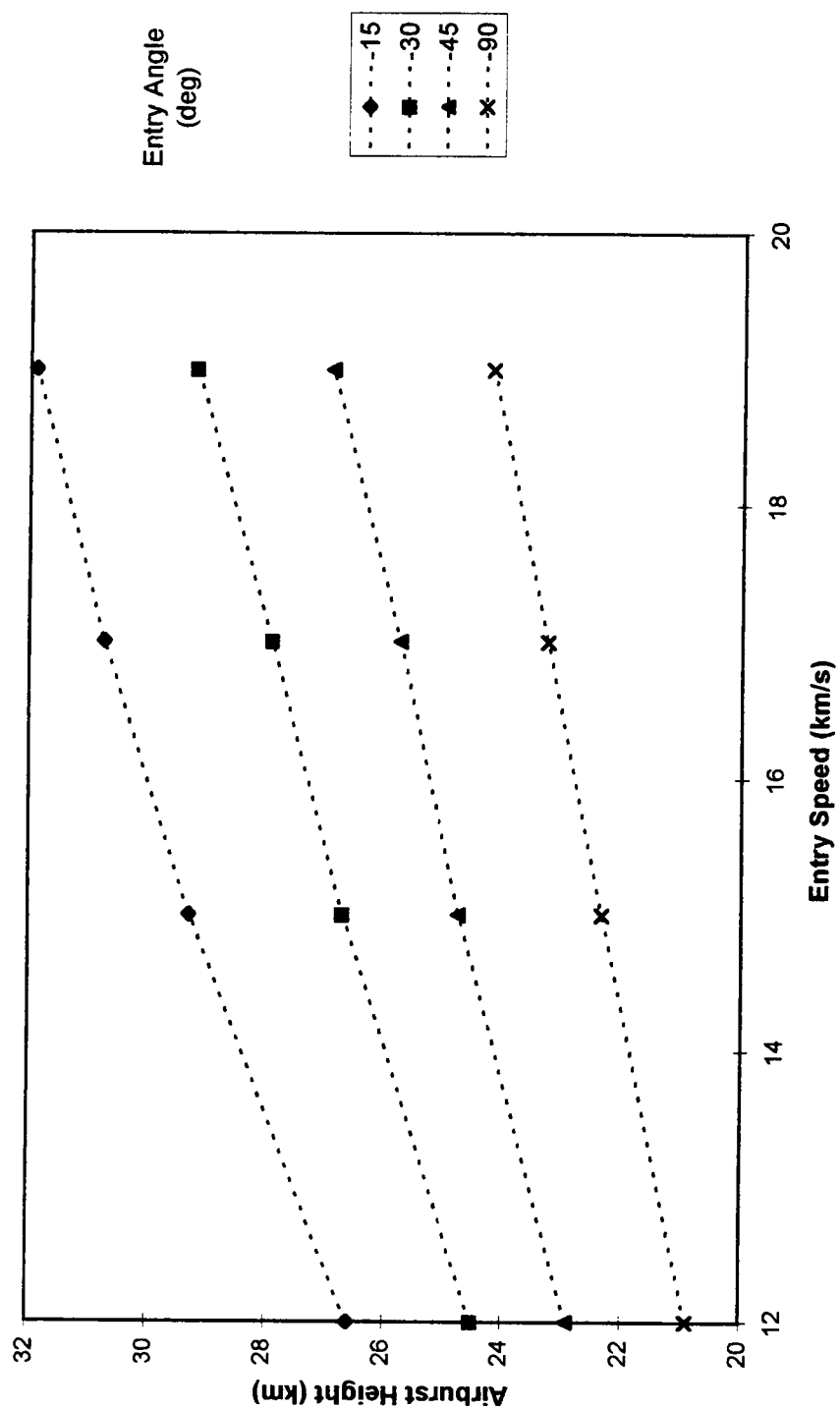


G. 8. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 500-m stone body.

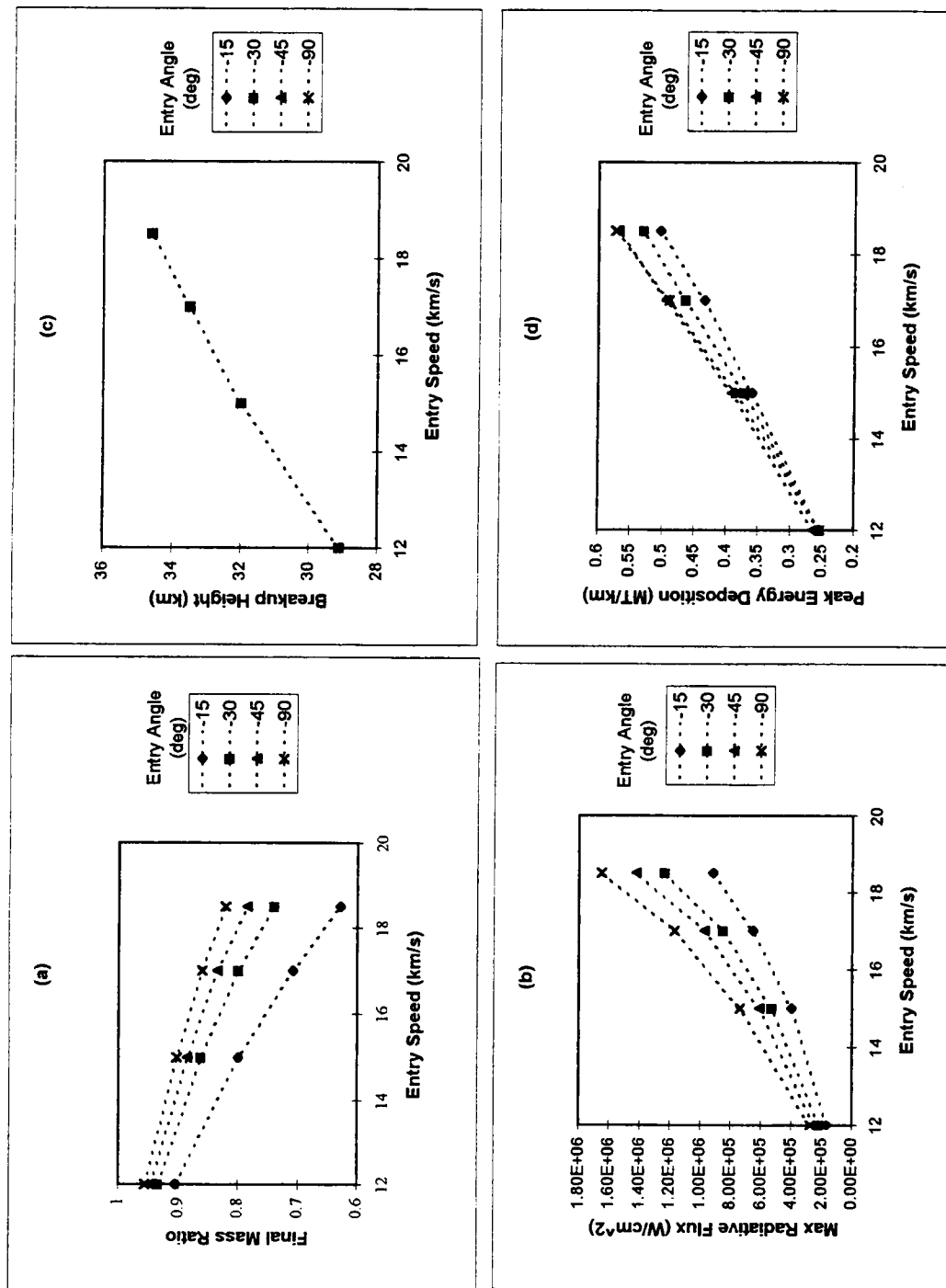


G. 9. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 10-m carbonaceous body.

(e)

