Fireball Propagation in Preformed Plasma Channels in the Light Ion Beam Driven Target Development Facility

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

http://fti.neep.wisc.edu

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Abstract

In most proposed light ion beam driven fusion devices, preformed plasma discharge channels are proposed for propagation of the beams from the diodes to the fusion target. After the target explodes, the non-neutronic fraction of the fusion energy may propagate preferentially back up the plasma channels, causing very large heat fluxes on the diodes or other reactor cavity structures at the ends of the channels.

This problem is investigated for the Sandia Target Development Facility. Models of analysis and results are presented.

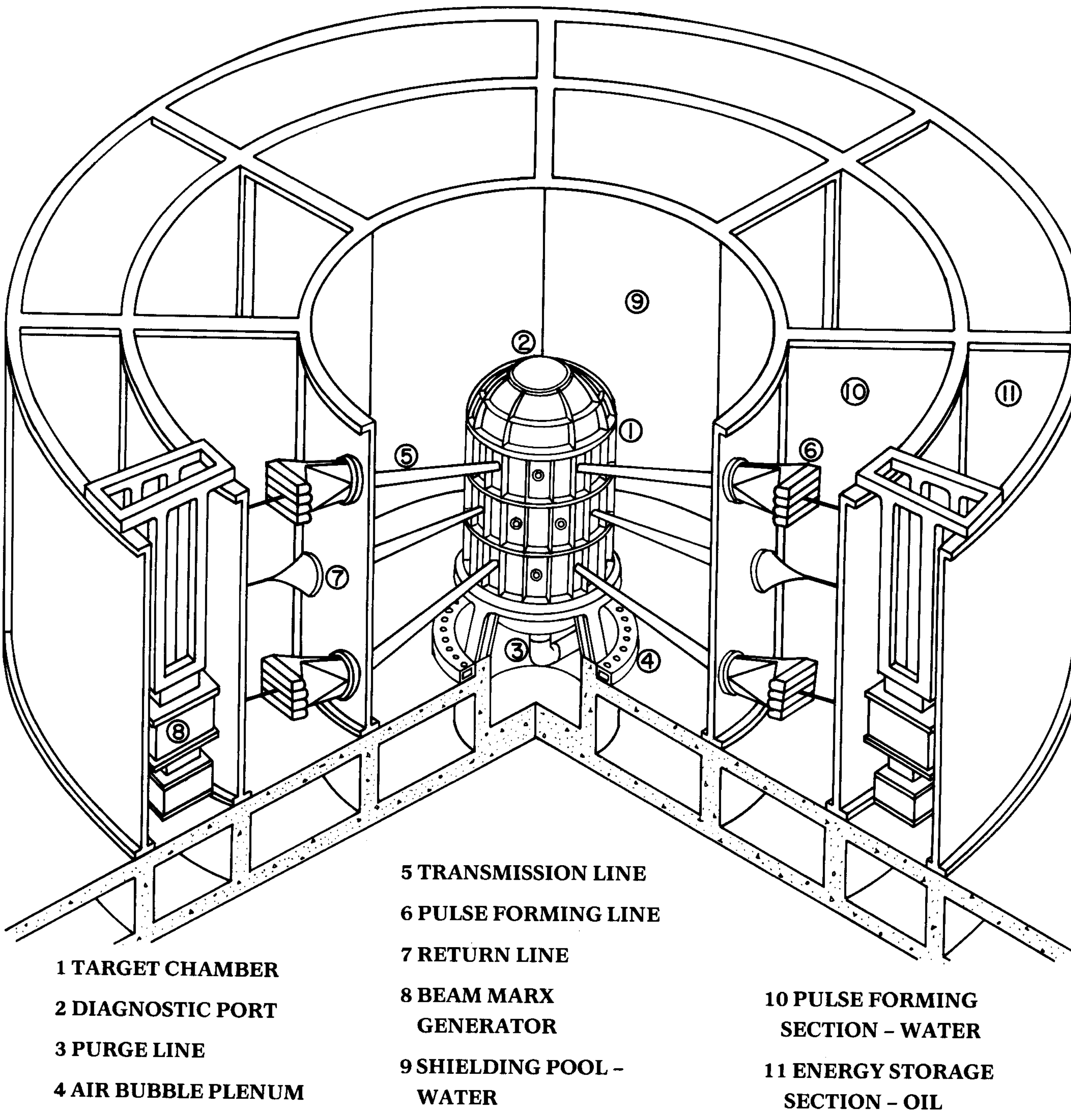
I. Introduction

A conceptual picture of the Light Ion Beam Target Development Facility is shown in Fig. 1. The preliminary parameters assume that there are 40 beams of light ions, 20 current return lines and that the reactor cavity is 3 meters in radius. The problem considered in this paper is the propagation of non-neutronic fusion energy down preformed plasma channels, a problem of potential importance to light ion beam driven reactors as well as the Target Development Facility.

In most proposed light ion beam driven fusion devices, the ions propagate from the diodes to the target down plasma channels which are lower in density than the surrounding gas.[1-4] The beams of ions drive the implosion of D-T fusion targets which burn, yielding 50 to 100 times the beam energy in 14 MeV neutrons, x-rays and target debris ions and electrons.[5] The neutronic energy, which accounts for approximately 70% of the yield, is not stopped to any significant degree by the cavity gas and is not affected by the presence of channels. On the other hand, the soft x-rays, ions and electrons[6] are slowed down or absorbed by the cavity gas; hence their movement away from the explosion and towards the cavity walls may be enhanced by the presence of channels. This means that 30% of the target yield may propagate back up the plasma channels where the densities and stopping powers are lower. This could lead to very high heat fluxes on the materials at the end of the channels.

In this study,[7] we have developed models to simulate the propagation of non-neutronic energy down the plasma channels and have obtained some preliminary values for the heat fluxes both axially down the channel and radially out from the channel into the colder surrounding cavity gas. All of the non-neutronic energy is assumed to be initially converted to thermal radiation.

