Conf-740104--9

FLUXES OF CHARGED AND NEUTRAL PARTICLES FROM TOKAMAKS*

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Introduction

Tokamak devices have produced stable, long-lived plasmas which have transport properties scaling favorably with size.(1-4)Because of this success, the study of plasma-wall interactions has been added to such traditional concerns as plasma equilibrium, stability and transport.

Wall evolved impurity ions and neutral hydrogen have a significant effect on the properties of present machines. Energy loss by line radiation from both 'low-Z' carbon and oxygen and 'high-Z' tungsten, molybdenum or gold is an important part of the electron loss channel. Charge exchange reactions between protons and hydrogen atoms carry ion energy directly to the walls. (This flux, in turn, sputters metallic ions back into the discharge).

Conditions for ignition of a D-T burning tokamak strongly depend on the impurity content. The classical minimum ignition temperature is that at which proton-electron bremsstrahlung loss balances heating by alpha particle reaction products. Admixture of a relatively small number of impurities introduces a large change in the energy balance: now electron-ion bremsstrahlung and line radiation are important and there are fewer reacting fusion ions.

Some important qualifications must be borne in mind:

(1) Present impurity and neutral charge exchange losses are 'series' losses. Plasma energy flows from the hot core by conduction and convection processes. Then much of it is simply transferred to the wall by line radiation and charge exchange. Plasma parameters and $N\tau$ are limited by plasma diffusion processes.

(2) There is a well-recognized gulf for tokamaks preventing ignition which must be bridged by some form of supplementary heating. Future large experiments will be driven by large amounts of injected power, and the power balance, in some respects, is under our control.

(3) There are theoretical predictions of new instabilities occurring as the plasma becomes more collisionless. Admixture of impurities can mitigate them.

*Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.

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(4) The macroscopic stability of present experiments is a result of favorable current density profiles created by impurities.

1. Present Experiments

We show in Figure 1a the general arrangement of a tokamak device. A toroidal electric field is induced, and the resulting plasma current produces a magnetic field. This self-field, combining with an externally applied toroidal magnetic field, has satisfactory confinement and stability properties. In Figure 1b we show typical radial profiles of plasma temperatures, densities and the neutral particle density. These profiles are obtained from a numerical code(5,6) which simulates discharge dynamics.

Figure 2 shows a schematic diagram of energy flow in tokamaks.

There have been recent demonstrations of heating by injection of energetic neutral atoms, but most tokamaks have been Ohmically heated. The applied toroidal electric field gives energy to the electrons, and the protons receive energy only by collision processes.(1,7) In injection experiments both electrons and protons are heated directly as the injected particles slow down.

The electron loss channels are radial thermal conduction and convection (mass flow), transfer to protons, and excitation of impurity ions. The impurity ions transfer this energy as line radiation to the walls.

Proton losses are mainly by radial convection and conduction and by charge exchange with colder neutral atoms.

We must distinguish the hot central core of the plasma from the cooler edge region. Figure 3a shows the radial variation of the electron power balance for an ORMAK discharge. We see that plasma convection is the dominant loss process in the center, and energy is transported by this mechanism to the edge. Near the edge, however, incompletely stripped carbon and oxygen impurities are excited and radiate much of the energy away. The power flow must be accommodated, and uniform illumination of the walls is preferable to deposition in a small area on the limiter.

The ion energy balance is also affected by surface interactions. In Figure 3b we see that radial convection and conduction determine the central energy balance, while charge exchange transfers most ion energy to the wall. Measurements on ORMAK with a calorimetric limiter confirm this picture.(2)

In present experiments at low plasma density ($n_{central} \leq 2.10^{13}$ cm^{-3}) charge exchange may be a significant loss mechanism even for the hot core. Concern for larger experiments centers around the role of the charge exchange effect in causing wall sputtering. Since sputtering yields for Au, Fe, Nb (present or proposed wall materials) increase in the 0 - 5 keV region, and since ion temperatures must increase by at least an order of magnitude, there is an obvious danger that impurity densities will be higher from this simple mechanism.

We have examined the role of neutrals because of their influence on our experiments, and we can extend the analysis to future machines. We assume a slab geometry and solve

$$v \cos\theta \frac{\partial}{\partial x} f(x_1\ v_1\ \theta) = - N_e\ f\ \overline{\sigma_i\ v_e} - N_p f\ \overline{\sigma_{cx}\ v_{REL}} + N\ f_p(x_1 v)\ \overline{\sigma_{cx}\ v_{REL}} \tag{1}$$

where

$f = f_{FC} + f_{HOT}$, $n = \int d\underset{\sim}{v}\ f$

$f_{e,p}$ = electron, proton distribution functions

$n_{e,p} = \int d\underset{\sim}{v}\ f_{e,p}$

$\overline{\sigma v}$ = rate coefficients for ionization by electrons and for charge exchange.

f_{FC} is the distribution of incident atoms formed by dissociative ionization of H_2. (Assumed to be isotropic at the plasma boundary.)

f_{HOT} is the distribution of neutrals resulting from charge exchange of these incident particles with hotter plasma protons.

The results of this calculation can be compared in detail with experiments (Figure 4a) and the theoretical model agrees. We find that most of the neutrals are emitted from the cooler outer region, while the distribution has a high energy tail characteristic of the central ion temperature (Figure 4b).

To extrapolate the model to other conditions we define:

Γ_{cx} = flux (#/cm^2/sec) of neutral produced by charge exchange

f_s = number of sputtered particles/incident neutral, averaged over the neutral energy distribution.

ORMAK has a gold liner chosen for its chemical inertness. Table 1 shows results for ORMAK and other plasmas, for the specific example of gold. [Sputtering data from (8).]