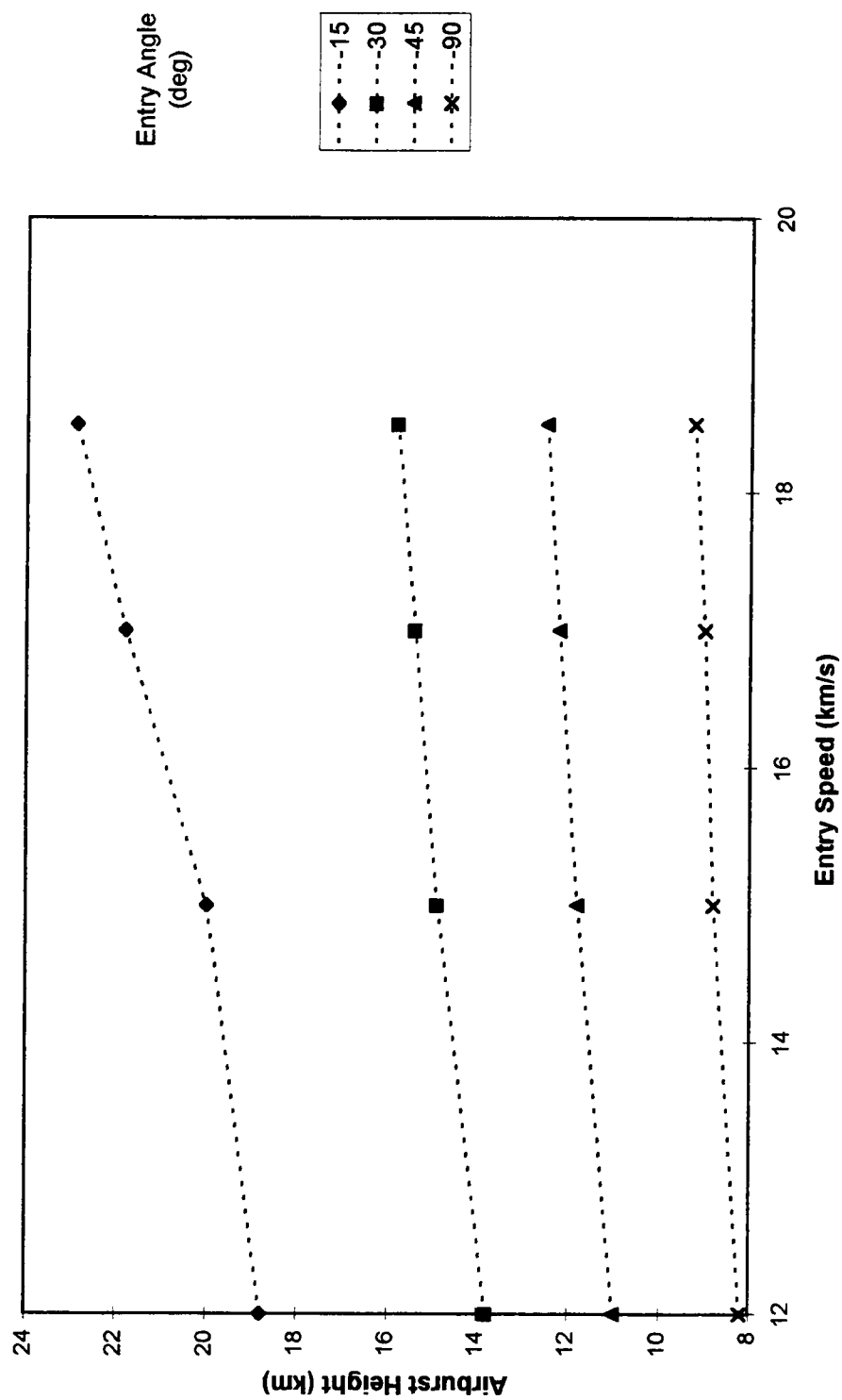


G. 9. (continued) Airburst height (e) for 10-m carbonaceous body.

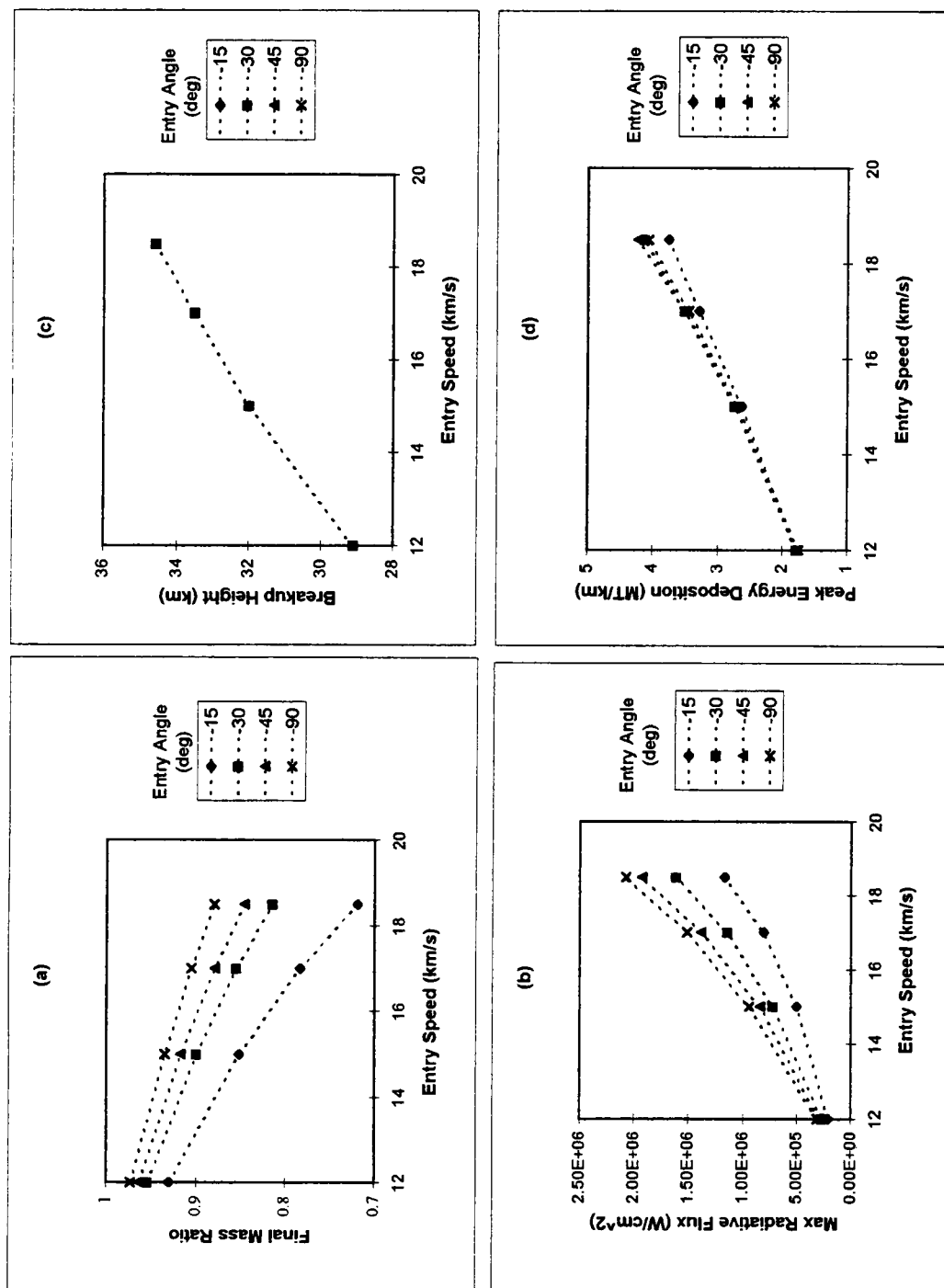


G.10. Final mass ratio (a), max. radiative flux (b), breakup altitude (c) and peak energy deposition (d) for 50-m carbonaceous body.

(e)