Figure 1 Light Ion Beam Target Development Facility



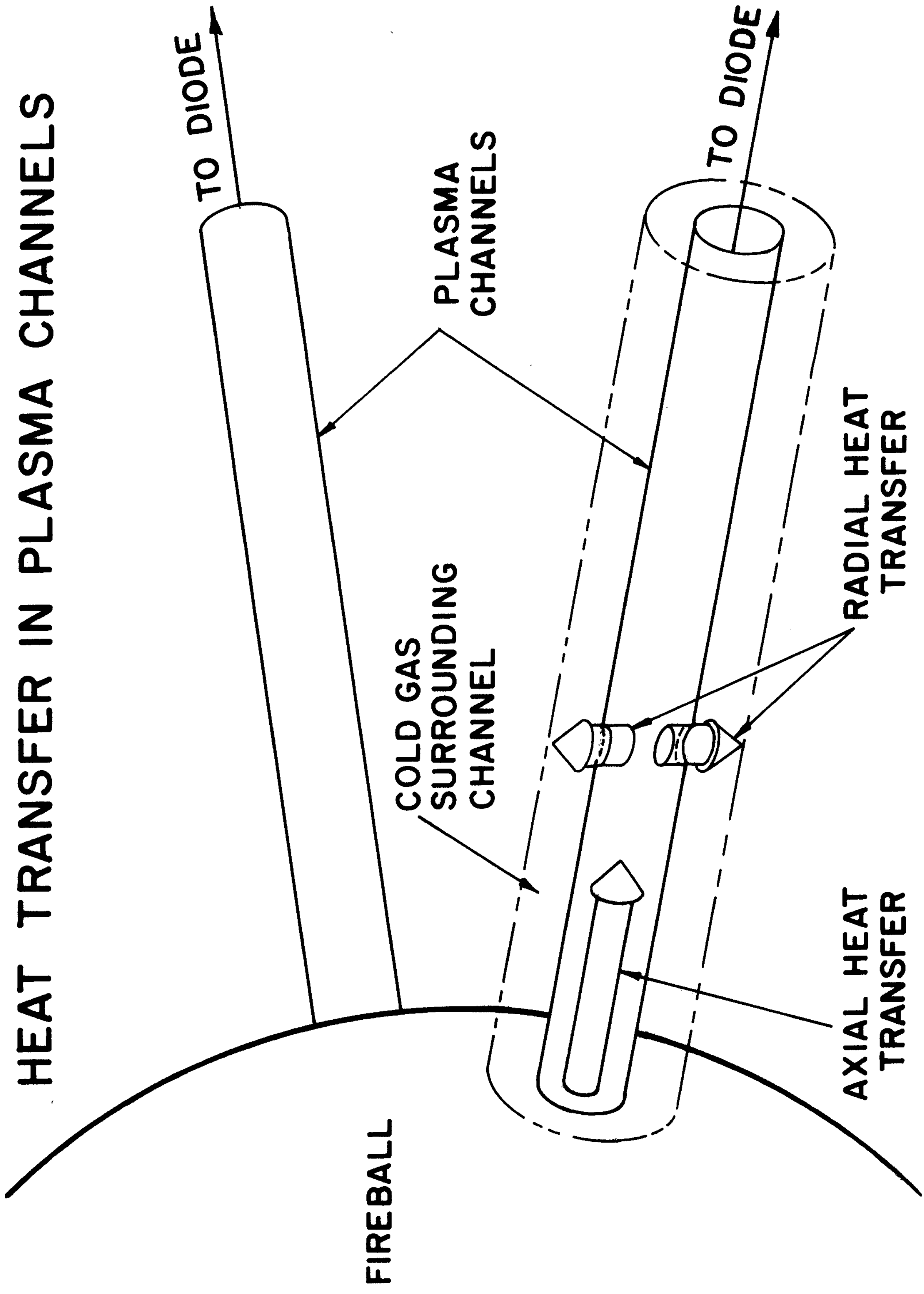
In Section II, the computer model, which is a one-dimensional simulation of a two- or three-dimensional effect, is described. Preliminary results are presented in Section III and conclusions and recommendations are made in Section IV.

II. Computer Model

A one-dimensional Lagrangian hydrodynamics computer code, FIRE, has been modified to simulate the multi-dimensional nature of blast wave propagation through the cavity gas and down the plasma channels. This is done by first running a series of one-dimensional simulations of the radial heat transfer from the hot center of a channel to the surrounding cavity gas. From this, a phenomenological law for the radial heat loss from a channel is obtained as a function of the radiation energy density in the channel. This law for the radial heat loss is then used in the calculation of the axial heat transfer down the channel. These two types of heat transfer are depicted schematically in Fig. 2 where channels are shown to be connected to the fusion generated fireball. All x-ray, ion and electron energy from the microexplosion is assumed to be stopped in an initial spherical fireball. The energy flows out of the fireball into the plasma channel, then either down the channel or out into the surrounding cavity gas.

The one-dimensional hydrodynamics code, FIRE,[8] includes radiation diffusion and uses tabulated values of equation of state and opacity data. This data is provided by the atomic physics code, MIXER,[9] which uses either Saha or Coronal equilibrium models to compute ionization states, depending on the temperature and density of the gas, and uses a semi-classical optical model to calculate photo-ionization, atomic line absorption, and inverse Bremsstrahlung.

Figure 2
Schematic representation of heat transfer in plasma channels.



Where appropriate, Thomson scattering and absorption by plasma waves are also included.

There are two changes needed in FIRE to do the axial transport calculation. The addition of a source term which represents the energy added to the channel from the fireball is the first. This is written as

$$S_F = \sigma T_F^4 A_C \tag{1}$$

where T_F is the temperature of the fireball, σ is the Stefan-Boltzmann constant, and A_C is the cross sectional area of the channel. The other is a loss term representing the radial heat loss which is written as

$$S_L = \omega_L E_R \tag{2}$$

where ω_L is the loss coefficient determined by simulations of the radial transport and E_R is the energy of the radiation in the channel. S_F is non-zero only for the Lagrangian zone nearest the fireball while S_L depends on the radiation energy density in each zone.

The plasma and radiation energy transport equations are then rewritten. For the plasma,

$$C_{vp} \frac{\partial T_p}{\partial t} = \frac{\partial}{\partial m_o} (K_p \frac{\partial T_p}{\partial r}) - \frac{\partial P_p}{\partial T_p} (\frac{\partial V}{\partial t}) T_p + J_R - J_p + S_F , \tag{3}$$

where C_{vp} is the specific heat at constant volume, T_p is the plasma temperature, m_o is the Lagrangian mass, K_p is the plasma conductivity, P_p is the plasma pressure, V is the specific volume of the plasma, J_R is the radiant power density absorbed by the plasma and J_p is the power density lost to emission by the plasma. For the radiation,

$$\frac{\partial}{\partial t} E_R = \frac{\partial}{\partial m_o} (K_R \frac{\partial}{\partial r} E_R) - P_R \frac{\partial}{\partial m_o} u - J_R + J_p - S_L , \tag{4}$$

where K_R is the radiation conductivity, P_R is the radiation pressure, and u is the hydrodynamic velocity. In both Eqs. (3) and (4), plane geometry is assumed.

III. Results

The model outlined in Section II was used to calculate the propagation of fusion generated energy down the plasma channels. Since the model is only one-dimensional and the effects may be multi-dimensional, these results must be considered preliminary until some two-dimensional calculations are done to verify them. The purpose of presenting these preliminary results here is to demonstrate which effects are important. Table I shows a list of parameters for the calculations done which are consistent with a Light Ion Beam Target Development Facility.

