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**A Zero Dimensional Plasma Model and
the Study of the Initial Performance
of the ZT-40 Experiment**

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A Zero Dimensional Plasma Model and the Study of the Initial Performance of the ZT-40 Experiment

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Fig

A ZERO DIMENSIONAL PLASMA MODEL AND THE STUDY OF THE INITIAL PERFORMANCE OF THE ZT-40 EXPERIMENT

by

S. ORTOLANI

ABSTRACT

A plasma zero-dimensional model is described and some results obtained to study the initial performance of the ZT-40 experiment are discussed.

I. INTRODUCTION

The initial performance of the ZT-40 experiment has been studied by a zero-dimensional plasma model. A computer code [ZCODEX] has been written on the PDP-10 to solve the equations of the model. The code has been written by adding other equations and terms to the OXYALU code developed by F. Jahoda and which is described in the note enclosed here as Appendix I.

This report summarizes the main features of the model, describes some aspects of how to use the code and briefly discusses some results obtained in simulating the ZT-40 experimental performance. The model is essentially an extension of the time dependent impurity radiation calculations described elsewhere.^{1,2} The code written on the PDP-10 is similar to the one written in Padua on the IBM computer using the CSMP package.³ The model has been applied to many experiments such as ETA-BETA I^{4,5} and ETA-BETA II,^{6,7,8} HBTX-1A, RFX and ZETA,⁹ as well as to reactor calculations.¹⁰

II. BASIC EQUATIONS

The equations solved in the code are listed below:
electron energy equation:

$$\frac{d}{dt} \left(\frac{3}{2} n_e k T_e \right) = P_{OHM} - P_{EQ,EI} - P_{LR,OX} - P_{LR,AL} - P_{BREM} \quad (1)$$

$$- P_{RAD,FE} - P_{ION,D} - P_{ION,OX} - P_{ION,AL}$$

$$- P_{REC,D} - P_{CDIFF} - P_{TDIFF} - P_{ADD,E}$$

ion energy equation:

$$\frac{d}{dt} \left(\frac{3}{2} n_{ik} T_i \right) = P_{EQ,EI} - P_{ADD,I} \quad (2)$$

ionization rate equation for the main filling gas (D₂)

$$\frac{d}{dt} n_{e,D} = (n_F - n_{e,D}) n_e S_D - n_{e,D} n_e \alpha_D \quad (3)$$

where n_F is the filling density of neutral atoms.

oxygen ions rate equations

$$\frac{dn_{Oxi}}{dt} = n_{Ox(i-1)} S_{(i-1)} - (n_{Oxi}) (S_i + \alpha_i) + n_{Ox(i+1)} \alpha_{i+1} \quad (4)-(12)$$

with $i = 1, \dots, 9$; $n_{Ox0} = n_{Ox15} \equiv 0$ and $\sum_1^9 n_{Oxi} = n_{oxygen}$

aluminum ions rate equations

$$\frac{dn_{Al i}}{dt} = n_{Al(i-1)} S_{i-1} - n_{Al i} (S_i + \alpha_i) + n_{Al(i+1)} \alpha_{i+1} \quad (13)-(26)$$

with $i = 1, \dots, 14$; $n_{Al 0} = n_{Al 15} \equiv 0$ and $\sum_{i=1}^{14} n_{Al i} = n_{aluminum}$

circuit equation

$$\frac{d}{dt} Q = I \quad (27)$$

$$\frac{dI}{dt} = \frac{1}{L_E + L_P + I \frac{dL_P}{dI}} \cdot \left[V_{CO} - \frac{Q}{C} - (R_E + R_P) I \right] \quad (28)$$

where V_{CO} is the capacitor charging voltage at $t = 0$, and the other symbols of the circuit which is drawn in Fig. 1 are discussed in the next section.

III. DISCUSSION OF THE VARIOUS TERMS

The ionization, S , and recombination, α , rate coefficients; the terms describing the electron-ion equipartition, $P_{EQ, EI}$ and the oxygen and aluminum line radiation powers, $P_{LR, OX}$ and $P_{LR, AL}$ are equal to those described in Appendix I and here only the new terms and equations are discussed. P_{OHM} , as in Appendix I, represents the ohmic heating power and is computed by assuming classical (Spitzer) parallel resistivity (including the Z_{eff} factor calculated self-consistently with the impurity ion distribution). However, here it is multiplied by a form factor to effectively account for the resistance change when a current distribution is actually present. The resistance form factor considered in the model^{11, 3, 9} is given by the following expression:

