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DEPARTMENT OF PHYSICS AND GEOPHYSICAL SCIENCES
SCHOOL OF SCIENCES AND HEALTH PROFESSIONS
OLD DOMINION UNIVERSITY
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Technical Report PGSTR-PH77-62

FISSION INDUCED PLASMAS

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By

Wynford L. Harries

Progress Report

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

Under
Research Grant NSG 1362
December 15, 1976 - June 30, 1977
Frank Hohl, Technical Monitor
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FISSION INDUCED PLASMAS

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Wynford L. Harries[1]

1. INTRODUCTION

The grant commenced on December 15, 1976 and runs for one year. This report covers the period through June 30, 1977.

The purpose of the work was to investigate the possibility of creating a plasma from fission fragments, and if possible to utilize the energy of the particles to create population inversion that would lead to laser action. Eventually it is hoped that the same medium could be used for both fissioning and lasing thus avoiding inefficiences in converting one form of energy to the other.

It was originally intended that a research associate be hired, and two applicants with backgrounds in nuclear pumped lasers were interviewed; however, neither accepted the position. Accordingly, after June 15 the writer undertook the investigation; but prior to that (because of the academic year and other grants), only seven percent time was charged on this grant.

One of the central problems in understanding a fission induced plasma is to obtain a model of the electron behavior, and some calculations are presented in section 2. The purpose of this section is to provide a handy compendium of processes for reference. Some sections, especially 2.1.1. and 2.1.2. are largely due to John Wilson, but are included for convenience and because the numbers are needed later. The calculations are simple, and intended to get orders of magnitude only in many instances.

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Section 3 describes possible future work, especially experiments for checking the parameters in section 2.

2. ELECTRONS IN A FISSION INDUCED PLASMA

We consider the electrons to be in a background gas of He^3 for this discussion, but the results will also apply for small admixtures of other gases.

2.1. Production of Electrons

The electrons are produced by the products of the action of thermal neutrons on He^3:

$$n + He^3 \rightarrow p(0.57\ \text{MeV}) + T(0.19\ \text{MeV})$$

Both proton and triton ionize.

2.1.1. Number of Electrons Produced Per Second

On the average, 34 eV are needed to produce one electron-ion pair, and the electron receives an average of 8 eV kinetic energy; thus, 20 percent goes in kinetic energy (ref. 1). Hence, the number of electrons produced per neutron, Q, is

$$Q = \left[(0.57 + 0.19)\text{MeV}/(34 + 8)\text{eV}\right] \simeq 2 \times 10^4 \text{ electrons.}$$

If the fast burst reactor produces a flux, F, of 10^{17} neutrons per cm^2 per sec, and they are absorbed with an average range r = 6 cm, then the number of electrons produced per sec per cc is

$$\left(\frac{dN}{dt}\right)_{\text{prod}} \approx QNr^{-1} = 3 \times 10^{20} \text{ el per cc per sec.}$$

A more accurate estimate is based on a calculation by Wilson (ref. 1) for the energy deposited per neutron per cm^2, in unit volume, which is 0.3 MeV per cc per neutron per cm^2 for $p = 3$ atmospheres. Multiplying this by the flux gives the energy input per cc per sec, namely, 3×10^{22} eV per cc per sec. Assume that at one atmosphere the energy deposited is one-third as much, or 10^{22} eV per cc per sec. The production rate of electrions is this number divided by (34 + 8)eV or 2×10^{22} el per cc per sec. Both these numbers roughly agree, and so we assume

$$\left(\frac{dN}{dt}\right)_{prod} \approx 2 \times 10^{20} \text{ el per cc per sec.}$$

2.1.2 Initial Electron Energy Distribution*

The fission fragments ionize the He^3 and release electrons. For high energy fragments whose velocity exceeds that of the orbital velocity of the electron, the binding energy of the electron can be neglected, and the collision regarded as Rutherford scattering. The differential cross-section subtended is proportional to E_f^{-1}, where E_f is the energy of the fission fragment, and the electrons are expected to be in an initial energy distribution function, $f_1(\varepsilon) \propto \varepsilon^{-2}$, where ε is the energy of the electron. The maximum amount of energy handed over to the electron is given by $\varepsilon_c \approx (2m/M)E_f$, where m is the electron mass, and M the mass of the fission fragment. The initial distribution function for electrons created by a fragment of energy $E_{f,1}$ is shown in figure 1 (solid curve). The picture fails around 1.5 ε_i, where ε_i is the ionization energy, or around 30 eV, as there are no more excitation levels, and the curve goes to a maximum and falls off at lower energies.