The radial energy loss was calculated for a number of channel radiation energy densities. Results of a typical calculation are shown in Figs. 3 and 4 where the radiation temperature and the plasma temperature are respectively plotted against distance from the center of the channel for various times. These plots show how radiation from the hot channel center heats up the cavity gas surrounding the channel. These calculations were done with FIRE in its cylindrically symmetric form.

From these calculations, the radial loss coefficient, ω_L, has been determined for several initial channel center radiation energy densities. These

Table I

LIGHT ION BEAM CHANNEL PARAMETERS

GAS TYPE	ARGON WITH 0.2% SODIUM
AMBIENT GAS DENSITY	7×10^{17} ATOM/CC
GAS DENSITY IN CHANNEL	1.8×10^{17} ATOM/CC
AMBIENT GAS TEMPERATURE	0.05 eV
GAS TEMPERATURE IN CHANNEL (AT TIME OF MICROEXPLOSION)	25 eV
NUMBER OF CHANNELS	60
LENGTH OF CHANNELS	3 m
RADIUS OF CHANNELS	0.8 cm
INITIAL FIREBALL ENERGY	60 MJ
INITIAL FIREBALL VOLUME	6.5×10^{4} CC

Figure 3

Radial radiation temperature profiles.

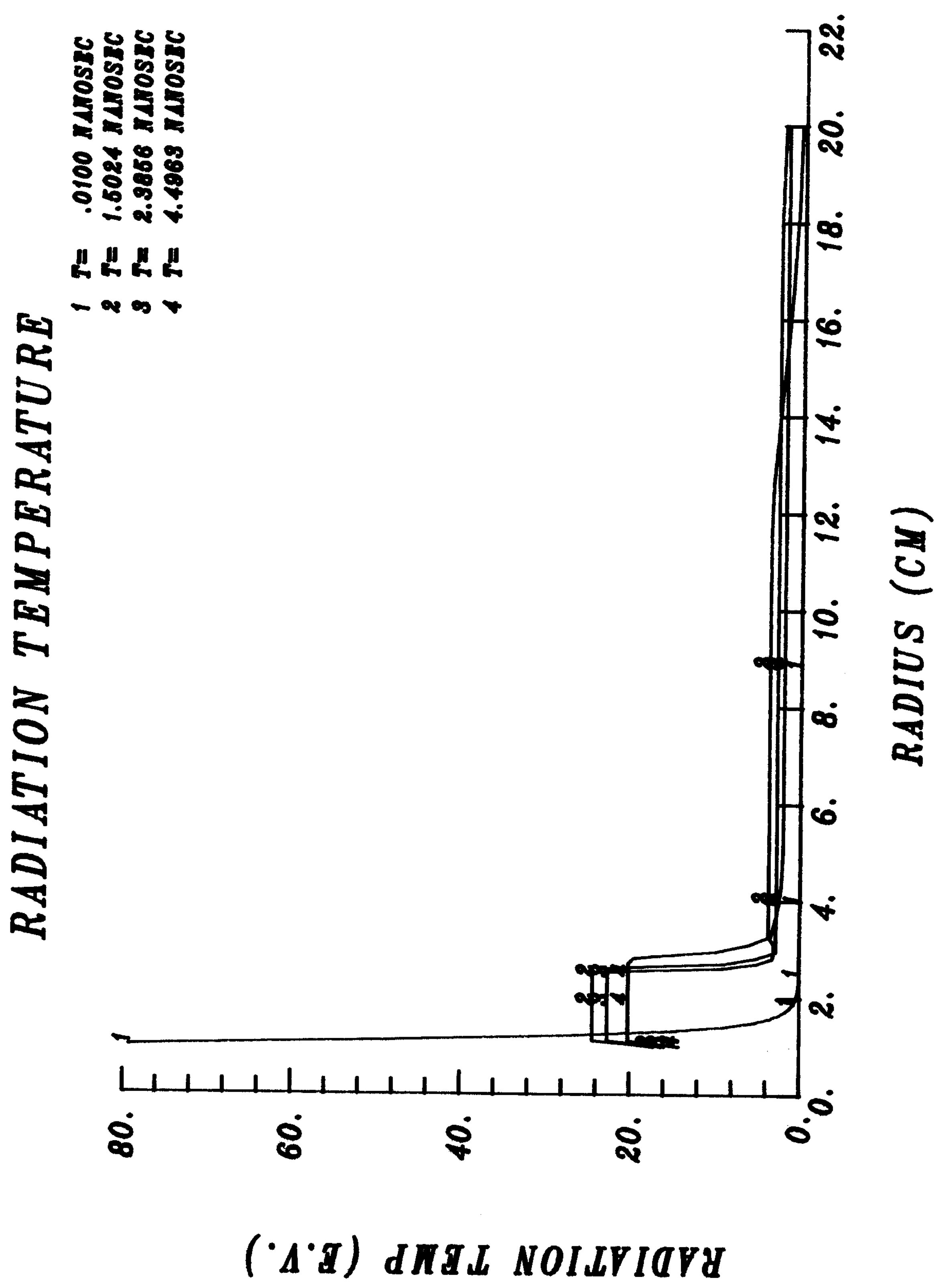
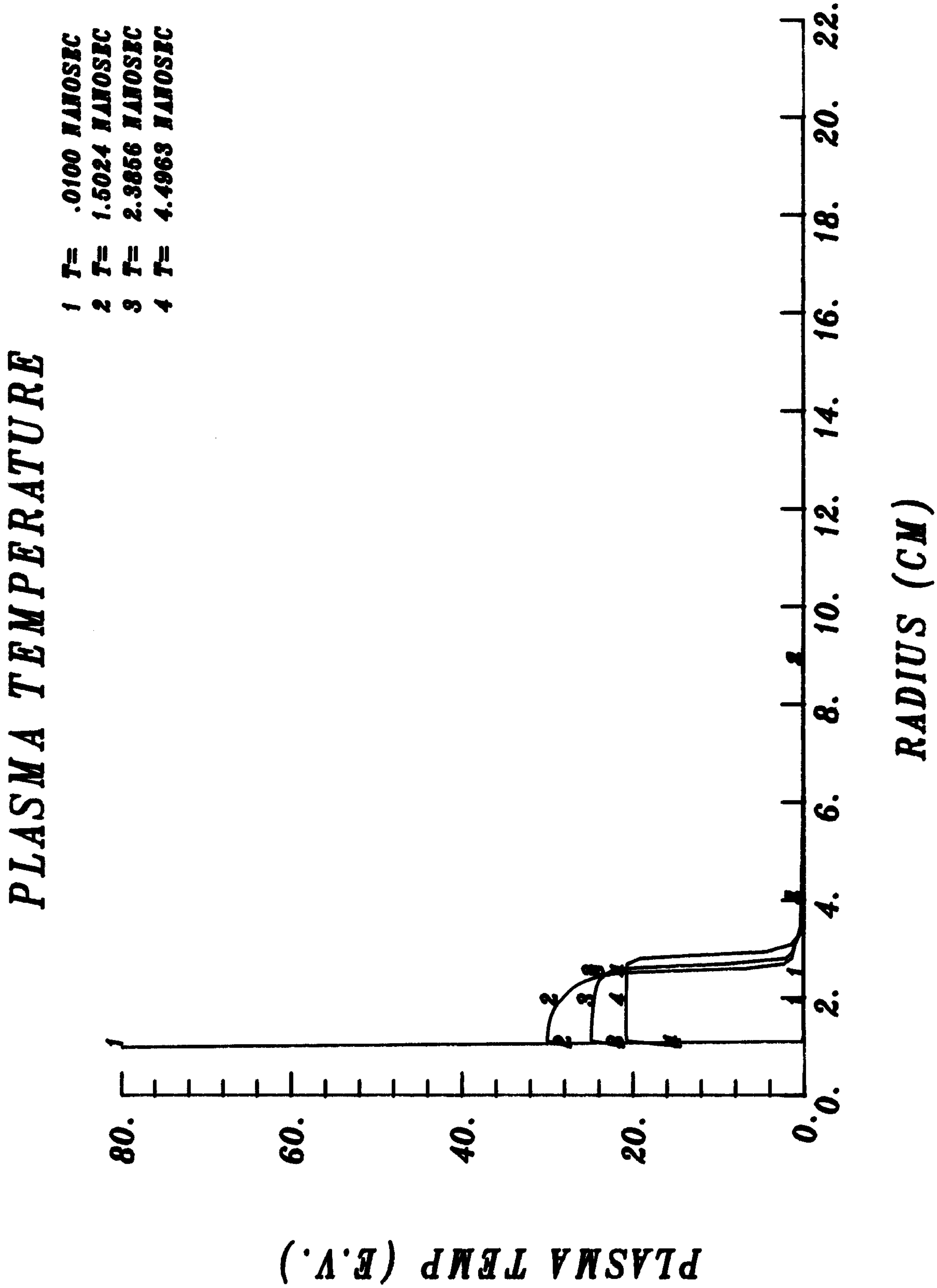


