ORNL/TM-8616
Dist. Category UC-20 a

ORNL/TM--8616

DE83 010447

Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

NEW ALGORITHM FOR COMPUTING THE ABLATION OF HYDROGENIC PELLETS IN HOT PLASMAS

S. L. Milora

NOTICE This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

Date Published: April 1983

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CONTENTS

ABSTRACT

A method is presented for calculating the evaporation rate of hydrogenic pellets immersed in an unmagnetized plasma with a suprathermal particle component of arbitrary distribution function. The computational procedure is based on hydrodynamic solutions for the expansion of the gaseous cloud, obtained in a previous treatment that considered the effects of thermal particles only. The appropriate heat source terms, derived from the stopping power of the gaseous shield, are worked out for energetic ions produced by neutral beam injection heating. The model predicts 27-cm penetration in a Poloidal Divertor Experiment (PDX) plasma, compared with experimentally measured values in the range of 29-32 cm. An application to the Tokamak Fusion Test Reactor (TFTR) gives an estimated 21-cm penetration for a 2.5-mm-diam tritium pellet injected at 2000 m/s into a 55-cm-bore plasma heated to a central electron temperature of 4 keV by 34 MW of neutral injection.

1. INTRODUCTION

In this paper we describe a modification to the ORNL version of the neutral gas shielding model that allows for an accounting of the effects of fast ions in a manner consistent with the methodology of an earlier model that was developed to treat the ablation of hydrogenic pellets by thermal electrons alone in an unmagnetized plasma.[1-3] This new algorithm retains the construct of the earlier version and the hydrodynamic solutions that pertain for the expansion of the ablation products. The essential differences are that the heat flux terms are replaced by terms that include the combined effects of electrons and fast ions and that the fast ion component is allowed to have an arbitrary distribution function. The formalism is applicable to problems that include other non-Maxwellian components (i.e., suprathermal or slideaway electrons). The new model is compared with data from the Poloidal Divertor Experiment (PDX) and a sample calculation for the Tokamak Fusion Test Reactor (TFTR) is presented.

2. REVIEW

The basic elements of the neutral gas shielding model are described in detail in Refs. 1-3. The model treats the cloud resulting from surface evaporation of molecular hydrogen as a stopping medium for plasma electrons. Electrons are prevented from impacting the pellet surface at full energy by multiple elastic and inelastic collisions with the dense hydrogen cloud. The electron motion through the gas is treated as a monoenergetic beam subject to a continuous slowing-down process that degrades the electron energy.[4] Elastic collisions, which are important at low energy (∿100 eV), further reduce the heat flux by backscattering and consequent removal of electrons from the incident particle flux. In the present treatment, fast ions are also allowed to impact the cloud, and their motion through the gaseous medium is similarly described by the continuous slowing-down approximation (elastic scattering is neglected). The energy lost in the collisions is treated as heat in the hydrodynamic equations that describe the expansion of the gas in terms of the Mach number M and the normalized density $\hat{\rho}$ and radius $\hat{r}$ as

$$(1 - M^2)\frac{dM}{d\hat{r}} = \frac{1}{2}\left(\frac{\rho_p}{\rho_s}\right)^3 \left|\frac{dr_p}{dt}\right|^{-3} e q_e r_p (\gamma - 1)\hat{\rho}^3\hat{r}^6 M^3(\gamma M^2 + 1) - \frac{2M}{\hat{r}}\left(1 + \frac{\gamma - 1}{2}M^2\right) , \quad (1)$$

$$\frac{d}{d\hat{r}}(\hat{\rho}\hat{r}^2)^{-1} + \frac{\hat{r}^2}{\gamma}\frac{d}{d\hat{r}}(M^2\hat{\rho}\hat{r}^4)^{-1} = 0 , \quad (2)$$

where the mass density and radius are normalized to their respective values at the pellet surface (ρ_p, r_p). Here γ is the gas specific heat ratio (7/5), ρ_s is the pellet mass density, dr_p/dt is the surface recession rate, and q_e ($\mathrm{eV \cdot s^{-1} \cdot kg^{-1}}$) is the rate of heat deposition in the cloud <u>per unit mass</u>. The value of e is 1.6×10^{-19} joule/electron volt. In Ref. 3, numerical solutions were obtained for uniform heating (q_e = constant) of the cloud — a situation that approximates the energy input from electrons. Penetrating electrons slow down via multiple inelastic collisions, according to

$$\frac{dE_e}{dr} = \frac{\rho}{m} L_e(E_e) \qquad (\mathrm{eV \cdot m^{-1}}) \ , \tag{3}$$

where m is the molecular mass of the cloud, E_e is the electron energy (in electron volts), and $L_e(E_e)$ is the stopping power for incident electrons. If we assume that the electron flux is a monoenergetic beam ($E_e = 3/2T_e$) and that elastic scattering is negligible (i.e., J_e = particle flux = constant), then the heating term can be written as

$$q_e = \frac{1}{\rho} \vec{\nabla} \cdot (E_e \vec{J}_e) \approx \frac{1}{\rho} J_e \frac{dE_e}{dr} = J_e \frac{L_e(E_e)}{m} \qquad (\mathrm{eV \cdot s^{-1} \cdot kg^{-1}}) \ . \tag{4}$$

For electron energies between 10 eV and 2 keV, the stopping power varies by a factor of 4, but the variation is slow in comparison to the rapid changes in the fluid parameters in general and the density in particular. This was the justification for the assumption of uniform heating in Ref. 3. Given the premise of uniform q_e, inspection of Eqs. (1) and (2) reveals that the flow field is determined uniquely by the dimensionless parameter

$$\xi = \frac{\gamma - 1}{2}\left(\frac{\rho_p}{\rho_s}\right)^3 \left|\frac{dr_p}{dt}\right|^{-3} eq_e r_p \ . \tag{5}$$

From the numerical solutions of Ref. 3, the shape factor $\int_1^\infty \hat{\rho}\ d\hat{r}$ was found to vary as

$$\int \hat{\rho}\ d\hat{r} = (1.25\xi^{1/3})^{-1} \ , \tag{6}$$

which results in a linear relationship between the surface recession rate and the column density of mass between the pellet surface and the plasma,

$$\frac{dr_p}{dt} = \frac{1.25}{r_p\rho_s}\left(\frac{\gamma - 1}{2}\ eq_e r_p\right)^{1/3} \int_{r_p}^{\infty} \rho\ dr \qquad (\text{m/s}) \ . \tag{7}$$

In the discussion that follows we assume that the hydrodynamic solutions are unchanged when additional heat sources are considered. We merely replace q_e in Eq. (7) with an applicable heat source term.

