Improvements in the FIRE Code for Simulating the Response of a Cavity Gas to Inertial Confinement Fusion Target Explosions

G.A. Moses, R.R. Peterson, and T.J. McCarville

June 1981
(revised February 1982)

UWFDM-407

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Improvements in the FIRE Code for Simulating the Response of a Cavity Gas to Inertial Confinement Fusion Target Explosions

G.A. Moses, R.R. Peterson, and T.J. McCarville

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

June 1981 (revised February 1982)

UWFDM-407

Improvements in the FIRE Code for Simulating the Response of a Cavity Gas to Inertial Confinement Fusion Target Explosions

T.J. McCarville

R.R. Peterson

G.A. Moses

Fusion Engineering Program
Nuclear Engineering Department
University of Wisconsin
Madison, WI 53706

June 1981

(Revised February 1982)

UWFDM-407

Table of Contents

FIRE - A CODE FOR COMPUTING THE RESPONSE OF AN INERTIAL CONFINEMENT FUSION CAVITY GAS TO A TARGET EXPLOSION

Thomas J. McCarville, Robert R. Peterson, and Gregory A. Moses
Department of Nuclear Engineering, University of Wisconsin, Madison, WI, USA

PROGRAM SUMMARY

Title of program: FIRE

Catalogue number:

Program obtainable from: CPC Program Library, Queen's University of Belfast, Northern Ireland (see application form in this issue)

Computer: Univac 1110; **Installation:** MACC, University of Wisconsin, Madison, Wisconsin

Operating System: Univac 1110 EXEC VIII

Programming language used: FORTRAN

High speed storage required: 60,045 words

No. of bits in a word: 36

Overlay structure: none

No. of magnetic tapes required: none

Other peripherals used: line printer, up to ten mass storage files or magnetic tapes

No. of cards in combined program and test deck:

Card punching code: EBCDIC

Keywords: inertial confinement fusion reactor design, gas protection concept, deposition of target x-rays, deposition of target debris, cavity gas response

Nature of the physical problem:
One of the methods that has been suggested for protecting the first wall of a commercial inertial confinement fusion (ICF) reactor from the x-rays and ions emitted by an exploding target is to fill the cavity with a gas [1]. The FIRE code described in this article simulates the interaction of the target x-rays and ions with the gas, and computes the response of the gas to a target explosion. The results computed by the FIRE code are useful for analyzing the thermal and mechanical response of a first wall that is protected with a cavity gas.

Method of solution:
The deposition of target x-rays into the gas is computed with an exponential attenuation model. A table of x-ray attenuation coefficients for atoms with

atomic numbers ranging from 1 to 100 and x-ray energies ranging from 0.01 keV to 1 MeV are supplied with this version of the code [2]. The initial x-rays that are absorbed ionize the gas near the target, and reduce the photoelectric attenuation coefficient for subsequent x-rays. The x-ray deposition model used by the FIRE code accounts for the reduction in the attenuation coefficient with increasing ionization [3].

The internal energy and momentum transferred from the target debris to the gas is computed from the results of an ion transport code. The results of the ion transport code are fit to analytic functions, and these analytic functions are used to estimate the rates that internal energy and momentum are deposited as a function of time and space [3].

The FIRE code simulates the response of a cavity gas to the deposition of target x-rays and ions by solving differential equations of energy and momentum conservation. These equations are solved in the Lagrangian reference frame by finite difference methods. A tabulated equation of state and tabulated Planck and Rosseland mean free paths are needed to compute the response of the gas. The MIXER code [4] has been developed to compute this data for the FIRE code. The TSTRESS code [5] then uses the heat fluxes and overpressures at the first wall computed by FIRE to analyze the response of the first wall.

Restrictions on the complexity of the problem:
The FIRE code assumes one-dimensional symmetry in computing the interaction of the target x-rays and ions with the gas, and also in computing the gas response. The cavity gas can be divided into a maximum of 97 Lagrangian zones, and either planar, cylindrical, or spherical geometry can be assumed.

The gas is assumed to be composed of only one atomic number in computing the x-ray deposition. At present, the model for computing the reduction in the photoelectric attenuation coefficient with increasing ionization is only used if the gas is neon, argon, or xenon. To compute the reduction in the attenuation coefficient for additional gases, the energy of the K, L, and M shells of the neutral gas and the number of electrons in each shell must be added to the subroutine EDATA.

Typical running time:
The CPU time required to compute the deposition of target x-rays and ions into the gas is minimal compared to the time required to compute the gas response. On the Univac 1110, the CPU time required to compute the gas response is about 2×10^{-3} s/zone/cycle.

Unusual features of the program:
The FIRE code is written in standard FORTRAN except for the manner in which the COMMON blocks are used. The COMMON blocks are listed only at the beginning of the program, where they are equated to INCLUDE statements. Thereafter, the INCLUDE statements are used to represent the COMMON blocks. The use of INCLUDE statements abbreviates the listing of a program that uses the same COMMON blocks in many subroutines, because an INCLUDE statement occupies only one line, whereas a COMMON block might occupy many lines. INCLUDE statements only have meaning to a Univac compiler, so the user may wish to replace them with the respective COMMON blocks.

References:

[1] R.W. Conn et al., "SOLASE: A Conceptual Laser Fusion Reactor Design," University of Wisconsin Fusion Engineering Program Report UWFDM-220 (Dec. 1977).

[2] K.G. Adams and F. Biggs, "Efficient Computer Access to Sandia Photon Cross Sections," Sandia Lab., SC-RR-72-0683, Albuquerque, NM (Dec. 1973).

[3] T.J. McCarville, G.A. Moses, and G.L. Kulcinski, "A Model for Depositing Inertial Confinement Fusion X-Rays and Pellet Debris into a Cavity Gas," University of Wisconsin Fusion Engineering Program Report UWFDM-406 (April 1981).

[4] R.R. Peterson and G.A. Moses, "MIXER - A Multi-Species Optical Data and Equation of State Computer Code," UWFDM-372, Univ. of Wisconsin (Sept. 1980).

[5] R.R. Peterson, R.D. Watson, W.G. Wolfer, and G.A. Moses, "TSTRESS - A Transient Stress Computer Code," UWFDM-382, Univ. of Wisconsin (Dec. 1980).

I. Introduction

One of the methods that has been suggested for protecting the first wall of a commercial inertial confinement fusion reactor from the x-rays and ions emitted by an exploding target is to fill the cavity with a gas [1]. The x-ray and ion energy is attenuated by the gas and converted to hydrodynamic and internal energy, whereas the neutrons emitted by the target are unaffected by the gas. The energy of the gas can then be transferred through heat exchangers to a working fluid.

If the gas protection concept is to be a viable method of protecting the first wall from target x-rays and ions, then the gas must be dense enough to attenuate the target x-rays and ions without degrading driver beam propagation, and the first wall must be capable of withstanding the response of the gas. The FIRE code has been developed to help determine whether these criteria can be met. The code simulates the interaction of the target x-rays and ions with the gas, as well as the gas response. The output of the code can be used to compute the thermal response of the first wall to blackbody radiation emitted by the gas and unattenuated target x-rays and ions. The results can also be used to compute the mechanical response of the first wall to gas motion [2]. The thermal and mechanical response of the first wall can then be used to estimate the first wall lifetime.

This documentation describes the equations solved by the FIRE code and the numerical methods used to solve these equations. Some of the physical models used by the code are unique, such as the two temperature radiation diffusion model, but the development of these models has been documented elsewhere and will not be repeated here.

II. Target X-Ray Deposition

The time required for the deposition of target x-rays into the cavity gas ($\sim 10^{-8}$ s) is much shorter than the hydrodynamic response time, so the gas is stationary as the x-rays are deposited. Hence, the thermodynamic state of the gas after x-ray deposition can be used as an initial condition in computing the gas response to the exploding target. The code assumes exponential x-ray attenuation, which should be adequate for most target x-ray spectra [3]. As the code is presently written, gases composed of only one element can be used to attenuate the x-rays. A table of attenuation coefficients for elements with atomic numbers ranging from 1 to 100 and x-ray energies ranging from 0.01 to 1000 keV are provided with the FIRE code [4].

The initial x-rays that are photoabsorbed by the gas reduce the number of bound electrons available to interact with subsequent x-rays, so the attenuation coefficient decreases as x-rays are deposited. A method of modifying the photoelectric attenuation coefficient of the gas to account for increasing ionization has been developed for the FIRE code [3]. By counting the number of electrons ejected from each electron shell as the x-rays are deposited, the contribution to the photoelectric attenuation coefficient from each shell can be reduced by an amount proportional to the number of missing electrons. Although simple, this model does at least give the correct attenuation for the limiting cases of a completely neutral and completely ionized atom. The accuracy of this model at intermediate levels of ionization has not been determined. In this version of the FIRE code, the model for computing the reduction in photoelectric absorption can only be used with neon, argon or xenon gas. To extend the model to other gases, the number of electrons in each

shell of the neutral atom and the energies of the K, L, and M shells must be added to the EDATA subroutine.

The x-ray spectrum emitted by the target can be assumed to be Planckian, or an arbitrary histogram can be input. In either case, the code divides the x-ray spectrum into energy groups, giving each group a constant energy width. The x-rays in each group are then attenuated as if they were monoenergetic.

III. The Equation of Motion

THe equations solved by the FIRE code are written in the Lagrangian coordinate system, meaning the equations describe a point that moves with the local fluid velocity. The advantage of this coordinate system is that the mass flux is zero, so the conservation equations are simplified considerably. The FIRE code automatically chooses a suitable Lagrangian mesh from the cavity geometry and dimensions input by the user. Either planar, cylindrical, or spherical coordinates can be assumed. The units used by the FIRE code are

length	- cm
time	- second
mass	- gram
speed	- cm/s
energy	- Joule
temperature	- eV
pressure	- J/cm^3
charge	- esu

Figure 1 illustrates the index system used to denote spatial boundaries. The Lagrangian mass of each zone, $m_{o_{j-1/2}}$, is defined by integrating

$$\partial m_o = \rho(r)\, r^{\delta-1}\, dr \qquad (1)$$

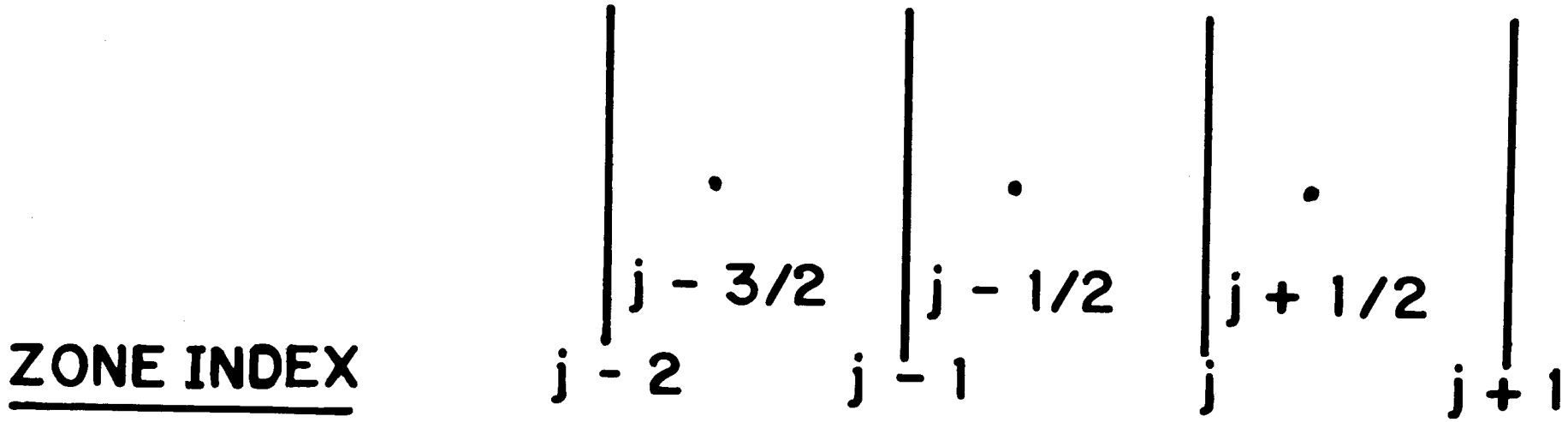


Figure 1. The index system used to denote spatial boundaries.

from boundary j to j+1, where ρ is the mass density and r is the spatial coordinate. The symbol δ denotes planar (δ=1), cylindrical (δ=2), or spherical coordinates (δ=3). The Lagrangian mass is a constant for each zone, so it is a convenient replacement for the product $\rho(r)r^{\delta-1}dr$ when writing the conservation equations in finite difference form. The average Lagrangian mass of two zones, m_{o_j}, will appear in the finite difference form of the equation of motion, and is defined as

$$m_{o_j} = \frac{(m_{o_{j+1/2}} + m_{o_{j-1/2}})}{2} \quad . \tag{2}$$

In Lagrangian coordinates, the equation of motion is

$$\frac{\partial u}{\partial t} = -V \frac{\partial}{\partial r}(P + q) - \frac{V}{V_d} \frac{\partial u_{dr}}{\partial t} \quad , \tag{3}$$

where: V is the specific volume of the gas,

V_d is the specific volume of the debris,

u is the radial velocity of the gas,

u_{dr} is the radial velocity of the debris,

P is the sum of the gas and radiation pressure,

q is the artificial viscosity [5].

The explicit, finite difference form of Eq. (3) that is solved by the FIRE code is

$$\frac{u_j^{n+1/2} - u_j^{n-1/2}}{\Delta t^n} = - \frac{(r_j^n)^{\delta-1}[\Delta P_j^n + \Delta q_j^{n-1/2}]}{\Delta m_{o_j}} - \frac{1}{G\Delta m_{o_j}} \frac{\Delta MOM_j^n}{\Delta t^n} \quad , \tag{4}$$

where: G = 1 for δ=1 (planar coordinates),

$G = 2\pi$ for $\delta=2$ (cylindrical coordinates),

$G = 4\pi$ for $\delta=3$ (spherical coordinates),

and ΔMOM_j^n is the momentum lost by the debris during Δt^n.

The superscript n is the time index. The terms in brackets are defined as

$$\Delta P_j^n = P_{j+1/2}^n - P_{j-1/2}^n \quad \text{and} \quad \Delta q_j^{n-1/2} = q_{j+1/2}^{n-1/2} - q_{j-1/2}^{n-1/2} \ . \tag{5}$$

The artificial viscosity is a function of the zone specific volume, so to make Eq. (4) explicit, Δq_j is evaluated at $t^{n-1/2}$. The artificial viscosity used in the FIRE code is

$$\begin{aligned} q_{j-1/2}^{n-1/2} &= 0 && \text{for } \dot{V}_{j-1/2}^{n-1/2} > 0 \ , \\ &= \frac{\sqrt{2}\,(u_j^{n-1/2} - u_{j-1}^{n-1/2})}{V_{j-1/2}^{n-1/2}} && \text{for } \dot{V}_{j-1/2}^{n-1/2} < 0 \ . \end{aligned} \tag{6}$$

The quantity $\dot{V}$ is the time rate of change of the specific volume.

The gas pressure, P_P, is computed from the perfect gas law,

$$P_{P_{j\pm1/2}}^n = 1.602 \times 10^{-19} \, (1 + Z_{j\pm1/2}^n) * n_{P_{j\pm1/2}}^n * T_{P_{j\pm1/2}}^n \ , \tag{7}$$

where: Z is the charge state of the gas,

n_P is the number density of gas atoms,

T_p is the gas temperature.

The radiation pressure, P_R, is computed from the radiation energy density, E_R, by

$$P^n_{R_{j\pm1/2}} = \frac{1}{3}\left(\frac{E_R}{V}\right)^n_{j\pm1/2} \quad , \tag{8}$$

where the radiation energy density has been assumed to be isotropic. Although in some instances the radiation field may not be isotropic, the radiation pressure is very small compared to the gas pressure for the temperature and densities of interest here, so the assumption of an isotropic radiation field does not affect the gas motion.

After solving Eq. (4) for $u_j^{n+1/2}$, the new radii are computed from

$$r_j^{n+1} = r_j^n + u_j^{n+1/2}\ \Delta t^{n+1/2} \quad . \tag{9}$$

New specific volumes and other quantities are then computed in preparation for the next time step.

To evaluate the momentum imparted by the target debris, the debris is assumed to consist of only one element. The initial energy spectrum can be assumed to be Maxwellian or Gaussian, or an arbitrary histogram can be input. The code divides the initial energy spectrum into energy groups that have equally spaced increments in velocity, and assigns an equal fraction of the debris mass to each group. The total momentum deposited into a gas zone is the sum of the contributions from each group. However, to simplify the notation in the equations that follow, the index denoting the energy group will be omitted. The momentum imparted by the debris, in finite difference form, is

$$\Delta MOM^n_j = \Delta m^n_{d_{j-1/2}}\left(u^{n+1/2}_{dr} - u^{n-1/2}_{dr}\right) \quad . \tag{10}$$

The quantity $\Delta m^n_{d_{j-1/2}}$ is the debris mass in zone j-1/2, and is evaluated from analytic functions that are programmed into the FIRE code [3]. The analytic functions simulate ion transport in the gas. The quantities $u_{dr}^{n\pm1/2}$ are the average radial speed of ions in an energy group, so are independent of the spatial index. Equation (10) can be written in the form evaluated by the FIRE code by noting that at time $t^{n+1/2}$,

$$u_{dr}^{n+1/2} = u_{dr}^{n-1/2} + \left(\frac{du_{dr}}{dt}\right)^{n-1/2} \Delta t^n \quad . \tag{11}$$

The time derivative u_{dr} has been written as a total derivative because the average deceleration of each energy group is independent of the spatial index. The deceleration is also evaluated from the analytic expressions that are programmed into the FIRE code. Combining Eqs. (10) and (11) gives the expression evaluated in the code,

$$\Delta MOM_j^n = \Delta m^n_{d_{j-1/2}} \left(\frac{du_{dr}}{dt}\right)^{n-1/2} \Delta t^n \quad . \tag{12}$$

The analytic expressions that are programmed into the FIRE code and used to evaluate the deceleration and spatial distribution of the debris are functions of the average radial distance that the debris travel through the gas, r_d. From the expression

$$u_{dr}^{n+1/2} = \frac{r_d^{n+1} - r_d^n}{\Delta t^{n+1/2}} \quad , \tag{13}$$

and Eq. (11), the distance the debris have traveled through the gas (in the Lagrangian reference frame), is

$$r_d^{n+1} = r_d^n + \Delta t^{n+1/2}\, u_{dr}^{n-1/2} + \left(\frac{du_{dr}}{dt}\right)^{n-1/2} \Delta t^n \Delta t^{n+1/2} \quad . \tag{14}$$

When computing the distance traveled by the debris in the Eularian reference frame, the gas motion is accounted for.

IV. The Energy Equations

Because of the high temperatures encountered in the cavity gas (up to tens of eV), thermal radiation can be the dominant energy transport mechanism. The FIRE code uses flux limited diffusion to model radiation transport. The absorption and emission of thermal radiation are strongly temperature dependent, so the radiation diffusion equation is solved simultaneously with the temperature equation. The equations solved by the FIRE code are

$$C_v \frac{\partial T_P}{\partial t} = \frac{\partial}{\partial m_o}\left(r^{\delta-1} K_P \frac{\partial T_P}{\partial r}\right) - \frac{\partial P_P}{\partial T_P} \dot{V} T_P - q\dot{V} + \omega_R E_R - \omega_P T_P + S \tag{15-a}$$

$$\frac{\partial E_R}{\partial t} = \frac{\partial}{\partial m_o}\left(r^{\delta-1} K_R \frac{\partial E_R}{\partial r}\right) - \frac{\rho E_R}{3} \dot{V} \qquad - \omega_R E_R + \omega_P T_P \tag{15-b}$$

where: C_v is the specific heat at constant volume,

K_P is the gas thermal conductivity,

K_R is the radiation thermal conductivity,

ω_R is the radiation absorption coefficient,

ω_P is the radiation emission coefficient,

S is the rate that internal energy is added by the debris.