Figure 4

Radial plasma temperature profiles.



are plotted against radiation energy density in Fig. 5. This is not a single valued function because at a given radiation energy density the gas surrounding the channel may be at any of a range of plasma temperatures. At a radiation energy density of 10^5 J/g, ω_L varies by an order of magnitude. This variation shows that in converting the problem from two-dimensional to one-dimensional, there is an unavoidable loss of accuracy. However, the range of ω_L is known so that the sensitivity of the axial heat transport calculation to this uncertainty may be tested. Also shown in Fig. 5 is the phenomenological value for ω_L,

$$\omega_L = 1.4 \times 10^9 \, E_R^{0.138} \, \sec^{-1} ,$$

where E_R is in J/g. This is the value of ω_L used in all axial calculations but those done to test the sensitivity to ω_L.

Once ω_L has been determined, the axial fireball propagation can be simulated. Figure 6 shows how the total energy in the fireball decreases with time. It has an irregular shape because the fireball loses energy at a rate proportional to T_F^4 and the specific heat of the gas is a strong function of temperature. The hydrodynamic motion of the gas in the channels is shown in Figs. 7 and 8, where first the positions of the Lagrangian zone boundaries are plotted against time and then the plasma mass density is plotted against distance down the channel for various times. A four-fold increase in the mass density is caused by the propagating blast wave. In Figs. 9 and 10, the plasma and radiation temperatures are shown versus axial position and time. From these two plots, one can see that channels cool off rapidly from initial temperatures of 25 eV to about 1 eV. This is due to large losses in radiant

Figure 5 Radial loss coefficient versus radiation energy density in center of channel.