$$F(\theta) = \theta/J_1(2\theta) \quad \text{for } 0 < \theta < 1.46 \quad (29)$$

and is $F(0) = 1$, and $F(\theta) = 4$ for $\theta > 1.46$ where θ is the pinch parameter $\theta = \mu_0 I / 2\pi a B_{z0}$ where a is the minor radius of the plasma (vacuum wall) and B_{z0} is the average field, within the vacuum wall, assumed constant in time. J_1 is the first kind, first order Bessel function. P_{OHM} is then computed multiplying the resistivity by the average current density $(I/\pi a^2)$ squared. P_{BREM} represents the bremsstrahlung radiation of the electrons in the field of the deuterium, oxygen, and aluminum ions, and also appears in Appendix I. The contribution due to the iron impurity ions is accounted for directly in the iron radiation terms as discussed below.

$P_{LR,FE}$ represents the total radiation losses associated with iron ions including: bremsstrahlung, radiative and dielectronic recombination and line transitions. This radiation loss term is described in the code by using the steady state radiative cooling rates as computed by Post, et al.¹² Also the mean ion charge $\langle Z \rangle = \Sigma n_Z Z / \Sigma n_Z$ and the mean square charge $\langle Z^2 \rangle = \Sigma n_Z Z^2 / \Sigma n_Z$ are computed¹² to include the iron contribution to the total electron density and to the $Z_{eff} = \Sigma n_Z Z^2 / \Sigma n_Z Z$ factor in the resistivity. Whereas the time dependent ionization history is important for low Z ions, the steady state approximation for the iron ion populations seems reasonable, besides being more practical; the justification being as follows: the rate of change of plasma temperature scales approximately as $P_{OHM}/W_p \sim T^{-5/2}$. Therefore at the higher temperature at which the ion radiation peaks (~ 100 eV) the ionization distribution will be closer to steady state than at the oxygen radiation peak (~ 20 eV).

$P_{ION,D}$ represents the ionization losses associated with the ionization of the main filling gas; the power per unit volume lost is given by:

$$P_{ION,D} = E_{ION} (n_F - n_{e,D}) n_e S_D \quad (30)$$

Being that the excitation coefficient (for the resonant transition) and the ionization coefficient are about equal, some line radiation loss from the main gas is also accounted for by simply considering $E_{ION} \approx 20$ eV similarly to Ref. 13 and 14.

$P_{ION,OX}$ AND $P_{ION,AL}$ represent the losses associated with the ionization of the oxygen and aluminum ions and are calculated similarly to $P_{ION,D}$ by summing over all the ionization states. $P_{REC,D}$ is the power lost through

electron-ion recombination processes (the recombination with the impurity ions is neglected) and is written as:

$$P_{\text{REC,D}} = \frac{3}{2} kT_e n_{e,D}^2 \alpha_D \quad (31)$$

Only the free energy of the electrons is lost in terms of the thermal energy Eq. (1). However, the bound energy is of course also radiated, but this energy has been lost during the ionization process which happens at a different rate (the ionization rate).

P_{CDIFF} is a term accounting for the transport losses for a steady-state classical plasma¹⁹ for which it results:

$$\frac{3}{2} \frac{nkT}{\tau_E} = \frac{1}{2} P_{\text{OHM}} \quad (32)$$

As long as $T_e \approx T_i = T$, it does not matter if this term is included in the electron or ion energy equation. In practice it means that half of the instantaneous ohmic heating power is assumed to be lost through transport.

P_{TDIFF} is a term attempting to account for enhanced transport losses associated with magnetic field fluctuations.^{15,16} Two expressions are considered: one in which the level of fluctuation is held constant and one in which it varies according to $S_0^{-1/2}$,¹⁸ S_0 being the magnetic Reynold number defined as $S_0 = (\mu_0/\rho)^{1/2} \sigma a B_0(a)$ where σ is the electrical conductivity, ρ is the mass density and $B_0(a)$ is the azimuthal magnetic field at the plasma boundary [$B_0(a) = \mu_0 I / 2\pi a$]. $P_{\text{ADD,E}}$ and $P_{\text{ADD,I}}$ as discussed in Appendix I are additional phenomenological loss terms which require the specification of a time constant by the user and can account for other losses, e.g., transport losses described differently from the two terms discussed above.