Table 1

Minor Radius	Central Plasma Density	Central T_i (keV)	Γ_{cx}	$f_s (\times 10^3)$
23	$5 \cdot 10^{13}$	.5	$6.5 \cdot 10^{15}$	2.12
23	$5 \cdot 10^{13}$	3.	$1.99 \cdot 10^{16}$	4.16
45	$5 \cdot 10^{13}$	3.	10^{16}	2.6
175	$5 \cdot 10^{13}$	6.	10^{16}	2.0

In Figure 5 we see the strong diminution of the energent charge exchange flux with density. Fewer neutrals penetrate to the high temperature central region. There is also a strong dependence on ion temperature, so that sputtering from charge exchange neutrals is at its worst in machines with present dimensions. Average sputtering yields might actually be lower in more energetic plasmas, since large size seems to be necessary to produce them.

2. Larger Machines

Certainty about energy balance in large-scale feasibility machines awaits the outcome of experiments on neutral beam heating and on plasma transport in the collisionless regime. Figure (6a) shows some theoretical projections for plasma transport scaling:

1) Neoclassical: All diffusive losses as calculated from binary collisions.
2) Pseudo/neoclassical: Ion losses given by neoclassical theory, electron losses an extension of the presently observed empirical scaling[1] $D = 10\,\hat{\rho}^2\nu$.
3) Trapped-particle mode instability. Losses caused by new collective instabilities in the 'collisionless' regime.(9)

Figure (6b) shows a comparison between observations in ORMAK and the predictions of the instability theory. Definitive results are expected from experiments at higher current and with injection, but we see no evidence for anomalous loss.

The energy balance in D-T systems is shown in Figure 2. Heating by alpha particle reaction products, synchrotron radiation and bremsstrahlung losses are significant. Since the theoretically predicted transport laws (both pessimistic and optimistic) all scale favorably with plasma size, we present results for a device being studied as a reference design at ORNL. The plasma size is large enough to permit attainment of the Lawson criterion in the presence of the trapped-ion mode. With 10 MW of injected neutrals the experiment should reach its objectives on a time scale of seconds.

In Fig. 7a we see the effects of impurities on discharge dynamics for pseudo/neoclassical scaling. With

$$Z_{eff} \equiv \frac{1 + \sum_i (n_i/n_{DT}) Z_i^2}{1 + \sum_i \frac{n_i}{n_{DT}} Z_i}$$

where

n_i is the impurity ion density
n_p is the D-T density (assuming $n_D = n_T$)
Z_i is the charge.

We see that a Z of 9 prevents ignition, while lower values prolong the time required to reach ignition. If the impurities were purely Molybdenum (Z = 42), Z = 9 would require that the molybdenum density be 0.58% of the plasma density, and would require an increase in the planned injection power level.

New collisionless instabilities pose a threat and the role of impurities here is helpful. The instabilities arise for high values of

$$\tau^*_{ei} \equiv \frac{\omega_b^{e,i}}{\nu}$$

where

ν: Electron, ion collision frequency.

$\omega_b^{e,i}$: 'Bounce' frequency of electrons, ions trapped by the toroidal variation in magnetic field.

Since the collision frequency is proportional to Z_{eff}, admixture of impurities is helpful

Figure 7b shows a comparison between the neoclassical result and the trapped ion results. In Table 2 we present the relative amounts of volume and surface losses.

Table 2

ORMAK F/BX: 5 Seconds

	Trapped Ion Mode	Pseudo/neoclassical	Neoclassical
Plasma Diffusion and Radiation Losses (MW, w/cm^2 at plasma)	12.06/2.91	6.28/1.52	7.17/1.73
% Conduction/ Convection	82	22	5
% Synchrotron (μ wave)	14	32	30
% Bremsstrahlung, Line Radiation (soft x-ray, optical)	4	46	65
Neutron Power Out (MW, w/cm^2 at plasma	15.7/3.79	57.8/14	68.4/16.5

The conduction/convection losses may be handled in a variety of ways: a 'gas blanket" can be used to distribute the energy uniformly by charge exchange, multiple or rotating(10)limiters would allow direct scrape-off, local diversion by vertical field coils can be utilized to get a uniform deposition.

Conclusions

Effects of wall evolved impurities will be significant for the relatively small, energetic machines proposed for the near future. Benefits of scale will help ease their impact on feasibility devices, but mechanisms for distributing the heat load uniformly will be desirable.

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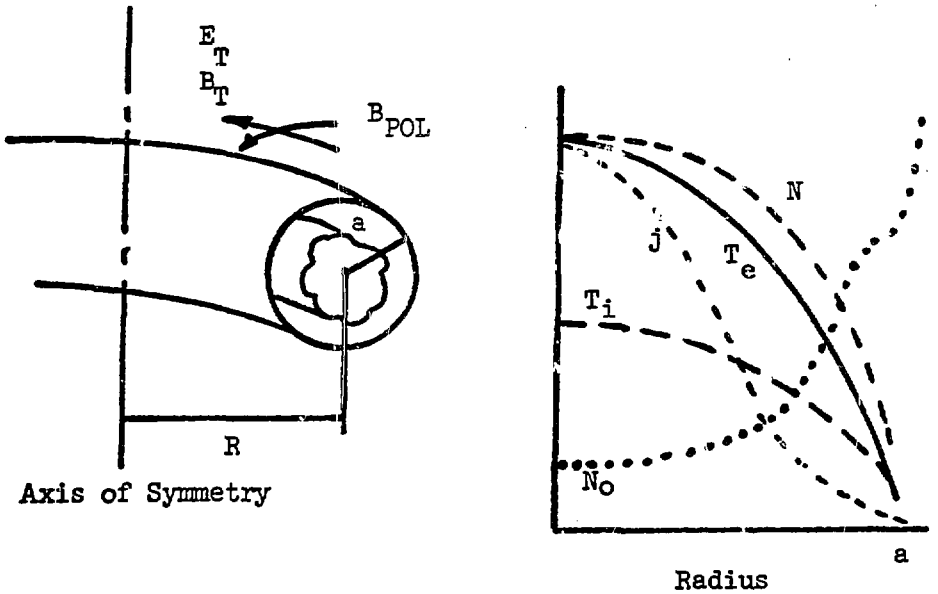