The energy balance requirement at the pellet surface provides a relationship between the heat flux (Q_{ep}) at the pellet and the evaporation rate,

$$\frac{dr_p}{dt} = \frac{Q_{ep}A_e}{4\pi r_p^2 \lambda \rho_s} \ , \tag{8}$$

where λ ($\text{eV}\cdot\text{kg}^{-1}$) is the heat of evaporation and A_e is the effective cross section for interception of the plasma electrons ($2\pi r_p^2$ for a magnetized plasma). Finally, the surface heat flux Q_{ep} is related to the column density of mass and the plasma heat flux through the relationships that describe the loss of energy of penetrating electrons. This is treated as a two-step process. Electrons in the incident "beam" suffer inelastic collisions without loss of flux down to some intermediate energy E_e^* (taken to be 20 eV). At lower energies, elastic scattering and consequent particle removal are included in the description of the slowing-down process.

Following Heaps,[5] we write the energy flux Q_{ep} at the pellet surface in terms of the flux at the position in the cloud where the energy is equal to E_e^* and the integrated mass in the interval between the two locations,

$$\frac{Q_{ep}}{Q_e^*} = \frac{C + 1}{C + \exp\left(\frac{\alpha_e}{m} \int_{r_p}^{r^*} \rho \, dr\right)} , \tag{9}$$

where C is a constant of order unity and $\alpha_e = 2 \times 10^{-20}\ m^{-2}$ is a cross section with a value dependent on E_e^*. The integral is written in terms of the total column density:

$$\int_{r_p}^{r^*} \rho \, dr = \int_{r_p}^{\infty} \rho \, dr - \int_{r^*}^{\infty} \rho \, dr \qquad (kg \cdot m^{-2}) . \tag{10}$$

In the region between r* and the external plasma, elastic scattering has been neglected; consequently, we can use the slowing-down formulation of Miles et al.[4] to evaluate the second integral in Eq. (10); that is,

$$\int_{r^*}^{\infty} \rho \, dr = m \int_{E_e^*}^{E_{eo}} \frac{dE_e}{L_e(E_e)} , \tag{11}$$

where $L_e(E_e) = (2.35 \times 10^{18} + 4 \times 10^{15}E_e + 2 \times 10^{21}E_e^{-2})^{-1}$. With this result, the expression for the column density becomes

$$\int \rho \, dr = \frac{m}{\alpha_e} \ln \left[(C + 1) \frac{Q_e^*}{Q_{ep}} - C \right] + m \int_{E_e^*}^{E_{eo}} \frac{dE_e}{L_e(E_e)} . \tag{12}$$

The ablation rate dr_p/dt follows from solving the system of Eqs. (7), (8), and (12). The authors of Ref. 3 used an average $L_e(E_e)$ to evaluate q_e in Eqs. (4) and (7) and took for Q_e^* the expression from simple kinetic theory $Q_e^* = 2J_{eo} \times T_e^*$, where $T_e^* = 2/3E_e^*$ and $J_{eo} = (N_e\overline{C}_e/4)_o$ is the particle flux of the background plasma (N_e is the electron number density and $\overline{C}_e$ is the mean thermal speed).

3. GENERALIZED MODEL

The model can now be generalized to include additional heat source terms, although we restrict the analysis to fast ions in general and to those produced by neutral beam injection in particular. We develop appropriate expressions for the heating term in Eq. (1), the surface heat flux in Eq. (8), and the slowing-down function for ions that is analogous to Eq. (3). Owing to differences in the stopping power of the cloud for ions and electrons, the condition for uniform q for both species is in general not satisfied. To account for the possibility that the influence of a species might not extend through the entire cloud, we define an average q that is equal to the ratio of the power dissipated in the column of gas between pellet and plasma to the corresponding column mass,

$$q = \frac{\int q_e \, dm + \int q_f \, dm}{\int dm} , \tag{13}$$

where $dm = \rho \, dr$ and the second term represents the contribution of the fast ions. This approximation effectively distributes the heat (per unit mass) uniformly throughout the cloud. The error associated with this simplification is small because of the cube root dependence in Eq. (7). For electrons, which are treated as an equivalent monoenergetic beam, we use Eqs. (3) and (4) to obtain

$$\frac{\int q_e \, dm}{\int dm} = \frac{J_{eo} \int_{E_{ep}}^{E_{eo}} dE_e}{\int \rho \, dr} = \frac{J_{eo}(E_{eo} - E_{ep})}{\int \rho \, dr} , \tag{14}$$

where E_{ep} is taken to be either the energy of electrons that impact the surface (if they have sufficient energy to penetrate the cloud) or E_e^* (if they are stopped outside the surface) as determined by solving Eq. (3).