Finally the simple circuit drawn in Fig. 1 is considered to describe the toroidal plasma current, where C is the total capacity of the capacitor bank; R_E and L_E are external circuit resistance and inductance and L_p and R_p are variable plasma inductance and resistance. The magnetizing inductance is assumed to be sufficiently large ($\sim 10 L_p$) to be neglected and iron saturation

effects are not considered. A simple single mesh circuit is appropriate to describe both the formation (current rise) phase and the post-crowbar (either active or passive) phase provided the circuit parameters C , R_E and L_E are appropriately changed when switching from the formation to the post crow-bar phase. Because the ZT-40 circuit could be changed in the future, e.g., when the power crow-bar circuit will be installed, it may be useful to specify that the present circuit parameters¹⁷ are assigned in the Subroutine CIRPAM, (see the code listing enclosed as Appendix II) and can be easily changed. In the subroutine G, which builds the differential equations for integration, the crow-bar is applied at the specified time (input parameters) or in any case at zero bank voltage and the external circuit parameters are changed as appropriate to the crow-barred circuit¹⁷ (see statements 741-751 of the code). This part of the code can also be easily changed to include the power crow-bar circuit parameters, etc. The plasma resistance is given by $R_p = \eta L/S$ where η is the plasma resistivity discussed above including the form factor, L is the length of the plasma ($2\pi R$, with R being the torus major radius) and S is the plasma cross section (πa^2).

The plasma inductance is modeled in agreement to what is discussed in Ref. 7 and is written as

$$L_p = \frac{1}{2} L_{p0} \text{ for } \theta < 0.4 \quad (33)$$

$$L_p = \frac{3}{2} L_{p0} \text{ for } \theta > 1.5 \quad (34)$$

and

$$L_p = \frac{1}{2} L_{p0} \{2.3 - 1.3 \cos [\pi 0.625 (\theta - 0.4)]\} \quad (35)$$

for $0.4 \leq \theta \leq 1.5$

with

$$Lp_0 = \frac{\mu_0}{2} R; \text{ with } R \text{ being the torus major radius.} \quad (36)$$

This model allows one to describe the $I dLp/dt$ term which is important during the formation phase. A simpler constant inductance model can be appropriate if the final energy balance is of interest more than the time evolution. By assigning a very large bias field, Bz_0 , the user can exclude the effect of the form factors both in the resistance and in the inductance automatically, by forcing $\theta \sim 0$. Lp_0 is defined in the same subroutine CIRPAM discussed above and if a $\theta \sim 0$ (no time variable form factor) case is of interest, the constant Lp_0 value should be changed as well to represent the final value corresponding to the end of the current rise phase; this can be done in the CIRPAM subroutine of the code by using the variable FACTOR.

IV. THE CODE

A listing of the code is enclosed for reference in Appendix II and three sample printouts are enclosed in Appendix IV. The execution of the code is obtained by the command file: EX @ ZCODEX.CMD which is very similar to the file IMPUR.CMD described in Appendix I with only the addition of the IMSL library which is accessed to compute the Bessel function J_1 . The input dialog is easily interpretable (an example is reported in Appendix III). It is worthwhile only to specify that the transformer ratio is intended to be the primary to secondary turn ratio (0.25 presently on ZT-40) and that three printouts (see Appendix IV) are available; all three eventually give the plots of the electron temperature and the plasma current, but each individually prints details of the impurity ion distribution or of the circuit quantities or of the flux and energy balance respectively.

The user is asked to provide values for various switches which allow selection of the type of printout, the inclusion or not of transport losses, etc... .

It should also be noted that the time integrals to obtain the various flux and energy terms are performed for simplicity on timesteps equal to the printout timesteps; so exact balance cannot be presumed unless reasonably

small steps (much less than the current rise time) are prescribed by the user. Also because the circuit parameters are changed after the crow-bar, the magnetic energy present in the circuit portion from the bank to the crow-bar, just before the crow-bar time, must be added to get, after the crow-bar time, total energy conservation.