FIG. 1

a) Tokamak Geometry, b) Typical Radial Profiles

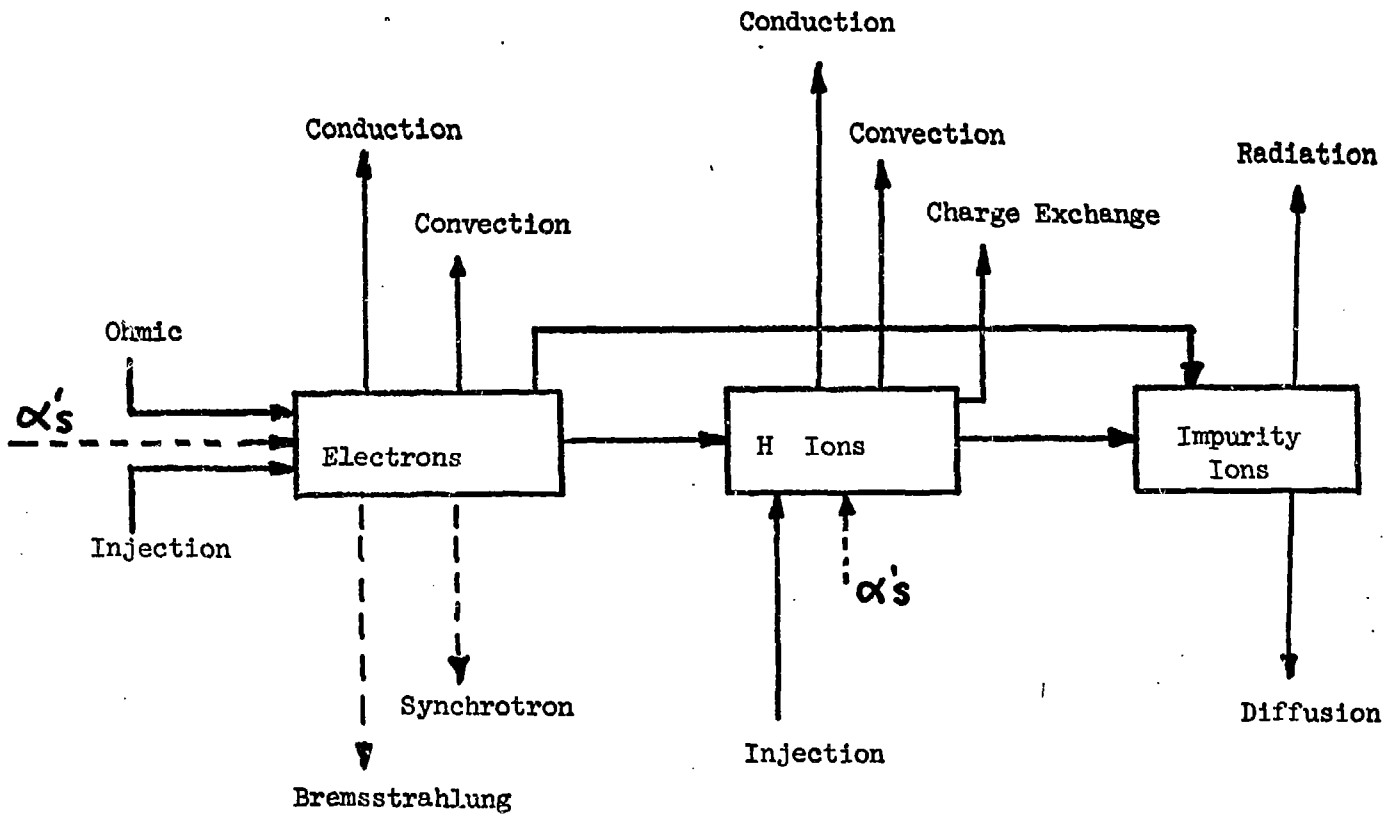

FIG. 2

Tokamak Power Flow

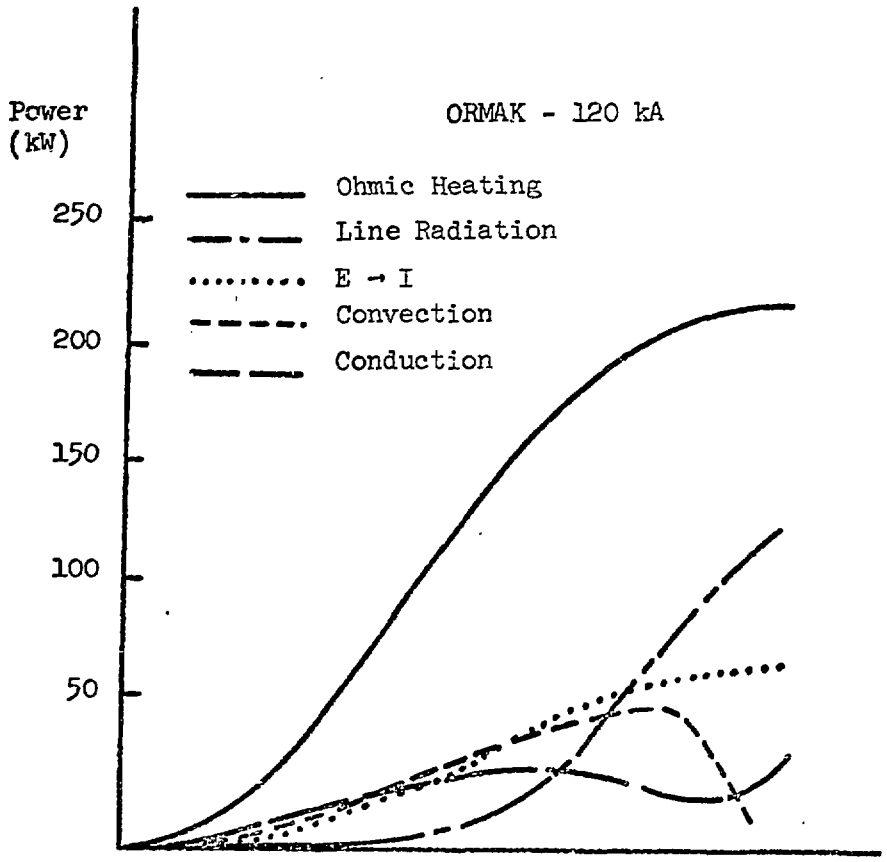