For energetic ions we cannot write simple expressions for q_f or the surface heat flux Q_{fp} because the velocity distribution function $f(V)$ is non-Maxwellian and time-dependent, as determined by the slowing-down rate on the background plasma. We take for $f(V)$ a simple solution to the Fokker-Planck equation for an isotropized beam with a volumetric source term S ($m^{-3} \cdot s^{-1}$),

$$f(V) = \begin{cases} \dfrac{S\tau_s}{4\pi(V^3 + V_c^3)} & \text{for} \quad V > V(t) \\ 0 & \text{for} \quad V < V(t) \end{cases} , \tag{15}$$

where τ_s [$= 0.12 M_i Te_o(\mathrm{keV})^{1.5}/Ne_o(10^{19} m^{-3})$] is the ion-electron momentum exchange time and $V(t)$ is the lower velocity limit for the distribution function, defined in terms of the time t after the source is applied as

$$\begin{aligned} V(t)^3 &= e^{-3t/\tau_s} (V_o^3 + V_c^3) - V_c^3 , \\ V(t) &= 0 \quad \text{for} \quad t > \tau_f = \frac{\tau_s}{3} \ln (1 + V_o^3/V_c^3) . \end{aligned} \tag{16}$$

In Eq. (16), V_o is the velocity at which ions are injected ($\sqrt{2eE_{fo}/m_f}$), and V_c is the critical velocity at which they preferentially slow down on plasma ions ($V_c^2 = 25.6 eT_{eo} M_p^{-2/3} m_H^{-1}$). Here m_f and m_H refer to the fast ion and proton mass, M_p is the plasma atomic number, and E_{fo} is the injection energy. As defined above, the distribution function evolves in time up to $t = \tau_f$, and consequently the ablation rate will essentially be independent of time for $t > \tau_f$. The usual moments of the distribution function (N_f, $\langle E_f \rangle$) can be readily performed analytically. From the analogy with the electron case, we also require a knowledge of the heat flux incident on the cloud Q_{fo} and the residual ion heat flux at the pellet surface Q_{fp}. The former is given by

$$Q_{fo}\ (\mathrm{eV \cdot s^{-1} \cdot m^{-2}}) = \frac{1}{e} \int_{V(t)}^{V_o} \frac{1}{2} m_f V^5 f(V)\, dV \int_0^{\pi/2} \cos\phi \sin\phi\, d\phi \int_0^{2\pi} d\theta$$

$$= \frac{S\tau_s}{12e} m_f \left\{ [V_o^3 - V(t)^3] - V_c^3 \ln \frac{V_o^3 + V_c^3}{V(t)^3 + V_c^3} \right\} . \qquad (17)$$

Likewise, the heat flux at the pellet surface is given by

$$Q_{fp} = \frac{S\tau_s}{2e} \int_{V(t)}^{V_o} \frac{1}{2} m_f V_p^2 \frac{V^3}{V^3 + V_c^3}\, dV . \qquad (18)$$

The velocities V_p and V are related by the stopping power of the hydrogen cloud. As for electrons, we use an expression of the form

$$\frac{dE_f}{dr} = L_f(E_f) \frac{\rho}{m} , \qquad (19)$$

where $L_f(E_f) = \alpha_f E_f^{0.4}$ and $\alpha_f = 1.93 \times 10^{-20}$ for ion energies less than 50 keV (Ref. 6). Integrating Eq. (19) gives the desired relationship between V_p and V in terms of the line density $\int \rho\, dr$. It follows that

$$Q_{fp} = \frac{S\tau_s}{2} \int_{V(t)}^{V_0} \left[\left(\frac{m_f V^2}{2e} \right)^{3/5} - \frac{3}{5} \frac{\alpha_f}{m} \int \rho \, dr \right]^{5/3} \frac{V^3}{V^3 + V_c^3} \, dV \; , \tag{20}$$

where the integration is performed only over the region where the integrand is positive (i.e., only for fast ions with sufficient energy to penetrate the cloud). Similar expressions are obtained for the contributions from the one-half and one-third energy components of the beam. In the discussion that follows it is understood that all three energy components are included in the ion heat flux terms.

We can now complete the expression for q,

$$q = \frac{J_e(E_{eo} - E_{ep})}{\int \rho \, dr} + \frac{Q_{fo} - Q_{fp}}{\int \rho \, dr} \; . \tag{21}$$

With the addition of the ion heat flux term, the energy balance at the pellet surface becomes

$$\frac{dr_p}{dt} = \frac{Q_{ep}A_e + Q_{fp}A_f}{4\pi r_p^2 \lambda \rho_s} \; , \tag{22}$$

where $A_f = 4\pi r_p^2$ is the pellet area exposed to the fast ion heat flux (twice as large as the electron cross section because of the finite Larmor radius for ions). The description is completed by an expression that replaces Eq. (7),

$$\frac{dr_p}{dt} = \frac{1.25}{r_p \rho_s} \left[\frac{(\gamma - 1)}{2} eqr_p \right]^{1/3} \int \rho \, dr \; , \tag{23}$$

and by Eq. (12), which relates Q_{ep} to the known Q_e^* and the column density,

$$\int \rho \, dr = \frac{m}{\alpha_e} \ln \left[(C + 1) \frac{Q_e^*}{Q_{ep}} - C \right] + m \int_{E_e^*}^{E_{eo}} \frac{dE_e}{L_e(E_e)} . \qquad (24)$$

The system is solved by numerical iteration.

4. CASE I -- PDX

A numerical simulation was performed for the conditions typical of experiments performed on PDX with single hydrogen pellets injected into neutral-beam-heated discharges. The parameters of this experiment are given in Table 1. The electron temperature and density profiles were taken from Thomson scattering measurements; the fast ion source terms were obtained from a beam deposition calculation using known neutral beam geometry, power, energy, and species mix. The pellets for this case are large enough to have a significant impact on the plasma parameters. To account for possible perturbations in the electron temperature and density during ablation, the plasma was assumed to maintain thermal equilibrium with the cold fuel by a simple flux-surface-averaged dilution model described in Ref. 7. Experimentally it has been found that this interaction effectively reduces the electron temperature encountered by the pellet and considerably lengthens the pellet lifetime (and hence the penetration). The time scale for equilibration of the fast ions is much longer than the characteristic ablation time; consequently, a nonperturbative model is employed for the fast ion contribution.