As the fission fragment slows down to an energy $E_{f,2}$, the cutoff drops to $E_{c,2}$, and the distribution is now as shown by the dotted curve. The distribution function for all the electrons produced by one fission fragment is the sum of such curves, and will have a slope steeper than ε^{-2}

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* This description is due to J. Wilson.

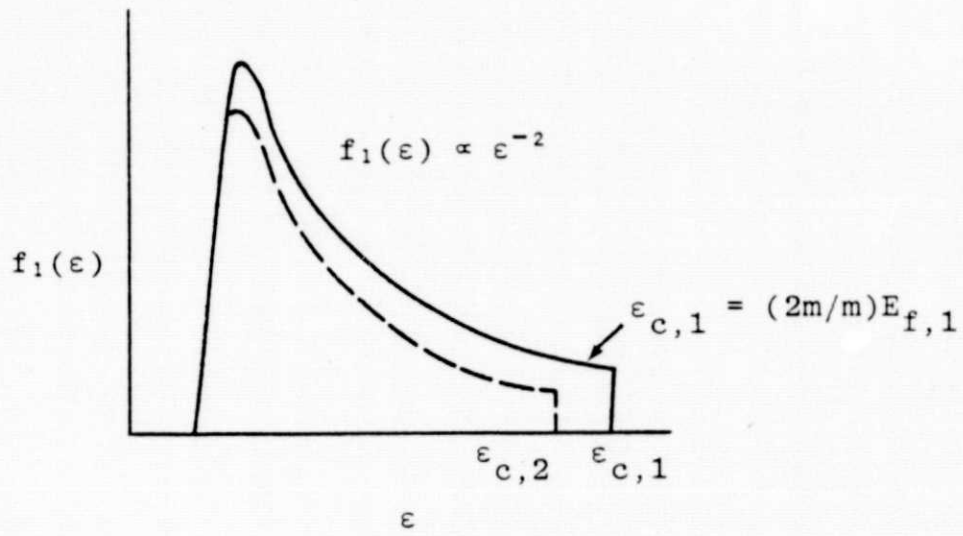

Figure 1. Initial distribution function $f_1(\varepsilon)$ for electrons; the curves are not normalized.

This is the energy distribution function of electrons just created by ionization; thereafter they lose their energy by inelastic and elastic collisions.

2.2. Electron Energy Losses

2.2.1. Energy Losses by Inelastic Collisions

In the range $20 < \varepsilon < 2000$ eV, the most rapid energy loss rate for electrons is due to inelastic collisions of ionization and excitation of both neutrals and ions. The rate of change of the energy ε of <u>one</u> electron with time is

$$\frac{d\varepsilon}{dt} = -\nu_1 E_1 - \nu_2 E_2 - \ldots = -\overline{\nu E} \tag{1}$$

where ν_n is the collision frequency for level n, and E_n is the energy given up by the electron. The quantity $\overline{\nu E}$ is an average for all levels, where

$$\nu = \frac{v_r}{\lambda} = N\,\overline{\sigma v_r} \tag{2}$$

and v_r is the electron random velocity, λ is the mean free path, N is the density of targets, and σ the cross section for inelastic collisions. Here we are concerned with orders of magnitude only and assume λ = constant. Then

$$v_r = (2\varepsilon/m)^{1/2} \tag{3}$$

and

$$\frac{d\varepsilon}{dt} = N\sigma\left(\frac{2\varepsilon}{m}\right)^{1/2} E = \left(\frac{2}{m}\right)^{1/2} \frac{E}{\lambda}\,\varepsilon^{1/2} \tag{4}$$