FIG. 3a
Integrated Radial Power Flow-Electrons

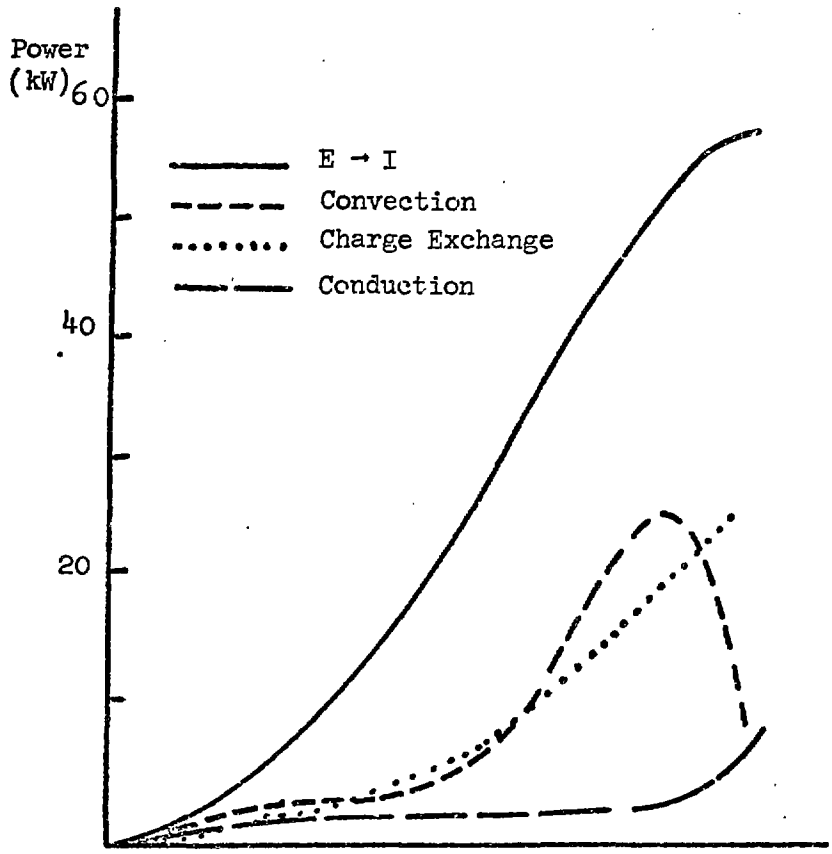

FIG. 3b)
Integrated Radial Power Flow- Ions