The results of the calculation are displayed in Table 2.* The plasma radius at which the pellet is consumed is 18 cm (where the pellet

---

*In the tables R = plasma radius (m), NEO = prepellet plasma density (m^{-3}), NF = fast ion density (m^{-3}), TEO = prepellet electron temperature (eV), EF = average fast ion energy (eV), DN/DT = pellet source (s^{-1}), RP = pellet radius (m), NE = postpellet plasma density (m^{-3}).

Table 1. PDX conditions

Neutral beam power ($D^0 \rightarrow D^+$)	1.1 MW absorbed
Injection energy, E_{fo}	50 keV
Fraction at E_{fo}; $E_{fo}/2$; $E_{fo}/3$	0.45; 0.30; 0.25
Beam pulse	0.030 s
Plasma minor radius, a	45 cm
Plasma major radius, R	138 cm
Central electron temperature	1100 eV
Central density	4×10^{19} m^{-3}
Plasma atomic number	2.1
Pellet species	H_2
Pellet radius	0.85 mm
Pellet atomic content	1.35×10^{20}
Pellet speed	900 m/s

Table 2. PDX simulation

```
PELLET RADIUS= .00085 METERS
VELOCITY=   900. M/SEC
MINOR RADIUS= 0.45 M
MAJOR RADIUS=  1.38 M
PELLET ATM. WEIGHT=  1.0
PLASMA ATOMIC NO.=  2.1
BEAM POWER(MW)=  1.1
BEAM VOLTAGE(V)= 50000.
BEAM ATOMIC NO.=  2.
BEAM PULSE(S)= .030

      R       NE0        NF       TEO       EF    DN/DT       RP        NE

  0.445 .649E+18 .000E+00       18.       0. .162E+22 0.00085 .723E+18
  0.435 .174E+19 .102E+16       46.    5352. .999E+22 0.00085 .221E+19
  0.425 .249E+19 .102E+16       62.    5747. .155E+23 0.00085 .323E+19
  0.415 .331E+19 .159E+17       78.    6582. .742E+23 0.00085 .695E+19
  0.405 .461E+19 .134E+17       90.    6813. .716E+23 0.00086 .820E+19
  0.395 .591E+19 .120E+17      102.    7022. .693E+23 0.00088 .948E+19
  0.385 .764E+19 .431E+17      112.    8008. .206E+24 0.00084 .185E+20
  0.375 .943E+19 .382E+17      121.    8250. .207E+24 0.00084 .206E+20
  0.365 .112E+20 .999E+17      136.    9987. .411E+24 0.00083 .339E+20
  0.355 .131E+20 .979E+17      153.   10299. .440E+24 0.00082 .380E+20
  0.345 .160E+20 .186E+18      175.   11332. .617E+24 0.00081 .507E+20
  0.335 .170E+20 .193E+18      204.   11791. .672E+24 0.00080 .568E+20
  0.325 .190E+20 .306E+18      232.   12377. .823E+24 0.00078 .690E+20
  0.315 .209E+20 .309E+18      259.   12739. .958E+24 0.00076 .746E+20
  0.305 .229E+20 .311E+18      287.   13073. .878E+24 0.00073 .793E+20
  0.295 .253E+20 .404E+18      306.   13426. .948E+24 0.00070 .876E+20
  0.285 .276E+20 .392E+18      325.   13635. .927E+24 0.00067 .904E+20
  0.275 .297E+20 .504E+18      348.   14066. .978E+24 0.00063 .974E+20
  0.265 .315E+20 .508E+18      375.   14333. .937E+24 0.00059 .981E+20
  0.255 .331E+20 .660E+18      407.   14760. .948E+24 0.00054 .101F 21
  0.245 .343E+20 .698E+18      451.   15150. .880E+24 0.00049 .984E+20
  0.235 .355E+20 .828E+18      495.   15674. .811E+24 0.00042 .938E+20
  0.225 .363E+20 .874E+18      541.   16032. .666E+24 0.00035 .816E+20
  0.215 .371E+20 .916E+18      587.   16366. .486E+24 0.00025 .635E+20
  0.205 .376E+20 .109E+19      627.   16842. .106E+24 0.00012 .411E+20
  0.195 .380E+20 .113E+19      666.   17091. .000E+00 0.00000 .380E+20
  0.185 .383E+20 .135E+19      701.   17413. .000E+00 0.00000 .383E+20
  0.175 .385E+20 .140E+19      736.   17614. .000E+00 0.00000 .385E+20
  0.165 .387E+20 .161E+19      770.   17980. .000E+00 0.00000 .387E+20
  0.155 .389E+20 .165E+19      804.   18165. .000E+00 0.00000 .389E+20
  0.145 .391E+20 .217E+19      838.   19011. .000E+00 0.00000 .391E+20
  0.135 .393E+20 .218E+19      873.   19505. .000E+00 0.00000 .393E+20
  0.125 .396E+20 .219E+19      909.   19969. .000E+00 0.00000 .396E+20
  0.115 .398E+20 .305E+19      938.   20511. .000E+00 0.00000 .398E+20
  0.105 .399E+20 .306E+19      966.   20839. .000E+00 0.00000 .399E+20
  0.095 .400E+20 .391E+19      992.   20828. .000E+00 0.00000 .400E+20
  0.085 .400E+20 .393E+19     1015.   21094. .000E+00 0.00000 .400E+20
  0.075 .400E+20 .433E+19     1035.   21195. .000E+00 0.00000 .400E+20
  0.065 .400E+20 .434E+19     1048.   21332. .000E+00 0.00000 .400E+20
  0.055 .400E+20 .406E+19     1062.   21446. .000E+00 0.00000 .400E+20
  0.045 .400E+20 .407E+19     1075.   21575. .000E+00 0.00000 .400E+20
  0.035 .400E+20 .408E+19     1088.   21702. .000E+00 0.00000 .400E+20
  0.025 .400E+20 .454E+19     1094.   22270. .000E+00 0.00000 .400E+20
  0.015 .400E+20 .455E+19     1098.   22314. .000E+00 0.00000 .400E+20
  0.005 .400E+20 .455E+19     1100.   22330. .000E+00 0.00000 .400E+20
```