Thus the energy of the electrons varies with time according to

$$\varepsilon = \varepsilon_o \left(1 - \left[\frac{E}{\varepsilon^{1/2}} \lambda \sqrt{2m}\right]^t\right)^2 = \varepsilon_o\left(1 - \frac{t}{T_{in}}\right)^2 \tag{5}$$

where ε_o is the initial energy of the electron and T_{in} is a characteristic time for inelastic energy loss,

$$T_{in} = \left[\frac{\varepsilon_o^{1/2} \lambda \sqrt{2m}}{E}\right] \tag{6}$$

The excitation cross section for He above 19 eV is 0.5×10^{-7} cm^2 (ref. 2), and the number of atoms per sec at 760 torr is 2.7×10^{19}. Hence $\lambda = (N\sigma)^{-1} = 7.4 \times 10^{-5}$ m. The value of T_{in} depends on the choice of ε_o, and if $\varepsilon_o \approx 1$ KeV, and $E \approx 20$ eV, then $T_{in} \approx 4 \times 10^{-10}$ sec.

In the energy regime from 2 KeV down to a few volts, elastic collisions will contribute little to energy loss (see below).

2.2.2. Energy Losses Below 20 eV

Equation (5) will describe the energy versus time down to a few eV. The last inelastic collision will take place at the first excited state of He which is 19.6 eV. The impacting electron will have energy somewhat over 20 eV, and will possess ≈ 1 eV after the collision. At 19.6 eV the inelastic cross section becomes zero, and below this energy the electrons can only lose energy by elastic collisions. The elastic collisions will be of two kinds--against neutrals (assumed at around room temperture) and against other electrons or ions, where long range Coulomb type collisions take place.

2.2.3. Elastic Collisions with Neutrals

The rate of change of electron energy versus time for one electron from collisions with neutrals is

$$\frac{d\varepsilon}{dt} = -\kappa\ \varepsilon\ \nu_e \tag{7}$$

where κ is the fraction of its energy lost in the collision, and on the average

$$\kappa = 2m/M = 1/3000$$

for electrons in He . The collision frequency ν_e here is the elastic collision frequency and is equal to v_r/λ_e. From equations (7) and (3) an energy versus time relation is obtained when elastic collisions with neutrals dominate,

$$\frac{d\varepsilon}{dt} = -\frac{\kappa}{\lambda}\sqrt{\frac{2}{m}}\ \varepsilon^{3/2} \tag{8}$$

and if the electron starts with an energy ε_1 then

$$\varepsilon = \varepsilon_1\left[1 + \left(\frac{\kappa}{\lambda_e}\ \sqrt{\frac{2}{m}}\ \varepsilon_1^{1/2}\right)t\right]^{-2} = \varepsilon_1\left[1 + \frac{t}{T_{e,n}}\right]^{-2} \tag{9}$$

Here $T_{e,n}$ is a characteristic time to reduce the energy to $\varepsilon_1/4$:

$$T_{e,n} = \frac{\lambda_e}{\kappa}\sqrt{\frac{m}{2}}\ \ \varepsilon_1^{-1/2} \tag{10}$$

Assuming $\varepsilon_1 \approx 1$ eV and λ_e, the mean free path for electron-neutral collisions in He^3 at 1 torr is 17.6×10^{-3} (ref. 3), then $\lambda_e = 2.3 \times 10^{-7}$ m at one atmosphere, and

$$T_{e,n} \approx 10^{-9} \text{ sec}$$

for the range 1 to 1/4 eV. The function $\varepsilon(t)$ approaches $\varepsilon = 0$ asymptotically. The time required to reduce ε from $\varepsilon_1 = 1$ eV down to 1/40 eV is 24 nanoseconds. Note $T_{e,n} \propto v_r^{-1}$, and the range of ε_1 must be taken into account.