V. ZT-40 INITIAL PERFORMANCE

An important step in the performance of any magnetic confinement experiment is to overcome the line radiation losses due to the presence of light elements (C, N, O...) as impurities in the plasma. The model has therefore been applied to study the effect of the radiation losses associated with oxygen impurities on the initial performance of the ZT-40 experiment. In Fig. 2 is drawn the time for the plasma current to decrease to $1/e$ of the peak value versus the deuterium filling density for various concentrations of oxygen impurity ions as computed by the model discussed above. For these runs only the ionization and recombination losses of the main gas, the bremsstrahlung radiation and the so-called classical diffusion losses are included besides the oxygen line radiation which by far is the dominant effect. The calculations indicate that before encountering the circuit limit for the current decay time, due to the relatively high external circuit resistance, the behaviour is dominated by the plasma resistance at the higher filling pressures considered (5-10 mtorr) even if only 1% of 2 mtorr ($1.4 \cdot 10^{12} \text{ cm}^{-3}$) oxygen impurity ions are present. The results shown in Fig. 2 are for a bank voltage of 6 kV corresponding to ~ 370 kA plasma current (the peak current obtained actually varies $\sim 10\%$ going from 10 to 2 mtorr). The experimental results obtained with comparable conditions are also shown indicating that an oxygen concentration between 3.5 and $7 \cdot 10^{12} \text{ cm}^{-3}$ could explain the observed independence of the current decay time on the filling pressure unless other phenomena dominate. The computed electron temperatures at the time of current peak are drawn in Fig. 3 indicating that the observed current decay times are consistent with average temperatures of the order of 10 eV but that substantially higher temperatures could be reached when burning through the oxygen impurities occurs. The calculations have been performed also at 8 and 10 kV bank voltage for both 3.5 and $7 \cdot 10^{12} \text{ cm}^{-3}$ oxygen impurity concentration. The results for the current decay time and for the temperature reached at peak current are shown in Figs. 4 and 5. Eventually by operating

at 10 kV even $7 \cdot 10^{12} \text{ cm}^{-3}$ oxygen impurity should not prevent to extend the plasma lifetime up to the limit imposed by the present circuit, provided the operating pressure is at 2-3 mtorr.

A comparison between the computed and the measured variation of the current decay time and amplitude versus the bank charging voltage is shown in Figs. 6 and 7. As examples of the sort of agreement which is obtained between the measured and computed plasma current the two curves have been drawn in Figs. 8 and 9 for a 10 mtorr and a 2 mtorr discharge respectively. Examples of the computed oxygen ion populations versus time are shown in Fig. 10 (a and b) and this behaviour could be compared with experimentally measured line intensities versus time and with temperature measurements, to study the consistency of various independent measurements. Finally an example of the volt-seconds consumption and of the time dependence of the various terms of the energy balance is shown in Fig. 11 (a and b) and the time evolution for the plasma current and electron temperature is drawn in Fig. 12. It is seen how the temperature is held down during the ionization growth (first 20 μs) and subsequently increases up to $\sim 20 \text{ eV}$ but the oxygen radiation barrier is not quite overcome in the example and the temperature falls rapidly after the crow-bar and so does the current.

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Fig. 1. Toroidal current equivalent circuit.

Fig. 2. Time for the current to decrease to $1/e$ of the peak value versus the filling pressure. The solid curves are computed and the ■ are measured values.

Fig. 4. Time for the current to decrease to $1/e$ of the peak value versus the filling pressure. The curves are computed and the ■ are measured values.

Fig. 3. Computed variation of the electron temperature at the time of current peak versus the filling pressure.

Fig. 5. Computed variation of the electron temperature at the time of current peak versus the filling pressure.

Fig. 6. Computed and measured current decay times versus the applied bank voltage.

Fig. 7. Computed and measured current peak amplitude versus the applied bank voltage.

Fig. 8. Computed and measured current vs time. A = computed, B = measured.

Fig. 9. Computed and measured current vs time. A = computed, B = measured.

Fig. 10. (a and b) Fractional abundances of the oxygen ions versus time.

Fig. 11. ZT-40 Run: Filling pressure = 5 mtorr
Toroidal current bank voltage = 8 kV
Oxygen impurity = 1%

Fig. 11a. Volt seconds consumption
A = Vs generated = $\int V_c dt$
B = Vs applied to the plasma = $\int V_p dt$
C = poloidal flux in the plasma = $L_p I$

Fig. 11b. Energy balance
A = energy generated = $\int V_c I dt$
B = energy input to the plasma = $\int V_p I dt$
C = magnetic energy in the plasma = $\frac{1}{2} L_p I^2$
D = energy associated with the inductance variation = $\frac{1}{2} \int I^2 dL_p$
E = energy dissipated in the plasma = $\int R_p I^2 dt$

Fig. 11c. Computed plasma current and electron temperature versus time.

APPENDIX I

IMPURITY RADIATION POWER LOSS CODE

F. C. Jahoda

INTRODUCTION

This report describes the computer code OXYALU, as implemented on the PDP-10. It calculates the temporal temperature behavior of an ohmically heated uniform plasma as a function of oxygen and aluminum impurity concentrations. These are chosen as the most likely dominant low Z impurities, and serve as prototypes for other low Z impurities. Since no detailed spectral results are derived, generally a single impurity element approximation is sufficient. The following description refers only to oxygen, though as just stated, the actual code handles aluminum as well.