In writing Eq. (15-a), the thermodynamic identity [6]

$$\frac{\partial E_P}{\partial t} + P_P \dot{V} = C_v \frac{\partial T_P}{\partial t} + \frac{\partial P_P}{\partial T_P} \dot{V} T_P \tag{16}$$

was used to replace $\frac{\partial E_P}{\partial t}$ and $P_P \dot{V}$ with terms involving T_p. To simplify the notation in the finite difference equations that follow, the time index of quantities evaluated at $t^{n+1/2}$ will be omitted. In fully implicit finite difference form, Eqs. (15-a) and (15-b) are

$$C_{v_{j-1/2}} \frac{T_{P_{j-1/2}}^{n+1} - T_{P_{j-1/2}}^{n}}{\Delta t^{n+1/2}} = \frac{1}{\Delta m_{o_{j-1/2}}} \left[\frac{r_j^{\delta-1}}{(\frac{\Delta r}{K_P})_j} (T_{P_{j+1/2}}^{n+1} - T_{P_{j-1/2}}^{n+1}) \right.$$

$$\left. - \frac{r_{j-1}^{\delta-1}}{(\frac{\Delta r}{K_P})_{j-1}} (T_{P_{j-1/2}}^{n+1} - T_{P_{j-3/2}}^{n+1}) \right] - (\frac{\partial P_P}{\partial T_P})_{j-1/2} \dot{V}_{j-1/2} T_{P_{j-1/2}}^{n+1} \qquad (17\text{-a})$$

$$- q_{j-1/2} \dot{V}_{j-1/2} + \omega_{R_{j-1/2}} E_{R_{j-1/2}}^{n+1} - \omega_{P_{j-1/2}} T_{P_{j-1/2}}^{n+1} + S_{j-1/2}^{n}$$

and

$$\frac{E_{R_{j-1/2}}^{n+1} - E_{R_{j-1/2}}^{n}}{\Delta t^{n+1/2}} = \frac{1}{\Delta m_{o_{j-1/2}}} \left[\frac{r_j^{\delta-1}}{(\frac{\Delta r}{K_R})_j + \frac{\Delta E_{R_j}}{F_{R_j}}} (E_{R_{j+1/2}}^{n+1} - E_{R_{j-1/2}}^{n+1}) \right.$$

$$\left. - \frac{r_{j-1}^{\delta-1}}{(\frac{\Delta r}{K_R})_{j-1} + \frac{\Delta E_{R_{j-1}}}{F_{R_{j-1}}}} (E_{R_{j-1/2}}^{n+1} - E_{R_{j-3/2}}^{n+1}) \right] - E_{R_{j-1/2}}^{n+1} \frac{\dot{V}_{n-1/2}}{3V_{j-1/2}} \qquad (17\text{-b})$$

$$- \omega_{R_{j-1/2}} E_{R_{j-1/2}}^{n+1} + \omega_{P_{j-1/2}} T_{P_{j-1/2}}^{n+1} .$$

The denominators of the terms in brackets represent the resistance per unit area to thermal and radiative diffusion between zone centers. For instance,

$$\left(\frac{\Delta r}{K_P}\right)_j = \frac{1}{2}\left(\frac{r_{j-1} - r_j}{K_{P_{j+1/2}}} + \frac{r_j - r_{j-1}}{K_{P_{j-1/2}}}\right) \quad , \tag{18}$$

and so on for $\left(\frac{\Delta r}{K_P}\right)_{j-1}$, $\left(\frac{\Delta r}{K_R}\right)_j$, and $\left(\frac{\Delta r}{K_R}\right)_{j-1}$. Equations (17-a) and (17-b) can be written in matrix form as

$$\underline{\underline{\alpha}}_{j-1/2}\left(\underline{\theta}^{n+1}_{j-1/2} - \underline{\theta}^{n}_{j-1/2}\right) = \underline{\underline{a}}_j\left(\underline{\theta}^{n+1}_{j+1/2} - \underline{\theta}^{n+1}_{j-1/2}\right) - \underline{\underline{a}}_{j-1}\left(\underline{\theta}^{n+1}_{j-1/2} - \underline{\theta}^{n-1}_{j-3/2}\right) \tag{19}$$

$$- \underline{\underline{\gamma}}_{j-1/2}\,\underline{\theta}^{n+1}_{j-1/2} - \underline{\underline{\omega}}_{j-1/2}\,\underline{\theta}^{n+1}_{j+1/2} + \underline{\beta}_{j-1/2}$$

where

$$\underline{\underline{\alpha}}_{j-1/2} = \begin{pmatrix} C_{v_{j-1/2}} & 0 \\ 0 & 1 \end{pmatrix} \frac{\Delta m_{o_{j-1/2}}}{\Delta t^{n-1/2}} \quad ,$$

$$\underline{\underline{a}}_j = \begin{pmatrix} r_j^{\delta-1}/(\Delta r/K_P)_j & 0 \\ 0 & r_j^{\delta-1}/\left((\Delta r/K_R)_j + \Delta E_{R_j}/F_{R_j}\right) \end{pmatrix} ,$$

$$\underline{\underline{\gamma}}_{j-1/2} = \begin{pmatrix} (\partial P_P/\partial T_P)_{j-1/2}\dot{V}_{j-1/2} & 0 \\ 0 & \dot{V}_{j-1/2}/3V_{j-1/2} \end{pmatrix} \Delta m_{o_{j-1/2}} ,$$

$$\underline{\underline{\omega}}_{j-1/2} = \begin{pmatrix} \omega_P & -\omega_R \\ -\omega_P & \omega_R \end{pmatrix}_{j-1/2} \Delta m_{o_{j-1/2}} ,$$

$$\underline{\beta}_{j-1/2} = \begin{pmatrix} -q_{j-1/2}\,\dot{V}_{j-1/2} + S^{n}_{j-1/2} \\ 0 \end{pmatrix} \Delta m_{o_{j-1/2}} \quad ,$$

and $$\underline{\theta}^{n+1}_{j-1/2} = \begin{pmatrix} T_{P}{}^{n+1}_{j-1/2} \\ E_{R}{}^{n+1}_{j-1/2} \end{pmatrix} \quad .$$

A more compact matrix equation can be written by redefining the coefficients as follows:

$$\underline{\underline{A}}_{j-1/2} = \underline{\underline{a}}_{j} \quad ,$$

$$\underline{\underline{B}}_{j-1/2} = \underline{\underline{\alpha}}_{j-1/2} + \underline{\underline{a}}_{j} + \underline{\underline{a}}_{j-1} + \underline{\underline{\gamma}}_{j-1/2} + \underline{\underline{\omega}}_{j-1/2} \quad ,$$

$$\underline{\underline{C}}_{j-1/2} = \underline{\underline{a}}_{j-1} \quad ,$$

$$\underline{D}_{j-1/2} = \underline{\underline{\alpha}}_{j-1/2}\,\underline{\theta}^{n}_{j-1/2} + \underline{\beta}_{j-1/2} \quad .$$

With these redefinitions, Eq. (19) becomes

$$-\underline{\underline{A}}_{j-1/2}\,\underline{\theta}^{n+1}_{j+1/2} + \underline{\underline{B}}_{j-1/2}\,\underline{\theta}^{n+1}_{j-1/2} - \underline{\underline{C}}_{j-1/2}\,\underline{\theta}^{n+1}_{j-3/2} = \underline{D}_{j-1/2} \quad . \tag{20}$$

If JMAX is the number of zone boundaries, then Eq. (20) represents a JMAX by JMAX tridiagonal matrix equation that has two by two matrices for elements. If the coefficients of Eq. (20) are evaluated at t^{n}, it can be solved by

Gaussian elimination. Solutions can be shown to be of the form [7]

$$\underline{\theta}^{n+1}_{j-1/2} = \underline{\underline{E}}_{j-1/2}\,\underline{\theta}^{n+1}_{j+1/2} + \underline{F}_{j-1/2} \quad , \quad \text{for } 1 \leq j < \text{JMAX}$$

$$\theta^{n+1}_{\text{JMAX}+1/2} = \text{BOUNDARY CONDITIONS} \quad , \quad \text{for } j = \text{JMAX} \quad . \tag{21}$$

The $\underline{\underline{E}}$ matrix and $\underline{F}$ vector can be related to known quantities by decreasing the spatial index of Eq. (21) by one, and substituted into Eq. (20). One finds that

$$\underline{\underline{E}}_j = (\underline{\underline{B}}_{j-1/2} - \underline{\underline{C}}_{j-1/2} * \underline{\underline{E}}_{j-3/2})^{-1} * \underline{\underline{A}}_{j-1/2} \quad ,$$

and

$$\underline{F}_{j-1/2} = (\underline{\underline{B}}_{j-1/2} - \underline{\underline{C}}_{j-1/2} * \underline{\underline{E}}_{j-3/2})^{-1} * (\underline{D}_{j-1/2} + \underline{\underline{C}}_{j-1/2} * \underline{F}_{j-3/2}) \tag{22}$$

for $1 \leq j < \text{JMAX}$, and

$$\underline{\underline{E}}_{1/2} = (\underline{\underline{B}}_{1/2})^{-1} * \underline{\underline{A}}_{1/2} \quad ,$$

$$\underline{F}_{1/2} = (\underline{\underline{B}}_{1/2})^{-1} * \underline{D}_{1/2} \quad ,$$

for j=1. To solve Eq. (21), a sweep is made from the first zone out to the wall to evaluate $\underline{\underline{E}}$ and $\underline{F}$, and then back to the center to evaluate the components of the $\underline{\theta}^{n+1}$ vector.

The expression for the thermal conductivity of the gas, K_p, that is used in the FIRE code is the theoretical expression developed for electrons interaction with stationary ions [8]. The theoretical expression includes an

experimentally determined constant to prevent K_P from diverging as the average ionization state approaches zero. The expression is

$$K_P = 20 \left(\frac{2}{\pi}\right)^{3/2} \frac{T_P^{5/2}}{\sqrt{m_e}\, e^4 (Z + 4) \ln \Lambda} , \tag{23}$$

where: e is the electron charge,

m_e is the electron mass,

$\ln \Lambda$ is the Coulomb logarithm.

To save computational effort, the Coulomb logarithm is computed from a curve fit that has an accuracy better than 10% for $\ln \Lambda$ greater than 5. In finite difference form, the thermal conductivities are

$$\begin{aligned} K_{P_{j\pm1/2}} &= \frac{1.22 \times 10^2 \, T_{P_j}^2 \, T_{P_{j\pm1/2}}^{1/2}}{(4 + Z_{j\pm1/2}) \ln \Lambda_{j\pm1/2}} , \\ K_{P_{j-3/2}} &= \frac{1.22 \times 10^2 \, T_{P_{j-1}}^2 \, T_{P_{j-3/2}}^{1/2}}{(4 + Z_{j-3/2}) \ln \Lambda_{j-3/2}} . \end{aligned} \tag{24}$$

The T_P^2 terms are evaluated at the zone boundaries rather than the zone centers to enhance the numerical stability of the solution.

The expression for the radiation conductivity that is used in the FIRE code is a frequency averaged value. If the radiation mean free path is much smaller than the gradients in the radiation energy density, then the frequency dependent radiation flux, $q_{R\nu}$, is given by [9]

$$q_{R\nu} = \frac{\ell_\nu(T_P)\, c}{3V} \frac{\partial E_{R\nu}}{\partial r} , \tag{25}$$

where: ℓ_ν is the frequency dependent radiation mean free path,

$E_{R\nu}$ is the frequency dependent radiation specific energy,

c is the speed of light.

The frequency averaged conductivity is arrived at by integrating Eq. (25) over frequency. The frequency dependence of ℓ_ν is known from theoretical models of radiation absorption, but in general the frequency dependence of $E_{R\nu}$ is not known prior to solving the frequency dependent radiation transport equations. For the radiation diffusion model used in the FIRE code, the frequency dependence of $E_{R\nu}$ is assumed to be a dilute Planckian, that is

$$E_{R\nu} = \varepsilon V \frac{8\pi h\nu^3}{c^3} \frac{1}{\exp\left(\frac{h\nu}{T_R}\right) - 1} \quad , \tag{26}$$

where ε is a proportionality factor and T_R is the radiation temperature. The radiation temperature is defined so as to reflect the temperature of the gas that emitted the radiation occupying the point of interest. The radiation temperature at a point is evaluated by averaging the temperature of the transported radiation, the temperature of the emitted radiation, and the temperature of the radiation already present. In finite difference form, this average is

$$T^{n+1}_{R_{j+1/2}} = \frac{W_1 * T^{n+1/2}_{R_{j-1/2}} + W_2 * T^{n+1/2}_{R_{j+3/2}} + W_3 * T^{n+1/2}_{P_{j+1/2}} + W_4 * T^{n+1/2}_{R_{j+1/2}}}{W_1 + W_2 + W_3 + W_4} \qquad 1 \leq j < JMAX \tag{27}$$

where the weighting functions are defined as

$$W_1 = \left(\frac{q_R r^{\delta-1} \Delta t}{\Delta m_o}\right)^{n+1/2}_{j-1/2} \qquad \text{if } q_{R_{j-1/2}} > 0$$

$$= 0 \qquad \text{if } q_{R_{j-1/2}} < 0 \tag{28}$$

$$W_2 = 0 \qquad \text{if } q_{R_{j+3/2}} > 0$$

$$= \left(\frac{q_R r^{\delta-1} \Delta t}{\Delta m_o}\right)^{n+1/2}_{j+3/2} \qquad \text{if } q_{R_{j+3/2}} < 0 \tag{29}$$

$$W_3 = (\omega_P T_P \Delta t)^{n+1/2}_{j+1/2} \tag{30}$$

$$W_4 = (E_R)^{n+1/2}_{j+1/2} \quad . \tag{31}$$

The frequency averaged radiation flux across zone boundaries is represented by q_R in Eqs (28) and (29), which after integrating Eq. (25) over frequency can be written as

$$q_R = - \frac{\ell(T_P,T_R)c}{3V} \frac{\partial E_R}{\partial r} \quad , \tag{32}$$

where

$$\ell(T_P,T_R) = \frac{15}{4\pi^4} \int_0^\infty \ell_\nu(T_P) \frac{U^4 e^{-U}}{(1 - e^{-U})^2} dU \quad , \tag{33}$$

and

$$U(T_R) = \frac{h\nu}{T_R} \quad . \tag{34}$$

Equation (33) defines the Rosseland mean free path (including spontaneous emission [9]), and is a function of the gas density, the local gas temperature, and the local radiation temperature. From Eq. (32), the frequency averaged radiation conductivity can be written in finite difference form as

$$K_{R_{j\pm1/2}} = 10^{10} \frac{\ell_{j\pm1/2}}{V_{j\pm1/2}} \quad ,$$

$$K_{R_{j-3/2}} = 10^{10} \frac{\ell_{j-3/2}}{V_{j-3/2}} \quad . \tag{35}$$

If the Rosseland mean free path is larger than the spatial zoning, then radiation may stream from zone to zone without being absorbed. In this case the diffusion model overestimates the radiation flux, and must be modified with a flux limiter. The maximum radiation flux, $\frac{cE_R}{V}$, occurs when the radiation intensity of free streaming radiation approaches complete anisotropy. If the radiation intensity is completely isotropic, then the flux limit is $\frac{cE_R}{4V}$. This latter expression is used in the FIRE code. In finite difference form, the flux limit is

$$F_j = 3.75 \times 10^9 \left[\left(\frac{E_R}{V}\right)^{n+1/2}_{j+1/2} + \left(\frac{E_R}{V}\right)^{n+1/2}_{j-1/2}\right] \qquad 1 < j < JMAX$$

$$F_{JMAX} = 7.5 \times 10^9 \left(\frac{E_R}{V}\right)^{n+1/2}_{JMAX+1/2} \qquad j = JMAX \quad . \tag{36}$$

The expression for the absorption coefficient used in the FIRE code can be arrived at by integrating the frequency dependent absorption rate over frequency. From the definition of the radiation mean free path, the frequency dependent absorption rate is

$$\omega_{R\nu} E_{R\nu} = \frac{cE_{R\nu}}{\ell_\nu(T_p)} \quad . \tag{37}$$

Using Eq. (26) to integrate Eq. (37) over frequency results in (including spontaneous emission)

$$\omega_R E_R = \frac{cE_R}{\ell_1(T_R,T_P)} \quad , \tag{38}$$

where

$$\frac{1}{\ell_1(T_P,T_R)} = \frac{15}{\pi^4} \int_0^\infty \frac{U^3(T_R)\, dU}{\ell_\nu(T_P)(e^{U(T_R)} - 1)} \quad , \tag{39}$$

and

$$U(T_R) = \frac{h\nu}{T_R} \quad . \tag{40}$$

Equation (39) defines the nonequilibrium Planck mean free path, which is the frequency averaged distance that radiation with a temperature T_R will travel in a gas at temperature T_P before being absorbed. The finite difference form of the absorption coefficient is

$$\omega_{R_{j-1/2}}^{n+1/2} = \frac{3 \times 10^{10}}{\ell_1(T_R,T_P)_{j-1/2}^{n+1/2}} \quad . \tag{41}$$

The expression for the radiation emission coefficient that is used in the FIRE code is arrived at by assuming that the gas is in local thermodynamic equilibrium (LTE) [10]. The gas is in LTE if the electrons and ions are in collisional equilibrium with each other. The radiation spectrum emitted by a gas in LTE has a Planckian frequency distribution, because the electron-ion recombination processes are the same as those that occur in a blackbody. Then the frequency dependent emission rate can be written as

$$\omega_{P\nu} T_P = \frac{cV}{\ell_\nu(T_P)} \frac{8\pi h\nu^3}{c^3} \frac{1}{\exp\left(\frac{h\nu}{T_P}\right) - 1} \quad . \tag{42}$$

Averaging Eq. (42) over frequency yields

$$\omega_P T_P = V \frac{4\sigma T_P^4}{\ell_1(T_P)} \quad , \tag{43}$$

where

$$\frac{1}{\ell_1(T_P)} = \frac{15}{\pi^4} \int_0^\infty \frac{U^3(T_P)\, dU}{\ell_\nu(T_P)(e^{U(T_P)} - 1)} \quad , \tag{44}$$

and

$$U(T_P) = \frac{h\nu}{T_P} \quad . \tag{45}$$

Equation (43) defines the equilibrium Planck mean free path, which is the average distance that radiation at a temperature T_P will travel in a gas at temperature T_P before being absorbed. The finite difference form of the emission rate is

$$\omega_{P_{j-1/2}}^{n+1/2} = 4.12 \times 10^5 \left[\frac{VT_P^3}{\ell_1(T_P)}\right]_{j-1/2}^{n+1/2} \quad . \tag{46}$$

An expression for the internal energy deposition rate from target debris can be arrived at by equating the decrease in debris kinetic energy to the increase in the kinetic and internal energy of the gas:

$$-\frac{1}{V_d} u_d \frac{\partial u_d}{\partial t} = \frac{S}{V} + \frac{u}{V} \left(\frac{\partial u}{\partial t}\right)_{P=0} \quad , \tag{47}$$

where u_d is the speed of the debris ions, and the quantity in parenthesis is the acceleration of the gas in the radial direction due to the debris alone, that is, excluding the pressure forces. From conservation of debris momentum it is clear that

$$\frac{1}{V} \left(\frac{\partial u}{\partial t}\right)_{P=0} = -\frac{1}{V_d} \frac{\partial u_{dr}}{\partial t} \quad . \tag{48}$$

Note that $u_{dr} < u_d$ if the trajectory of the debris ions is not straight as they slow down in the gas (such as when the ions scatter off the gas nuclei). Combining Eqs. (47) and (48) and solving for the internal energy source term gives

$$S = - \frac{V}{V_d} u_d \frac{\partial u_d}{\partial t} + \frac{V}{V_d} u \frac{\partial u_{dr}}{\partial t} \quad . \tag{49}$$

In finite difference form, Eq. (49) is

$$S^n_{j-1/2} = - \frac{\Delta m_{d_{j-1/2}}}{\Delta m_{o_{j-1/2}}} \frac{\Delta KE^n_{d_{j-1/2}}}{\Delta t^{n-1/2}} + \frac{u_d^{n+1/2}}{\Delta m_{o_{j-1/2}}} \frac{\Delta MOM^n_{j-1/2}}{\Delta t^{n+1/2}} \quad , \tag{50}$$

where ΔKE_d is the change in debris kinetic energy during Δt^n. The change in debris kinetic energy, the change in debris momentum, and the debris mass are all evaluated from the analytic functions stored in the FIRE code that simulate ion transport in the gas [3].