2.2.4. Elastic Collisions with Cold Electrons

A measure of the rate of energy loss of electrons of temperature T to electrons of temperature T_1 can be obtained from the equipartition time τ_{e-e}. Strictly speaking this time is a measure of the rate at which equipartition of energy is established between two groups of particles, namely test particles in a Maxwellian distribution and at a temperature T, and field particles at a temperature T_1. The collisions are assumed to be long range Coulomb collisions. The equipartition time τ_{eq} is defined by the equation (ref. 4)

$$\frac{dT}{dt} = -\frac{T - T_1}{\tau_{eq}} \tag{11}$$

and

$$\tau_{eq} = \frac{3.3 \times 10^5\ \varepsilon^{3/2}}{n \ln \Lambda}\ \text{(sec)};\quad T_1 \to 0 \tag{12}$$

with $\varepsilon = T$ (eV), electron density, n in cm^{-3}, and Λ is the ratio of the Debye length to the impact parameter. Assume here that $T_1 = 1/40$ eV, $<< T$, and let T be 10 eV and 1 eV respectively. The values of $\ln \Lambda$ change little with n and T, and the values for τ_{eq} are shown in the table below.

		Values of τ_{eq} in sec for	
Ne cm^{-3}	$\ln \Lambda$	$T_1 = 1$ eV	$T_1 = 10$ eV
10^{11}	10.7	3.0×10^{-7}	10^{-5}
10^{12}	9.6	3.4×10^{-8}	10^{-6}
10^{13}	8.5	3.8×10^{-9}	10^{-7}
10^{14}	7.3	4.4×10^{-10}	1.4×10^{-8}

For $n = 10^{13}$ cm^{-3}, $T_1 = 1$ eV, the time for the hot electrons to be cooled by electrons at room temperature is of order $T_{e,n}$. For energies less than 1 eV the electron-electron collisions dominate as $\tau_{eq} \propto v_r^3$.

2.2.5. Elastic Collisions with Ions

The ions, being of equal mass with the neutrals, should be quickly cooled, and would then cool the electrons. However, the equipartition time for the electrons to be cooled by ions at room temperature, $\tau_{eq,e-i}$ is far greater than $\tau_{eq,e-e}$ for electron-electron cooling (ref. 4):

$$\tau_{eq,e-e}/\tau_{eq,e-i} = m/M_i = 1/6000 \tag{13}$$

where M_i is the mass of the ion, and the cooling of electrons by ions can be neglected.

2.3. Loss Mechanisms and Plasma Containment Time

Experimentally, the pulses are a $\approx 1/2$ ms long, but the electron containment time, τ_c could be must shorter. Rough estimates of τ_c can be made by (1) assuming the electrons diffuse out of the plasma to the walls, or (2) by assuming that recombination dominates the life time.

2.3.1. Containment Time by Diffusion to the Walls

The containment time, assuming diffusion of electrons to the wall, is given by

$$\tau_{c,D} \approx \frac{x^2}{D_a}$$

where x is a characteristic distance ≈ 1 cm, and D_a the ambipolar diffusion coefficient. The diffusion coefficient for helium has been measured (ref. 5) as $D_a = 700 \pm 50$ cm^2 sec^{-1} at 1 torr, so $\tau_c \approx 1$ sec at 760 torr, much longer than the observed pulse length. Hence, diffusion is not important.

2.3.2. Containment Time by Recombination

The recombination rate depends on whether He^+ or He_2^+ dominates. For the former, three recombination processes can occur, namely (1) radiative, (2) collisional radiative ($He^+ + e + e \rightarrow He^* + e$), or (3) neutral stabilized ($He^+ + e + He \rightarrow He^* + He$). Processes (2) and (3) are orders of magnitude faster than (1). However, with the type of discharges here it seems He_2^+ should dominate. In addition to processes analogous to (2) and (3), dissociative recombination ($He_2^+ + e \rightarrow He^* + He$) is also possible. The recombination rates of He^+ from (2) and (3), and the recombination of He_2^+, turn out to be the same order of magnitude, which yields $(dn/dt)_{loss}$ for electrons in terms of n the electron density.