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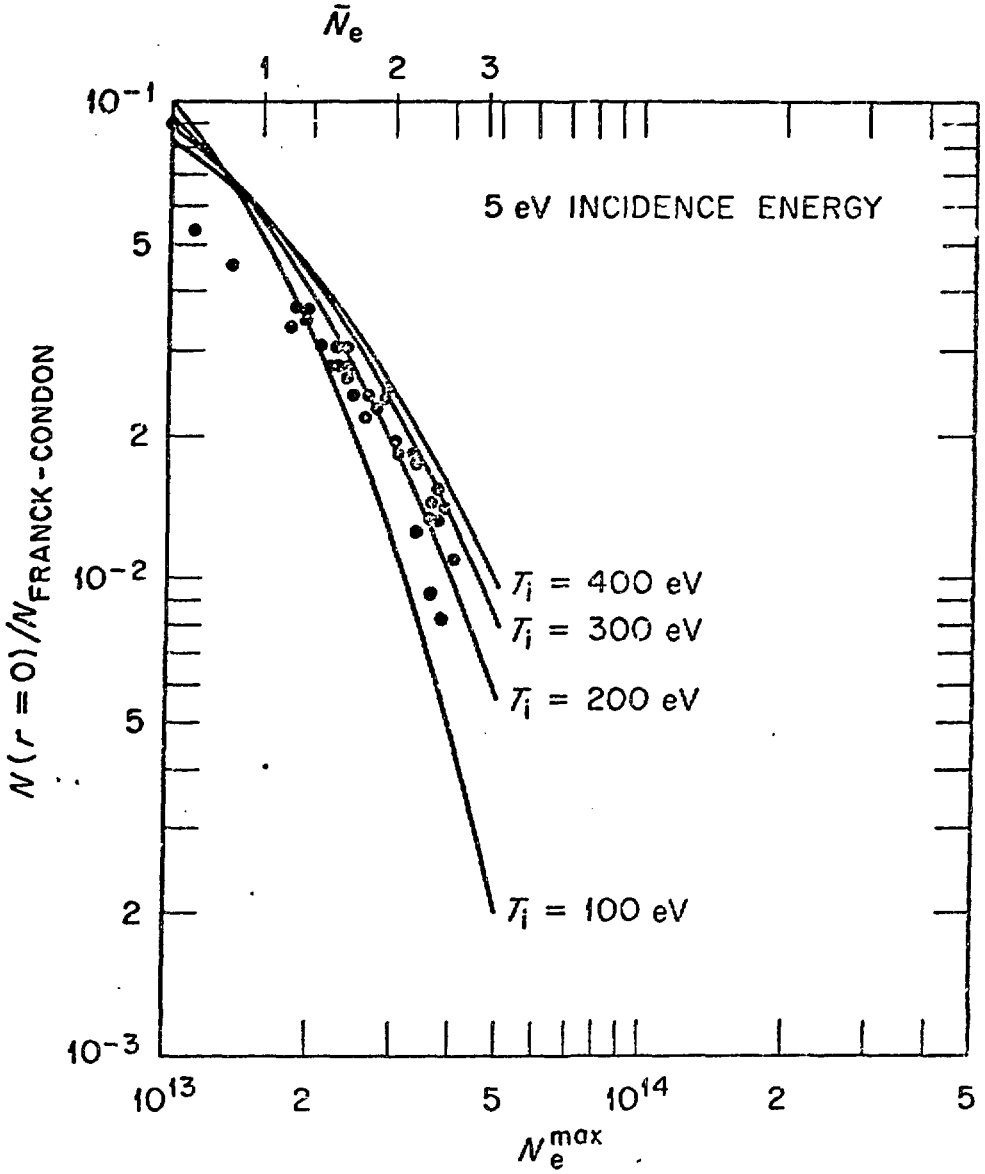
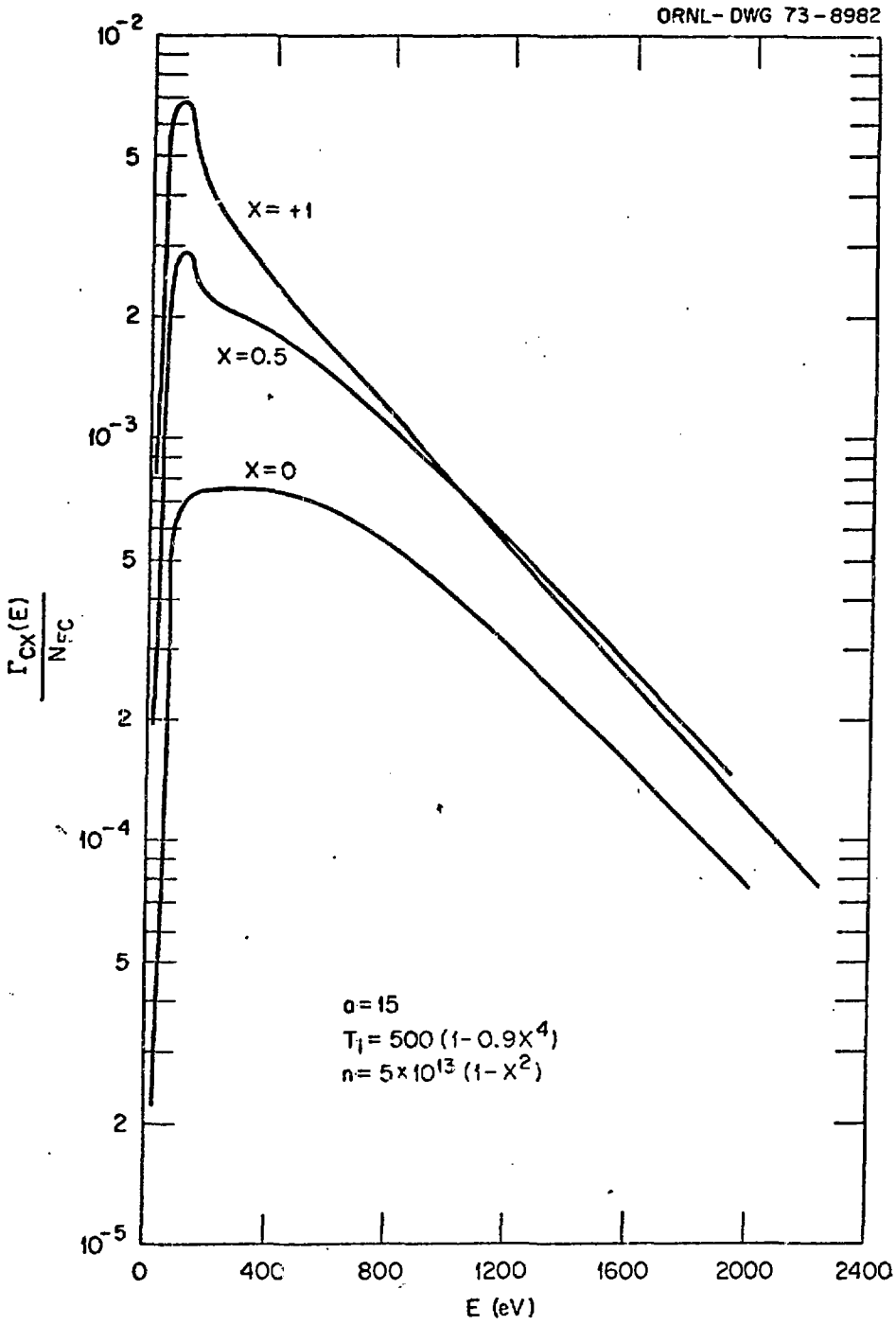


ORMAK : Central Neutral Density vs Electron Density.