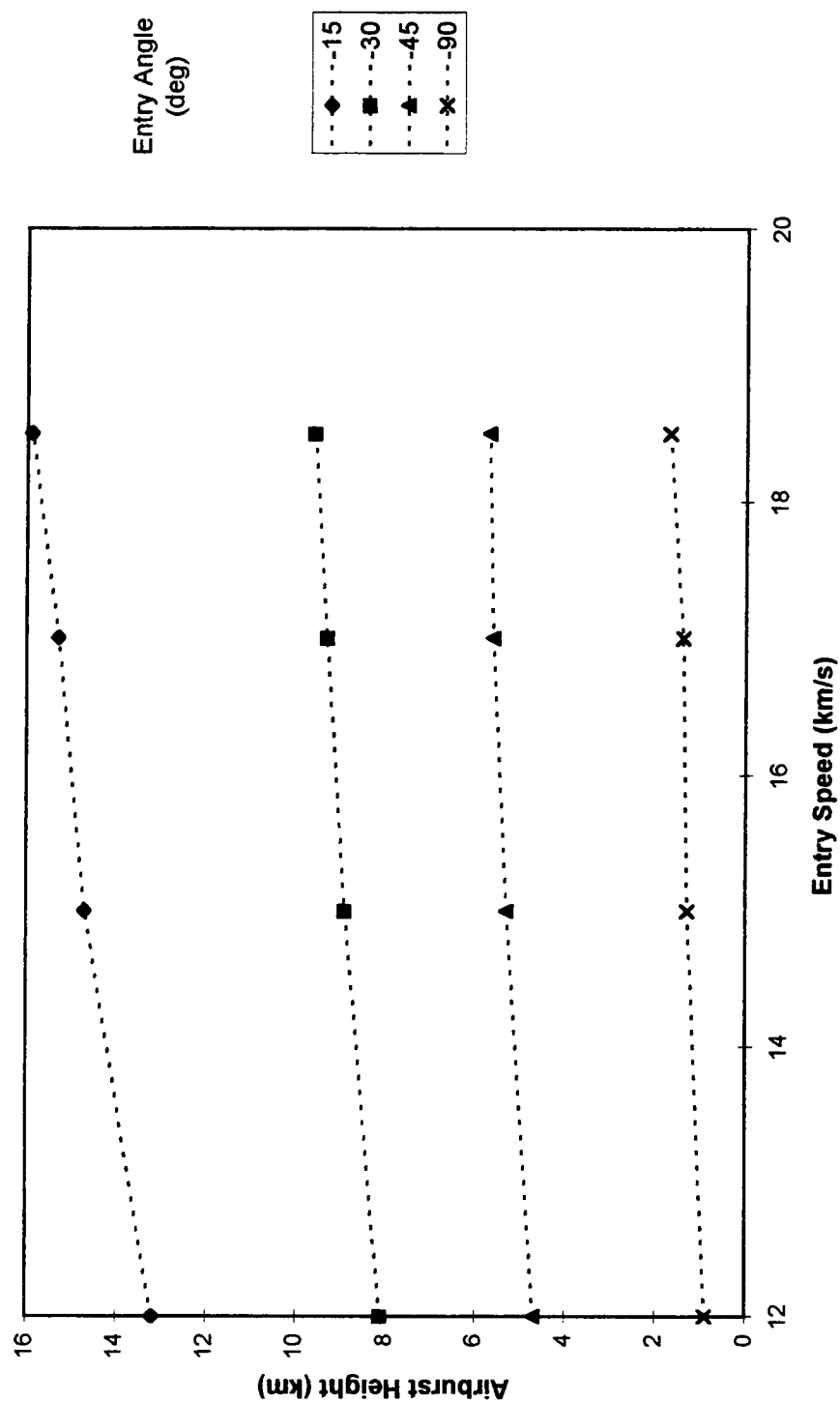


G. 10. (continued) Airburst height (e) for 50-m carbonaceous body.

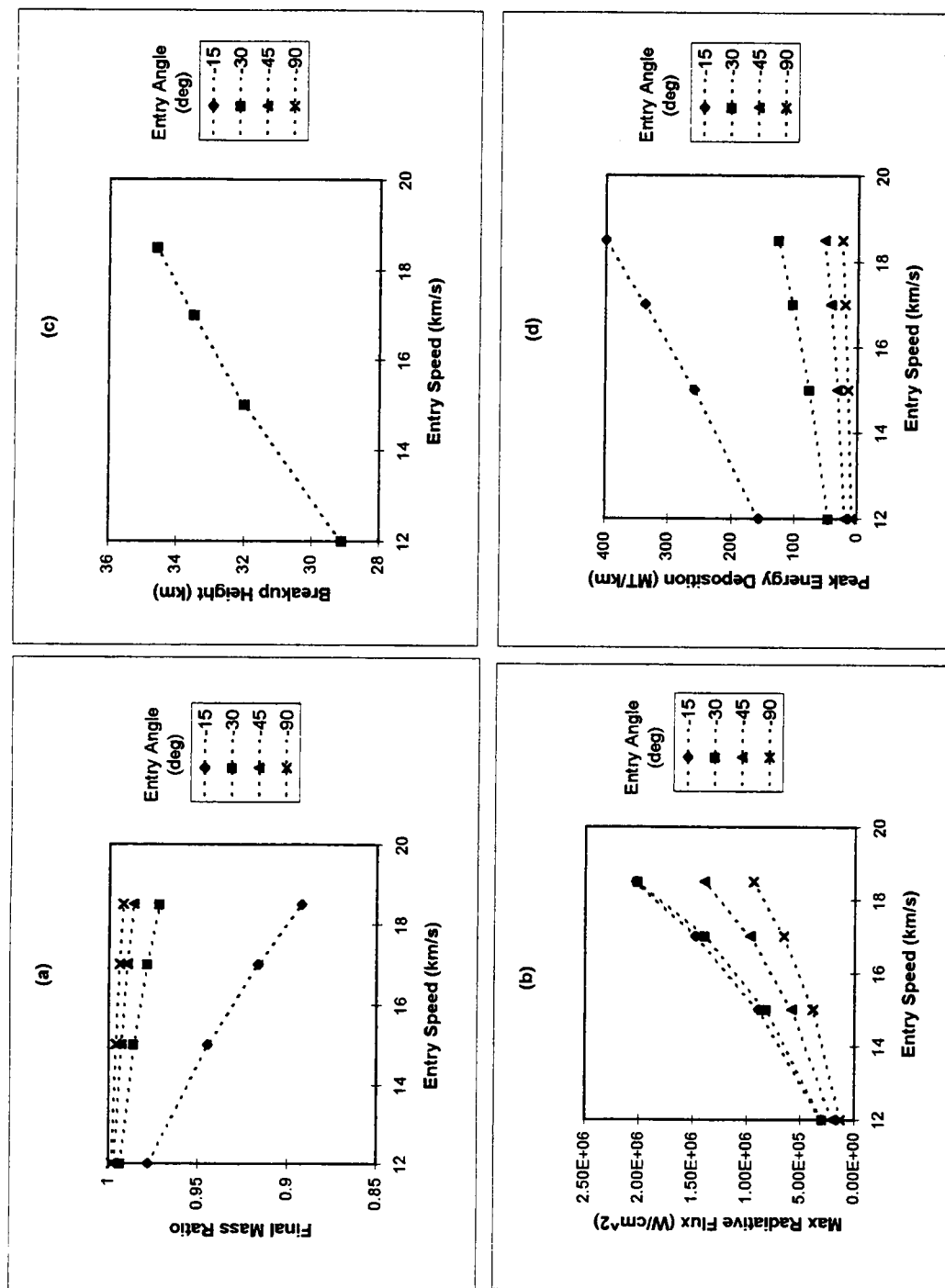