2.3.3. Steady State Density of Electrons

In the steady state, the production rate of electrons

$$\left(\frac{dn}{dt}\right)_{prod} = \left(\frac{dn}{dt}\right)_{loss} \tag{14}$$

and

$$\left(\frac{dn}{dt}\right)_{prod} = 2 \times 10^{20} \text{ el/cm}^{-3}/\text{sec}^{-1}$$

from section 1.1. The solution of equation (14) yields

$$n \approx 10^{13} \text{ cm}^{-3}$$

and the containment time, τ_c, defined by

$$\left(\frac{dn}{dt}\right)_{loss} = \frac{n}{\tau_c}$$

is of order 10^{-7} sec, and much less than the pulse duration of 5×10^{-4} sec. The values of n and τ are roughly the same irrespective of whether He^+ or He_2^+ dominates.

2.3.4. Neutral Gas Temperature

The final electron temperature, T, should approach the temperature of the neutral gas, which is now estimated. Assume as above the neutron flux from the moderator is 10^{17} per cm^2 per sec, their average range is 6 cm at one atmosphere (ref. 1), and each neutron delivers 0.76 MeV. On the average, 34 eV are required per ionization event, and a further 8 eV goes into kinetic energy of the electrons. Of the 34 eV, 24 eV goes into ionizing, which is recovered after recombination, and probably ends up as metastable energy which provides lasing. The remaining 10 eV goes into excitation and both these contributions end up as photons. So, only 8 eV, or 20 percent of the (34 + 8) eV, ends in electron kinetic energy, which in turn heats the neutral gas (section 2.2.3.). The rate of kinetic energy delivery to the neutral gas is therefore

$$10^{17} \times 0.76 \times 10^{6} \times 0.2/6 = 2.5 \times 10^{21} \text{ eV per cc per sec.}$$

The pulse length is 5×10^{-4} sec so the kinetic energy per cc is 1.3×10^{18} eV. In one cc, the number of neutrals is 2.7×10^{19}, so each atom gains 0.048 eV, equivalent to a temperature rise ≈ 500 K.

Again, for an average pulse, the amount of power absorbed by one cc of gas per sec ≈ 1 KW (ref. 1). With a pulse duration of 5×10^{-4} sec, 0.5 joules/cc is deposited, and if 20 percent goes into kinetic energy, the temperature of the neutrals should be raised by 150 K. The numbers 500 and 150 K are in order of magnitude only.

2.4. Electron Energy Distribution Function

2.4.1. Overall Description of the Average Energy of One Electron Versus Time

Consider one electron created at a kinetic energy ≈ 1 KeV. It energy first decays rapidly by inelastic collisions with a characteristic time T_{in}, and by elastic collisions with a characteristic time $T_{e,n}$ (T_{in}, $T_{e,n} \propto v_r^{-1}$). In addition, cold electrons can cool the hot ones. Strong electron-electron cooling does not take place until the energies are as low as $\tau_{eq} \propto v_r^3$. However, at $\varepsilon \approx 1$ eV, $\tau_{eq,e-e} \approx T_{e,n}$, although there are 10^6 times more neutrals than electrons. The characteristic times for cooling are much less than the plasma containment time.

The electrons can gain energy from other electrons when at low energies by Coulomb collisions (section 2.2.4.), and by collisions of the second kind with excited neutrals (superelastic collisions). However, the density of excited neutrals is probably of the order of the electron density and much less than that of unexcited neutrals; so collisions of the second kind are neglected.

The picture then is the electrons start off in a distribution such as figure 1, and then continuously lose energy until at low energies. For energies below 1 eV and $n \approx 10^{13}$, $\tau_{eq,e-e} << \tau_c$, and therefore at low energies a Maxwellian distribution of electrons is attained, with a temperature approximately that of the neutral gas. Note that only electron-electron collisions ($\tau_{eq,e-e}$) lead to a Maxwellian distribution, while electron-neutral elastic collisions ($T_{e,n}$) need not. The latter reduce the electron energy, the former redistribute it. This model enables an estimate of the steady state electron energy distribution to be made.