FIG. 4a



Charge Exchange Neutral Spectrum vs X= r/a .

FIG. 4b

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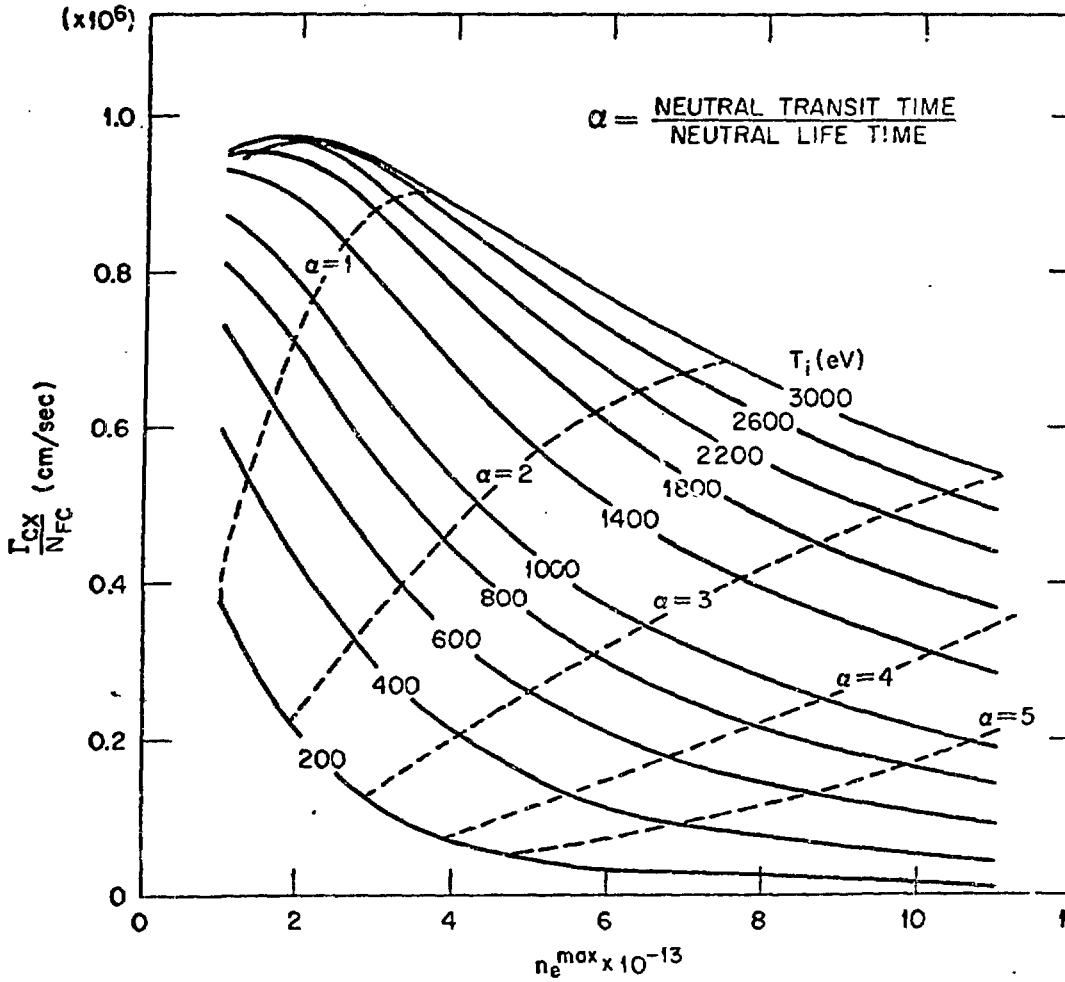
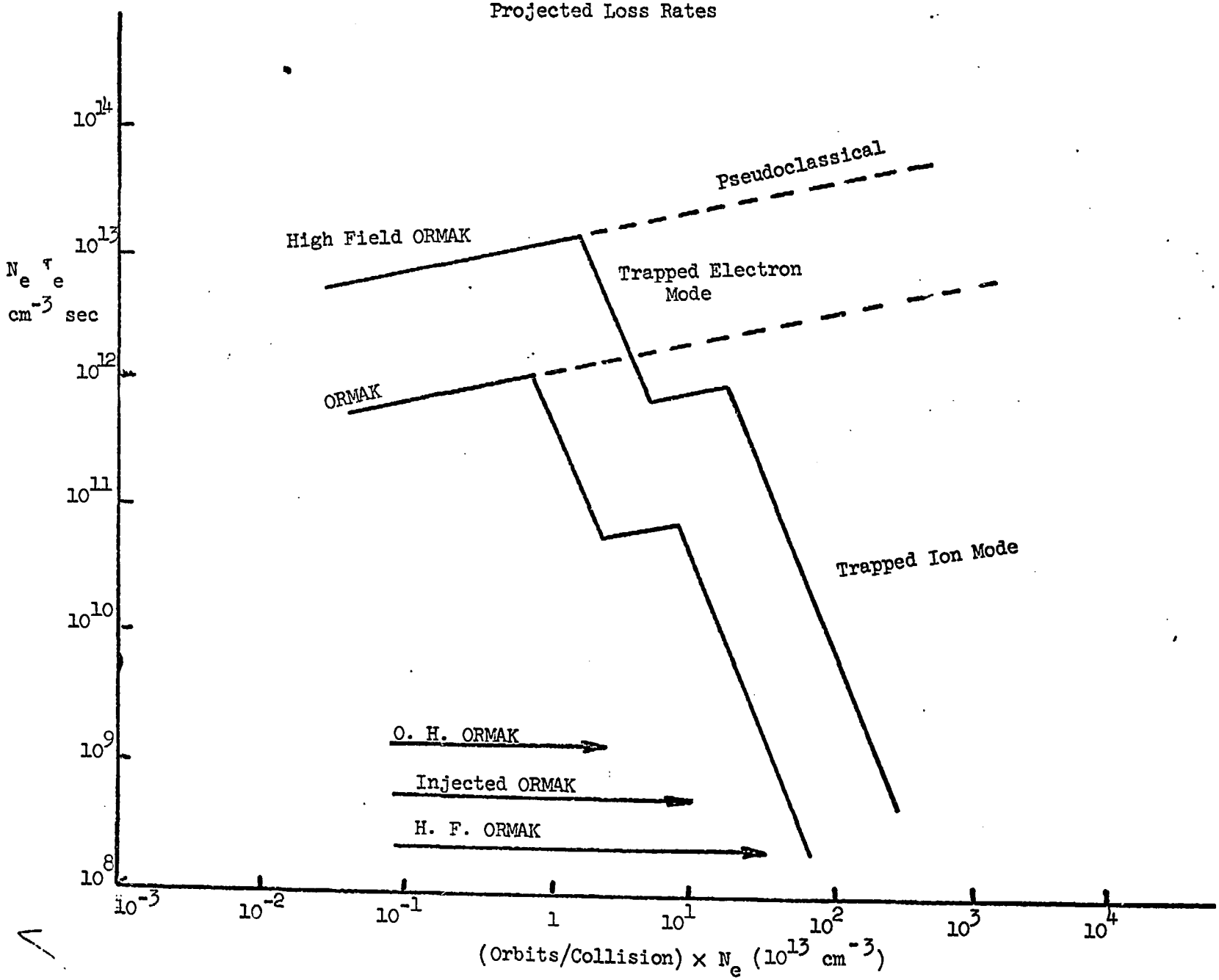