radius RP = 0), giving a penetration of 27 cm. The large pellet increases the electron density above the initial values by as much as a factor of 2 locally. The corresponding large electron temperature reduction and the low initial level of T_e combine to ensure that the ablation is dominated by the fast ion component. The ions are fully stacked in this case, owing to the fact that the beam pulse length exceeds τ_f ($\sim$10 ms) everywhere.

The experimentally measured pellet lifetime for this case varied between 320 and 360 μs, which corresponds to a penetration range of 29-32 cm. The model underestimates the penetration, but the agreement is satisfactory, considering the many uncertainties in the fast ion population and the simplicity of the model chosen for the distribution function. (Charge exchange and bad orbit losses have been neglected.)

5. CASE II – TFTR

TFTR represents an interesting challenge for pellet injection. The electron temperature and injection power are high, and the beam voltage is 120 kV. These effects combine to give levels of fast ion densities and energies that have not been approached in present experiments. Tritium pellet injection into such discharges has been proposed[8,9] primarily as a means to minimize the tritium inventory in the device and to enhance the neutron power output. In this section we consider the scenario described by Singer:[9] injection of a large (2.5-mm-diam) tritium pellet into a 55-cm-bore, precompression TFTR plasma that has been heated by 33.5 MW of deuterium neutral beam injection. The pellet velocity was assumed to be 2 km/s, which is a modest extrapolation of the present state of the art for hydrogen gun-type injectors (1.4 km/s).[10] The conditions for the calculation are given in Table 3, and the results are presented in Table 4. The predicted penetration for this example is 21 cm, giving an inverted postpellet density profile. At its deepest penetration the pellet experiences an electron temperature of 2 keV, but the ablation is primarily driven by the extraordinarily high levels of fast ion density and energy (greater by factors of 10 and 3, respectively, than in the previous PDX example). With the fast ion option suppressed, the penetration is 35 cm (in an actual experiment, the penetration would be far greater because in the absence of intense beam heating the electron temperatures would be very much lower). Accordingly, the penetration can be tailored by moving the pellet injection time with respect to the beam turnon or by ramping the beam power. If pellet injection occurred at $t < \tau_f$ (∿20 ms) into the beam

Table 3. TFTR conditions

Neutral beam power ($D^0 \rightarrow D^+$)	33.5 MW
Injection energy E_{fo}	120 keV
Fraction at E_{fo}; $E_{fo}/2$; $E_{fo}/3$	0.59; 0.22; 0.19
Beam pulse	1.0 s
Plasma minor radius, a	55 cm
Plasma major radius, R	310 cm
Central electron temperature	4290 eV
Central electron density	6.4×10^{19} m^{-3}
Plasma atomic number	2.1
Pellet species	T_2
Pellet radius	1.25 mm
Pellet speed	2,000-10,000 m/s