2.4.2. Simple Intuitive Description of the Steady State Electron Energy Distribution Function

The intent of this section is to provide simple intuitive arguments to indicate the essential features of the electron energy distribution function and compare them with that of Hassan (ref. 9). The duration of a pulse is 5×10^{-4}, and the lifetime of an electron $\approx 10^{-7}$ sec; hence we assume there is a continuous constant source of electrons for the duration of the pulse. Each electron then starts at a high energy, loses energy with time, becomes Maxwellian at low energies, and is recombined.

The density, dn, of electrons in the energy interval ε to $\varepsilon + d\varepsilon$ is proportional to the amount of time, Δt, each electron spends in this interval,

$$dn \propto \Delta t \quad .$$

Now for one electron,

$$\underset{\Delta\varepsilon \to 0}{\text{limit}} \frac{\Delta t}{\Delta \varepsilon} = \left(\frac{d\varepsilon}{dt}\right)^{-1}$$

where $\frac{d\varepsilon}{dt}$ is the rate of change of energy versus time for an average electron. Therefore,

$$dn = f(\varepsilon)d\varepsilon \propto \left(\frac{d\varepsilon}{dt}\right)^{-1} d\varepsilon$$

where $f(\varepsilon)$ is the steady state electron energy distribution function, and

$$f(\varepsilon) \propto \left(\frac{d\varepsilon}{dt}\right)^{-1} \quad .$$

We now construct $f(\varepsilon)$ versus ε on a logarithmic plot (fig. 2). Starting from high energy, the region DE shows a sharp drop for increasing ε, the initial distribution of electrons is the sum of curves similar to figure 1; the exact shape of DE is not discussed further. Below about 35 eV, the electron energy loss is mainly from inelastic collisions, where $d\varepsilon/dt \propto \varepsilon^{1/2}$ from