G.11. Final mass ratio (a), max. radiative flux (b), breakup altitude (c) and peak energy deposition (d) for 100-m carbonaceous body.

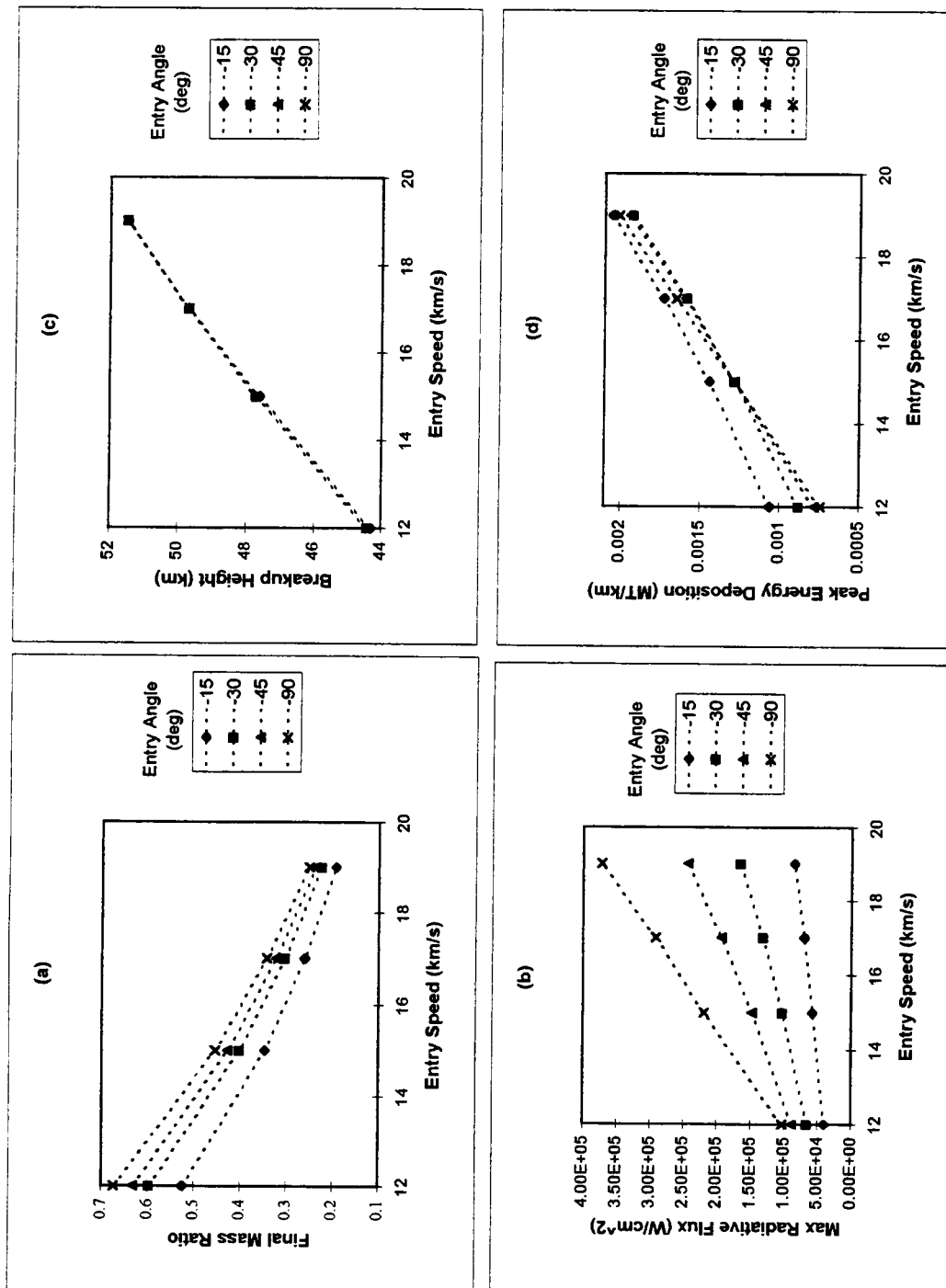
(e)