Table 4. TFTR simulation

```
PELLET RADIUS= .00125 METERS
VELOCITY=  2000. M/SEC
MINOR RADIUS= 0.55 M
MAJOR RADIUS=  3.10 M
PELLET ATM. WEIGHT=  3.0
PLASMA ATOMIC NO.=  2.1
BEAM POWER(MW)= 33.5
BEAM VOLTAGE(V)=120000.
BEAM ATOMIC NO.=   2.
BEAM PULSE(S)=1.000

      R        NE0        NF       TEO       EF     DN/DT       RP        NE

  0.545  .395E+19  .160E+18      45.   12904.  .804E+24  0.00125  .994E+19
  0.535  .118E+20  .204E+18     134.   16506.  .126E+25  0.00125  .214E+20
  0.525  .197E+20  .221E+18     223.   16689.  .174E+25  0.00124  .331E+20
  0.515  .242E+20  .211E+19      23.   26587.  .448E+25  0.00123  .590E+20
  0.505  .275E+20  .252E+19     427.   28566.  .499E+25  0.00121  .670E+20
  0.495  .309E+20  .283E+19     532.   30233.  .543E+25  0.00118  .744E+20
  0.485  .342E+20  .306E+19     636.   31683.  .570E+25  0.00115  .808E+20
  0.475  .375E+20  .324E+19     740.   32968.  .597E+25  0.00112  .871E+20
  0.455  .404E+20  .508E+19     848.   35808.  .676E+25  0.00108  .973E+20
  0.455  .420E+20  .553E+19     968.   37059.  .684E+25  0.00104  .100E+21
  0.445  .436E+20  .593E+19    1089.   38192.  .681E+25  0.00099  .103E+21
  0.435  .453E+20  .627E+19    1209.   39227.  .669E+25  0.00093  .104E+21
  0.425  .469E+20  .657E+19    1330.   40179.  .646E+25  0.00087  .104E+21
  0.415  .485E+20  .683E+19    1450.   41059.  .607E+25  0.00081  .103E+21
  0.405  .496E+20  .808E+19    1569.   43496.  .587E+25  0.00074  .102E+21
  0.395  .506E+20  .841E+19    1687.   44263.  .524E+25  0.00065  .971E+20
  0.385  .515E+20   871E+19    1805.   44981.  .446E+25  0.00056  .899E+20
  0.375  .524E+20  .898E+19    1923.   45654.  .358E+25  0.00045  .805E+20
  0.365  .534E+20  .923E+19    2041.   46288.  .276E+25  0.00031  .670E+20
  0.355  .543E+20  .103E+20    2155.   48422.  .636E+23  0.00008  .545E+20
  0.345  .549E+20  .105E+20    2257.   48919.  .000E+00  0.00000  .549E+20
  0.335  .555E+20  .107E+20    2359.   49392.  .000E+00  0.00000  .555E+20
  0.325  .561E+20  .109E+20    2461.   49843.  .000E+00  0.00000  .561E+20
  0.315  .567E+20  .111E+20    2563.   50273.  .000E+00  0.00000  .567E+20
  0.305  .573E+20  .113E+20    2665.   50685.  .000E+00  0.00000  .573E+20
  0.295  .579E+20  .127E+20    2754.   52381.  .000E+00  0.00000  .579E+20
  0.285  .585E+20  .128E+20    2840.   52702.  .000E+00  0.00000  .585E+20
  0.275  .591E+20  .129E+20    2925.   53011.  .000E+00  0.00000  .591E+20
  0.265  .596E+20  .131E+20    3010.   53310.  .000E+00  0.00000  .596E+20
  0.255  .602E+20  .132E+20    3096.   53599.  .000E+00  0.00000  .602E+20
  0.245  .607E+20  .165E+20    3178.   55185.  .000E+00  0.00000  .607E+20
  0.235  .611E+20  .167E+20    3249.   55410.  .000E+00  0.00000  .611E+20
  0.226  .616E+20  .168E+20    3320.   55629.  .000E+00  0.00000  .616E+20
  0.215  .620E+20  .169E+20    3390.   55841.  .000E+00  0.00000  .620E+20
  0.205  .625E+20  .170E+20    3461.   56048.  .000E+00  0.00000  .625E+20
  0.195  .629E+20  .171E+20    3532.   56250.  .000E+00  0.00000  .629E+20
  0.185  .633E+20  .217E+20    3587.   57325.  .000E+00  0.00000  .633E+20
  0.175  .637E+20  .218E+20    3636.   57459.  .000E+00  0.00000  .637E+20
  0.165  .640E+20  .218E+20    3685.   57589.  .000E+00  0.00000  .640E+20
  0.155  .644E+20  .219E+20    3734.   57718.  .000E+00  0.00000  .644E+20
  0.145  .648E+20  .219E+20    3783.   57844.  .000E+00  0.00000  .648E+20
  0.135  .652E+20  .253E+20    3826.   58426.  .000E+00  0.00000  .652E+20
  0.125  .656E+20  .252E+20    3850.   58485.  .000E+00  0.00000  .656E+20
  0.115  .659E+20  .252E+20    3873.   58544.  .000E+00  0.00000  .659E+20
  0.105  .663E+20  .252E+20    3897.   58602.  .000E+00  0.00000  .663E+20
  0.095  .666E+20  .251E+20    3920.   58659.  .000E+00  0.00000  .666E+20
  0.085  .670E+20  .251E+20    3944.   58716.  .000E+00  0.00000  .670E+20
  0.075  .667E+20  .310E+20    3996.   59170.  .000E+00  0.00000  .667E+20
  0.065  .661E+20  .315E+20    4058.   59314.  .000E+00  0.00000  .661E+20
  0.055  .655E+20  .321E+20    4120.   59455.  .000E+00  0.00000  .655E+20
  0.045  .650E+20  .326E+20    4182.   59593.  .000E+00  0.00000  .650E+20
  0.035  .644E+20  .332E+20    4244.   59728.  .000E+00  0.00000  .644E+20
  0.025  .640E+20  .336E+20    4290.   59827.  .000E+00  0.00000  .640E+20
  0.015  .640E+20  .336E+20    4290.   59827.  .000E+00  0.00000  .640E+20
  0.005  .640E+20  .336E+20    4290.   59827.  .000E+00  0.00000  .000E+00
```

pulse, the electron temperatures and fast ion heat flux would both be reduced. Another possible method of enhancing the central region with tritium would be to inject a large, sacrificial pellet of deuterium, followed closely in time by the tritium pellet The deuterium pellet would raise the plasma density in the edge region (the first 20 cm), which would thermalize the fast ion component and reduce the electron temperature (the strong cooling due to dilution would probably exceed rethermalization from the slowing down of fast ions, as observed on ISX-B[7]). A careful analysis of these scenarios, which is outside the scope of this report, must await detailed transport code calculations.

The alternative to these measures would be to increase the pellet speed to achieve central penetration. The results of a calculation for a pellet speed of 10 km/s are shown in Table 5. At this speed, the pellet penetrates to within a few centimeters of the minor axis, giving a centrally peaked density profile. Again, the optimal approach to this problem will depend not so much on these penetration calculations as on more elaborate calculations of the subsequent transport of the fuel and on further experimentation.