ORMAK/HFO: Charge Exchange Flux.

FIG. 5

FIG. 6a)

Projected Loss Rates



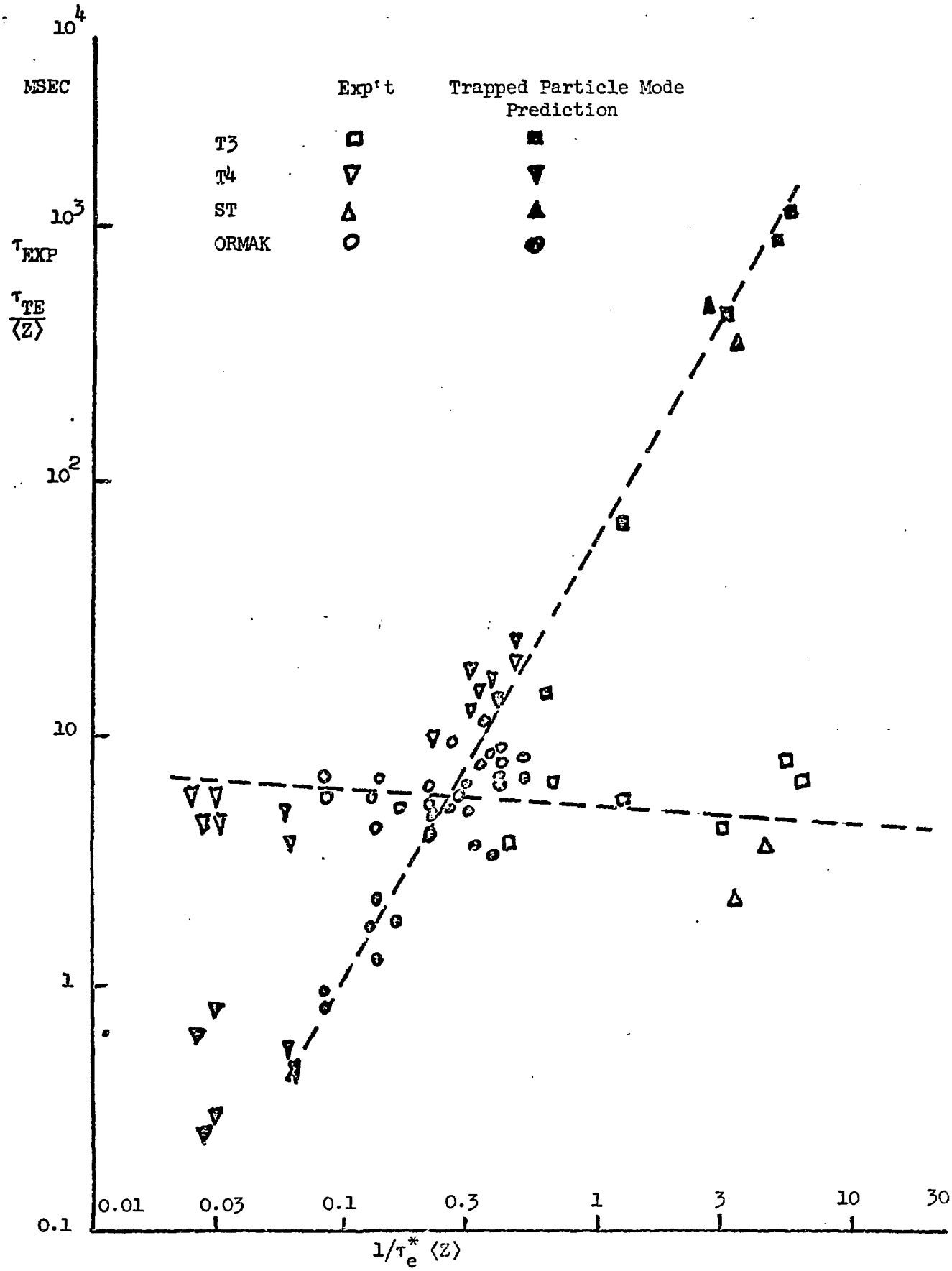


FIG. 6b)
Measured and Predicted Lifetimes