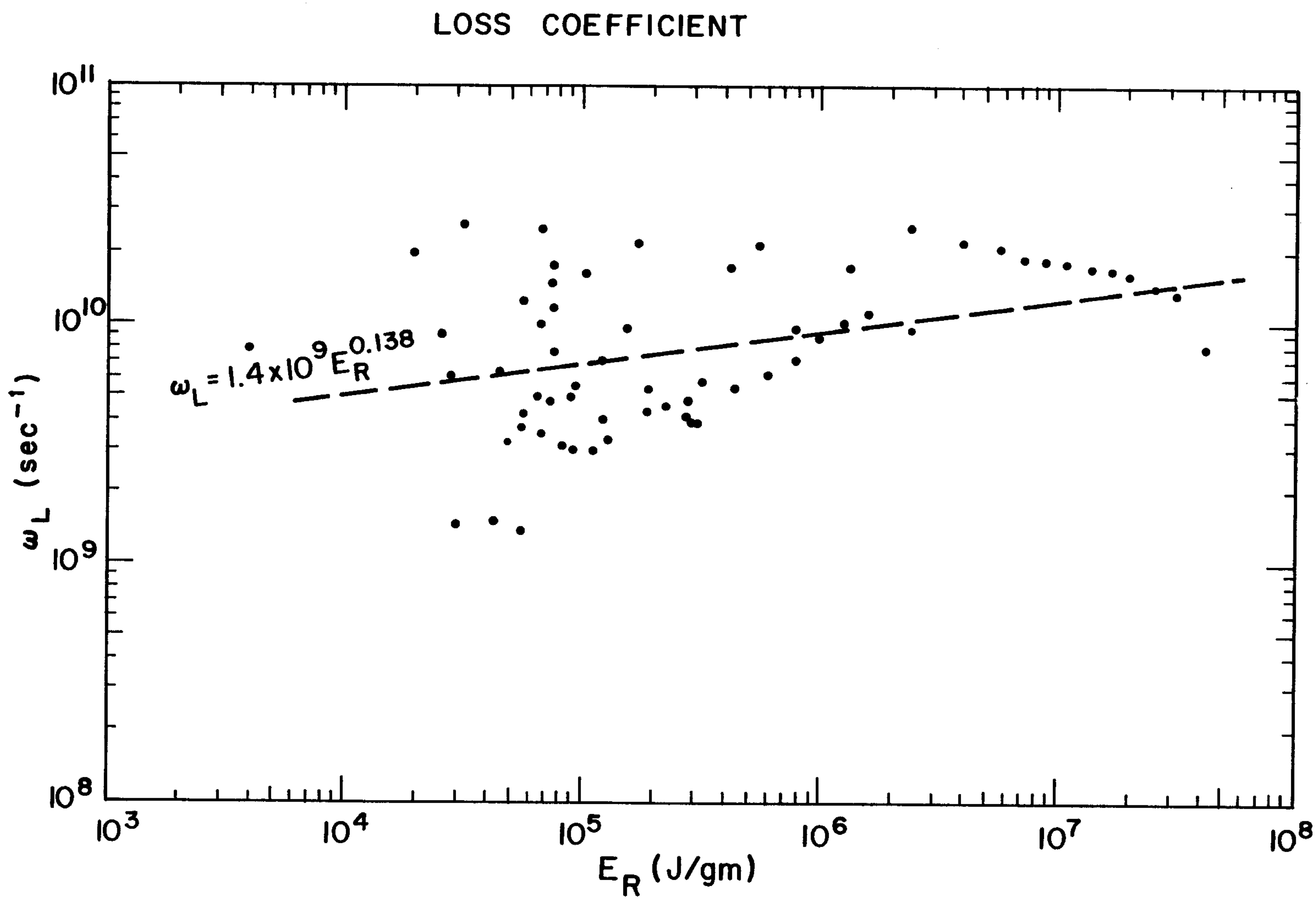


Figure 6 Energy in fireball vs. time.

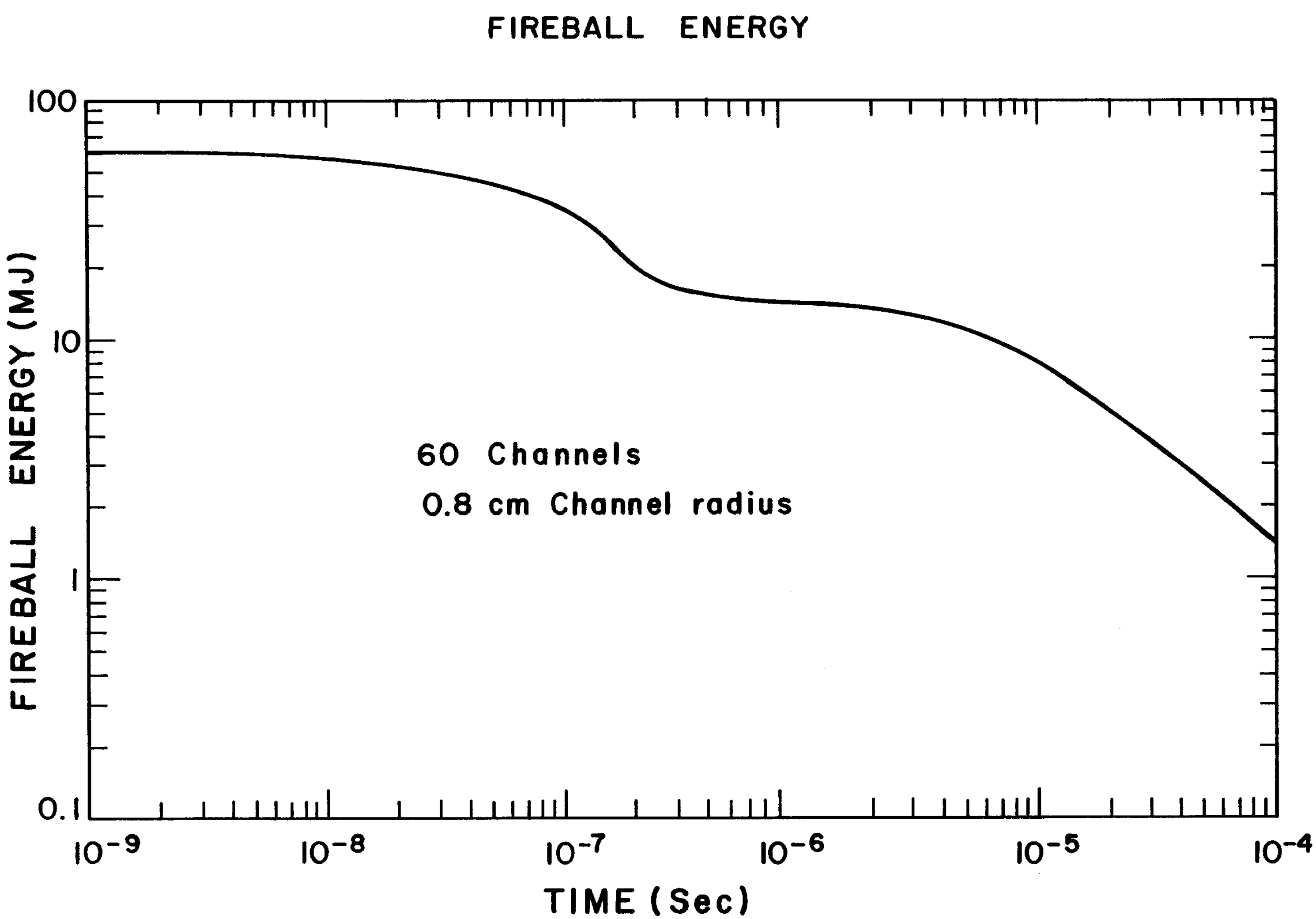


Figure 7

Positions of Lagrangian zone boundaries versus time.