Table 5. TFTR simulation witn 10-km/s pellet speed

```
PELLET RADIUS= .00125 METERS
VELOCITY= 10000. M/SEC
MINOR RADIUS= 0.55 M
MAJOR RADIUS=  3.10 M
PELLET ATM. WEIGHT=  3.0
PLASMA ATOMIC NO.=  2.1
BEAM POWER(MW)= 33.5
BEAM VOLTAGE(V)=120000.
BEAM ATOMIC NO.=   2.
BEAM PULSE(S)=1.000


      R       NE0        NF       TEO      EF     DN/DT       RP        NE

  0.545 .395E+19 .160E+18     45.  12904. .816E+24 0.00125 .517E+19
  0.535 .118E+20 .204E+18    134.  16506. .131E+25 0.00125 .138E+20
  0.525 .197E+20 .221E+18    223.  18689. .181E+25 0.00125 .225E+20
  0.515 .242E+20 .211E+19    323.  26587. .463E+25 0.00125 .315E+20
  0.505 .275E+20 .252E+19    427.  28566. .529E+25 0.00124 .360E+20
  0.495 .309E+20 .283E+19    532.  30233. .588E+25 0.00124 .405E+20
  0.485 .342E+20 .306E+19    636.  31683. .642E+25 0.00123 .449E+20
  0.475 .375E+20 .324E+19    740.  32968. .687E+25 0.00122 .492E+20
  0.465 .404E+20 .508E+19    848.  35808. .807E+25 0.00122 .545E+20
  0.455 .420E+20 .553E+19    968.  37059. .857E+25 0.00121 .573E+20
  0.445 .436E+20 .593E+19   1089.  38192. .902E+25 0.00120 .600E+20
  0.435 .453E+20 .627E+19   1209.  39227. .946E+25 0.00119 .628E+20
  0.425 .469E+20 .657E+19   1330.  40179. .986E+25 0.00118 .656E+20
  0.415 .485E+20 .683E+19   1460.  41059. .100E+26 0.00117 .680E+20
  0.405 .496E+20 .808E+19   1569.  43496. .107E+26 0.00116 .709E+20
  0.395 .506E+20 .841E+19   1687.  44263. .109E+26 0.00114 .729E+20
  0.385 .515E+20 .871E+19   1805.  44981. .111E+26 0.00113 .747E+20
  0.375 .524E+20 .898E+19   1923.  45654. .113E+26 0.00112 .766E+20
  0.365 .534E+20 .923E+19   2041.  46288. .114E+26 0.00110 .785E+20
  0.355 .543E+20 .103E+20   2155.  48422. .118E+26 0.00109 .809E+20
  0.345 .549E+20 .105E+20   2257.  48919. .119E+26 0.00107 .826E+20
  0.335 .555E+20 .107E+20   2359.  49392. .118E+26 0.00106 .839E+20
  0.325 .561E+20 .109E+20   2461.  49843. .119E+26 0.00104 .854E+20
  0.315 .567E+20 .111E+20   2563.  50273. .119E+26 0.00102 .871E+20
  0.305 .573E+20 .113E+20   2665.  50685. .119E+26 0.00101 .887E+20
  0.295 .579E+20 .127E+20   2754.  52381. .119E+26 0.00099 .901E+20
  0.285 .585E+20 .128E+20   2840.  52702. .118E+26 0.00097 .917E+20
  0.275 .591E+20 .129E+20   2925.  53011. .117E+26 0.00095 .930E+20
  0.265 .596E+20 .131E+20   3010.  53310. .115E+26 0.00093 .943E+20
  0.255 .602E+20 .132E+20   3096.  53599. .113E+26 0.00091 .956E+20
  0.245 .607E+20 .165E+20   3178.  55185. .115E+26 0.00089 .979E+20
  0.235 .611E+20 .167E+20   3249.  55410. .111E+26 0.00087 .988E+20
  0.225 .616E+20 .168E+20   3320.  55629. .109E+26 0.00084 .100E+21
  0.215 .620E+20 .169E+20   3390.  55841. .107E+26 0.00082 .101E+21
  0.205 .625E+20 .170E+20   3461.  56048. .103E+26 0.00080 .102E+21
  0.195 .629E+20 .171E+20   3532.  56250. .100E+26 0.00077 .103E+21
  0.185 .633E+20 .217E+20   3587.  57325. .994E+25 0.00074 .106E+21
  0.175 .637E+20 .218E+20   3636.  57459. .954E+25 0.00072 .106E+21
  0.165 .640E+20 .218E+20   3685.  57589. .901E+25 0.00069 .107E+21
  0.155 .644E+20 .219E+20   3734.  57718. .863E+25 0.00066 .108E+21
  0.145 .648E+20 .219E+20   3783.  57844. .813E+25 0.00063 .108E+21
  0.135 .652E+20 .253E+20   3826.  58426. .777E+25 0.00059 .109E+21
  0.125 .656E+20 .252E+20   3850.  58485. .724E+25 0.00056 .110E+21
  0.115 .659E+20 .252E+20   3873.  58544. .661E+25 0.00053 .110E+21
  0.105 .663E+20 .252E+20   3897.  58602. .605E+25 0.00049 .110E+21
  0.095 .666E+20 .251E+20   3920.  58659. .545E+25 0.00045 .109E+21
  0.085 .670E+20 .251E+20   3944.  58716. .481E+25 0.00041 .108E+21
  0.075 .667E+20 .310E+20   3996.  59170. .433E+25 0.00036 .107E+21
  0.065 .661E+20 .315E+20   4058.  59314. .363E+25 0.00031 .104E+21
  0.055 .655E+20 .321E+20   4120.  59455. .286E+25 0.00025 .973E+20
  0.045 .650E+20 .326E+20   4182.  59593. .211E+25 0.00018 .864E+20
  0.035 .644E+20 .332E+20   4244.  59728. .398E+24 0.00009 .675E+20
  0.025 .640E+20 .336E+20   4290.  59827. .000E+00 0.00000 .640E+20
  0.015 .640E+20 .336E+20   4290.  59827. .000E+00 0.00000 .640E+20
  0.005 .640E+20 .336E+20   4290.  59827. .000E+00 0.00000 .000E+00
```

6. CONCLUSIONS

Although the algorithm presented is consistent with the previous treatment of ablation due to electrons alone and is in agreement with the single PDX result, it is nevertheless provisional. The assumption of hydrodynamic similarity, which was made in order to reformulate the scaling laws of the earlier treatment to account for the effects of fast ions, is basically untested. This question and others concerning the ion ablation model should be resolved in forthcoming experiments on the ISX-B and PDX devices.

ACKNOWLEDGMENTS

The author would like to thank G. L. Schmidt and R. J. Goldston for making available the code used to calculate the deposition of neutral beam particles. S. E. Attenberger contributed many useful suggestions.