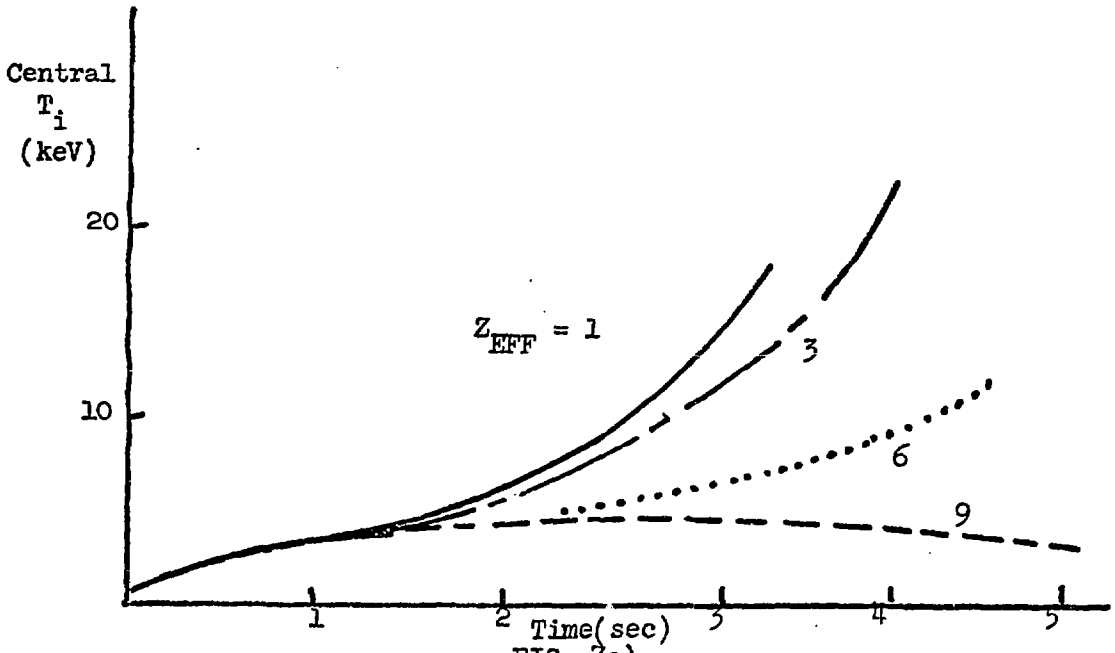


FIG. 7a)
Effect of Z_{eff} on Ignition

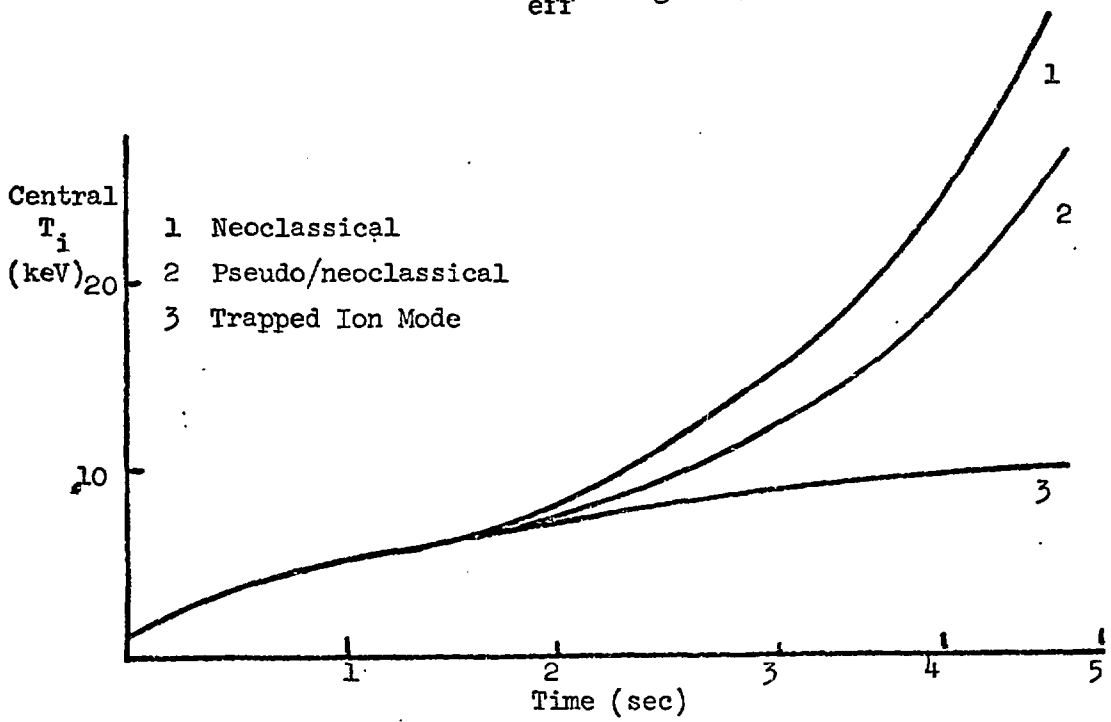


FIG. 7b)
Transport Models