G. 11. (continued) Airburst height (e) for 100-m carbonaceous body.

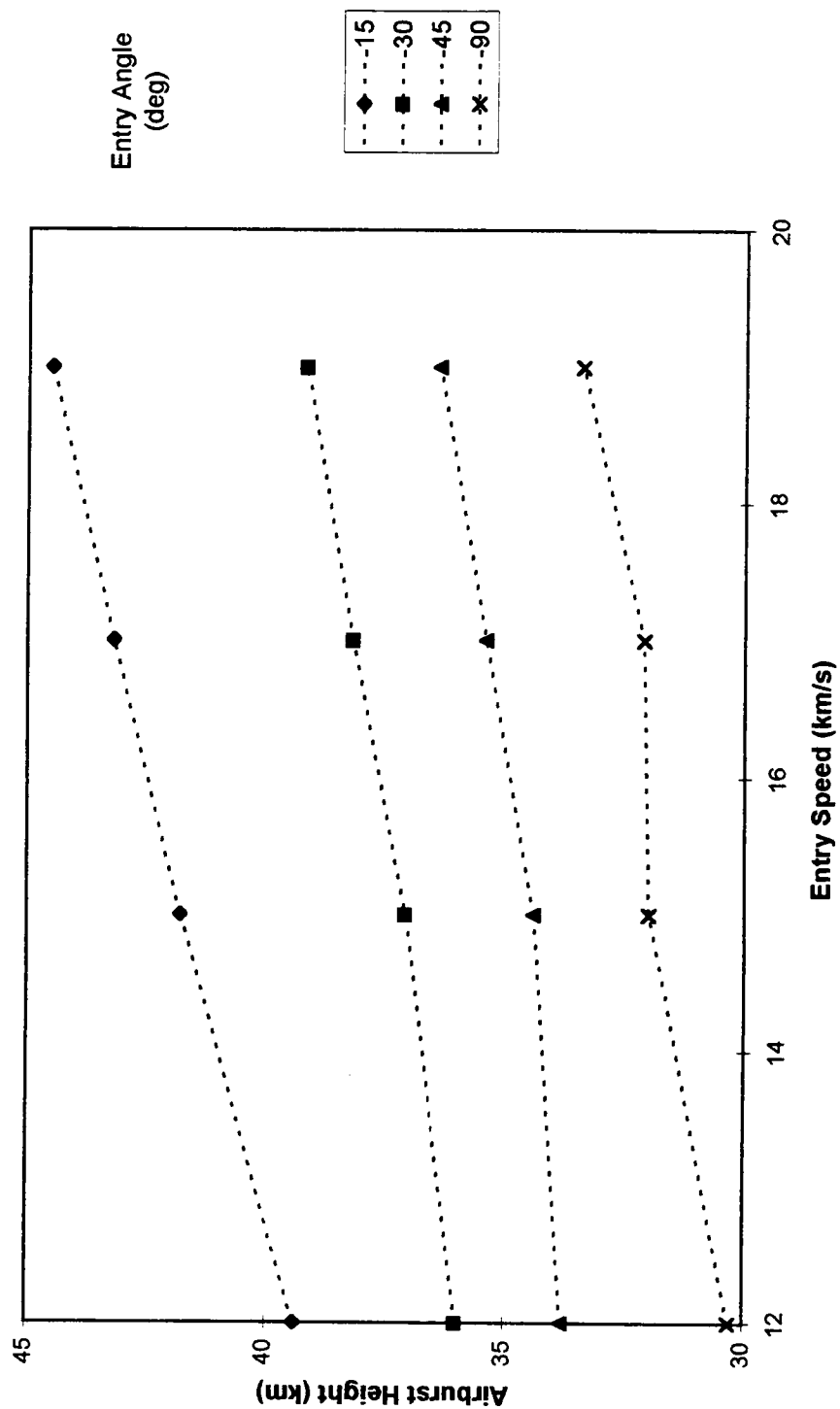


G. 12. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 500-m carbonaceous body.

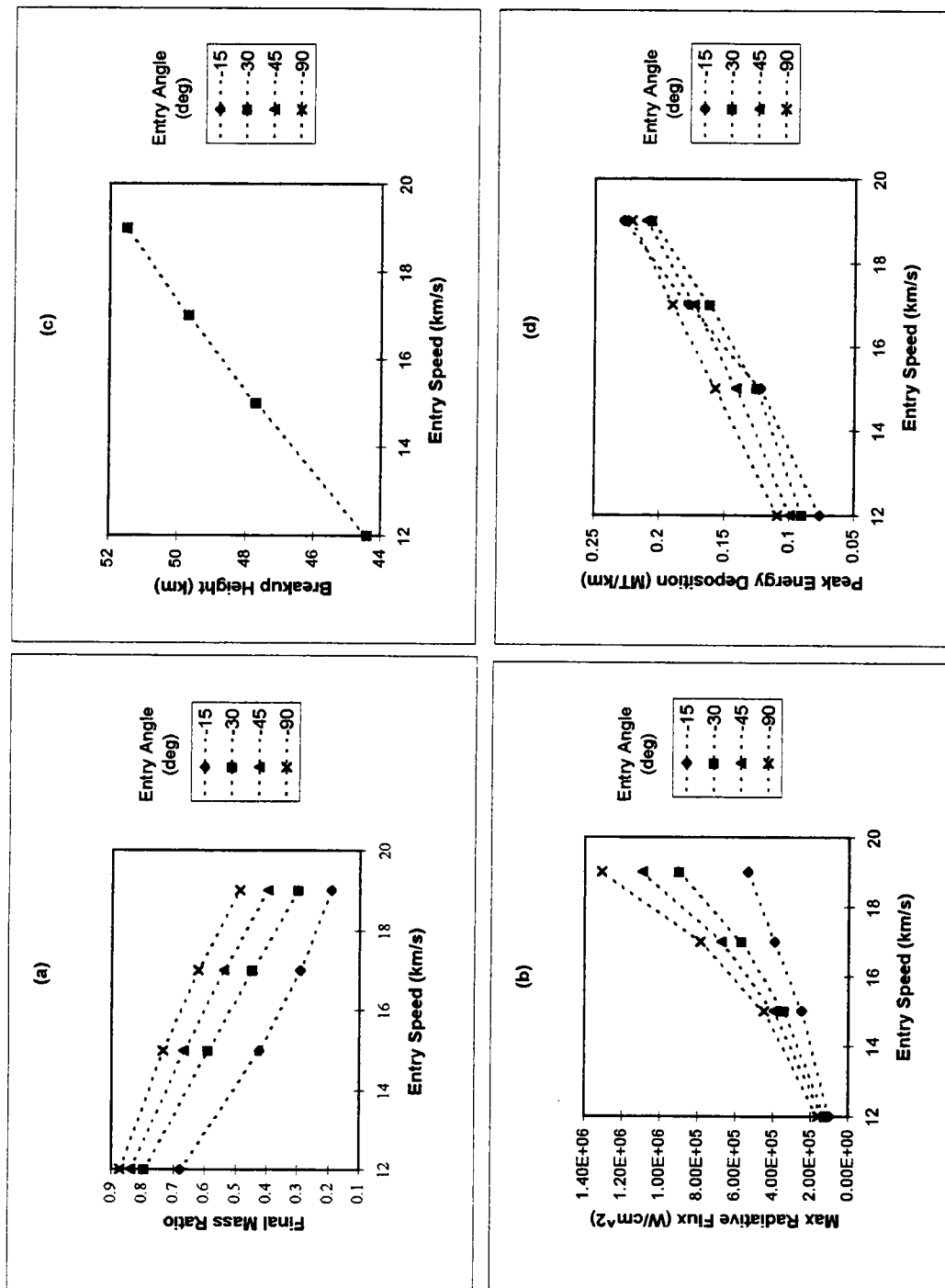


G. 13. Final mass ratio (a), max. radiative flux (b), breakup altitude (c) and peak energy deposition (d) for 10-m cometary body.