V. The Equation of State and Opacity Tables

There are five quantities that must be supplied in tabular form by the user of the FIRE code. These are

$Z(n_p,T_p)$	Charge State
$E_p(n_p,T_p)$	Specific Internal Energy
$C_v(n_p,T_p)$	Specific Heat
$\ell(n_p,T_p,T_R)$	Rosseland Mean Free Path
$\ell_1(n_p,T_p,T_R)$	Planck Mean Free Path

These tables are generated for FIRE by the MIXER code [11]. Logarithmic interpolation is used to interpolate between points in the tables. For instance, the charge state is stored as log $Z(\log n_p, \log T_p)$. In what follows, the indices associated with the dependent variables are

$$K - \log T_R \quad ,$$

$$L - \log T_p \quad ,$$

$$M - \log n_p \quad .$$

Points in the two dimensional tables can be represented as a two-dimensional grid, as shown in Fig. 2. The indices with stars denote the location of a quantity located between points in the table, for instance log $Z(L^*,M^*)$. To compute the desired quantity we first interpolate along the M axis:

$$\log Z(L,M^*) = \log Z(L,M) + \frac{Z(L,M+1) - Z(L,M)}{n_p(M+1) - n_p(M)} * (n_p - n_p(M)) \quad , \tag{51}$$

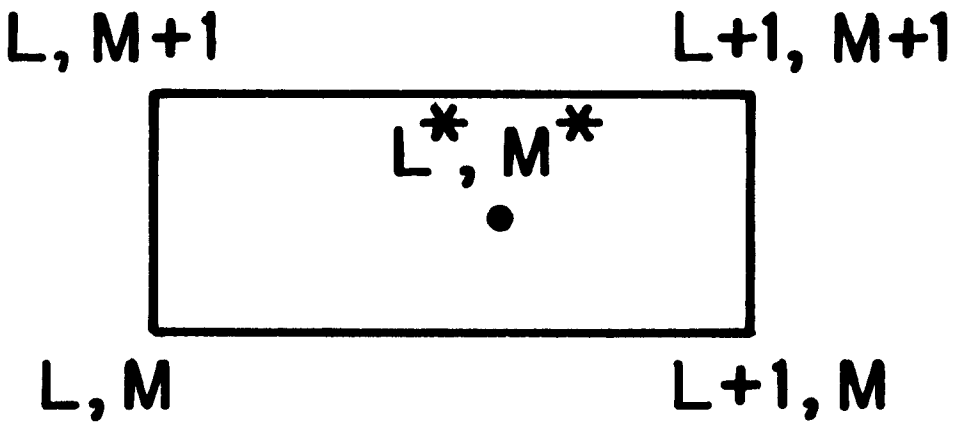
$$\log Z(L+1,M^*) = \log Z(L+1,M) + \frac{\log Z(L+1,M+1) - \log Z(L+1,M)}{n_p(M+1) - n_p(M)} * (n_p - n_p(M)) \quad , \tag{52}$$

where n_p is the number density corresponding to log $Z(L^*,M^*)$. Now interpolating along the L axis,

$$\log Z(L^*,M^*) = \log (L,M^*) + \frac{\log Z(L+1,M^*) - \log Z(L,M^*)}{T_p(L+1) - T_p(L)} * (T_p - T_p(L)) \quad , \tag{53}$$

where T_p is the temperature corresponding to log $Z(L^*,M^*)$.

Figure 2. The indices used to interpolate in a two-dimensional grid.



The grids used to interpolate in the three-dimensional tables are shown in Fig. 3. First we interpolate for log $\ell(M,K^*,L^*)$ and log $\ell(M+1,K^*,L^*)$ in the manner prescribed above. Then interpolating in the third dimension,

$$\log \ell(M^*,K^*,L^*) = \log \ell(M,K^*,L^*) + \frac{\log \ell(M+1,K^*,L^*) - \log \ell(M,K^*,L^*)}{n_p(M+1) - n_p(M)} (n_p - n_p(M)) \quad . \tag{54}$$

If the gas temperature computed by solving the energy equations is less than the lowest temperature in the equation of state tables, then the code automatically computes Z and E_p by interpolating between the bounds of the table and the values for a perfect un-ionized gas. This procedure preserves the accuracy of the calculation at low temperatures. The number density, n_p, should never exceed the bounds of the tables, or inaccurate results will be obtained.

VI. The Energy Conservation Check

At the end of each time step, a check is made to insure that the difference equations are conserving energy. This is done by integrating the energy equations over time and space. The two energy equations can be written as

$$\dot{E}_p + P_p\dot{V} = \dot{S}_p + \dot{Q}_{PR} + \dot{Q}_{DP} \tag{55}$$

$$\dot{E}_R + P_R\dot{V} = \dot{S}_R - \dot{Q}_{PR} + \dot{Q}_{DR} \tag{56}$$

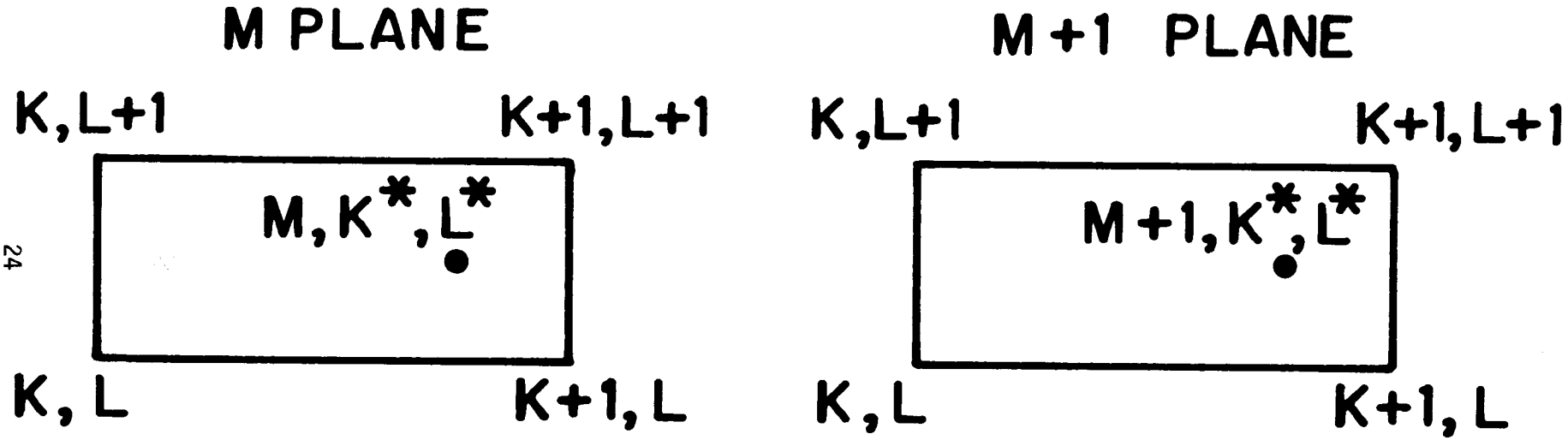


Figure 3. The indices used to interpolate in the three-dimensional tables.

where: $\dot{Q}_{PR} = \omega_R E_R - \omega_P T_P$

$$\dot{Q}_{Dx} = \frac{\partial}{\partial m_o} r^{\delta-1} K_x \frac{\partial(T_P \text{ or } E_R)}{\partial r} \qquad \text{where } x = P \text{ or } R \ ,$$

S_P = source of internal energy,

S_R = source of radiation (S_R = 0 in this version of the code).

After integration over space and time these equations take the form

GAS $$e_P^{n+1} + T^{n+1} = e_P^o + T^o + H_P^{n+1} + E_{RP}^{n+1} - F_P^{n+1} - W_P^{n+1} - G_R^{n+1} \qquad (57)$$

RADIATION $$e_R^{n+1} = e_R^o + H_R^{n+1} - E_{RP}^{n+1} - F_R^{n+1} - W_R^{n+1} + G_R^{n+1} \qquad (58)$$

TOTAL $$e^{n+1} + T^{n+1} = e^o + T^o + H^{n+1} - F^{n+1} - W^{n+1} \qquad (59)$$

The physical definitions of each term are:

e_x -- total internal energy of the gas or radiation.

T -- total kinetic energy of the gas.

H_x -- total source of energy to the gas or radiation.

E_{RP} -- total radiation energy exchanged between the gas to the radiation field.

W_x -- total work done on the outer boundary by the gas or radiation. These are zero in the FIRE code because the outer edge of the gas is stationary.

F_x -- total energy conducted to the first wall from the gas or radiation.

G_R -- work exchanged between the gas and radiation.

Each of these terms are given in finite difference form as follows:

$$e_x^{n+1} = \sum_{j=1}^{JMAX} (E_x)_{j-1/2}^{n+1} \, \Delta m_{o_{j-1/2}} \tag{60}$$

$$T^{n+1} = \frac{1}{4} \Delta m_{o_{JMAX-1/2}} (u_{JMAX}^{n+1/2})^2 + \frac{1}{2} \sum_{j=1}^{JMAX} \Delta m_{o_j} (u_j^{n+1/2})^2 \tag{61}$$

$$H_x^{n+1} = H_x^n + \Delta t^{n+1/2} \sum_{j=1}^{JMAX} (S_x)_{j-1/2}^{n+1/2} \, \Delta m_{o_{j-1/2}} \tag{62}$$

$$E_{RP}^{n+1} = E_{RP}^n + \Delta t^{n+1/2} \sum_{j=1}^{JMAX} (\dot{Q}_{RP})_{j-1/2}^{n+1/2} \, \Delta m_{o_{j-1/2}} \tag{63}$$

$$G_R^{n+1} = G_R^n + \Delta t^{n+1/2} \sum_{j=1}^{JMAX} u_j^{n+1/2} (r^{\delta-1})_j^{n+1/2} (P_{R_{j+1/2}}^{n+1/2} - P_{R_{j-1/2}}^{n+1/2})$$

$$+ \Delta t^{n+1/2} \, u_{JMAX}^{n+1/2} (r^{\delta-1})_{JMAX}^{n+1/2} [P_{R_{JMAX+1}}^{n+1/2} - P_{R_{JMAX-1}}^{n+1/2}]/2 \tag{64}$$

$$W_x^{n+1} = W_x^n + \Delta t^{n+1/2} (u_{JMAX}^{n+1/2} (r^{\delta-1})_{JMAX}^{n+1/2} P_{x_{JMAX}}^{n+1/2}) \tag{65}$$

$$F_P^{n+1} = F_P^n + \Delta t^{n+1/2} \left[\frac{r^{\delta-1}}{\left(\frac{\Delta r}{K_P}\right)}\right]_{JMAX}^{n+1/2} (T_{P_{JMAX+1/2}}^{n+1/2} - T_{P_{JMAX-1/2}}^{n+1/2}) \tag{66}$$

$$F_R^{n+1} = F_R^n + \Delta t^{n+1/2} \left[\frac{r^{\delta-1}}{\left(\frac{\Delta r}{K_R}\right) + \frac{\Delta E_R}{F_R}}\right]_{JMAX}^{n+1/2} (E_{R_{JMAX+1/2}}^{n+1/2} - E_{R_{JMAX-1/2}}^{n+1/2}) \tag{67}$$

The calculations made by the FIRE code do not conserve energy exactly because of the finite distance between points in the equation of state tables. The calculations usually conserve energy to within better than 10%.

VII. The Time Step Control

After each time step, the next time step is determined from a set of stability and accuracy constraints. The new time step is determined by

$$\Delta t^{n+3/2} = \mathrm{Max}\left[\Delta t_{min}, \mathrm{Min}\left(\Delta t_{max}, \frac{K_1}{R_1^{n+1}}, \frac{K_2 \Delta t^{n+1/2}}{R_2^{n+1}}, \frac{K_3 \Delta t^{n+1/2}}{R_3^{n+1}}, \frac{K_4 \Delta t^{n+1/2}}{R_4^{n+1}}\right)\right] \quad (68)$$

where:

$$R_1^{n+1} = \mathrm{Max}\left[\left(V_{j-1/2}^{n+1} P_{j-1/2}^{n+1}\right)^{1/2} / \Delta r_{j-1/2}^{n+1/2}\right] \quad (69)$$

$$R_2^{n+1} = \mathrm{Max}\left[\left(V_{j-1/2}^{n+1} - V_{j-1/2}^{n}\right) / V_{j-1/2}^{n+1/2}\right] \quad (70)$$

$$R_3^{n+1} = \mathrm{Max}\left[\left(E_{R_{j-1/2}}^{n+1} - E_{R_{j-1/2}}^{n}\right) / E_{R_{j-1/2}}^{n+1/2}\right] \quad (71)$$

$$R_4^{n+1} = \mathrm{Max}\left[\left(T_{P_{j-1/2}}^{n+1} - T_{P_{j-1/2}}^{n}\right) / T_{P_{j-1/2}}^{n+1/2}\right] . \quad (72)$$

The maximum values of R_1, R_2, R_3, and R_4 are found by sweeping over the zones. The input parameters K_1, K_2, K_3, and K_4 determine the severity of each constraint. The default value for K_1, K_2 and K_4 is 0.05. The default value of K_3 is set to 1.0×10^{35}, which in effect removes the radiation energy as a time step constraint. The justification for doing this is that the only place where the radiation energy is changing rapidly enough to constrain the time step is at a radiation wave front. Everywhere else the radiation field is in

quasi-equilibrium with the gas, because the speed of light is very fast. The shape of the radiation wave front cannot be resolved very accurately because of the size of the Lagrangian zones, so this time constraint can be removed.

VIII. The Subroutines and Their Functions

The FIRE code is written in FORTRAN IV, and can be run on any mainframe computer. It is written in a top-down modular style, as shown in Fig. 4. Each subroutine performs a specific function. These functions are briefly described below:

ABCDEF - computes the $\underline{A}$, $\underline{B}$, $\underline{C}$, $\underline{D}$, $\underline{E}$, and $\underline{F}$ matrices and vectors used to solve the energy transfer equations.

CLEAR - sets all common blocks to zero before the start of a calculation.

CROS - searches through the x-ray cross section table and computes the cross section of the gas.

DISTRB - computes the kinetic energy and momentum lost by the debris in each zone during a time step.

DUMP - writes all common blocks on unit 2 at the end of a calculation.

DYNDEP - computes the x-ray deposition and the new absorption cross section of each zone.

ECHECK - computes the integrals used in the energy conservation check.

EDATA - provides the electron shell structure of the gas for the x-ray deposition calculation.

ENERGY - computes T_P, E_R, and then T_R.

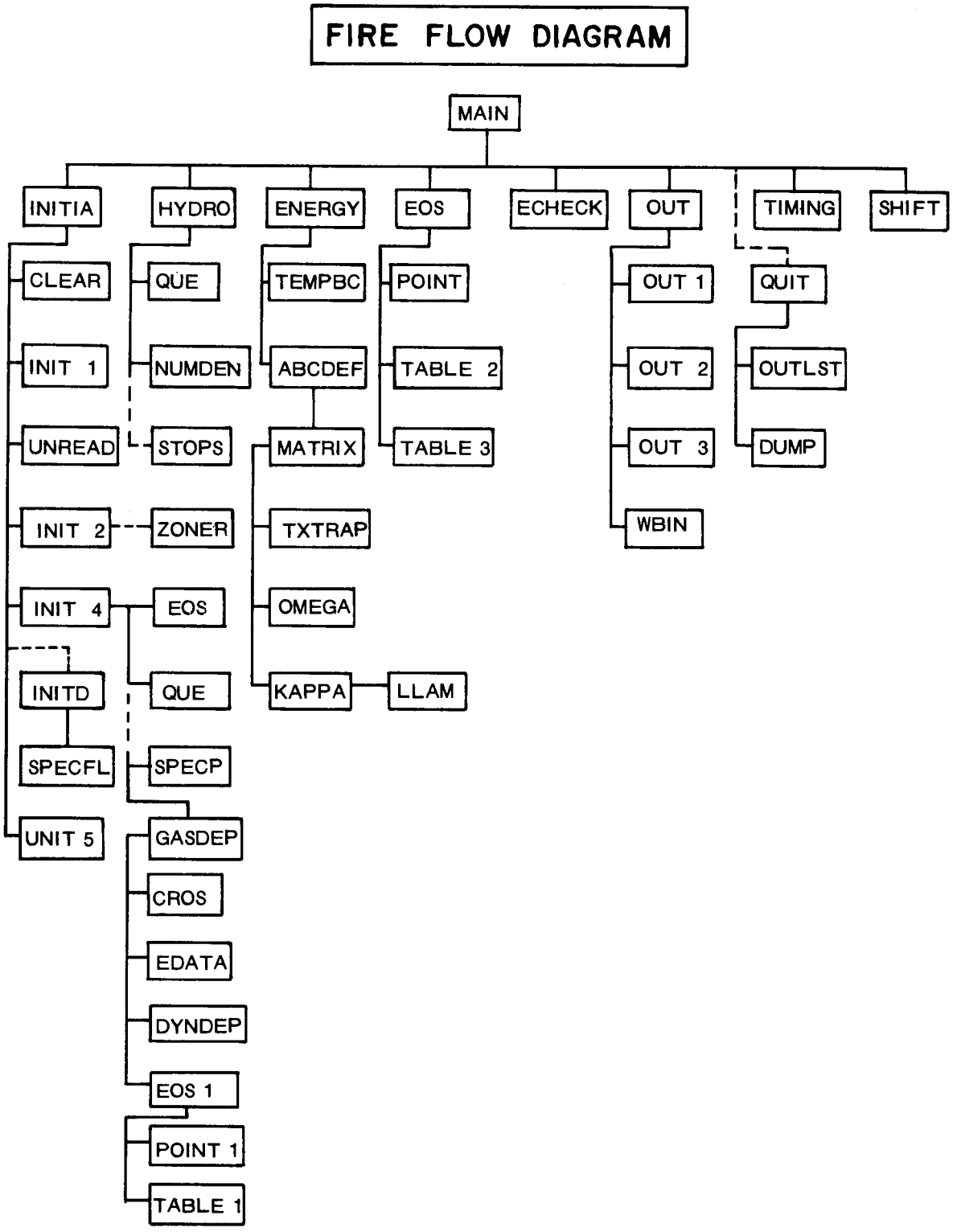
EOS,EOS1 - computes the equation of state quantities.

GASDEP - computes the temperature of the gas after x-ray deposition.

HYDRO - solves the equation of motion for the fluid velocity, new zone radii, Δr's, zone volumes, and specific volumes.

INITD - reads LOWEN namelist input and initializes the debris deposition calculation.

Figure 4. The flow diagram of the FIRE code. The dotted lines indicate conditional routes.



INITIA - reads namelist input and calls other initialization routines.

INIT1 - sets variable default values before reading input.

INIT2,4,5 - computes initial conditions and writes a summary of the initial conditions to unit 6.

KAPPA - computes plasma and radiation thermal conductivity and the radiation flux limit.

LLAM - computes log lambda.

MAIN - calls other routines to form the loop for one time step.

MATRIX - computes $\underline{\underline{a}}$, $\underline{\underline{\alpha}}$, $\underline{\underline{\gamma}}$, and $\underline{\underline{\omega}}$ matrices for use in the energy transfer calculation.

NUMDEN - computes number densities from the specific volume.

OMEGA - computes the radiation emission and absorption coefficients.

OUT,OUT1 - writes output to unit 6 at the end of specified time cycles.

POINT,POINT1 - finds pointers in the equation of state tables.

QUE - computes the artificial viscosity.

QUIT - wraps up the calculation at the end.

SHIFT - shifts values of variables at (n+1) to variables at (n) at the end of a time step.

SPECFL - computes the debris spectrum.

SPECP - computes the x-ray spectrum.

STOPS - computes the total kinetic energy and momentum lost by the debris during each time step.

TABLE2,TABLE1 - interpolates in the equation of state tables using the pointers.

TEMPBC - computes the plasma temperature and radiation specific energy boundary conditions.

TIMING - computes a new time step and determines whether the calculation is over.

UNREAD - reads in the common blocks from unit 4 at the beginning of a restarted calculation.

WBIN - writes binary output to unit 8 for postprocessing.

ZONER - computes the Lagrangian zoning automatically.

IX. Input/Output Units and Storage Requirements

The FIRE code uses ten different I/O units. These units are listed below along with their specific function.

Unit #	Function
2	FIRE writes all common blocks to this unit at the end of a calculation to allow a restart.
3	FIRE reads the equation of state tables from this unit.
4	FIRE reads the common blocks from this unit at the beginning of a restart calculation.
5	FIRE reads the namelist input from this unit.
6	FIRE writes lineprinter output to this unit.
8	FIRE writes binary output to this unit for postprocessing into plots.
9	FIRE writes the times corresponding to the stored heat fluxes on this unit.
10	FIRE writes the radiation heat fluxes to the wall on this unit.
11	FIRE reads x-ray cross section data on this unit.
12	FIRE writes the pellet x-ray spectrum reaching the wall on this unit.

FIRE requires about 60 K words of core storage on a UNIVAC 1110 computer and executes at a rate of approximately 2-5 msec/zone•cycle.

When adding a variable to the common blocks, the block length (set in INIT1) must be changed so that DUMP and UNREAD will write and read the correct number of words for a restart. Notice that the lengths are measured in double

words. This must be changed to single words if single precision is used. All of the variables should be changed to single precision if a CDC computer is used.

X. The Common Blocks

Nearly all of the real variables in the common blocks are in double precision, giving about 14 decimal places of accuracy on an IBM or UNIVAC computer. All real constants are specified with the "D" scientific notation (i.e., 1.=1.D0) to insure that all calculations are performed in double precision. The IBM FORGRAN G and H compilers will not define constants as double precision unless the "D" notation is used.