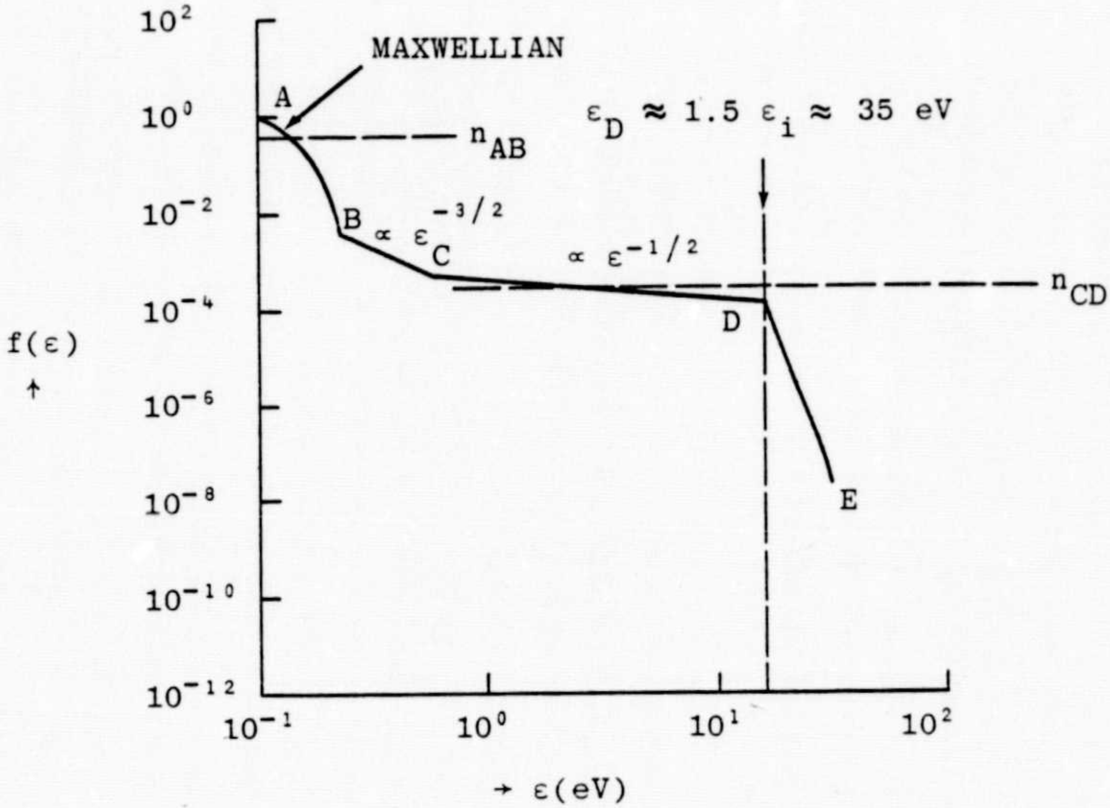

Figure 2. Steady state electron energy distribution function.

equation (4); hence in CD, $f(\varepsilon) \propto \varepsilon^{-1/2}$. The lower limit of the region C is around a volt (see section 2.2.2.). Near C there is less and less contribution from excitation, and in BC electron-neutral collisions dominate. Here equation (8) indicates $d\varepsilon/dt \propto \varepsilon^{3/2}$, so $f(\varepsilon) \propto \varepsilon^{-3/2}$. Below B electron-electron collisions dominate, and as $\tau_{eq} << \tau_c$, a Maxwellian distribution is formed, with its peak at the temperature of the neutral gas at some hundreds of degrees Kelvin.

The values of the ordinate in figure 2 are not absolute, and an order of magnitude calculation enables a comparison to be made of the average density, n_{AB}, of electrons per unit energy in AB versus n_{CD} in CD. Assume AB extends over a range $\Delta\varepsilon_{AB} = 1$ eV, and CD over a range of $\Delta\varepsilon_{CD} = 30$ eV. Then,

$$\frac{N_{AB}}{t_{AB}} \Delta\varepsilon_{AB} \approx \frac{N_{CD}}{t_{CD}} \Delta\varepsilon_{CD}$$

where the times t_{AB}, t_{CD} correspond to those an average electron spends in AB and CD. Now $t_{AB} = \tau_c = 10^{-7}$ sec, the recombination time, and $t_{CD} = T_{in} \simeq 0.4 \times 10^{-10}$ sec. Therefore

$$\frac{n_{AB}}{n_{CD}} \approx 10^3 \text{ or } 10^4 \quad .$$

The relative scale on the ordinate of figure 2 conforms with this ratio.

The essential details fo figure 2 agree with an electron energy distribution curve of Hassan (ref. 6) derived from the Boltzmann equation (fig. 3). Hassan actually plotted $f(\varepsilon)/\varepsilon^{1/2}$, and the curve for $f(\varepsilon)$ is due to Meador and Weaver (ref. 7). The points B and D in figure 2 occur in the same energy range as figure 3. Between B and D Hassan's curve shows $f(\varepsilon) \mathrel{\tilde{\propto}} \varepsilon^{-1}$, whereas figure 2 shows $f(\varepsilon) \propto \varepsilon^{-1/2}$ near D, and $\mathrel{\tilde{\propto}} \varepsilon^{-3/2}$ near B. Both curves show a Maxwellian distribution to the left of B with