(e)

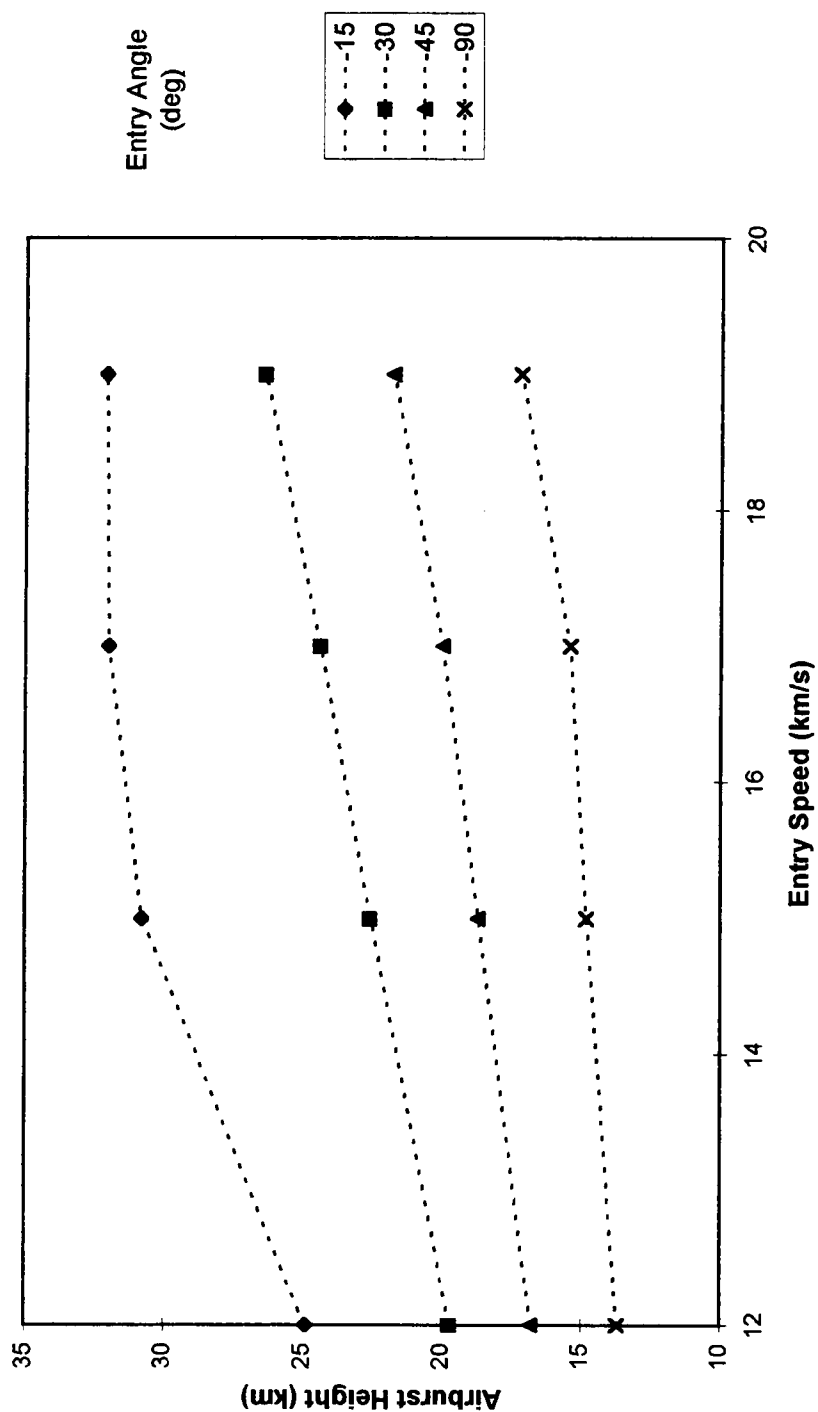


G. 13. (continued) Airburst height (e) for 10-m cometary body.

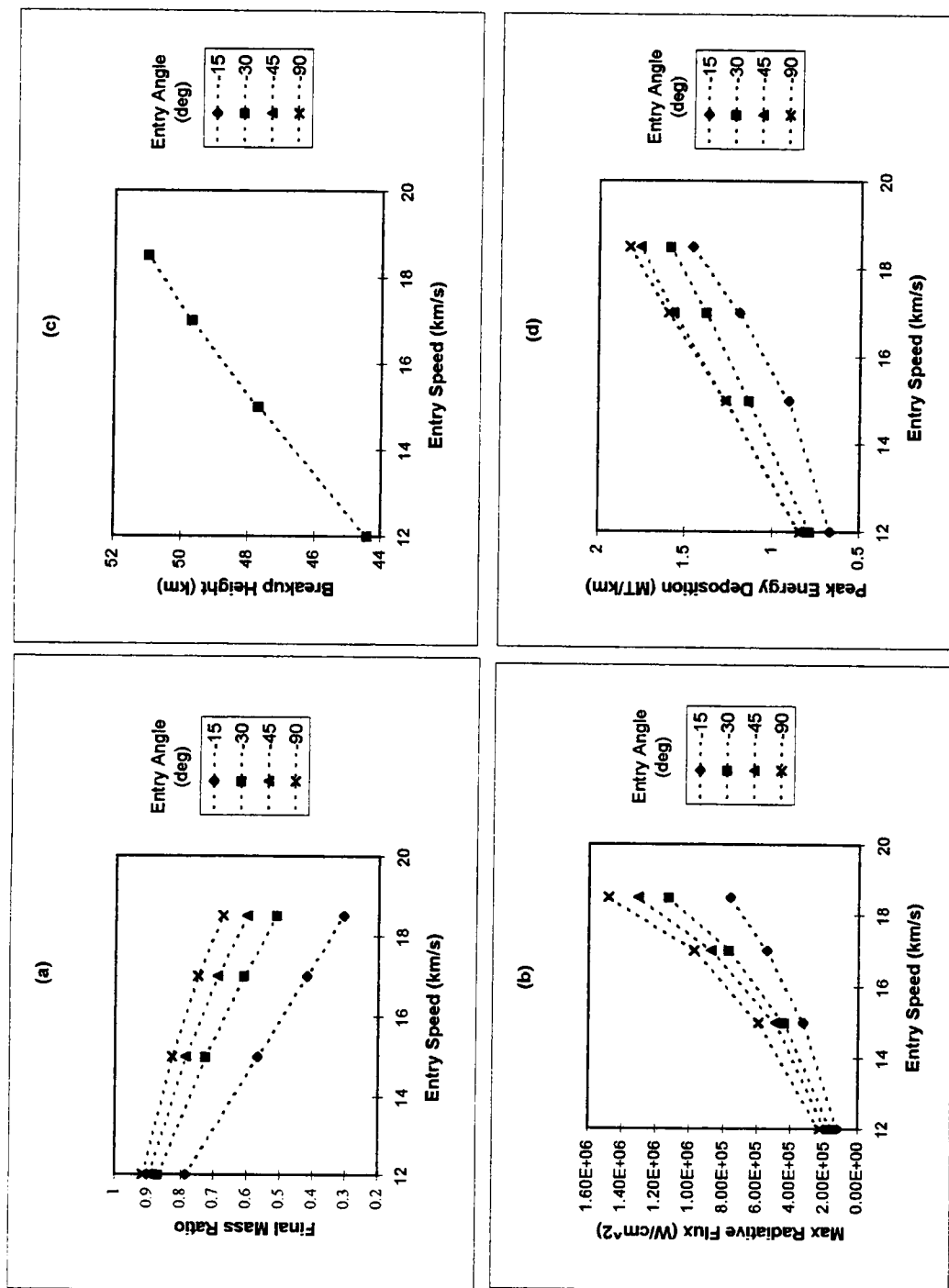


G. 14. Final mass ratio (a), max. radiative flux (b), breakup altitude (c) and peak energy deposition (d) for 50-m cometary body.

(e)