For many of the variables, the second to the last letter indicates whether the variable is at a zone center or zone boundary, and the last letter denotes the time level. The suffixes are:

1 -- zone boundary

2 -- zone center

A -- t^{n+1}

B -- $t^{n+1/2}$

C -- t^{n}

D -- $t^{n-1/2}$

The letter R will appear in a variable name if the quantity is associated with the radiation field, and N if the quantity is associated with the gas. Thus TR2B(J) is the radiation temperature in the center of zone j at time $t^{n+1/2}$, and U1D(J) is the fluid velocity on the zone j boundary at time $t^{n-1/2}$. The variables are grouped in common blocks so that a subroutine will find most of

the variables that it needs in fewer than all of the blocks. The common blocks are listed below along with their meaning and units. A * superscript denotes mandatory input variables, and a ** superscript denotes a variable with a default value.

Common Blocks

COMMON/TIME/

1)	TA	t^{n+1}	times (s)
2)	TB	$t^{n+1/2}$	
3)	TC	t^{n}	
4)	TD	$t^{n-1/2}$	
5)	DTB**	$\Delta t^{n+1/2}$	
6)	DTC	$\Delta t^{n} = (\Delta t^{n+1/2} + \Delta t^{n-1/2})/2$	
7)	DT	$\Delta t^{n+3/2}$, the new time step	
8)	TMAX*	Total time for the simulation	
9)	DTMIN**	Min allowed time step	
10)	DTMAX**	Max allowed time step	

COMMON/TEMPER/

1)	TN2A	$(T_P)^{n+1}_{j-1/2}$	Plasma temperatures (eV)
2)	TN2B	$(T_P)^{n+1/2}_{j-1/2}$	
3)	TN2C*	$(T_P)^{n}_{j-1/2}$	
4)	TN1B	$(T_P)^{n+1/2}_{j}$	
5)	TNSQ2B	$\sqrt{(T_P)^{n+1/2}_{j-1/2}}$	$(eV)^{1/2}$
6)	TR2A	$(T_R)^{n+1}_{j-1/2}$	Radiation temperatures (eV)

7) TR2B $(T_R)_{j-1/2}^{n+1/2}$

8) TR2C* $(T_R)_{j-1/2}^{n}$

9) TR1B $(T_R)_{j}^{n+1/2}$

10) TBC** temperature boundary condition (eV)

COMMON/CONTROL/

1) CON** real constants used in FIRE

2) TGRØW** max percentage that Δt can increase in one cycle

3) TEDIT** time at which output freq. switches from IO(1) to IO(11) (s)

4) GEOFAC a geometry factor; 1, 2π, 4π

5) TSCC** Courant condition time step control

6) TSCV** $\Delta V/V$ time step control

7) TSCTR** $\Delta E_R/E_R$ time step control

8) R1 worst case for Courant condition

9) R2 worst case for $\Delta V/V$

10) R3R worst case for $\Delta E_R/E_R$

11) R3N worst case for $\Delta T_P/T_P$

12) T1
13) T2
14) T3
15) T4

} temporary vectors to be used for any purpose within a subroutine

16) IDELTA** 1 = cartesian 2 = cylindrical 3 = spherical

17) IDELM1 0 = cartesian 1 = cylindrical 2 = spherical

18) NCYCLE time cycle index

19) NMAX* max number of time steps

20) JMAX* max number of spatial zones

21) JMAXM1 JMAX-1

22) JMAXP1 JMAX+1 } used for indexing

23) JMAXP2 JMAX+2

24) ISW** control switches

25) ILUNIT output units for flux quantities

26) JCOUR zone # of Courant condition worst case

27) JSPVOL zone # of $\Delta V/V$ worst case

28) JRTEMP zone # of $\Delta E_R/E_R$ worst case

29) JNTEMP zone # of $\Delta T_p/T_p$ worst case

30) INDEX a vector used for output indexing

31) IZONE zone # of worst case of Courant, $\Delta V/V$, $\Delta T_p/T_p$

32) ITYPE 1 = Courant 2 = $\Delta V/V$ 3 = $\Delta E_R/E_R$ 4 = $\Delta T_p/T_p$ worst restriction

33) IITYPE 0 = physical -1 = min Δt 1 = max Δt

34) IEDIT** intermediate output cycle frequencies

35) IIZONE zone # of worst case if the Δt is Δt_{max} or Δt_{min}

36) ICOND principal time step constraint

37) ICOND2 secondary time step constraint if primary is Δt_{min} or Δt_{max}

38) NVMAX time step of maximum compression

39) IUNIT cm^2, radian-cm, steradian for δ = 1, 2, 3

40) JVMAX zone # of maximum compression

41) TSCTN** $\Delta T_p/T_p$ time step control

42) IO* primary output frequency vector

43) IOBIN** output frequency of binary output

44) RADIUS** the radius of the gas layer (44-51 are for automatic zoning option)

45) PMASS** the mass of the pellet

46) RI** the radius of the inner constant mass region

47 RO1** the radius where the outer constant mass region starts

48) RO2** the radius where the outer constant mass region ends

49) NI** the number of zones in the inner constant mass region

50) NO** the number of zones in the outer constant mass region

51) RATIO** the ratio of zone masses in the nonconstant mass region

COMMON/HYDROD/

1)	U1D	$u_j^{n-1/2}$	fluid velocity (cm/s)
2)	U1B**	$u_j^{n+1/2}$	
3)	DR2B	$\Delta r_{j-1/2}^{n+1/2}$	zone widths (cm)
4)	DR2A	$\Delta r_{j-1/2}^{n+1}$	
5)	R1C	r_j^n	radius (cm)
6)	R1B	$r_j^{n+1/2}$	
7)	R1A	r_j^{n+1}	
8)	RS1C	$(r_j^n)^{\delta-1}$	
9)	RS1B	$(r_j^{n+1/2})^{\delta-1}$	
10)	RS1A	$(r_j^{n+1})^{\delta-1}$	
11)	PR2C	$(P_R)_{j-1/2}^n$	radiation pressure (J/cm^3)
12)	PR2B	$(P_R)_{j-1/2}^{n+1/2}$	
13)	PR2A	$(P_R)_{j-1/2}^{n+1}$	
14)	PN2C	$(P_P)_{j-1/2}^n$	gas pressure (J/cm^3)
15)	PN2B	$(P_P)_{j-1/2}^{n+1/2}$	
16)	PN2A	$(P_P)_{j-1/2}^{n+1}$	

17)	P2C	$P^{n}_{j-1/2}$	total pressure (J/cm^3)	
18)	P2A	$P^{n+1}_{j-1/2}$		
19)	V2C	$V^{n}_{j-1/2}$	specific volume (cm^3/g)	
20)	V2B	$V^{n+1/2}_{j-1/2}$		
21)	V2A	$V^{n+1}_{j-1/2}$		
22)	VO		initial specific volume	
23)	COMPR		VO/V compression	
24)	VDOT2B	$\dot{V}^{n+1/2}_{j-1/2}$	time derivative of sp. volume (cm^3/g-s)	
25)	DMASS2	$\Delta m_{o_{j-1/2}}$	Lagrangian mass	δ=1 g/cm^2 δ=2 g/cm-radian δ=3 g/steradian
26)	DMASS1	$\Delta m_{o_j} = (\Delta m_{o_{j-1/2}} + \Delta m_{o_{j+1/2}})/2$		
27)	Q2B	$q^{n+1/2}_{j-1/2}$	artificial viscosity (J/cm^3)	
28)	VMAX		max compression	
29)	TAVMAX		time of max compression (s)	
30)	VOL2B	$V^{n+1/2}_{j-1/2}$	zone volume (cm^3)	
31)	VOL2A	$V^{n+1/2}_{j-1/2}$		

COMMON/ESCOM/

1)	ER2C	$E_{R_{j-1/2}}^{n}$	radiation specific energy (J/g)
2)	ENT2B	$(C_v)_{j-1/2}^{n+1/2}$	gas specific heat (J/eV-g)
3)	ER2B	$E_{R_{j-1/2}}^{n+1/2}$	radiation specific energy (J/g)
4)	PNT2B	$(P_P)_{T_{j-1/2}}^{n+1/2}$	temperature derivative of gas pressure (J/cm^3-eV)
5)	ER2A	$(E_R)_{j-1/2}^{n+1}$	radiation specific energy (J/g)
6)	EN2A	$(E_P)_{j-1/2}^{n+1}$	gas specific internal energy (J/g)
7)	DE2A	$(n_e)_{j-1/2}^{n+1}$	electron number density ($1/cm^3$)
8)	DN2A	$(n_P)_{j-1/2}^{n+1}$	ion number density
9)	DE2B**	$(n_e)_{j-1/2}^{n+1/2}$	electron number density
10)	DN2B*	$(n_P)_{j-1/2}^{n+1/2}$	ion number density
11)	ATW2B*	$A_{j-1/2}^{n+1/2}$	average ion atomic weight (amu)
12)	ZT2B		temperature derivative of average charge (esu/eV)
13)	Z2B**	$Z_{j-1/2}^{n+1/2}$	average charge (esu)
14)	ZSQ2B	$(Z_{j-1/2}^{n+1/2})^2$	average squared charge $(esu)^2$
15)	VBC**		specific volume boundary condition (cm^3/g)

16) AD
17) AT
18) BD
19) BT

} coefficients defining the grid for the equations of state

20) EBC — radiation specific energy boundary condition

21) TN2AL — $\log (T_{P}^{n+1}{}_{j-1/2})$

22) TR2AL — $\log (T_{R}^{n+1}{}_{j-1/2})$

23) DN2AL — $\log (n_{P}^{n+1}{}_{j-1/2})$

24) KEOS
25) LEOS
26) MEOS

} vectors used for indexing into the equation of state tables

27) EPSLON — a parameter that indicates how far out of equilibrium the radiation energy density is

COMMON/ESCOM1/

1) ZTAB — gas charge state table

2) ENTAB — gas specific internal energy table

3) RMFTAB — Planck mean free path table

4) ROSTAB — Rosseland mean free path table

COMMON/COEFF/

1)	ROSS2B	$(\ell)_{j-1/2}^{n+1/2}$	Rosseland mean free path (cm)
2)	KANM1B	$(K_P^-)_j^{n+1/2}$	gas thermal conductivity (J/cm-eV-s)
3)	KANP1B	$(K_P^+)_j^{n+1/2}$	
4)	KARM1B	$(K_R^-)_j^{n+1/2}$	radiation thermal conductivity (J/cm-eV-s)
5)	KARP1B	$(K_R^+)_j^{n+1/2}$	
6)	OMP2B	$(\omega_P)_{j-1/2}^{n+1/2}$	gas emission coefficient (J/eV-g-s)
7)	OMR2B	$(\omega_R)_{j-1/2}^{n+1/2}$	gas absorption coefficient (J/eV-g-s)
8)	RMFP2B	$(\ell_1)_{j-1/2}^{n+1/2}$	Planck mean free path (cm)
9)	RMFT2B	$(\ell_1)_{j-1/2}^{n+1/2}$	Planck mean free path for $T_P = T_R$ (cm)
10)	SND2B	$\Delta KE_{d_{j-1/2}}^{n}$	change in debris kinetic energy during Δt^n (ergs)
11)	SHOK2B		shock heating (J/gm/s)
12)	LAMN2B	$(\ell n \Lambda_{ei})_{j-1/2}^{n+1/2}$	Spitzer log Λ
13)	FLIM1B		radiation flux limit (J/cm^2•s)
14)	RFLU1B		diffusion flux (J/cm^2•s)
15)	SNDI2B	$S_{j-1/2}^{n}$	the interal energy source term (J/gm/s)

COMMON/COEFF1/

1) BET12B $(\beta_1)_{j-1/2}^{n+1/2}$

Beta Vector

2) BET22B $(\beta_2)_{j-1/2}^{n+1/2}$

3) AL112B $(\alpha_{11})_{j-1/2}^{n+1/2}$

Diagonal Elements of Alpha Matrix

4) AL222B $(\alpha_{22})_{j-1/2}^{n+1/2}$

5) OM112B $(\omega_{11})_{j-1/2}^{n+1/2}$

Diagonal Elements of Omega Matrix

6) OM222B $(\omega_{22})_{j-1/2}^{n+1/2}$

7) GM112B $(\gamma_{11})_{j-1/2}^{n+1/2}$

Diagonal Elements of Gamma Matrix

8) GM222B $(\gamma_{22})_{j-1/2}^{n+1/2}$

9) AA111B $(a_{11})_{j}^{n+1/2}$

Diagonal Elements of "a" Matrix

10) AA221B $(a_{22})_{j}^{n+1/2}$

11) OM122B $(\omega_{12})_{j-1/2}^{n+1/2}$

Off Diagonal Elements of Omega Matrix

12) OM212B $(\omega_{21})_{j-1/2}^{n+1/2}$

COMMON/COEFF2/

1)	E11	(E_{11})	
2)	E12	(E_{12})	
			All Elements of the "E" Matrix
3)	E21	(E_{21})	
4)	E22	(E_{22})	
5)	F1	(F_1)	
			Both Components of the "F" Vector
6)	F2	(F_2)	
7)	B11	(B_{11})	
8)	B12	(B_{12})	
			All Elements of the "B" Matrix
9)	B21	(B_{21})	
10)	B22	(B_{22})	
11)	D1	(D_1)	
			Both Elements of the "D" Vector
12)	D2	(D_2)	

COMMON/ECKCOM/

1)	T1A	$(T)_j^{n+1}$	kinetic energy of fluid (J/x)
2)	GGGE2A	$(G_e)_{j-1/2}^{n+1}$	radiation-gas work (J/x)

3)	HHHR2B	$(H_R)_{j-1/2}^{n+1/2}$	radiation source (J/x)
4)	HHHN2B	$(H_P)_{j-1/2}^{n+1/2}$	gas source (J/x)
5)	EEEC2A	$(E_c)_{j-1/2}^{n+1}$	radiation-gas energy exchange (J/x)
6)	EEEERO	E_{R_o}	total initial radiation internal energy (J/x)
7)	EEEENO	E_{P_o}	total initial gas internal energy (J/x)
8)	EEEEER	$(E_R)^{n+1}$	total radiation internal energy (J/x)
9)	EEEEEN	$(E_P)^{n+1}$	total gas internal energy (J/x)
10)	TTTTTT	$(T)^{n+1}$	total fluid kinetic energy (J/x)
11)	HHHHHR	$(H_E)^{n+1}$	total radiation source (J/x)
12)	HHHHHN	$(H_P)^{n+1}$	total gas source (J/x)
13)	EEEEEC	$(E_c)^{n+1}$	total radiation-gas energy exchanged (J/x)
14)	GGGGGE	$(G_e)^{n+1}$	total radiation-gas work (J/x)
15)	WWWWWR	$(W_R)^{n+1}$	total work done on radiation (J/x)
16)	WWWWWN	$(W_P)^{n+1}$	total work done on gas (J/x)
17)	FFFFFR	$(F_R)^{n+1}$	total radiation heat lost across outer boundary (J/x)
18)	FFFFFN	$(F_P)^{n+1}$	total gas heat lost across outer boundary (J/x)
19)	WWWWR	$(W_R)^{n+1}$	total work done on radiation on last cycle (J/x)

20) WWWWN $(W_p)^{n+1}$ total work done on gas on last cycle (J/x)

21) FFFFR $(f_R)^{n+1}$ total radiation lost at outer bd. on last cycle (J/x)

22) FFFFN $(f_p)^{n+1}$ total gas energy lost at outer bd. on last cycle (J/x)

23) HHHHR $(h_R)^{n+1}$ total radiation source on last cycle (J/x)

24) HHHHN $(h_p)^{n+1}$ total gas source on last cycle (J/x)

25) EEEEC $(e_c)^{n+1}$ total radiation-gas heat exchange on last cycle (J/x)

26) GGGGE $(g_e)^{n+1}$ total work to maintain one fluid on last cycle (J/x)

27) ENLHS left side of gas energy balance equation (J/x)

28) ETLHS left side of total energy balance equation (J/x)

29) ERRHS right side of radiation energy balance equation (J/x)

30) ENRHS right side of gas energy balance equation (J/x)

31) ETRHS right side of total energy balance equation (J/x)

32) TTTTNO initial kinetic energy (J/x)

33) PMAX maximum pressure at the wall (J/cm^3)

34) TPMAX time of maximum pressure (s)

35) FMAX maximum radiation heat flux at the wall (J/cm^2-s)

36) TFMAX time of maximum heat flux (s)

37) FSAVE heat fluxes at first wall (J/cm^2-s)

38) PSAVE pressures at first wall (J/cm^3)

39) TSAVE times of heat fluxes and pressures (s)

40) NPMAX time step of max. pressure

41) NSAVE index into FSAVE, PSAVE, and TSAVE

42) NFMAX time step of max. heat flux

43) NDUMMY rounds out the common block to an even number of words

where δ=1 x = cm^2

δ=2 x = cm-radian

δ=3 x = steradian

COMMON/XRAY/

1) COEF coefficients computed from x-ray cross section tables

2) ELIM a vector used in computing the x-ray cross sections

3) ONEZOA a coefficient used on computing the x-ray scattering cross section

4) JK** the number of energy groups in the x-ray spectra

5) DE the width of the energy groups in the x-ray spectra (keV)

6) KEV** the blackbody temperature of a blackbody x-ray spectra (keV)

7) FLUX** the total energy in x-rays input by the user (J)

8) SUMFLU the energy in the x-ray spectra computed by FIRE (J)

9) E the energy of the x-rays in each group (keV)

10) F the energy in each x-ray group (J/keV)

11) NUM a number generated by the code in searching through the x-ray cross section tables

12) U x-ray attenuation coefficients computed from tables (cm^2/gm)

13) EDGE the minimum x-ray energy required for absorption by electrons in each shell (keV)

14) SHELEL the number of electrons in each shell

15) IZ** the atomic number of the gas

16) KEDGE the number of shells the gas atoms have

17) TN2AL1 $\log (T^o_{P_{j-1/2}})$ logs of the initial gas temperatures

18) DN2AL1 $\log (n^o_{P_{j-1/2}})$ logs of the initial gas densities

19) LEOS1 an index corresponding to TN2AL1

20) MEOS1 an index corresponding to DN2AL1

21) XAMP** the amplitude of an input x-ray spectrum (J/keV)

22) XEHIST** the energy of the x-rays in each group of the input spectrum (keV)

23) TOTAL the x-ray energy absorbed by the gas (Joules)

COMMON/DRIV2/

1)	FF	the number of debris projectiles in each energy group
2)	VSTAR	a constant used in computing the deceleration of each energy group
3)	AMP**	the amplitudes of energy groups in an arbitrary histogram spectrum (J/keV)
4)	NMHIST**	the number of energy groups in the spectra
5)	EHIST**	the kinetic energy of the debris in each energy group (keV)
6)	GAUSIG**	the standard deviation of a Gaussian energy spectrum (keV)
7)	EMN**	the characteristic energy of a Maxwellian energy spectrum (keV)
8)	ISPEC**	1, a Maxwellian spectrum is set up
		2, a Gaussian spectrum is set up
		3, an arbitrary histogram monoenergentic pulse is input
9)	EMIN	the minimum energy of the spectra (keV)
10)	EMAX	the maximum energy of the spectra (keV)
11)	FL**	the total number of debris projectiles
12)	PROGR	the projected range of the debris in each energy group if the gas is stationary (cm)
13)	SIGMA	the standard deviation in projected range for each group if the gas is stationary (cm)
14)	MARK	-1, the energy of a group has become insignificant
		0, the debris in a group has passed into the wall
		1, the kinetic energy and momentum of a group imparted to the gas are computed
15)	J1B	the indexes of zones containing the projected ranges of the debris groups
16)	SPEMIN	the debris speed below which MARK is set to -1 for a group (cm/s)

17) SMASS** the mass of each debris projectile (amu)

18) SPEED the speed of the debris in each energy group (cm/s)

19) RSAVE (r_j^o) the initial positions of the zones (cm)

20) DIS the distance between the average projected range and the last zone boundary crossed (cm)

21) C1
22) C2
23) C3
24) C4

constants used in computing the deceleration and spatial profile of the debris

25) SND the kinetic energy lost by each debris group during a time step (ergs)

26) DMOM the momentum lost by each debris group during a time step (g-cm/s)

27) RP the average projected range of each debris group (cm)

28) IRIPT an element of the vector J1B

29) TIME the time that the average projected range of each group passes into the wall (s)

30) DMOM1D the momentum imparted to each zone during a time step (g/cm/s)

31) DR2D ($\Delta r_{j-1/2}^{n-1/2}$) this vector is used to correct DIS for motion of zones

32) SIGMAL constants used to compute the range straggling of each group

XI. The Input Variables

The FIRE code reads namelist input from I/O unit 5. The variables that must appear in the namelist called INPUT are given in Table 1. Real variables are denoted by RV, and integer variables by IV. The variables with default values are given in Table 2, and they need not appear in the namelist unless another value is desired. Table 3 contains the variables used for an x-ray deposition calculation. Table 4 contains the variables used if the automatic zoning option is specified. Table 5 contains the variables used to run a debris deposition calculation. These are the only variables that appear in the namelist called LOWEN. Table 6 contains definitions of the integer switches used to control the code. Table 7 lists the real constants used by the code that can be changed by input. Table 8 gives the intermediate output vector that allows all internally computed quantities to be output for debugging.