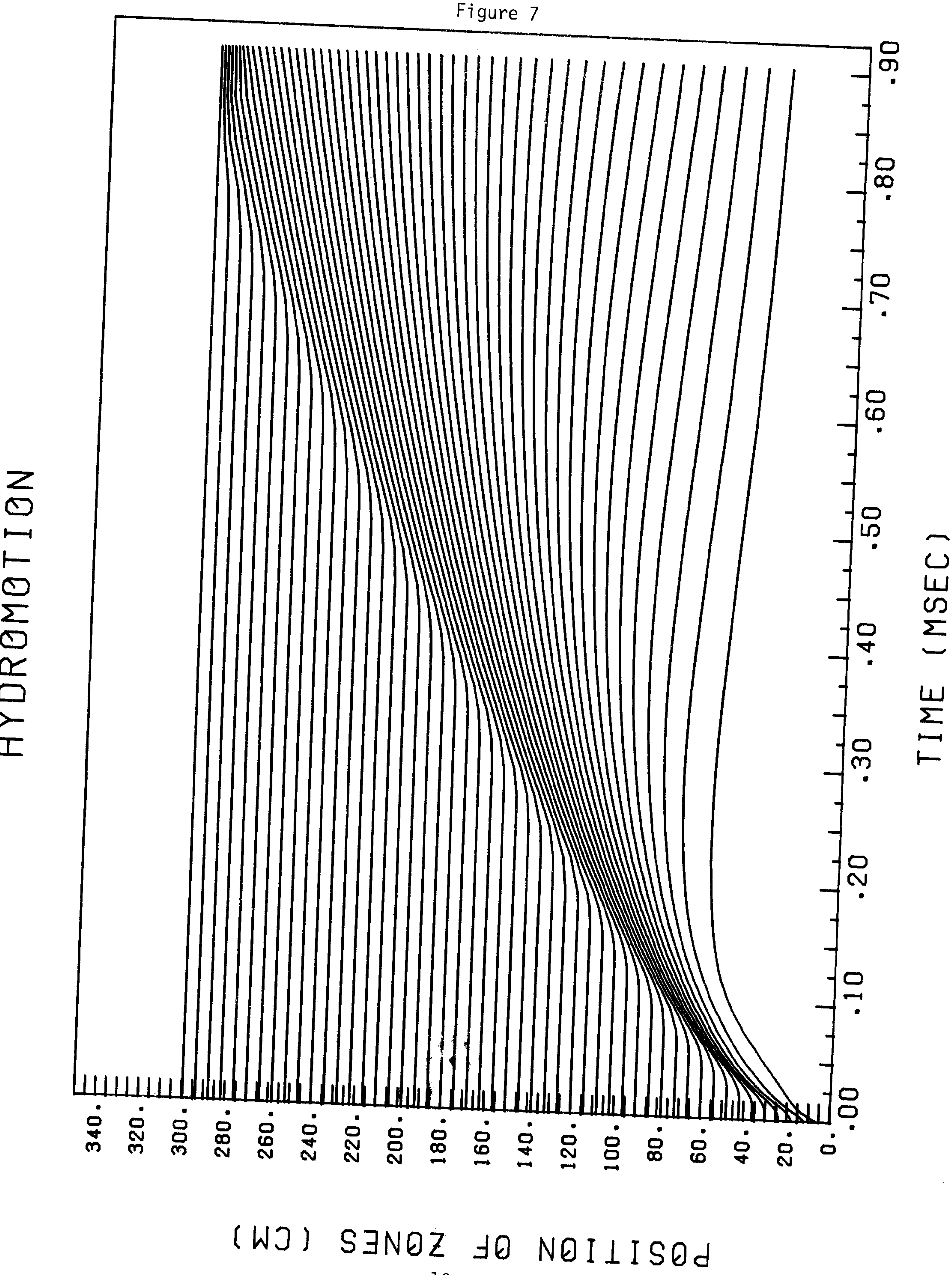


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Figure 8

Plasma mass density profiles axially down channels.

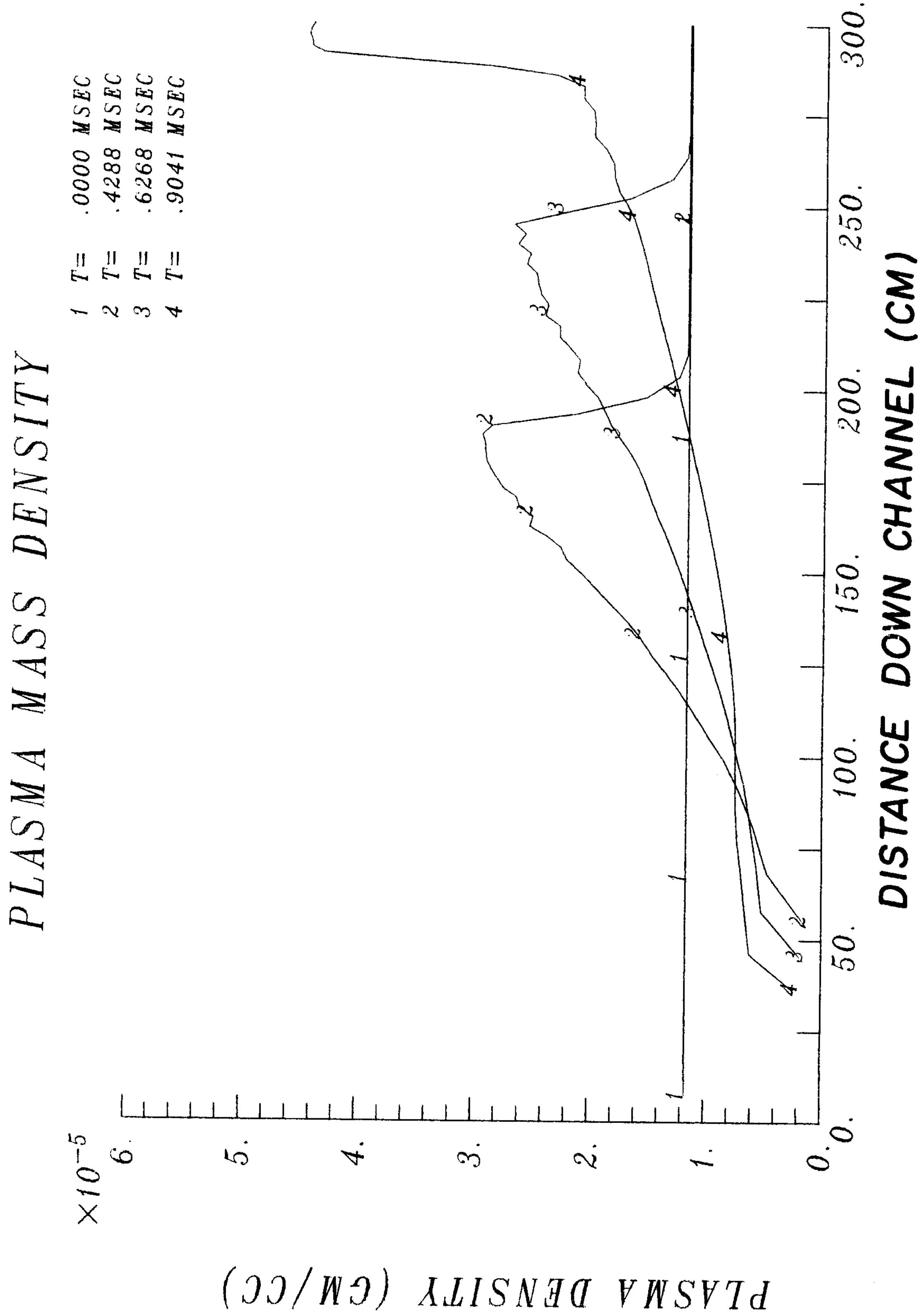


Figure 9

Plasma temperature profiles axially down channels.