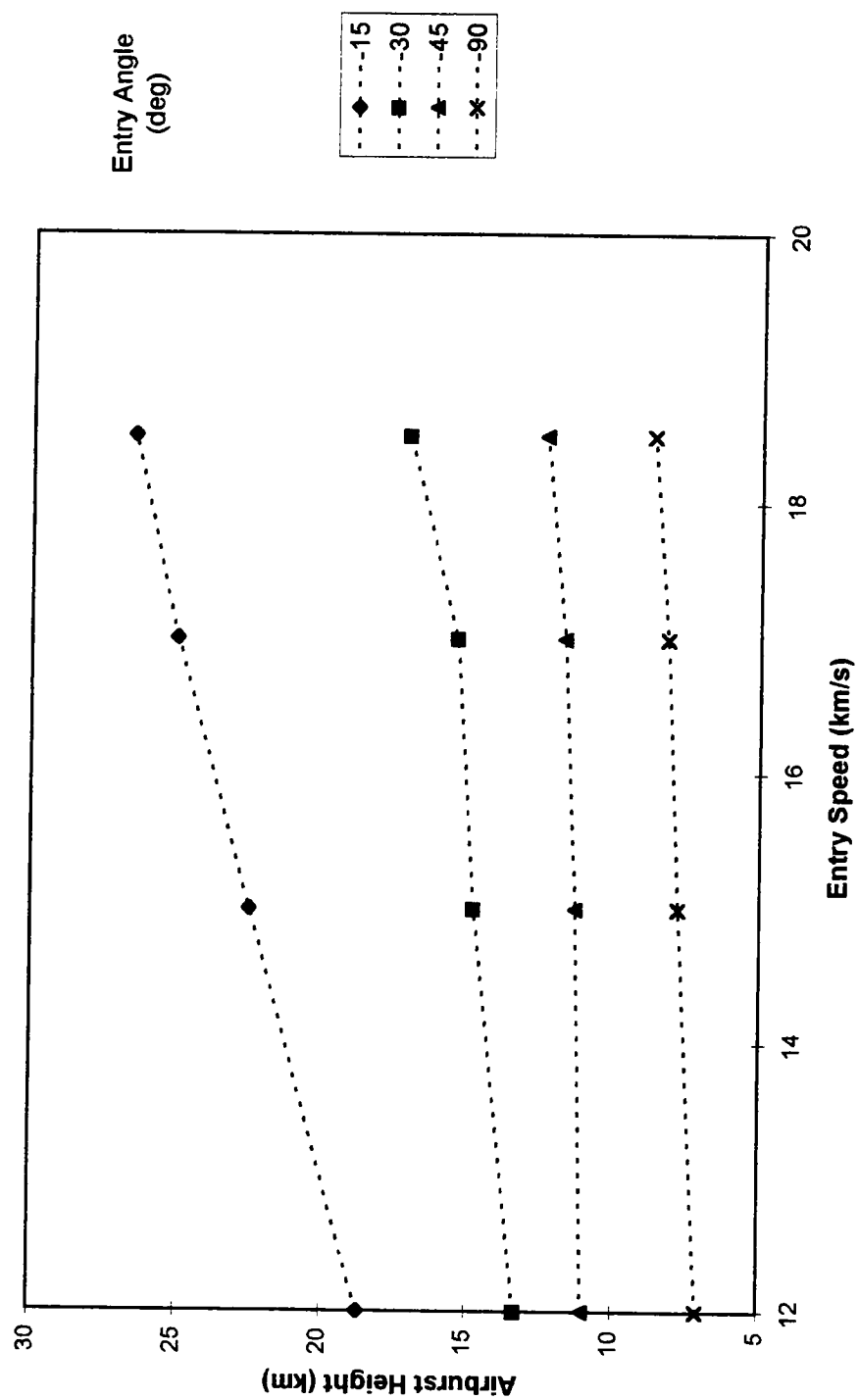


G. 14.(continued) Airburst height (e) for 50-m cometary body.

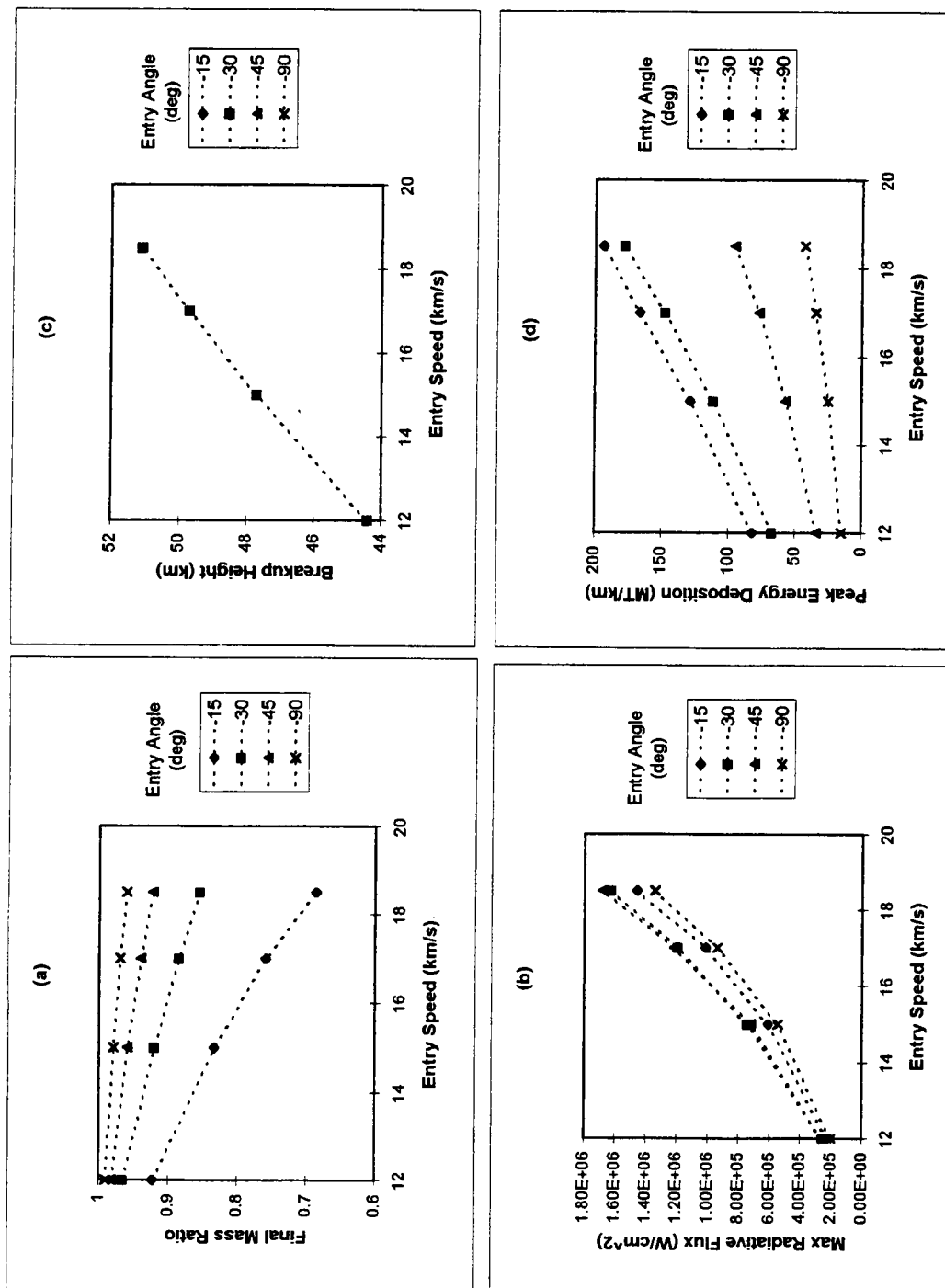


G. 15. Final mass ratio (a), max. radiative flux (b), breakup height (c) and peak energy deposition (d) for 100-m cometary body.

(e)

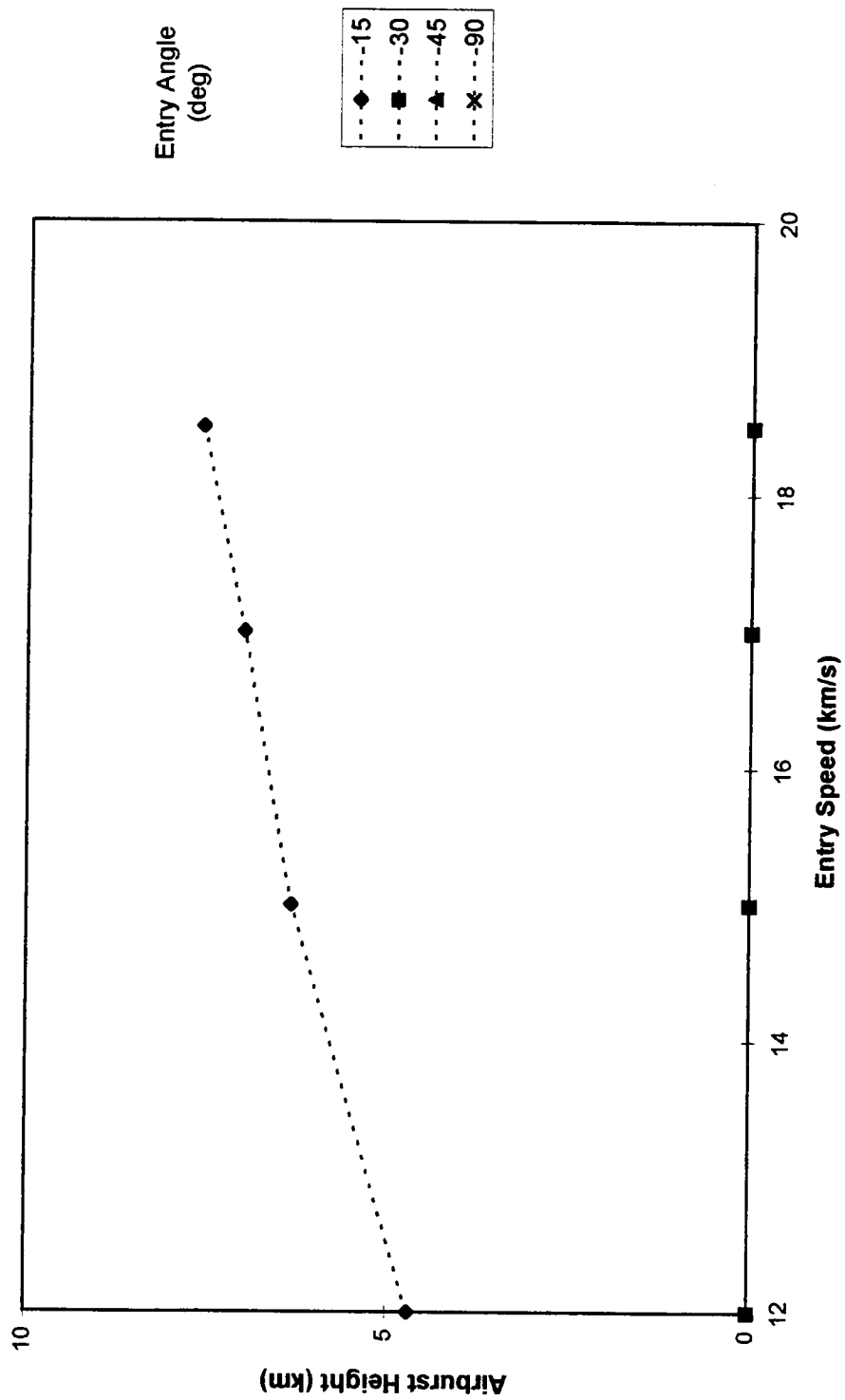


G.15. (continued) Airburst height (e) for 100-m cometary body.



G.16. Final mass ratio (a), max. radiative flux (b), breakup altitude (c) and peak energy deposition (d) for 500-m cometary body.

(e)



G. 16. (continued) Airburst height (e) for 500-m cometary body.

VITA

Richard Matthew Fought was born in Nashville, Tennessee on September 13, 1971. He attended the public school system of Nashville, Tennessee and graduated from McGavock High School in June of 1989. During his years growing up, he took an interest in science, particularly in aerospace which was offered as a course at McGavock. After considering an education in Astrophysics, he decided to pursue Aerospace Engineering, and a Bachelor of Science was earned in May of 1993 from the University of Tennessee, Knoxville. The following August he entered the University of Tennessee, Knoxville graduate program, with the aim of obtaining a Master of Science degree in Aerospace Engineering. The date of conferment for this degree is December of 1995. Using his education and computer skills developed while working on his Master's thesis, he will soon be starting work as a software engineer developing flight software.