Table 1. Input Variables

Variable	Type	Default Value	Description
JMAX	(IV)	---	Number of spatial zones $3 \leq JMAX \leq 97$
NMAX	(IV)	---	Maximum number of time steps
TMAX	(RV)	---	Maximum problem time (s)
IO	(IV)	---	Output frequencies IO(1) -- hydrodynamics IO(2) -- energy IO(3) -- mfp's and # densities IO(4) -- short edit IO(11) -- same as IO(1)-(4) except after IO(12) time TEDIT (see TEDIT description) IO(13) IO(14)
DR2B	(RV)	---	Δr of each zone (cm) (DR2B is only input if automatic zoning is not used)
DN2B	(RV)	---	Gas number density (cm^{-3})
TN2C	(RV)	---	Gas temperature (eV)
TR2C	(RV)	---	Radiation temperature (eV)
ATW2B	(RV)	---	Atomic weight (amu)

Table 2. Optional Input Variables

Variable	Type	Default Value	Description
IDELTA	(IV)	3	Geometry = 1 planar = 2 cylindrical = 3 spherical
DTB	(RV)	10^{-12}	Initial time step (s)
DTMIN	(RV)	10^{-1}*DTB	Minimum time step (s)
DTMAX	(RV)	10^{-2}*TMAX	Maximum time step (s)
TSCC	(RV)	5×10^{-2}	Time Step Controls - Courant
TSCV	(RV)	5×10^{-2}	- $\Delta V/V$
TSCTR	(RV)	1×10^{35}	- $\Delta E_R/E_R$
TSCTN	(RV)	5×10^{-2}	- $\Delta T_P/T_P$
TEDIT	(IV)	-1	If TEDIT $\neq$ 0 then before time TEDIT IO(1)-(4) are used and after IEDIT IO(11)-(14) are used as output frequencies
IOBIN	(IV)	-1	Binary output frequency written to unit 8 for postprocessing
TGROW	(RV)	1.5	Time step is allowed to increase no more than TGROW*DTB on each successive cycle
TBC	(RV)	2.5×10^{-2}	Temperature boundary condition (eV)
VBC	(RV)	0.1	Specific volume boundary condition (cm^3/g)
U1B	(RV)	0	Initial velocity (cm/s)
IRS	(IV)	0	Restart calculation flag = 0 Normal calculation = 1 Restarted calculation
JK	(IV)	25	See Table 3
ISW	(IV)	---	See Table 6 for definitions of these switches
CON	(IV)	---	See Table 7 for the definitions of these numerical coefficients

Variable	Type	Default Value	Description
IEDIT	(IV)	-1	See Table 8 for the definitions of these intermediate output frequencies
ROSS2B	(RV)	---	Rosseland mean free path must be input if ISW(12)=1 or ISW(15)=1
RMFP2B	(RV)	---	Planck mean free path must be input if ISW(12)=1 or ISW(14)=1
RMFT2B	(RV)	---	Planck mean free path for $T_R = T_p$ must be input if ISW(12)=1 or ISW(14)=1

Table 3. Input Variables for X-Ray Deposition

Variable	Type	Default Value	Description
FLUX	(RV)	---	The total energy of a blackbody x-ray spectrum in Joules
JK	(IV)	25	The number of energy groups in the x-ray spectrum $\leq$ 20 for arbitrary histogram $\leq$ 100 for a blackbody spectrum
IZ	(IV)	---	The atomic number of the gas
KEV	(RV)	---	The blackbody temperature of a blackbody x-ray spectrum
XEHIST	(RV)	---	The bounds of energy groups in an arbitrary histogram in keV
XAMP	(RV)	---	The amplitude of the groups of an arbitrary histogram in J/keV

Table 4. Input Variables for Automatic Zoning

Variable	Type	Default Value	Description
NI	(IV)	---	Number of zones in the inner, constant mass region
RI	(RV)	---	The radius of the inner, constant mass region (cm)
NO	(IV)	---	Number of zones in the outer, constant mass region
RO1	(RV)	---	The radius where the outer, constant mass regions starts (cm)
RO2	(RV)	---	The radius where the outer, constant mass region ends (cm)
RADIUS	(RV)	---	The radius of the gas (this is different from RO2 so that the last zone thickness can be varied)
PMASS	(RV)	---	The pellet mass (g)

Table 5. Input Variables for Ion Deposition

Variable	Type	Default Value	Description
ISPEC	(IV)	---	The type of energy spectra: ISPEC=1 - Maxwellian =2 - Gaussian =3 - histogram or monoenergetic pulse
NMHIST	(IV)	---	The number of energy groups in the histogram (=1 for a monoenergetic pulse)
AMP	(RV)	---	The amplitude of energy groups in a histogram (not needed for a monoenergetic pulse; see EHIST) (J/keV)
EHIST	(RV)	---	The energy of the ions if a monoenergetic pulse is used (keV)
EMN	(RV)	---	The characteristic energy if a Maxwellian energy spectrum is used (keV)
GAUSIG	(RV)	---	The standard deviation if a Gaussian energy spectrum is used (keV)
SMASS	(RV)	---	The atomic weight of the debris ions (amu)
FL	(RV)	---	The number of debris ions
REFPR	(RV)	---	The reference density for which the parameters listed below were computed ($atoms/cm^3$)
ENGY1	(RV)	---	The initial energy of a pulse of debris ions (keV)
RP1	(RV)	---	The final, average projected range corresponding to ENGY1 (cm)
SIG1	(RV)	---	The final, standard deviation in average projected range corresponding to ENGY1 (cm)
PATH1	(RV)	---	The final path length corresponding to ENGY1 (cm)
ENGY	(RV)	---	An intermediate energy of the pulse with initial energy ENGY1 (keV)
RP	(RV)	---	The average projected range at energy ENGY (cm)

Variable	Type	Default Value	Description
SIG	(RV)	---	The standard deviation in average projected range at energy ENGY (cm)
PATH	(RV)	---	The path length of the pulse at energy ENGY (cm)
ENGY2	(RV)	---	The initial energy of a pulse of debris ions (keV) (must be other than ENGY1)
RP2	(RV)	---	The final, average projected range corresponding to ENGY2 (cm)
SIG2	(RV)	---	The final, standard deviation in average projected range corresponding to ENGY1 (cm)

Listed below are some input parameters for various ions slowing down in argon, xenon, and helium. Input parameters for other ion-gas combinations can be generated using the RASE4 [12] code.

Input Values for Ions Slowing Down in Argon

Applicable Energy Range (keV)	ION	GAS	REFRO (/cm^3)	RP1 (cm)	SIG1 (cm)	PATH1 (cm)	ENGY1 (keV)	RP (cm)	SIG (cm)	PATH (cm)	ENGY (keV)	RP2 (cm)	SIG2 (cm)	ENGY2 (keV)
1-100	Au	Ar	2.68D22	3.22D-6	9.8 D-7	3.41D-6	50.D0	1.97D-6	8.6 D-7	2. D-6	20.D0	1.52D-6	4.9 D-7	20.D0
1-100	Fe	Ar	2.68D22	3.74D-6	1.64D-6	4.47D-6	30.D0	1.89D-6	1. D-6	1.96D-6	20.D0	2.64D-6	1.18D-6	20.D0
1-100	Si	Ar	2.68D22	1.04D-5	4.81D-6	1.46D-5	50.D0	8.44D-6	3.7 D-6	9.61D-6	20.D0	4.3 D-6	2.21D-6	20.D0
.1-10	He	Ar	2.68D22	7.38D-6	5.71D-6	2.28D-5	5.D0	7.09D-6	4.05D-6	1.22D-5	2.D0	2.9 D-6	2.8 D-6	2.D0
.1-10	T	Ar	2.68D22	1.64D-5	1.14D-5	4.8 D-5	5.D0	1.54D-5	7.72D-6	2.52D-5	2.D0	6.0 D-6	5.7 D-6	2.D0
.1-10	D	Ar	2.68D22	1.55D-5	1.07D-5	4.7 D-5	5.D0	1.43D-5	6.87D-6	2.31D-5	2.D0	5.9 D-6	5.6 D-6	2.D0
.1-10	H	Ar	2.68D22	1.37D-5	8.9 D-6	4.0 D-5	5.D0	1.21D-5	5.08D-6	1.81D-5	2.D0	5.4 D-6	5.0 D-6	2.D0

Input Values for Ions Slowing Down in Xenon

Applicable Energy Range (keV)	ION	GAS	REFRO (/cm^3)	RP1 (cm)	SIG1 (cm)	PATH1 (cm)	ENGY1 (keV)	RP (cm)	SIG (cm)	PATH (cm)	ENGY (keV)	RP2 (cm)	SIG2 (cm)	ENGY2 (keV)
1-100	Au	Xe	2.68D22	1.6 D-6	7.1 D-7	1.9 D-6	50	1.1 D-6	6.4 D-7	1.2 D-6	20	7.8 D-7	3.6 D-7	20
1-100	Fe	Xe	2.68D22	3.1 D-6	2.0 D-6	5.7 D-6	50	2.8 D-6	1.5 D-6	3.6 D-6	20	1.5 D-6	1.0 D-6	20
1-100	Si	Xe	2.68D22	5.0 D-6	3.9 D-6	1.3 D-5	50	4.8 D-6	2.8 D-6	7.4 D-6	20	2.2 D-6	2.0 D-6	20
.1-10	He	Xe	2.68D22	3.4 D-6	4.8 D-6	2.4 D-5	5	3.4 D-6	3.7 D-6	1.1 D-5	2	1.5 D-6	2.7 D-6	2
.1-10	T	Xe	2.68D22	6.9 D-6	9.3 D-6	4.8 D-5	5	6.9 D-6	7.2 D-6	2.3 D-5	2	2.8 D-6	5.1 D-6	2
.1-10	D	Xe	2.68D22	6.7 D-6	8.7 D-6	4.5 D-5	5	6.7 D-6	6.6 D-6	2.1 D-5	2	2.8 D-6	5.0 D-6	2
.1-10	H	Xe	2.68D22	6.3 D-6	7.3 D-6	3.6 D-5	5	6.2 D-6	5.2 D-6	1.6 D-5	2	2.6 D-6	4.2 D-6	2

Input Values for Ions Slowing Down in Hydrogen

Applicable Energy Range (keV)	ION	GAS	REFRO (/cm^3)	RP1 (cm)	SIG1 (cm)	PATH1 (cm)	ENGY1 (keV)	RP (cm)	SIG (cm)	PATH (cm)	ENGY (keV)	RP2 (cm)	SIG2 (cm)	ENGY2 (keV)
1-100	Au	H	2.68D22	6.06D-5	3.0 D-6	6.07D-5	50	3.0 D-5	1.5 D-6	3.1 D-5	25	3.2 D-5	1.7 D-6	20
1-100	Fe	H	2.68D22	6.5 D-5	6.0 D-6	6.57D-5	50	3.2 D-5	3.0 D-6	3.3 D-5	25	3.1 D-5	2.9 D-6	20
1-100	Si	H	2.68D22	9.1 D-5	1.1 D-6	9.2 D-5	50	4.5 D-5	5.0 D-4	4.6 D-5	25	3.7 D-5	4.9 D-6	20
.1-10	He	H	2.68D22	1.1 D-4	3.0 D-5	1.2 D-4	5	5. D-5	1.5 D-5	5.1 D-5	2.5	4.0 D-5	1.4 D-5	2
.1-10	T	H	2.68D22	5.0 D-5	2.3 D-5	1.1 D-4	5	2.5 D-5	1.1 D-5	2.6 D-5	2.5	2.2 D-5	1.3 D-5	2
.1-10	D	H	2.68D22	4.5 D-5	1.7 D-5	9.9 D-5	5	2.2 D-5	8.5 D-6	4.9 D-5	2.5	2.0 D-5	1.1 D-5	2
.1-10	H	H	2.68D22	3.8 D-5	1.1 D-5	8.1 D-5	5	1.9 D-5	5.0 D-6	4.0 D-5	2.5	1.8 D-5	8.1 D-6	2

Table 6. Control Switches

ISW	Description
1	not used
2	= 10* number of constant time steps used at the beginning of a calculation
3	not used
4	= 0* user specifies zoning with DR2B = 1 automatic zoning (see Table XII-4)
5	= 20* frequency of tabulation of overpressure and heat flux at the first wall
6	= 0* hydrodynamic motion is computed = 1 no hydro motion -- allows a pure temperature diffusion problem
7	not used
8	= 0* no pellet debris deposition = 1 pellet debris expands into the gas
9	not used
10	= 1* frequency of time step calculation
11	= 0* X-ray deposition is computed = 1 calculation begins from input temperatures
12	= 0* equation of state tables are used = 1 ideal gas equation of state is used. RMFP2B, RMFT2B, ROSS2B, and CON(5) must be input via &INPUT.
13	not used
14	= 0* Planck mean free path is computed from tables = 1 Planck mean free path is computed as a constant
15	= 0* Rosseland mean free path is computed from tables = 1 Rosseland mean free path is inputted as a constant

*Denotes the default value.

Table 7. Real Constants Used in FIRE

CON	Default	Description
1	1.2175×10^{2}	gas thermal conductivity
2	1×10^{10}	radiation thermal conductivity
3	0.1	the percentage by which the radiation can be out of equilibrium before the nonequilibrium mean free path is used in the absorption term
4	1×10^{-6}	small term to avoid zero divide in flux limited radiation conduction term AA221B
5	0	if non-zero then it is used as a constant value of log Λ. Normally log Λ is computed.
6		not used
7	4.12×10^{5}	radiation emission term
8	3×10^{10}	radiation absorption term
9	1.602×10^{-19}	gas pressure
10		not used
11		not used
12	1.602×10^{-19}	gas pressure derivative
13		not used
14	2.403×10^{-19}	gas specific heat
15	2.403×10^{-19}	gas specific internal energy
16	4.5778×10^{-6}	radiation specific internal energy
17		not used
18	1.0	ion shock heating term
19		not used
20		not used

Table 8. Description of the Intermediate Output Switches in IEDIT

IEDIT	Subroutine	Variables
1	ABCDEF	A11, A22, B11, B12, B21, B22, C11, C22, D1, D2, E11, E12, E21, E22, F1, F2
2	MATRIX	AL112B, AL222B
3	MATRIX	OM112B, OM122B, OM212B, OM222B
4	MATRIX	GM112B, GM222B
5	MATRIX	AA111B, AA221B
6	MATRIX	BET12B, BET22B
10	OMEGA	OMR2B, OMP2B
11	KAPPA	KARM1B, KARP1B, KANM1B, KANP1B, LAMN2B, FLIM1B
14	HYDRO	U1B, R1A, R1B, DR2A, DR2B, RS1A, RS1B, V2A, V2B, VDOT2B
15	QUE	Q2B
16	TEMPBC	T(1) → T1(9), TR2A (JMAXP1), TN2A (JMAXP1)
19	NUMDEN	DN2B, DE2B, DN2A, DE2A
80	STOPS	ICOUNT, IRIPT, DTC, TIMLEF, SPEED, DELTAT, DISLEF, DELTA1, DELTA2, DELTAR, DIS, RP, TA
85	STOPS	IRIPT, TIMLEF, SPEED, DELTAT, DISLEF, DELTA1, DELTA2, DELTAR, DIS, RP, TA

XII. An Example of the Input/Output

In the example given below, the FIRE code is used to simulate the response of a gas that fills a 4.0 meter spherical cavity to a target explosion. The target is assumed to emit 15 MJ of 0.3 keV blackbody x-rays into the gas, and 15 MJ of debris. The debris is assumed to consist of 1 gram of iron ions, and each ion initially has 15 keV of kinetic energy. The ambient density of the cavity gas is 1.77×10^{17} atoms/cm^3, and the ambient temperature is 0.05 keV. Pure argon was used as the gas. In an attempt to reduce the code output, only 20 zones were used in the example. The accuracy of the simulation can be improved significantly by using about twice as many zones. The input used in the example calculation is given below:

```
 1        &INPUT IDELTA=3,JMAX=20,NMAX=4000,TMAX=2.D-4,
 2          DTMAX=5.D-5,
 3          ISW(4)=1,NI=3,RI=50.D0,NO=3,RO1=2.75D2,RO2=3.77D2,RADIUS=4.0D2,
 4          PMASS=0.0D0,
 5          ATW2B=20*40.D0,
 6          TN2C=20*.05D0,
 7          TR2C=20*.05D0,
 8          DN2B = 20*1.77D17,
 9          TBC=5.D-3,
10          IO=3*250,
11          IOBIN=25,
12          IZ=18,JK=15,FLUX=15.D6,KEV=0.3D0,
13          ISW(5)=10,
14          ISW(8)=1,
15        &END
16        &LOWEN
17          RP1 = 374.D-8,SIG1 = 164.D-8,PATH1 = 447.D-8,ENGY1 = 30.D0,
18          RP = 189.6D-8, SIG = 106.6D-8, PATH = 196.D-8, ENGY = 20.D0,
19          RP2 = 264.7D-8, SIG2 = 118.D-8,ENGY2 = 20.D0,
20          ISPEC=3,FL = 6.25D21, SMASS = 56.D0,NMHIST = 1,EHIST = 15.D0
21          REFRO = 2.68D22
22        &END
```

Most of the output from the test run is self explanatory. After the initial conditions that have been specified are printed out, the x-ray flux that reaches the first wall is summarized. Next, some parameters relevant to

the deposition of the debris are printed out. Following that is the output from cyclic calculations of the gas response. Quantities associated with the radiation field are indicated by the letter R, such as RTEMP for the radiation temperature; whereas quantities associated with the gas are indicated by ION, such as ION→R for the net amount of energy radiated into the radiation field. A summary of the heat flux and overpressure at the first wall follows the output from cyclic calculations of the gas response, and the last items printed out are some parameters relevant to the target debris spectra.

The output of the FIRE code can be more easily digested with the aid of computer graphics. The computer graphics programs that have been written to process the output are not provided because they were designed specifically for a Univac operating system. Figure 5 illustrates the deformation of zone boundaries as a function of time for the example problem. Converging zone boundaries indicate regions of compression, such as at a shock front. The position of the shock front can also be seen from the pressure profile, as shown in Fig. 6.

Figures 7 and 8 show the gas and radiation temperature profiles. The radiation temperature at a point in front of the shock increases before the gas temperature does because at this density pure argon is semi-transparent to radiation. As a result, some of the radiation emitted behind the shock is transported ahead of the shock, and heats the gas before the shock does. Figure 9 shows the equilibrium Planck mean free path in the gas, but to better understand the radiation transport the user may wish to plot the nonequilibrium mean free paths as well.