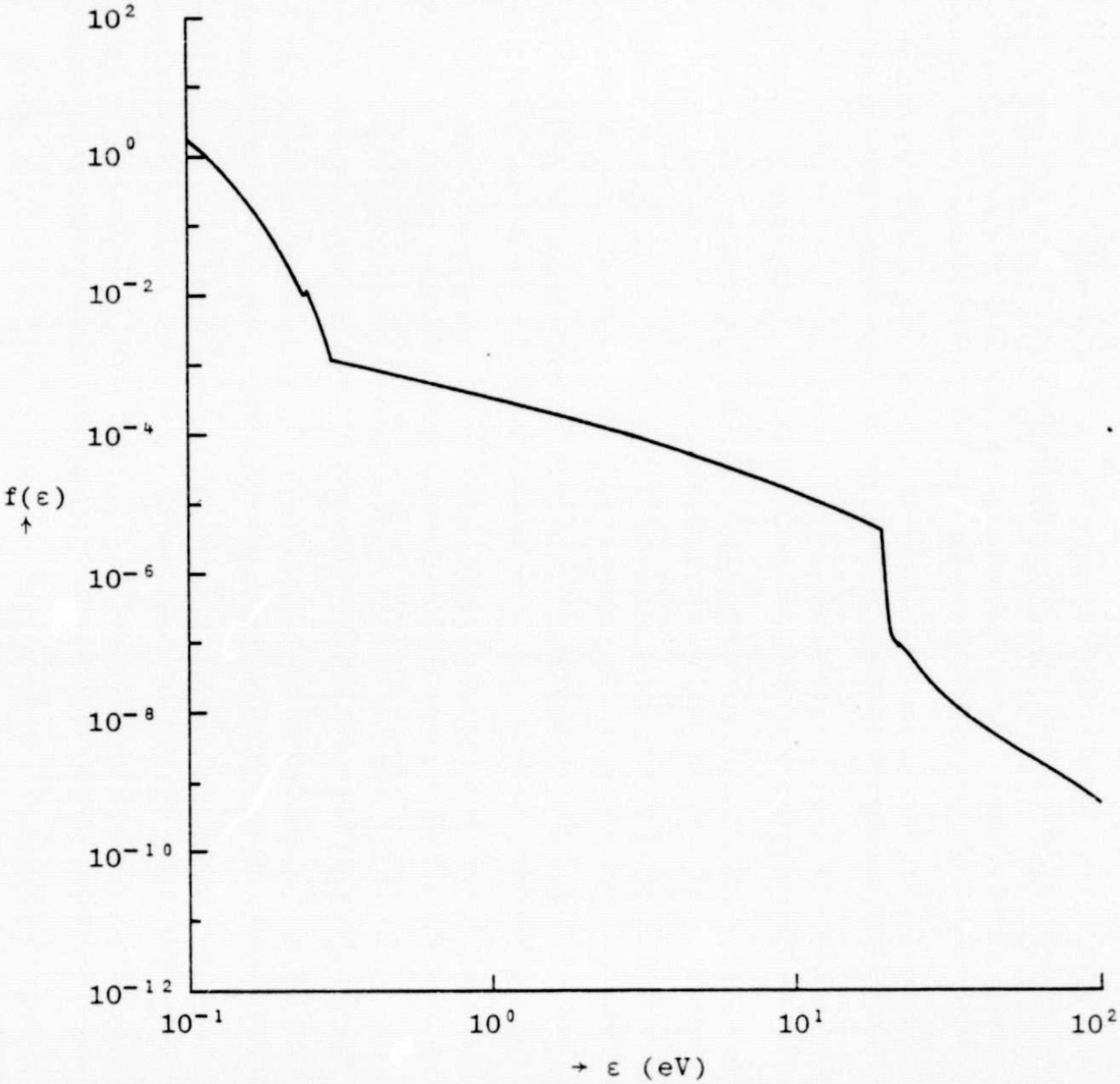

Figure 3. Electron energy distribution function $f(\varepsilon)$ after Hassan. (Flux 10^{16} cm^{-2}/sec^{-1}, $p = 100$ torr.)

about 10,000 times more electrons in the Maxwellian distribution below 1 eV than there are in the non-Maxwellian distribution above it.

3. FUTURE WORK

It would be desirable to measure the electron density and temperature, and a study has been made on the feasibility of using probes. A paper on high pressure probes by Cozens and von Engel (ref. 8) implies that the measurements are possible. Some preliminary experimental tests are to be performed in collaboration with N. Jalufka on an electrically created plasma, and if the probes work well, possibly the values checked using other nonprobe methods.

The work shown in section 2 is preliminary and refers to the electrons only. Future studies will include mathematical models which describe the ion processes including laser action.

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