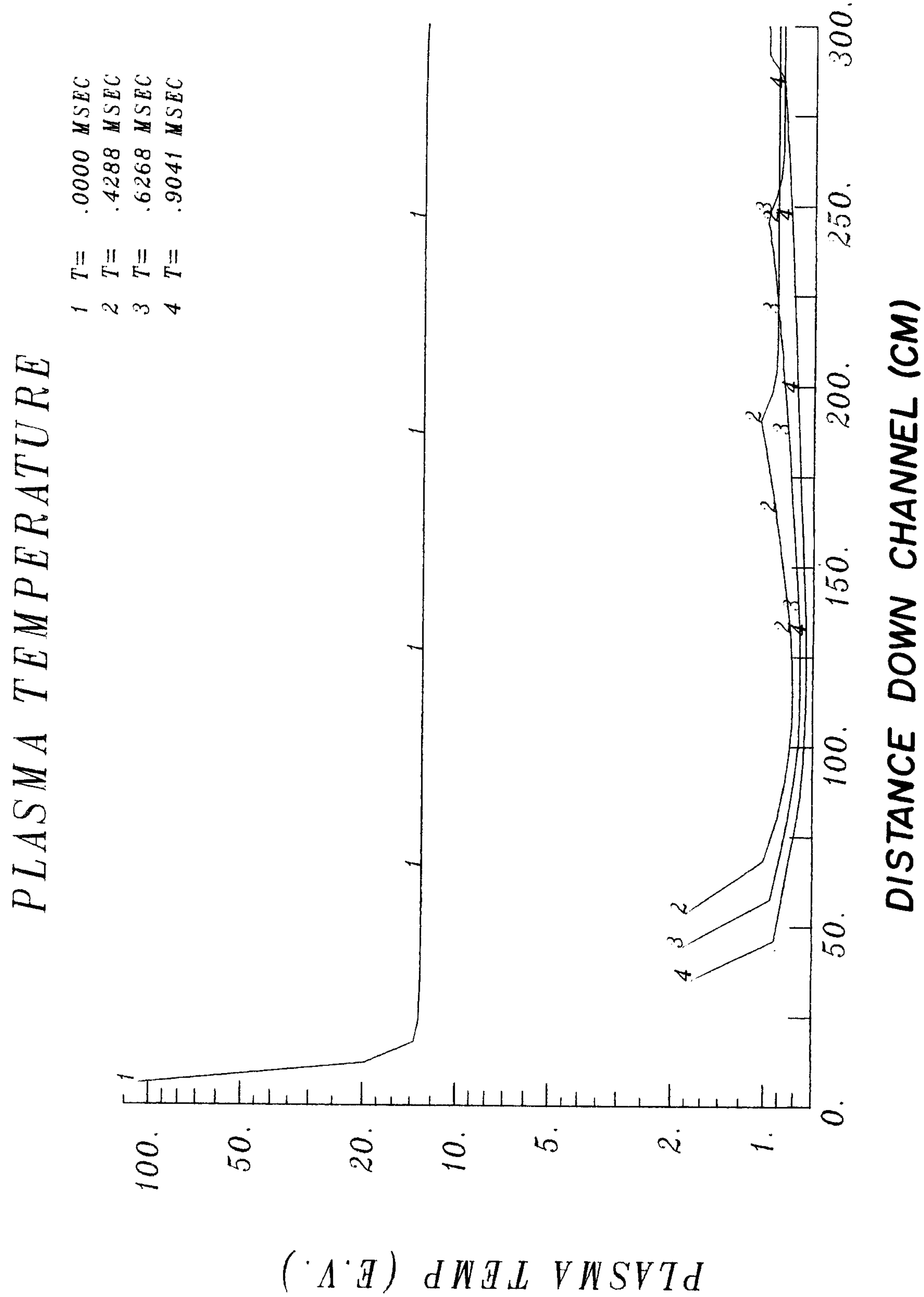
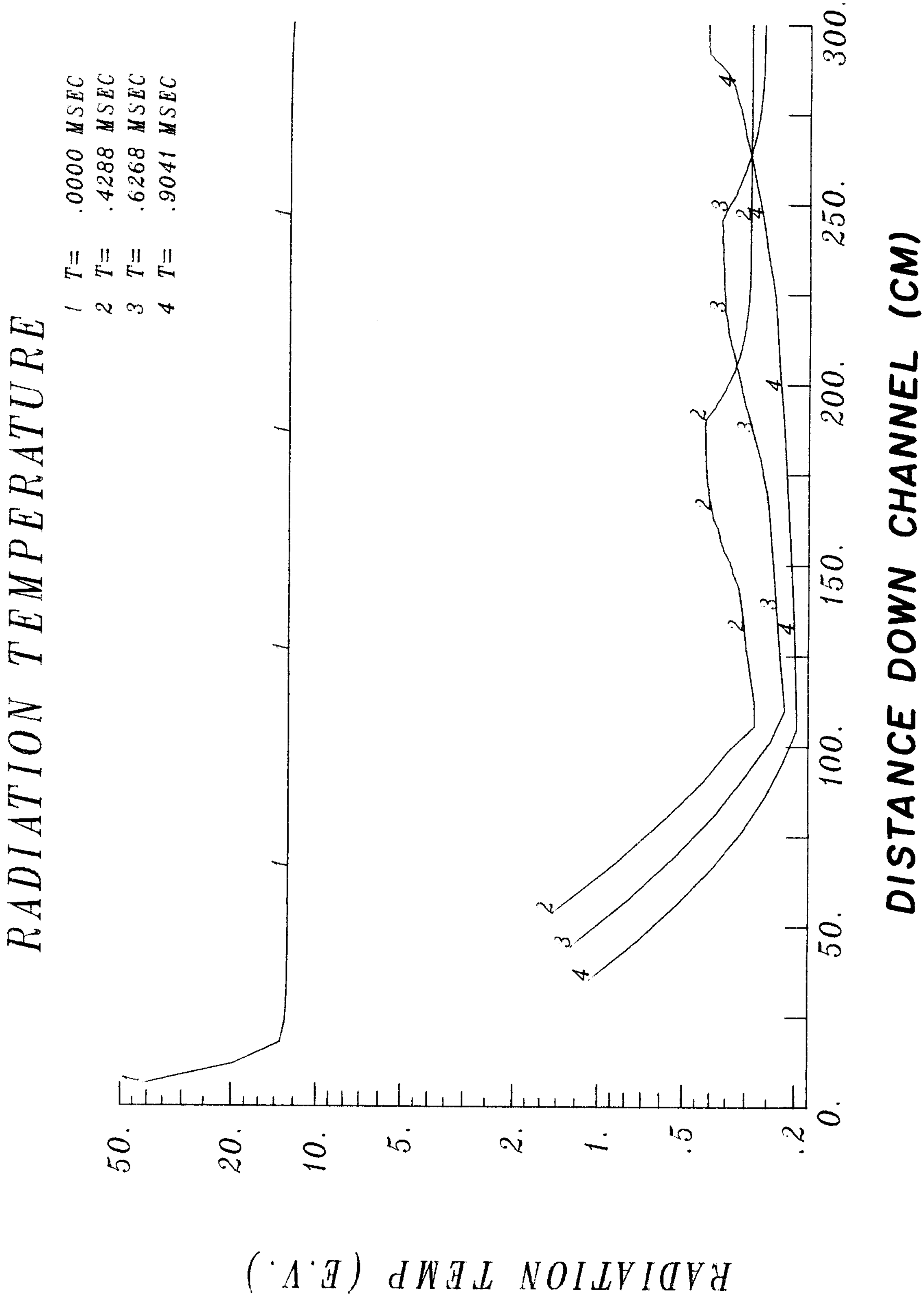


Figure 10

Radiation temperature profiles axially down channels.