Figure 10 is a plot of the pressure and heat flux at the first wall. This is the information that will be used to compute the thermal and

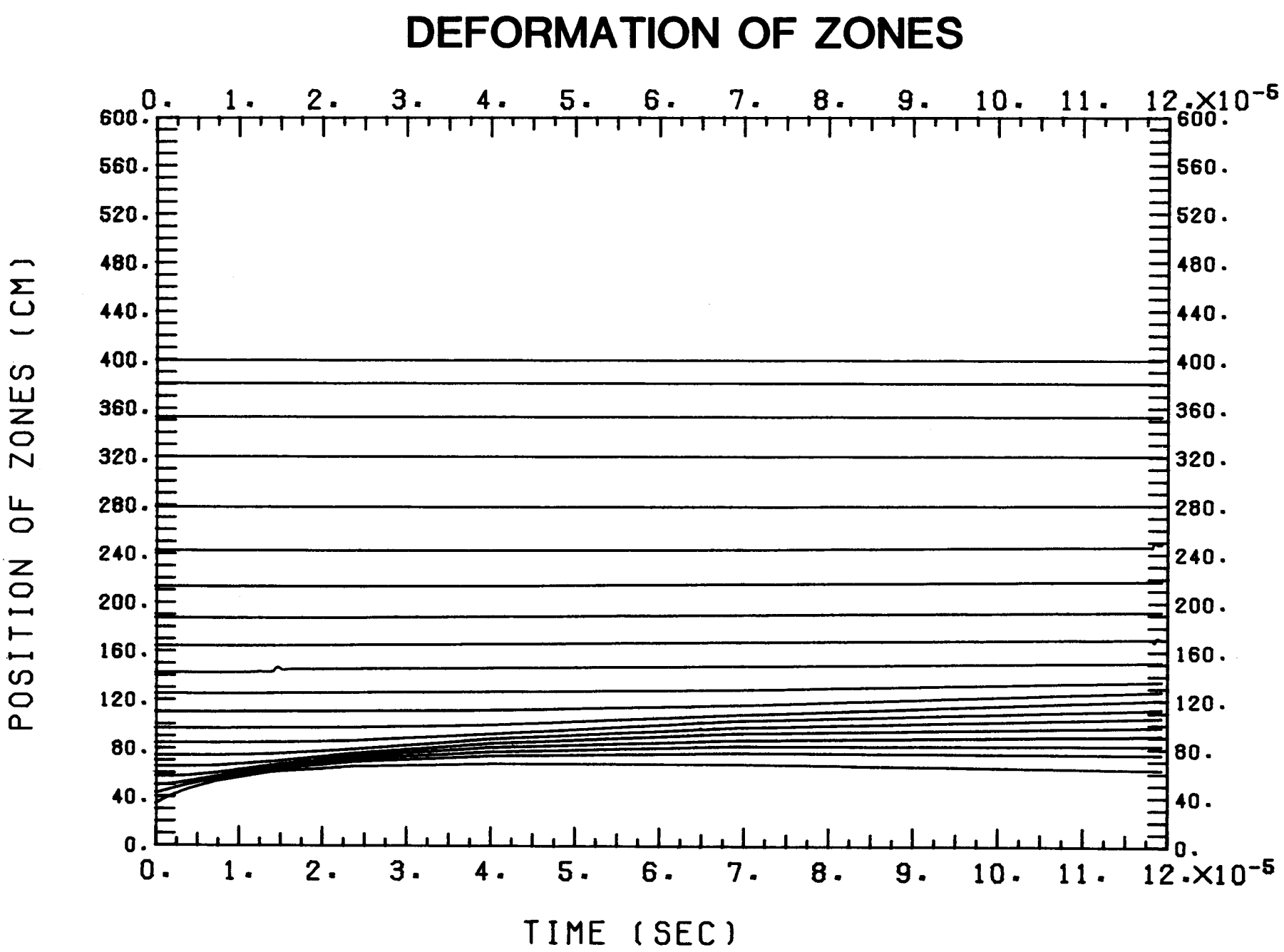


Figure 5. The deformation of zone boundaries as a function of time for the example problem.

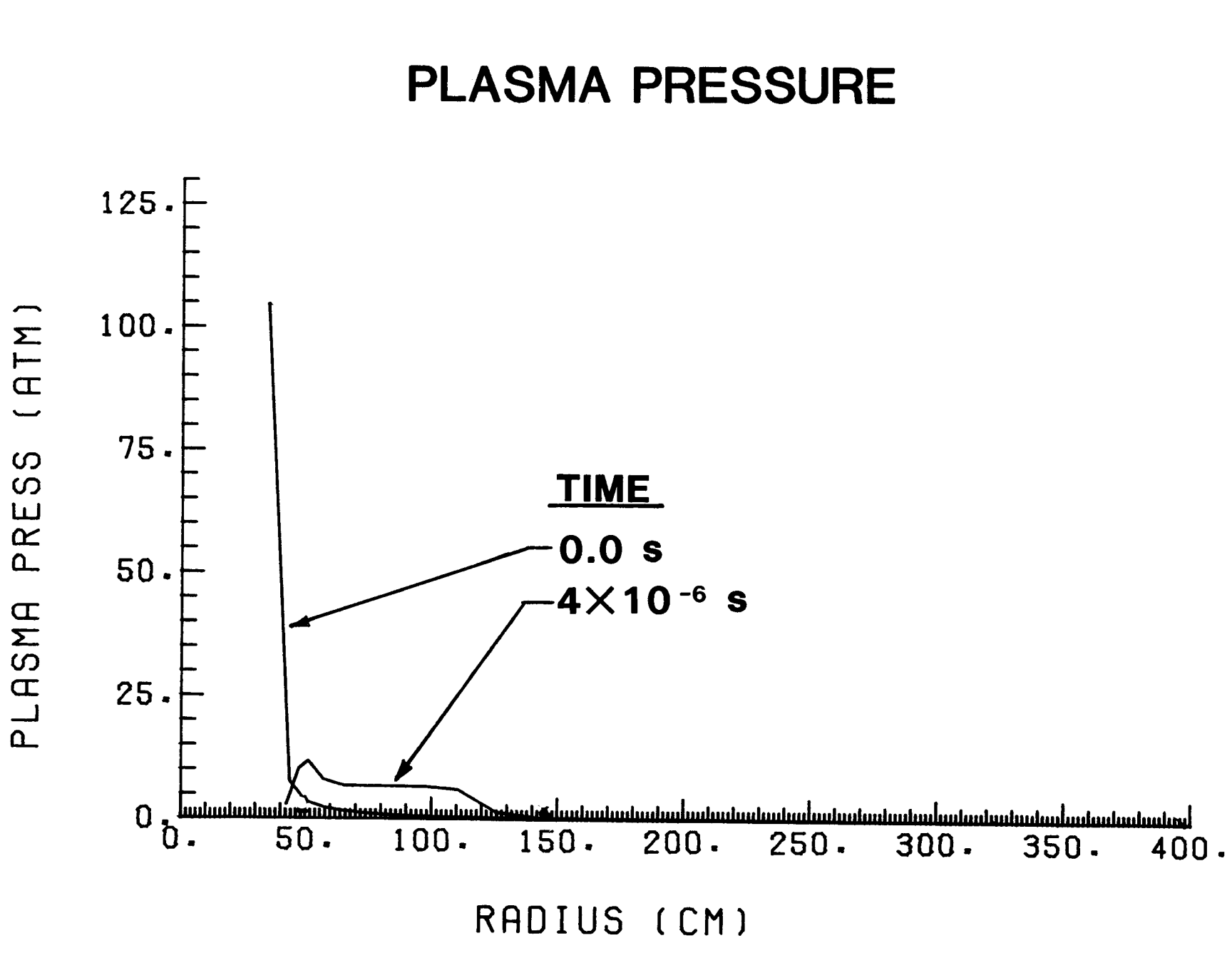


Figure 6. The gas pressure profile for the example problem.

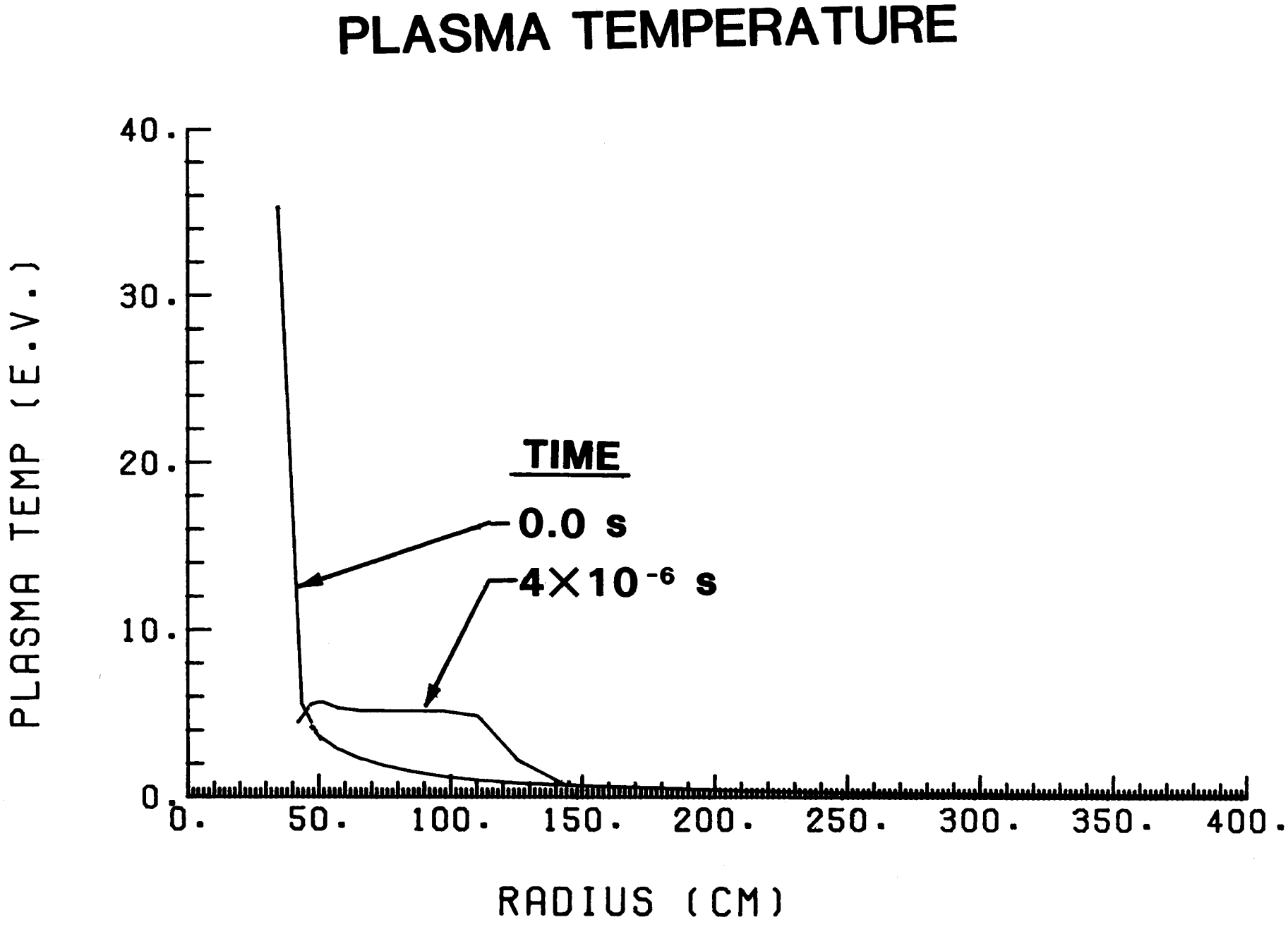


Figure 7. The gas temperature profile for the example problem.

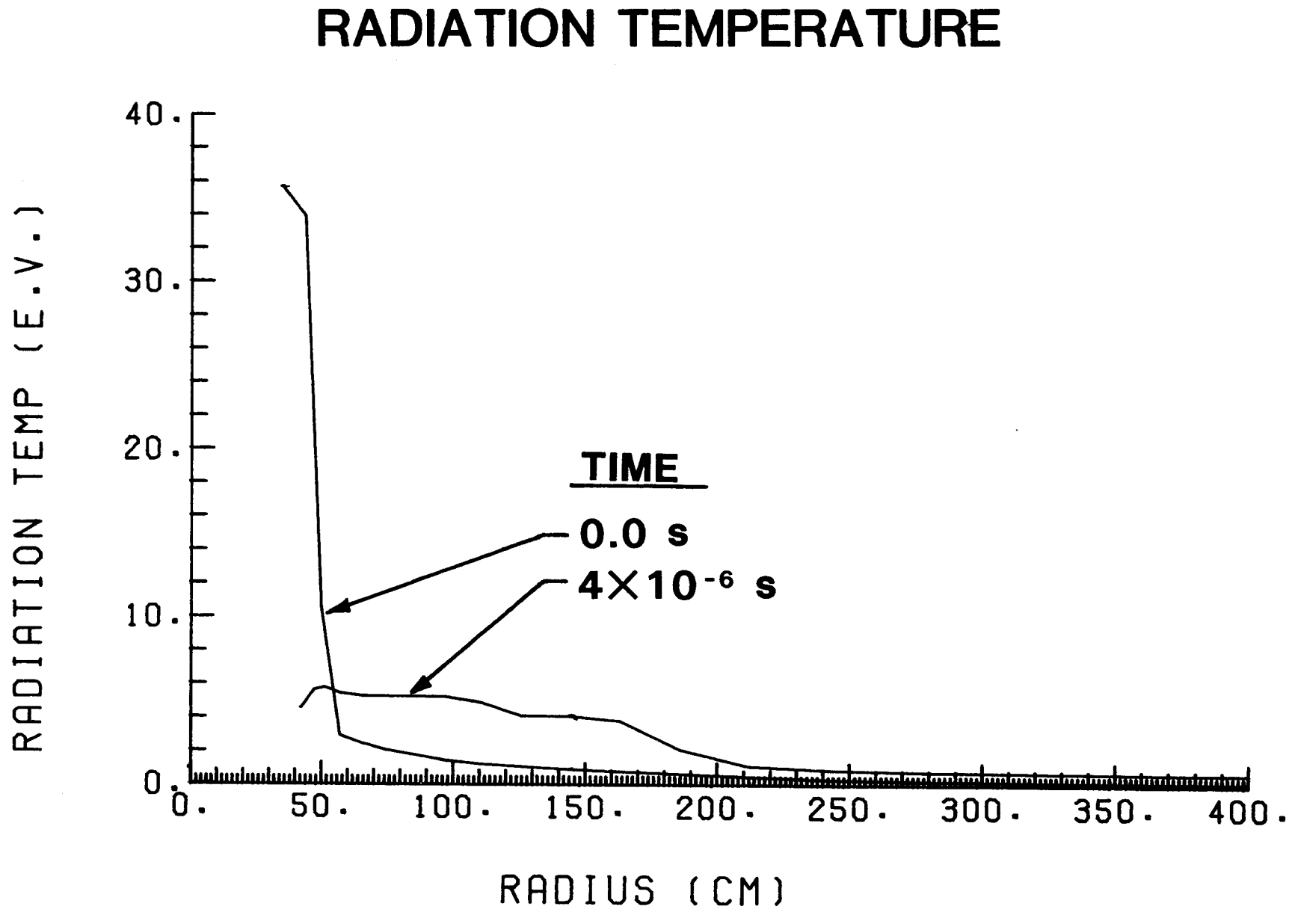


Figure 8. The radiation temperature profile for the example problem.

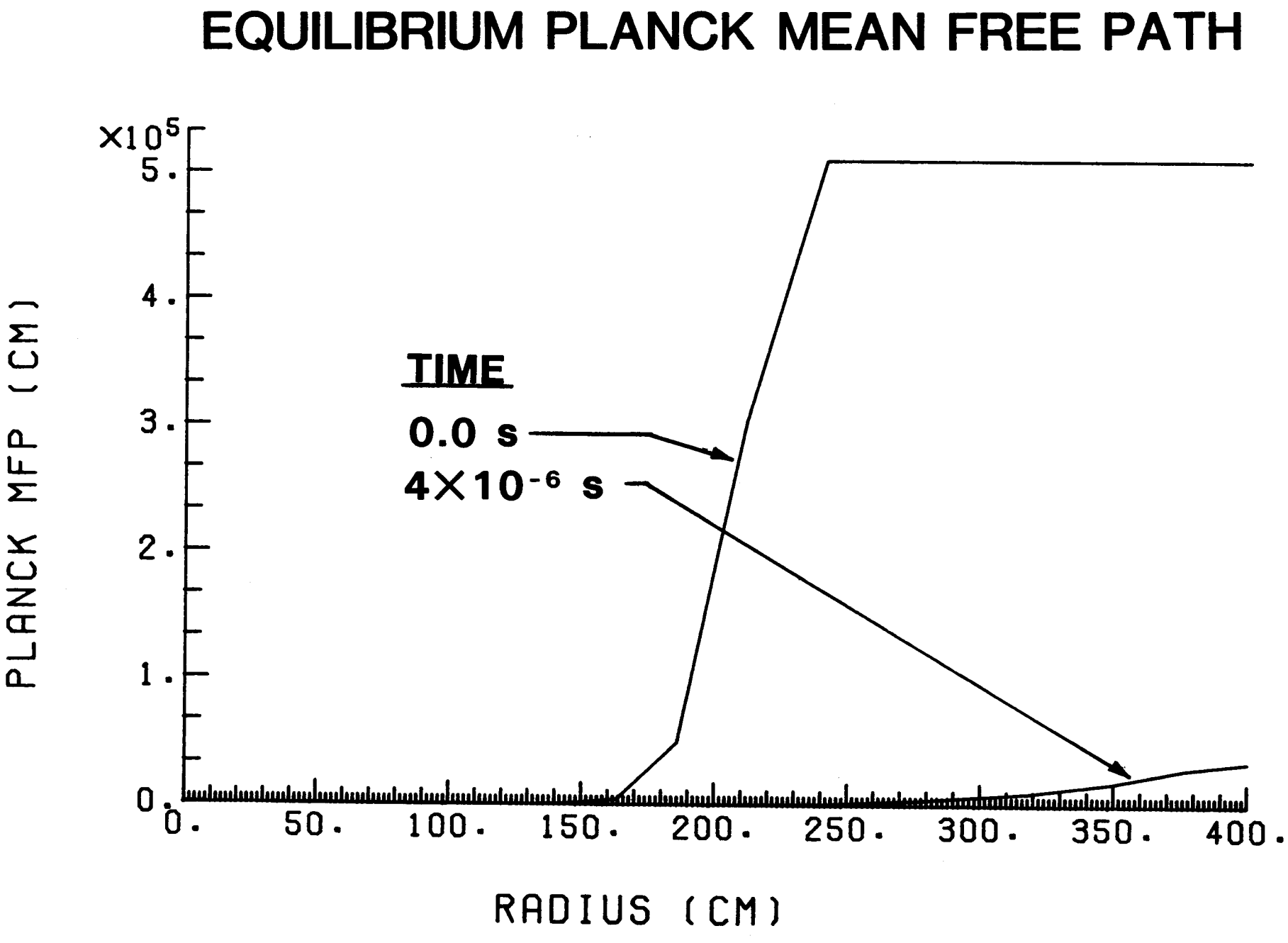


Figure 9. The equilibrium Planck mean free path for the example problem.

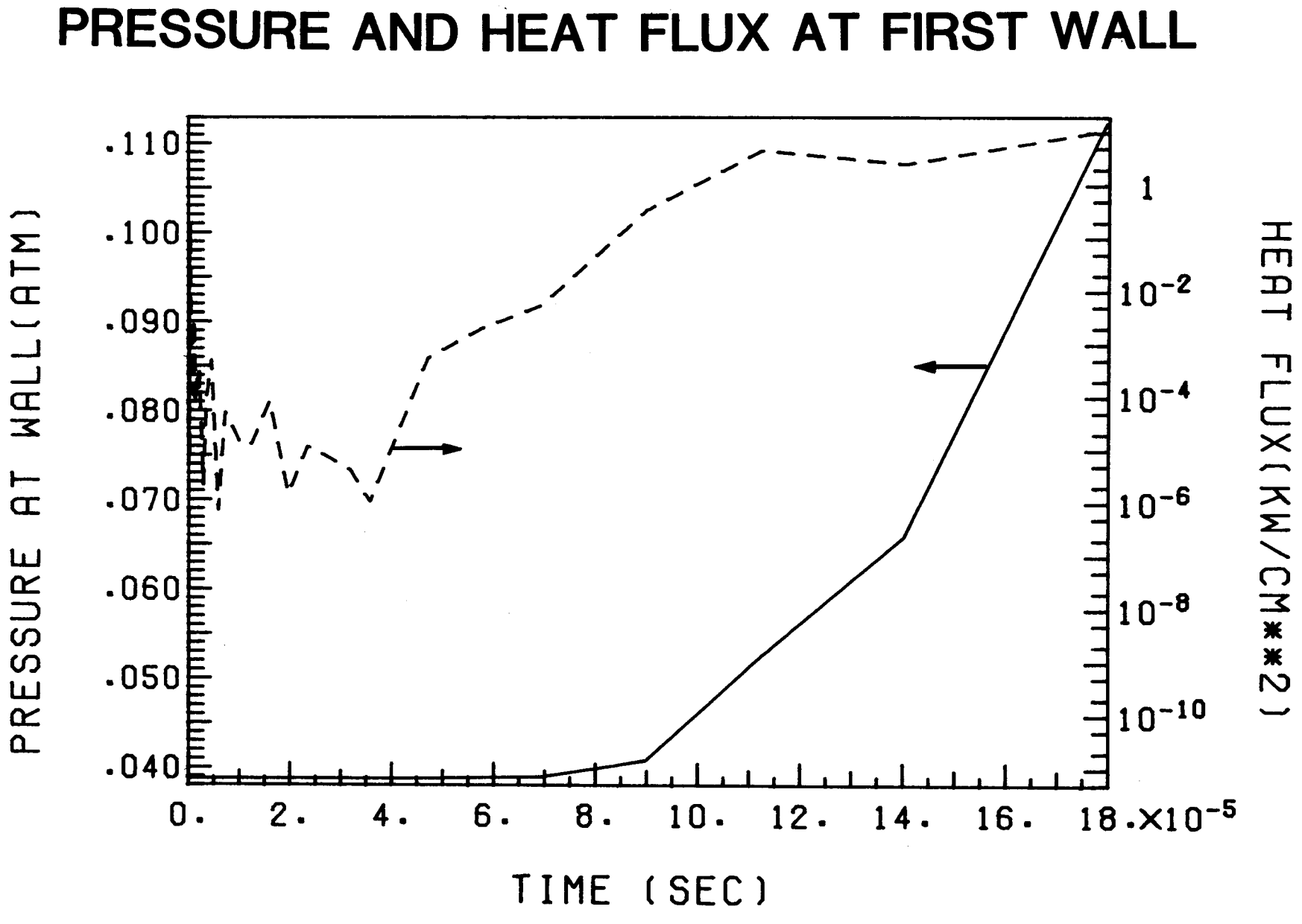


Figure 10. Plot of pressure and heat flux at the first wall.

mechanical response of the first wall.