REFERENCES

1. P. B. Parks, R. J. Turnbull, and C. A. Foster, Nucl. Fusion **17**, 595 (1977).
2. P. B. Parks and R. J. Turnbull, Phys. Fluids **21**, 1735 (1978).
3. S. L. Milora and C. A. Foster, *ORNL Neutral Gas Shielding Model for Pellet-Plasma Interactions*, ORNL/TM-5776, Oak Ridge, Tennessee (1977).
4. W. T. Miles, R. Thompson, and A. E. S. Green, J. Appl. Phys. **43**, 678 (1972).
5. M. G. Heaps and A. E. S. Green, J. Appl. Phys. **46**, 4718 (1975).
6. J. A. Phillips, Phys. Rev. **90**, 532 (1953).
7. S. L. Milora, C. A. Foster, C. E. Thomas, et al., Nucl. Fusion **20**, 1491 (1980).
8. W. A. Houlberg and R. M. Wieland, Oak Ridge National Laboratory, "Evaluation of Toroidal Field Ripple in TFTR and Tritium Pellet Injection as a Means of Reducing Tritium Inventory," private communication (1978).
9. C. E. Singer, "Neutron Production in TFTR with Pellet Injection Before Compression," J. Vac. Sci. Technol. (in press).
10. D. D. Schuresko, S. L. Milora, and J. T. Hogan, "Performance Characterization of Pneumatic Hydrogen Pellet Injectors," J. Vac. Sci. Technol. (in press).

ORNL/TM-8616
Dist. Category UC-20 a

INTERNAL DISTRIBUTION

1. C. E. Bush
2. S. K. Combs
3. W. A. Cooper
4. W. A. Houlberg
5. H. Howe
6. E. Lazarus
7. J. F. Lyon
8-12. S. L. Milora
13. M. Murakami
14. J. A. Rome
15. M. J. Saltmarsh
16. D. Schuresko
17. J. Sheffield
18. J. Whealton
19-20. Laboratory Records Department
21. Laboratory Records, ORNL-RC
22. Document Reference Section
23. Central Research Library
24. Fusion Energy Division Library
25. Fusion Energy Division Reports Office
26. ORNL Patent Office

EXTERNAL DISTRIBUTION

27. Office of the Assistant Manager for Energy Research and Development, Department of Energy, Oak Ridge Operations, Box E, Oak Ridge, TN 37830
28. J. D. Callen, Department of Nuclear Engineering, University of Wisconsin, Madison, WI 53706
29. R. W. Conn, Department of Chemical, Nuclear, and Thermal Engineering, University of California, Los Angeles, CA 90024
30. S. O. Dean, Director, Fusion Energy Development, Science Applications, Inc., 2 Professional Drive, Gaithersburg, MD 20760
31. H. K. Forsen, Bechtel Group, Inc., Research Engineering, P.O. Box 3965, San Francisco, CA 94105
32. R. W. Gould, Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125
33. D. G. McAlees, Exxon Nuclear Company, Inc., 777 106th Avenue, NE, Bellevue, WA 98009
34. P. J. Reardon, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08540
35. W. M. Stacey, Jr., School of Nuclear Engineering, Georgia Institute of Technology, Atlanta, GA 30332
36. G. A. Eliseev, I. V. Kurchatov Institute of Atomic Energy, P.O. Box 3402, 123182 Moscow, U.S.S.R.
37. V. A. Glukhikh, Scientific-Research Institute of Electro-Physical Apparatus, 188631 Leningrad, U.S.S.R.
38. I. Spighel, Lebedev Physical Institute, Leninsky Prospect 53, 117924 Moscow, U.S.S.R.
39. D. D. Ryutov, Institute of Nuclear Physics, Siberian Branch of the Academy of Sciences of the U.S.S.R., Sovetskaya St. 5, 630090 Novosibirsk, U.S.S.R.
40. V. T. Tolok, Kharkov Physical-Technical Institute, Academical St. 1, 310108 Kharkov, U.S.S.R.

41. R. Varma, Physical Research Laboratory, Navangpura, Ahmedabad, India
42. Bibliothek, Max-Planck Institut fur Plasmaphysik, D-8046 Garching bei Munchen, Federal Republic of Germany
43. Bibliothek, Institut fur Plasmaphysik, KFA, Postfach 1913, D-5170 Julich, Federal Republic of Germany
44. Bibliotheque, Centre de Recherches en Physique des Plasmas, 21 Avenue des Bains, 1007 Lausanne, Switzerland
45. Bibliotheque, Service du Confinement des Plasmas, CEA, B.P. 6, 92 Fontenay-aux-Roses (Seine), France
46. Documentation S.I.G.N., Departement de la Physique du Plasma et de la Fusion Controlee, Centre d'Etudes Nucleaires, B.P. No. 85, Centre du Tri, 38041 Cedex, Grenoble, France
47. Library, Culham Laboratory, UKAEA, Abingdon, Oxon, OX14 3DB, England
48. Library, FOM Institut voor Plasma-Fysica, Rijnhuizen, Jutphaas, The Netherlands
49. Library, Institute of Physics, Academia Sinica, Beijing, Peoples Republic of China
50. Library, Institute of Plasma Physics, Nagoya University, Nagoya 64, Japan
51. Library, International Centre for Theoretical Physics, Trieste, Italy
52. Library, Laboratorio Gas Ionizzati, Frascati, Italy
53. Library, Plasma Physics Laboratory, Kyoto University, Gokasho Uji, Kyoto, Japan
54. Plasma Research Laboratory, Australian National University, P.O. Box 4, Canberra, A.C.T. 2000, Australia
55. Thermonuclear Library, Japan Atomic Energy Research Institute, Tokai, Naka, Ibaraki, Japan

56-185. Given distribution as shown in TID-4500 Magnetic Fusion Energy (Category Distribution UC-20 a)