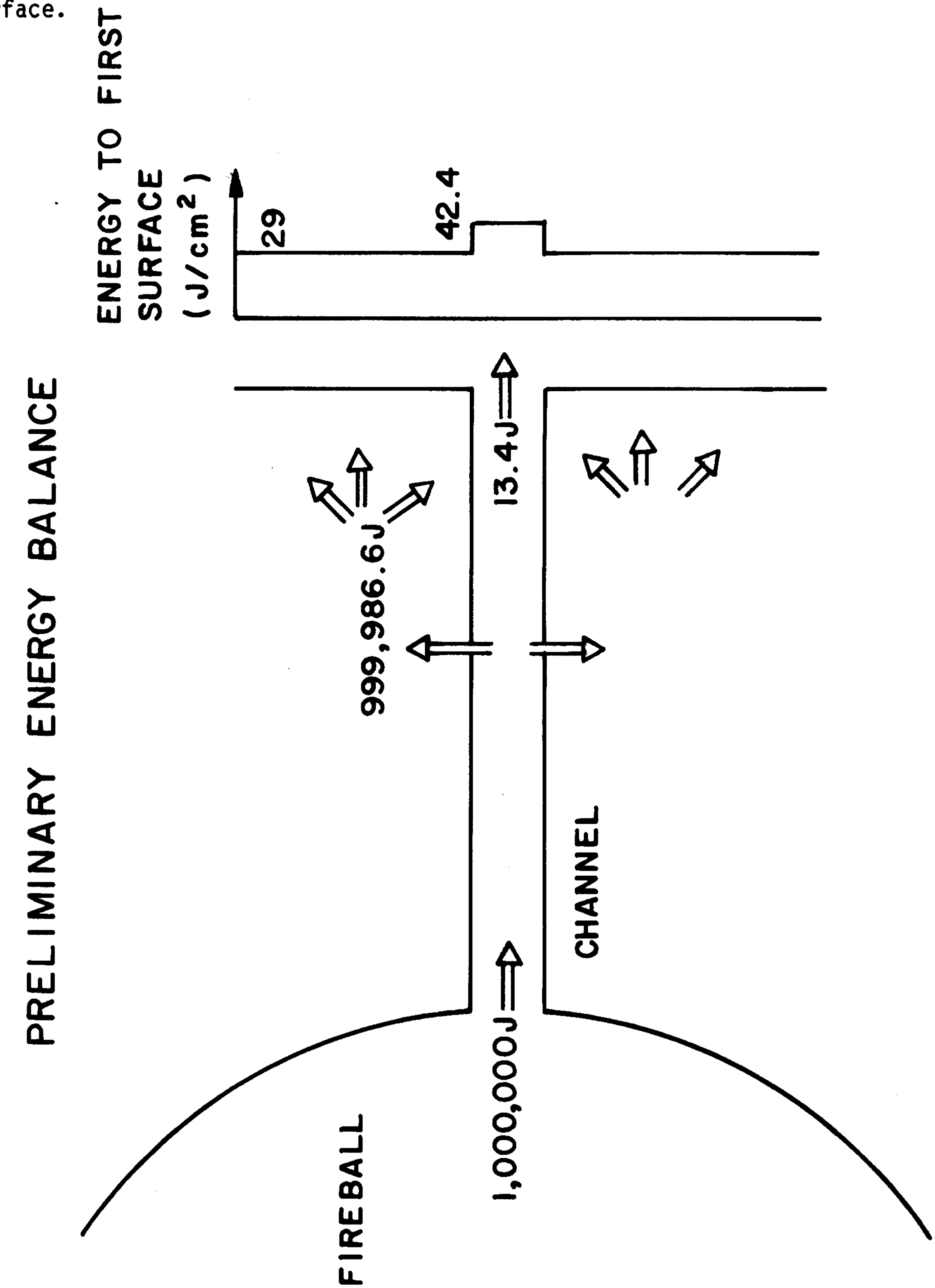
energy to the cold cavity gas surrounding the channels. One may also see the warm blast front propagating down the channel. Similar calculations have been made for values of ω_L that range over the order of magnitude of uncertainty shown in Fig. 5. They are not greatly different from the results presented here. This means that the results presented here are not very sensitive to changes in ω_L.

The energy balance for a channel is shown in Fig. 11. The fireball loses 60 MJ during the calculation and there are 60 channels so that each channel receives 1 MJ from the fireball. Of this, only 13.4 J reaches the end of the channels directly and 999,986.6 J are lost to the cavity gas. Once energy is in the cavity gas, it is assumed to follow the behavior previously predicted by spherical fireball calculations[10] (no channels). This spherical calculation predicts that 29 J/cm^2 are uniformly radiated to the first wall of the Target Development Facility. With the 13.4 J deposited at the end of the 1 cm^2 cross sectional area channels, the radiated energy density at the end of the channels becomes 42.4 J/cm^2. This is shown in the graph in Fig. 11.

The heat transfer to the cavity gas is roughly 10^5 times larger than the transfer down the length of the channel, a fact which can be explained by simple physical arguments. The area of the sides of a single cylindrical channel is 1.5×10^3 cm^2 compared with a cross sectional area of 2 cm^2, so that a factor of 10^3 is gained by the radial transport from the difference in area. The atomic physics calculations in MIXER have shown that the important radiation mean free paths for radial transport are typically 3×10^4 cm while those governing axial transport are roughly 7×10^2 cm. Thus radial transport gains another factor of 50 from the differences in opacities making a total difference of 5×10^4 which is close to the observed difference.

Figure 11

Schematic representation of preliminary energy balance in plasma channels and density of energy radiated to first surface versus position on surface.



IV. Conclusions and Recommendations

A potentially important problem for light ion driven fusion devices has been considered. The following conclusions may be made:

1. The results indicate that propagation of fireball energy down preformed plasma channels increases the thermal load on the wall by roughly 50%, an increase which can be accommodated by minor changes in the first wall design.
2. It must be re-emphasized that the analysis of this problem treats it as one-dimensional while it is actually a multi-dimensional effect. This causes unavoidable uncertainty in the accuracy of the results, though the sensitivity of the results to the loss coefficient was tested and found not to be great.

As a consequence of this study, the following recommendations are made.

1. A two-dimensional simulation of fireball propagation down plasma channels should be made to verify the results presented here.
2. The spherical fireball simulation should be done by including the losses from the channel as a source instead of assuming that it behaves as if there were no channels present.

Acknowledgment

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