The heat flux and pressure at the first wall were still increasing at the end of 4×10^{-4} s, so it might be desired to continue the calculation out to a later time. To continue a calculation out to a later time (or more cycles), unit 2 must be assigned at the beginning of a run. To continue the run, the data in unit 2 must be copied onto unit 4, and the new input parameters must be provided. For instance, if it is desired to continue the example run out to 9×10^{-4} s, the new input parameters might be:

```
1       &INPUT IRS = 1, &END
2       &INPUT TMAX = 9.D-4,NMAX = 2000
3       &END
```

XIII. Conclusions

The FIRE code provides an economical model for determining the viability of the gas protection concept. Given the cavity parameters and a target spectra, the code computes the deposition of the spectra into the gas and the gas response. The output of the code can then be used to analyze the thermal and mechanical response of the first wall.

Acknowledgment

This work was supported by Sandia Laboratory, Albuquerque, NM, under contract to the United States Department of Energy.

References

[1] R.W. Conn et al., "SOLASE: A Conceptual Laser Fusion Reactor Design," University of Wisconsin Fusion Engineering Program Report UWFDM-220 (Dec. 1977).

[2] R.R. Peterson, R.D. Watson, W.G. Wolfer, and G.A. Moses, "TSTRESS - A Transient Stress Computer Code," UWFDM-382, Univ. of Wisconsin (Dec. 1980).

[3] T.J. McCarville, G.A. Moses, and G.L. Kulcinski, "A Model for Depositing Inertial Confinement Fusion X-Rays and Pellet Debris Into a Cavity Gas," University of Wisconsin Fusion Design Memo UWFDM-406, April 1981.

[4] K.G. Adams and F. Biggs, "Efficient Computer Access to Sandia Photon Cross Sections II," SC-RR-71-0507, Sandia Laboratory, Albuquerque, NM, December 1971.

[5] J. Von Neumann and R. Richtmyer, "A Method for the Numerical Calculation of Hydrodynamic Shocks," J. Appl. Phys. 21, 232 (1950).

[6] R. Kidder and W. Barnes, "WAZER - A One Dimensional, Two-Temperature Hydrodynamic Code," UCRL-50583, Lawrence Radiation Laboratory, Livermore, California.

[7] R.D. Richtmyer and K.W. Morton, Difference Methods for Initial Value Problems, Interscience Publishers, New York, 1967, 200.

[8] L. Spitzer, Physics of Fully Ionized Gases, Second Edition, Interscience Publishers, New York, 1962, 144.

[9] Y.B. Zel'dovich and Y.P. Raizer, Physics of Shock Waves and Other High Temperature Hydrodynamic Phenomena, W.D. Hayes and P.F. Probstein, eds., Academic Press, New York, 1966, Vol. 1, Chapt. 2.

[10] G.C. Pomraning, The Equations of Radiation Hydrodynamics, Pergamon Press, New York, 1973.

[11] R.R. Peterson and G.A. Moses, "MIXER - A Multi-Species Optical Data and Equation of State Computer Code," University of Wisconsin Fusion Design Memo UWFDM-372, September 1980.

[12] D.K. Brice, "Ion Implantation Range and Energy Deposition Codes COREL, RASE4, DAMG2," SAND-75-0622, Sandia Laboratory, Albuquerque, NM, 1977.

```
**********************************************************
*                                                        *
*     FIRE - A CODE TO COMPUTE THE RESPONSE OF CAVITY-   *
*     GASES TO FUSION PELLET X-RAYS & DEBRIS             *
*                                                        *
*                                                        *
**********************************************************
```

SPHERICAL GEOMETRY - ENERGY QUANTITIES ARE ABSOLUTE

NO. OF ZONES	20
OUTER BOUNDARY(CM)	4.0000+002
STARTING TIME(S)	0.0000-001
STARTING CYCLE	1
NO. OF TIME CYCLES	4000
MAX. PROBLEM TIME(S)	2.0000-004
TIME STEP FOR FIRST 10 CYCLES(S)	1.0000-012
MIN. TIME STEP(S)	1.0000-013
MAX. TIME STEP(S)	5.0000-005
TIME STEP GROWTH LIMIT	1.5000+000
TIME STEP CONTROL PARAMETERS	
COURANT	5.0000-002
PERCENT V CHANGE	5.0000-002
PERCENT TN CHANGE	5.0000-002
PERCENT ER CHANGE	1.0000+035
TEMPERATURE BC.(EV)	5.0000-003

PRIMARY OUTPUT FREQUENCIES

HYDRODYNAMICS	250
ENERGY	250
NUMBER DENSITIES	250
SHORT EDIT	-1
BINARY OUTPUT	25

INTERMEDIATE VARIABLE FREQUENCIES - IEDIT

(1) -1	(2) -1	(3) -1	(4) -1	(5) -1	(6) -1	(7) -1	(8) -1	(9) -1	(10) -1
(11) -1	(12) -1	(13) -1	(14) -1	(15) -1	(16) -1	(17) -1	(18) -1	(19) -1	(20) -1
(21) -1	(22) -1	(23) -1	(24) -1	(25) -1	(26) -1	(27) -1	(28) -1	(29) -1	(30) -1
(31) -1	(32) -1	(33) -1	(34) -1	(35) -1	(36) -1	(37) -1	(38) -1	(39) -1	(40) -1
(41) -1	(42) -1	(43) -1	(44) -1	(45) -1	(46) -1	(47) -1	(48) -1	(49) -1	(50) -1
(51) -1	(52) -1	(53) -1	(54) -1	(55) -1	(56) -1	(57) -1	(58) -1	(59) -1	(60) -1
(61) -1	(62) -1	(63) -1	(64) -1	(65) -1	(66) -1	(67) -1	(68) -1	(69) -1	(70) -1
(71) -1	(72) -1	(73) -1	(74) -1	(75) -1	(76) -1	(77) -1	(78) -1	(79) -1	(80) -1
(81) -1	(82) -1	(83) -1	(84) -1	(85) -1	(86) -1	(87) -1	(88) -1	(89) -1	(90) -1
(91) -1	(92) -1	(93) -1	(94) -1	(95) -1	(96) -1	(97) -1	(98) -1	(99) -1	(

#	RADIUS (CM)	ZONE WIDTH (CM)	MASS DENS (G/CM3)	MASS (G/)	E DENSITY (1/CM3)	ION DENSITY (1/CM3)	R TEMP (EV)	ION TEMP (EV)	ATOMIC WT (AMU)	CHARGE (ESU)
0	0.0000-001									
1	3.4668+001	3.4668+001	1.1756-005	2.0518+000	1.7166+018	1.7700+017	5.0000-002	3.6127+001	4.0000+001	9.6981+000
2	4.3679+001	9.0110+000	1.1756-005	2.0518+000	6.2067+017	1.7700+017	5.0000-002	5.0752+000	4.0000+001	3.5066+000
3	5.0000+001	6.3210+000	1.1756-005	2.0518+000	4.4468+017	1.7700+017	5.0000-002	3.6399+000	4.0000+001	2.5123+000
4	5.7145+001	7.1453+000	1.1756-005	3.0340+000	3.3258+017	1.7700+017	5.0000-002	2.8854+000	4.0000+001	1.8790+000
5	6.5243+001	8.0961+000	1.1756-005	4.4864+000	2.4508+017	1.7700+017	5.0000-002	2.3390+000	4.0000+001	1.3846+000
6	7.4437+001	9.1936+000	1.1756-005	6.6342+000	1.7640+017	1.7700+017	5.0000-002	1.9144+000	4.0000+001	9.9663-001
7	8.4886+001	1.0449+001	1.1756-005	9.8100+000	1.1530+017	1.7700+017	5.0000-002	1.5413+000	4.0000+001	6.5142-001
8	9.6772+001	1.1886+001	1.1756-005	1.4506+001	7.2449+016	1.7700+017	5.0000-002	1.2353+000	4.0000+001	4.0932-001
9	1.1030+002	1.3526+001	1.1756-005	2.1451+001	4.2660+016	1.7700+017	5.0000-002	1.0156+000	4.0000+001	2.4102-001
10	1.2570+002	1.5399+001	1.1756-005	3.1719+001	2.4577+016	1.7700+017	5.0000-002	8.3926-001	4.0000+001	1.3885-001
11	1.4323+002	1.7535+001	1.1756-005	4.6904+001	9.7302+015	1.7700+017	5.0000-002	7.2698-001	4.0000+001	5.4973-002
12	1.6320+002	1.9971+001	1.1756-005	6.9358+001	3.8793+015	1.7700+017	5.0000-002	6.3040-001	4.0000+001	2.1917-002
13	1.8595+002	2.2747+001	1.1756-005	1.0256+002	2.8352+014	1.7700+017	5.0000-002	5.1418-001	4.0000+001	1.6018-003
14	2.1186+002	2.5911+001	1.1756-005	1.5166+002	8.1312+012	1.7700+017	5.0000-002	3.9123-001	4.0000+001	4.5939-005
15	2.4138+002	2.9517+001	1.1756-005	2.2426+002	6.2315+012	1.7700+017	5.0000-002	2.9983-001	4.0000+001	3.5206-005
16	2.7500+002	3.3621+001	1.1756-005	3.3156+002	4.8842+012	1.7700+017	5.0000-002	2.3500-001	4.0000+001	2.7594-005
17	3.1657+002	4.1570+001	1.1756-005	5.3816+002	3.9278+012	1.7700+017	5.0000-002	1.8899-001	4.0000+001	2.2191-005
18	3.4940+002	3.2828+001	1.1756-005	5.3816+002	3.3430+012	1.7700+017	5.0000-002	1.6085-001	4.0000+001	1.8887-005
19	3.7700+002	2.7602+001	1.1756-005	5.3816+002	3.0545+012	1.7700+017	5.0000-002	1.4697-001	4.0000+001	1.7257-005
20	4.0000+002	2.3000+001	1.1756-005	5.1298+002	2.8677+012	1.7700+017	5.0000-002	1.3798-001	4.0000+001	1.6202-005
				3.1515+003						

#	R PRESS (J/CM3)	ION PRESS (J/CM3)	R INT ENE (J/)	ION INT ENE (J/)	VELOCITY (CM/S)
0					0.0000-001
1	3.9186-016	1.0959+001	2.0518-010	9.4749+006	0.0000-001
2	3.9186-016	6.4854-001	2.0518-010	7.3889+005	0.0000-001
3	3.9186-016	3.6251-001	2.0518-010	4.1443+005	0.0000-001
4	3.9186-016	2.3555-001	3.0340-010	3.9369+005	0.0000-001
5	3.9186-016	1.5816-001	4.4864-010	3.7691+005	0.0000-001
6	3.9186-016	1.0839-001	6.6342-010	3.5703+005	0.0000-001
7	3.9186-016	7.2174-002	9.8100-010	3.3650+005	0.0000-001
8	3.9186-016	4.9365-002	1.4506-009	3.1860+005	0.0000-001
9	3.9186-016	3.5740-002	2.1451-009	2.9955+005	0.0000-001
10	3.9186-016	2.7102-002	3.1719-009	2.8224+005	0.0000-001
11	3.9186-016	2.1747-002	4.6904-009	2.6032+005	0.0000-001
12	3.9186-016	1.8267-002	6.9358-009	2.4097+005	0.0000-001
13	3.9186-016	1.4603-002	1.0256-008	2.2402+005	0.0000-001
14	3.9186-016	1.1094-002	1.5166-008	2.1468+005	0.0000-001
15	3.9186-016	8.5021-003	2.2426-008	2.4328+005	0.0000-001
16	3.9186-016	6.6638-003	3.3156-008	2.8192+005	0.0000-001
17	3.9186-016	5.3589-003	5.3816-008	3.6798+005	0.0000-001
18	3.9186-016	4.5610-003	5.3816-008	3.1319+005	0.0000-001
19	3.9186-016	4.1674-003	5.3816-008	2.8616+005	0.0000-001
20	3.9186-016	3.9125-003	5.1298-008	2.5609+005	0.0000-001
			3.1515-007	1.5681+007	0.0000-001

COEFFICIENTS USED IN FIRE - CON

ION THERMAL COND.....	(1)	1.2175+002	R THERMAL COND.....	(2)	1.0000+010
RAD. EQ. COND.....	(3)	1.0000-001	FLUX LIMIT EPSILON TERM..	(4)	1.0000-006
CONST LOG LAMBDA.....	(5)	0.0000-001		(6)	0.0000-001
PLASMA EMISS. COEF.....	(7)	4.1200+005	PLASMA ABSORP. COEF.....	(8)	3.0000+010
ION PRESS(I.GAS).....	(9)	1.6020-019		(10)	0.0000-001
	(11)	0.0000-001	ION PRESS DERIV(I.GAS)...	(12)	1.6020-019
	(13)	0.0000-001	ION SP HEAT(I.GAS).....	(14)	2.4030-019
ION INT ENERGY(I.GAS)....	(15)	2.4030-019	RAD SP. ENERGY COEF.....	(16)	1.3733-005
	(17)	0.0000-001	ION SHOCK HEATING.....	(18)	1.0000+000
	(19)	0.0000-001		(20)	0.0000-001
ARTIFICIAL VISCOSITY.....	(21)	1.4140+000		(22)	0.0000-001
	(23)	0.0000-001		(24)	0.0000-001
	(25)	0.0000-001		(26)	0.0000-001
	(27)	0.0000-001		(28)	0.0000-001
	(29)	0.0000-001		(30)	0.0000-001
	(31)	0.0000-001			

CALCULATION OPTIONS USED IN FIRE - ISW

	(1)	0	NO. OF CONST TIME STEPS..	(2)	10
	(3)	0	AUTOMATIC ZONING.....	(4)	1
FREQ OF WALL OUTPUT.....	(5)	10	HYDRODYNAMIC MOTION.....	(6)	0
	(7)	0	ION DEPOSITION SOURCE....	(8)	1
	(9)	0	FREQ. OF DTB CALCULATION.	(10)	1
AUTOMATIC XRAY DEPOSITION	(11)	0		(12)	0
	(13)	0	ARBITRARY RADIATION MFP..	(14)	0
ARBITRARY ROSSELAND MFP..	(15)	0		(16)	0
	(17)	0		(18)	0
	(19)	0			

EQUATION OF STATE TABLE INDICES

DENSITY SLOPE.....	5.0000-001
DENSITY BASE.....	1.6931+001
TEMPERATURE SLOPE...	1.6289-001
TEMPERATURE BASE....	-3.9794-001
MIN DENSITY(1/CM3)..	8.5389+016
MAX DENSITY(1/CM3)..	2.7002+021
MIN TEMPERATURE(EV)	4.0000-001
MAX TEMPERATURE(EV)	4.9781+002

THE BLACKBODY TEMPERATURE WAS 3.0000-001 KEV FOR THE X-RAYS
THE X-RAY SPECTRA CONTAINED 1.4878+007 JOULES
THE X-RAY ENERGY DEPOSITED WAS 1.4540+007 JOULES

********** XRAY FLUX TO WALL **********

ENERGY GROUP	ENERGY (KEV)	EXITING ENERGY (J/KEV)	ATTENUATION COEFFICIENT (/CM)
1	1.2900-001	2.2644-017	1.1610+004
2	3.2700-001	1.3785-073	3.8960+004
3	5.2500-001	4.3681-024	1.4836+004
4	7.2300-001	7.7080-008	6.9239+003
5	9.2100-001	1.9243-001	3.7955+003
6	1.1190+000	1.8108+002	2.3184+003
7	1.3170+000	6.2186+003	1.5274+003
8	1.5150+000	4.3095+004	1.0635+003
9	1.7130+000	1.2637+005	7.7204+002
10	1.9110+000	2.2442+005	5.7900+002
11	2.1090+000	2.9167+005	4.4562+002
12	2.3070+000	3.0887+005	3.5024+002
13	2.5050+000	2.8420+005	2.8007+002
14	2.7030+000	2.3661+005	2.2720+002
15	2.9010+000	1.8302+005	1.8654+002

INITIAL CONDITIONS FOR PROJECTILES

#	INITIAL ENERGY (KEV)	INITIAL SPEED CM/SEC	FINAL RANGE (CM)	FINAL STD.DEV. (CM)	NUMBER PARTICLES
1	1.50+001	2.27+007	3.14-001	1.41-001	6.25+021

1.50+001 MJ TOTAL 6.25+021 PARTICLES TOTAL
SLOW DEBRIS TURNED OFF AT CYCLE 176

CYCLE	TIME(S)	DELTA T(S)	CRITERION(TN/T) IN ZONE (10) OTHERWISE (TN/T) IN ZONE (10)
250	2.1541-006	4.8955-008	

#	RADIUS (CM)	ZONE WIDTH (CM)	MASS DENS (G/CM3)	COMPRESSION (VO/V)	VELOCITY (CM/S)	R TEMP (EV)	ION TEMP (EV)	R PRESS (J/CM3)	ION PRESS (J/CM3)	ART VISC (J/CM3)
0	0.0000-001				0.0000-001					
1	4.2419+001	4.2419+001	6.4175-006	5.4589-001	2.9273+006	4.6017+000	4.5481+000	1.8158-003	3.0310-001	0.0000-001
2	4.7398+001	4.9788+000	1.6244-005	1.3618+000	1.9817+006	5.6701+000	5.6318+000	4.5890-003	1.0547+000	2.8988+000
3	5.1165+001	3.7672+000	1.7837-005	1.5173+000	1.0247+006	5.8053+000	5.7640+000	5.0333-003	1.2019+000	3.2508+000
4	5.7292+001	6.1268+000	1.3386-005	1.1387+000	2.0455+005	5.4282+000	5.3672+000	3.7699-003	8.0779-001	1.7954+000
5	6.5317+001	8.0248+000	1.1821-005	1.0055+000	3.8370+004	5.2629+000	5.2038+000	3.3177-003	6.8121-001	6.5240-002
6	7.4510+001	9.1939+000	1.1731-005	9.9787-001	4.0244+004	5.2406+000	5.1884+000	3.2762-003	6.7285-001	0.0000-001
7	8.4950+001	1.0439+001	1.1747-005	9.9925-001	4.2301+004	5.2329+000	5.1816+000	3.2583-003	6.7217-001	0.0000-001
8	9.6814+001	1.1864+001	1.1764-005	1.0007+000	4.4012+004	5.2222+000	5.1708+000	3.2299-003	6.7059-001	0.0000-001
9	1.1031+002	1.3496+001	1.1776-005	1.0017+000	2.3337+004	4.8940+000	4.8768+000	2.6316-003	6.0586-001	1.0065-003
10	1.2570+002	1.5388+001	1.1763-005	1.0006+000	2.0153+003	4.0902+000	2.2078+000	5.5959-006	1.4153-001	1.0691-003
11	1.4323+002	1.7535+001	1.1756-005	1.0000+000	3.3263+002	4.0675+000	7.3241-001	4.1838-008	2.1968-002	6.6555-006
12	1.6320+002	1.9971+001	1.1756-005	1.0000+000	3.0391+002	3.7789+000	6.3062-001	3.3522-010	1.8276-002	0.0000-001
13	1.8595+002	2.2747+001	1.1756-005	1.0000+000	2.5566+002	2.0878+000	5.1436-001	3.8204-011	1.4610-002	0.0000-001
14	2.1186+002	2.5911+001	1.1756-005	1.0000+000	1.6566+002	1.1091+000	3.9132-001	3.7750-011	1.1098-002	1.9037-008
15	2.4138+002	2.9517+001	1.1756-005	1.0000+000	1.0322+002	8.9604-001	2.9992-001	3.5819-011	8.5054-003	9.1640-009
16	2.7500+002	3.3621+001	1.1756-005	1.0000+000	6.0765+001	7.9311-001	2.3504-001	3.2408-011	6.6655-003	4.2371-009
17	3.1657+002	4.1570+001	1.1756-005	1.0000+000	3.9778+001	7.3549-001	1.8900-001	2.8540-011	5.3598-003	1.0353-009
18	3.4940+002	3.2828+001	1.1756-005	1.0000+000	2.3902+001	6.9956-001	1.6086-001	2.5129-011	4.5616-003	5.9242-010
19	3.7700+002	2.7602+001	1.1756-005	1.0000+000	1.8452+001	6.7317-001	1.4697-001	2.1566-011	4.1679-003	6.9813-011
20	4.0000+002	2.3000+001	1.1756-005	1.0000+000	0.0000-001	6.6397-001	1.3798-001	1.5964-011	3.9129-003	8.0026-010
						5.0000-003	5.0000-003			

#	R ENERGY (J/)	ION ENERGY (J/)	KIN ENERGY (J/)	R SOURCE (J/)	ION SOURCE (J/)	ION->R EX (J/)	FLUX LIM (J/CM2-S)	HEAT FLUX (J/CM2-S)
0			0.0000-001					
1	1.7417+003	6.5527+005	8.7912+005	0.0000-001	0.0000-001	1.1866+004	7.4842+007	6.1128+006
2	1.7389+003	8.5068+005	4.0287+005	0.0000-001	0.0000-001	1.7884+004	1.1205+008	1.2802+007
3	1.7369+003	8.8054+005	1.3350+005	0.0000-001	0.0000-001	1.9626+004	1.0246+008	1.9386+007
4	2.5633+003	1.1826+006	7.8662+003	0.0000-001	0.0000-001	2.1046+004	8.2672+007	2.4042+007
5	3.7774+003	1.6853+006	4.0931+002	0.0000-001	0.0000-001	2.8215+004	7.7019+007	2.6796+007
6	5.5584+003	2.4819+006	6.6583+002	0.0000-001	0.0000-001	4.1810+004	7.6338+007	3.0192+007
7	8.1631+003	3.6611+006	1.0878+003	0.0000-001	0.0000-001	6.1665+004	7.5793+007	3.4770+007
8	1.1949+004	5.3934+006	1.7413+003	0.0000-001	0.0000-001	9.0974+004	6.6863+007	6.3539+007
9	1.4381+004	7.2124+006	7.2392+002	0.0000-001	0.0000-001	-7.2913+004	2.9178+007	2.9061+007
10	4.5269+001	2.3434+006	7.9834+000	0.0000-001	0.0000-001	-2.2075+005	4.5323+004	4.5299+004
11	5.0077-001	2.6677+005	3.2160-001	0.0000-001	0.0000-001	-6.0994+002	3.3131+002	3.3123+002
12	5.9332-003	2.4124+005	3.9696-001	0.0000-001	0.0000-001	-5.8998+000	3.5442+000	3.4701+000
13	9.9989-004	2.2414+005	4.1540-001	0.0000-001	0.0000-001	-8.9850-002	1.4436+000	5.1913-001
14	1.4610-003	2.1475+005	2.5792-001	0.0000-001	0.0000-001	4.8873-003	1.3528+000	8.1053-001
15	2.0499-003	2.4338+005	1.4806-001	0.0000-001	0.0000-001	4.7791-003	1.2004+000	7.9455-001
16	2.7421-003	2.8199+005	8.0283-002	0.0000-001	0.0000-001	3.1319-003	1.0307+000	6.7373-001
17	3.9195-003	3.6804+005	4.2575-002	0.0000-001	0.0000-001	2.2021-003	8.8199-001	5.2656-001
18	3.4510-003	3.1323+005	1.5372-002	0.0000-001	0.0000-001	1.1725-003	7.5331-001	4.4389-001
19	2.9617-003	2.8619+005	8.9470-003	0.0000-001	0.0000-001	8.2147-004	5.9717-001	4.0485-001
20	2.0898-003	2.5612+005	0.0000-001	0.0000-001	0.0000-001	6.0995-004	5.0433-001	4.2927-001

ENERGY CONSERVATION CHECK -- UNITS ARE (J/)

	INT ENE	T KE	INT ENE(O)	T BDFLUX	T I->R EX	T SOURCE	BDFLUX	I->R EX	SOURCE
R	5.1655+004		3.1515-007	4.1036+001	5.2223+004	0.0000-001	3.0094-002	-1.1953+003	0.0000-001
I	2.9043+007	1.4280+006	1.5681+007	1.1812-006		1.4280+007	2.6844-008		0.0000-001

RADIATION	5.1655+004	5.1638+004
ION	3.0471+007	2.9910+007
TOTAL	3.0522+007	2.9961+007

#	E DENSITY (1/CM3)	ION DENSITY (1/CM3)	CHARGE (ESU)	ROSS MFP (CM)	RAD MFP (CM)	EQM T MFP (CM)	EPSILON
1	3.2280+017	9.6631+016	3.3050+000	3.9317+003	2.2794+001	2.4833+001	9.2701-001
2	9.3381+017	2.4460+017	3.7795+000	7.7323+002	4.4867+000	4.6820+000	9.9652-001
3	1.0425+018	2.6858+017	3.8463+000	6.5227+002	3.9280+000	4.1091+000	9.9608-001
4	7.4423+017	2.0156+017	3.6609+000	1.1060+003	6.0484+000	6.5585+000	9.9237-001
5	6.4510+017	1.7800+017	3.5908+000	1.3814+003	7.6923+000	8.3366+000	9.8831-001
6	6.3883+017	1.7664+017	3.5828+000	1.3994+003	7.8956+000	8.4783+000	9.8757-001
7	6.3883+017	1.7688+017	3.5779+000	1.3969+003	7.9126+000	8.4869+000	9.8735-001
8	6.3837+017	1.7713+017	3.5702+000	1.3950+003	7.9316+000	8.5097+000	9.8697-001
9	5.9474+017	1.7732+017	3.3734+000	1.4209+003	9.3434+000	9.5762+000	1.0163+000
10	2.0687+017	1.7712+017	1.2593+000	9.6922+003	2.9750-001	1.4496+001	5.1451-002
11	1.0164+016	1.7702+017	5.7678-002	1.3204+005	1.2326+000	9.4319+003	3.1761-002
12	3.8880+015	1.7701+017	2.1965-002	1.6301+005	1.3718+000	6.0878+004	4.6302-004
13	2.8520+014	1.7701+017	1.6112-003	3.3466+005	7.5964+000	2.5086+005	1.1923-004
14	6.1338+012	1.7701+017	4.5950-005	4.8266+005	1.9523+002	5.1043+005	3.5165-004
15	6.2339+012	1.7701+017	3.5217-005	4.9403+005	1.1415+003	5.1043+005	9.6699-004
16	4.8854+012	1.7701+017	2.7599-005	4.9726+005	4.0558+003	5.1043+005	2.3195-003
17	3.9285+012	1.7701+017	2.2193-005	4.9747+005	1.0182+004	5.1043+005	4.8858-003
18	3.3434+012	1.7701+017	1.8888-005	4.9761+005	1.8763+004	5.1043+005	8.1991-003
19	3.0549+012	1.7701+017	1.7258-005	4.9771+005	2.9997+004	5.1043+005	1.0096-002
20	2.8680+012	1.7701+017	1.6202-005	4.9775+005	3.5484+004	5.1043+005	9.6205-003

CYCLE	TIME(S)	DELTA T(S)	CRITERION(V/V) IN ZONE (10) OTHERWISE (V/V) IN ZONE (10)
444	2.0038-004	6.2707-006	

#	RADIUS (CM)	ZONE WIDTH (CM)	MASS DENS (G/CM3)	COMPRESSION (VO/V)	VELOCITY (CM/S)	R TEMP (EV)	ION TEMP (EV)	R PRESS (J/CM3)	ION PRESS (J/CM3)	ART VISC (J/CM3)
0	0.0000-001				0.0000-001					
1	5.6918+001	5.6918+001	2.6564-006	2.2596-001	-7.2336+004	8.8545-001	8.8326-001	8.7221-007	6.7781-003	2.7459-003
2	6.9615+001	1.2697+001	3.2020-006	2.7237-001	-8.2163+004	8.9446-001	8.9485-001	1.0513-006	8.3230-003	6.1209-005
3	7.9501+001	9.8853+000	2.9669-006	2.5238-001	-7.4333+004	8.9286-001	8.8739-001	9.7417-007	7.6208-003	3.6220-005
4	8.9317+001	9.8163+000	3.4482-006	2.9332-001	-4.4260+004	9.0607-001	9.0564-001	1.1322-006	9.1182-003	0.0000-001
5	1.0005+002	1.0732+001	3.7068-006	3.1532-001	-3.6371+004	9.1777-001	9.1755-001	1.2171-006	9.9887-003	4.6113-005
6	1.1016+002	1.0110+001	4.7235-006	4.0180-001	2.0000+004	9.4621-001	9.4723-001	1.5509-006	1.3336-002	0.0000-001
7	1.2030+002	1.0140+001	5.7946-006	4.9291-001	3.2449+004	9.7151-001	9.7383-001	1.9026-006	1.7034-002	0.0000-001
8	1.3012+002	9.8170+000	7.4970-006	6.3773-001	8.5077+004	1.0007+000	9.9631-001	2.4615-006	2.2558-002	0.0000-001
9	1.4021+002	1.0096+001	9.2500-006	7.8684-001	8.9659+004	1.0302+000	1.0266+000	3.0369-006	2.8880-002	0.0000-001
10	1.5083+002	1.0616+001	1.1223-005	9.5468-001	1.5027+005	1.0619+000	1.0509+000	3.6843-006	3.6041-002	0.0000-001
11	1.6073+002	9.9052+000	1.5522-005	1.3204+000	1.4702+005	1.1081+000	1.1009+000	5.0946-006	5.2954-002	0.0000-001
12	1.7504+002	1.4303+001	1.3683-005	1.1639+000	9.6923+004	1.1006+000	1.0874+000	4.4885-006	4.5999-002	6.8231-003
13	1.9564+002	2.0601+001	1.1522-005	9.8007-001	5.6821+004	1.0814+000	1.0629+000	3.7760-006	3.7627-002	3.6917-003
14	2.2098+002	2.5343+001	1.0961-005	9.3239-001	5.1340+004	1.0697+000	1.0526+000	3.5865-006	3.5326-002	0.0000-001
15	2.4940+002	2.8417+001	1.1340-005	9.6460-001	5.3213+004	1.0672+000	1.0541+000	3.7011-006	3.6577-002	0.0000-001
16	2.8089+002	3.1493+001	1.1903-005	1.0126+000	5.7299+004	1.0697+000	1.0586+000	3.8688-006	3.8575-002	0.0000-001
17	3.1989+002	3.9005+001	1.2151-005	1.0336+000	4.5726+004	1.0507+000	1.0238+000	3.5004-006	3.7348-002	0.0000-001
18	3.5093+002	3.1035+001	1.2257-005	1.0426+000	2.3216+004	1.0457+000	7.8937-001	1.8789-006	2.5490-002	1.2397-003
19	3.7810+002	2.7175+001	1.1855-005	1.0084+000	1.9860+004	1.0453+000	6.4535-001	1.1520-006	1.8923-002	2.6689-005
20	4.0000+002	2.1897+001	1.2314-005	1.0474+000	0.0000-001	1.0453+000	4.5306-001	5.9319-007	1.3460-002	9.6849-004
						5.0000-003	5.0000-003			

#	R ENERGY (J/)	ION ENERGY (J/)	KIN ENERGY (J/)	R SOURCE (J/)	ION SOURCE (J/)	ION->R EX (J/)	FLUX LIM (J/CM2-S)	HEAT FLUX (J/CM2-S)
0			0.0000-001					
1	2.0211+000	2.3443+004	5.3679+002	0.0000-001	0.0000-001	3.5463+002	2.3227+004	7.7255+002
2	2.0211+000	2.4133+004	6.9256+002	0.0000-001	0.0000-001	3.3604+002	2.4551+004	1.0212+003
3	2.0211+000	2.3688+004	7.0253+002	0.0000-001	0.0000-001	3.2693+002	2.5740+004	1.1701+003
4	2.9886+000	3.6649+004	3.6830+002	0.0000-001	0.0000-001	5.5784+002	2.8749+004	1.4835+003
5	4.4192+000	5.5790+004	3.6777+002	0.0000-001	0.0000-001	8.8774+002	3.4115+004	1.8733+003
6	6.5347+000	8.8546+004	1.6445+002	0.0000-001	0.0000-001	1.5265+003	4.2611+004	2.6114+003
7	9.6629+000	1.3878+005	6.4008+002	0.0000-001	0.0000-001	2.4336+003	5.4002+004	3.6817+003
8	1.4288+001	2.0756+005	6.5065+003	0.0000-001	0.0000-001	4.2407+003	6.7930+004	5.5574+003
9	2.1128+001	3.1829+005	1.0686+004	0.0000-001	0.0000-001	7.7652+003	8.3308+004	8.6569+003
10	3.1239+001	4.8260+005	4.4387+004	0.0000-001	0.0000-001	1.2784+004	1.0853+005	1.3502+004
11	4.6183+001	7.5924+005	6.2826+004	0.0000-001	0.0000-001	2.3592+004	1.1694+005	2.1337+004
12	6.8258+001	1.1102+006	4.0375+004	0.0000-001	0.0000-001	3.2224+004	1.0036+005	2.9879+004
13	1.0084+002	1.5960+006	2.0519+004	0.0000-001	0.0000-001	4.0871+004	8.9721+004	3.6828+004
14	1.4887+002	2.3243+006	2.4771+004	0.0000-001	0.0000-001	5.7389+004	8.9016+004	4.3529+004
15	2.1958+002	3.4314+006	3.9347+004	0.0000-001	0.0000-001	8.6719+004	9.2464+004	5.2364+004
16	3.2329+002	5.0876+006	7.1386+004	0.0000-001	0.0000-001	1.3097+005	8.8590+004	6.6587+004
17	4.6510+002	7.6182+006	5.6260+004	0.0000-001	0.0000-001	6.7747+004	6.2995+004	6.2831+004
18	2.4749+002	3.8871+006	1.4503+004	0.0000-001	0.0000-001	-1.5413+005	3.4682+004	3.4670+004
19	1.5688+002	2.0166+006	1.0365+004	0.0000-001	0.0000-001	-9.9955+004	1.9622+004	1.9620+004
20	7.4136+001	9.0959+005	0.0000-001	0.0000-001	0.0000-001	-4.8927+004	1.3189+004	1.3189+004

ENERGY CONSERVATION CHECK -- UNITS ARE (J/)

	INT ENE	T KE	INT ENE(D)	T BDFLUX	T I->R EX	T SOURCE	BDFLUX	I->R EX	SOURCE
R	1.9470+003		3.1515-007	1.3354+006	1.3374+006	0.0000-001	1.6752+005	1.6771+005	0.0000-001
I	3.0140+007	4.0540+005	1.5681+007	2.3505-004		1.4280+007	2.1778-005		0.0000-001

RADIATION	1.9470+003	1.9353+003
ION	3.0545+007	2.8624+007
TOTAL	3.0547+007	2.8626+007

#	E DENSITY (1/CM3)	ION DENSITY (1/CM3)	CHARGE (ESU)	ROSS MFP (CM)	RAD MFP (CM)	EQM T MFP (CM)	EPSILON
1	7.9530+015	3.9998+016	1.9761-001	2.4003+005	2.4084+003	2.4562+003	3.1305-001
2	9.9296+015	4.8213+016	2.0420-001	2.0596+005	2.1730+003	2.1655+003	3.5817-001
3	9.0456+015	4.4675+016	1.9994-001	2.2767+005	2.2357+003	2.3473+003	3.4318-001
4	1.1156+016	5.1922+016	2.1044-001	1.7931+005	1.9258+003	1.9329+003	3.6766-001
5	1.2354+016	5.5815+016	2.1748-001	1.5417+005	1.7085+003	1.7117+003	3.7510-001
6	1.7294+016	7.1125+016	2.3561-001	1.0699+005	1.2966+003	1.2863+003	4.2084-001
7	2.2402+016	8.7252+016	2.5141-001	7.6315+004	1.0095+003	9.9219+002	4.6212-001
8	2.9293+016	1.1289+017	2.5197-001	4.4873+004	6.0520+002	6.2457+002	5.4571-001
9	3.7408+016	1.3928+017	2.6075-001	2.5406+004	3.8252+002	3.9172+002	5.9721-001
10	4.6902+016	1.6899+017	2.6683-001	1.5845+004	2.4662+002	2.6470+002	6.5997-001
11	6.9112+016	2.3373+017	2.8464-001	6.4907+003	1.2533+002	1.3075+002	7.5772-001
12	5.9840+016	2.0603+017	2.8172-001	8.6464+003	1.5213+002	1.6473+002	7.0138-001
13	4.6835+016	1.7349+017	2.7374-001	1.3605+004	2.1014+002	2.3593+002	6.4625-001
14	4.5737+016	1.6505+017	2.6930-001	1.6033+004	2.4061+002	2.6825+002	6.3819-001
15	4.7226+016	1.7075+017	2.6852-001	1.5145+004	2.3521+002	2.5559+002	6.5478-001
16	4.9700+016	1.7924+017	2.6903-001	1.3653+004	2.1878+002	2.3457+002	6.7288-001
17	4.5225+016	1.8296+017	2.4463-001	1.9742+004	2.4848+002	2.9769+002	6.9594-001
18	1.5655+016	1.8456+017	9.2175-002	2.2939+005	3.0387+002	3.7860+003	1.0572+000
19	4.0898+015	1.7851+017	2.5368-002	3.7855+005	3.1573+002	4.4792+004	1.4508+000
20	1.7852+013	1.8541+017	1.7980-004	4.6357+005	3.0426+002	3.4275+005	3.0757+000

MAX OVER-PRESSURE= 1.3460-002 (J/CM3) TIME= 2.0038-004 (S) CYCLE= 444

MAX HEAT FLUX= 1.3311+004 (J/CM2*S) TIME= 2.0038-004 (S) CYCLE= 444

PRESSURE AND HEAT FLUX AT THE FIRST WALL

TIME(S)

1.0000-11	1.8000-10	3.6682-09	8.6055-09	1.1991-08	1.6044-08	2.1270-08	2.5386-08	2.9301-08	3.6381-08
4.4665-08	5.0533-08	6.1271-08	8.5479-08	1.0629-07	1.7536-07	2.6464-07	3.5234-07	4.8599-07	6.2415-07
8.6405-07	1.0537-06	1.3457-06	1.7865-06	2.1541-06	2.9909-06	3.5867-06	4.6375-06	5.9545-06	7.3238-06
1.0199-05	1.2289-05	1.5999-05	1.9631-05	2.3426-05	3.1787-05	3.5654-05	4.7009-05	5.7300-05	6.9207-05
8.9677-05	1.1212-04	1.4002-04	1.7956-04	0.0000					

PRESSURE(J/CM3)

3.9128-03	3.9128-03	3.9128-03	3.9128-03	3.9128-03	3.9128-03	3.9128-03	3.9128-03	3.9128-03	3.9128-03
3.9128-03	3.9128-03	3.9128-03	3.9128-03	3.9128-03	3.9128-03	3.9129-03	3.9129-03	3.9129-03	3.9129-03
3.9129-03	3.9129-03	3.9129-03	3.9129-03	3.9129-03	3.9129-03	3.9129-03	3.9130-03	3.9130-03	3.9130-03
3.9130-03	3.9131-03	3.9132-03	3.9134-03	3.9136-03	3.9141-03	3.9144-03	3.9161-03	3.9277-03	3.9373-03
4.1283-03	5.3104-03	6.6580-03	1.1347-02	0.0000					

HEAT FLUX(J/CM2*S)

9.9617-09	1.2655-06	5.8278-04	4.8335-03	6.3289-02	4.8798-01	1.3544+00	1.4650+00	9.7559-01	2.4491-01
5.8254-02	3.1631-02	8.6017-02	7.1383-03	9.3909+00	3.2523+01	9.4617+01	1.8679+02	5.0757+00	2.2784-01
1.1066-01	3.1729+00	9.6921-02	1.8107-01	3.0574-01	2.2255-03	9.9664-02	5.2360-01	7.4038-04	5.4504-02
1.4234-02	1.2304-02	8.8124-02	1.4993-03	1.2312-02	4.3242-03	1.0792-03	5.8253-01	2.0717+00	5.7539+00
3.4982+02	4.6655+03	2.5650+03	1.1325+04	0.0000					

DEBRIS SPECTRA

NO. OF IONS	ENERGY PER ION (KEV)	POSITION	TIME OF ARRIVAL (SEC)
1 6.25+021	7.20-001	3.11-001	0.00-001

TOTAL PROJECTILES = 6.25+021 TOTAL ENERGY LEFT = 7.20-001 MJ