The heart of the calculation is a solution of the time dependent differential equation for electron energy, which is symbolically written as follows:

$$\frac{d}{dt} \left(\frac{3}{2} nkT_e \right) = \text{ohmic heating} \pm \text{ion-electron equilibration} - \text{oxygen}$$

line radiation - continuum radiation - additional loss terms

The second term on the right may be plus or minus depending on the (time-dependent) instantaneous ion temperature. It requires simultaneous solution of a second differential equation for ion energy.

The third term is a summation over the line radiation from each separate ionization stage of oxygen. The approximation for the line radiation from each ionization stage is described later. It depends linearly on the ground-state population of each stage. Given the total oxygen impurity content and the initial distribution of ionization stages, it requires nine additional simultaneous differential equations to determine the time dependent ground state populations. These equations involve temperature dependent ionization rate coefficients and temperature and density dependent

recombination rate coefficients. The generation of these rate coefficients and the solution of the ionization stage distribution comprise the major numerical tasks of the program. (Radiation losses are generally high for lower ionization stages and the energy loss rates during the approach to steady state are of primary interest. For this reason the assumption of instantaneous adjustment of ionization to steady state values is inadmissible.)

The fourth term on the right is the calculated bremsstrahlung and recombination radiation for both deuterium and the oxygen impurity. In general the impurity line radiation is more important but this term puts an upper limit on the attainable temperature for any amount (including zero) of impurity content.

The fifth term on the right is strictly phenomenological, requiring only specification of a time constant by the user, to account for extraneous loss terms, e.g., transport, that one may wish to approximate. A similar term with independent choice of time constant appears in the ion equation.

In summary, the code solves an initial value problem for 11 simultaneous differential equations.

(1)--(9):

$$\frac{dn_i}{dt} = n_{i-1} S_{i-1}(T_e) - n_i S_i(T_e) - n_i \alpha_i(T_e, n_e) + n_{i+1} \alpha_{i+1}(T_e, n_e)$$

$$i = 1, \dots, 9 \quad n_o = n_{10} \equiv 0 \quad \sum_1^9 n_i = n_{\text{oxygen}}$$

$$(10): \quad \frac{3}{2} nk \frac{dT_{\text{ion}}}{dt} = f(T_e - T_{\text{ion}}) - \frac{3}{2} nk \frac{T_{\text{ion}}}{\tau_{\text{ion}}}$$

$$(11): \quad \frac{3}{2} nk \frac{dT_e}{dt} = \text{ohmic heating} - f(T_e - T_{\text{ion}}) - \text{line radiation}$$

$$- \text{continuum radiation} - \frac{3}{2} nk \frac{T_e}{\tau_e}.$$

The 11 time dependent variables, each given an initial value, are $n_1 = 1$, $\dots$, 9, T_{ion} , T_e . Specified parameters are n_e , n_{oxygen} , $J(t)$, τ_e , τ_{ion} , with

n_e = electron density

n_{oxygen} = total oxygen impurity density

$J(t)$ = ohmic heating current density

τ_e , τ_{ion} = additional electron, ion energy loss time constants.

$S_i(T_e)$ and $\alpha_i(T_e, n_e)$ are the ionization and recombination rate coefficients, respectively. The time dependences of $J(t)$ is given by a simple analytical function.

The next section discusses the physics input and approximations for the calculation. The final section describes the program code organization.

PHYSICS

A. Ionization and Recombination Rate Coefficients

The ionization and recombination rate coefficients are taken from the 1974 Appleton Laboratory Report by Hugh P. Summers, "Tables and Graphs of Collisional Dielectronic Recombination and Ionization Coefficients of H-like to A-like Ions of Elements." A more accessible description of the rather sophisticated physical processes taken into account appears in Summers, Monthly Notices of Royal Astro. Soc. 169, 663-680 (1974). A private communication from R. W. P. McWhirter (Nov. 1978) indicated that this is still the best available source.

B. Impurity Line Radiation

The model assumes that all impurity line radiation results from radiative decay following collisional excitation of the ground state of the various ionization levels. Following R. W. P. McWhirter for the radiated power loss due to the resonance line of an ion in a corona model plasma (Eq. (96), p. 243 in Plasma Diagnostic Techniques, Academic Press, 1965, R. H. Huddleston and S. L. Leonard, Eds.),

$$P = n_e n_i \frac{5.44 \times 10^{-16} f}{T_e^{1/2}} \exp\left(-\frac{1.16 \times 10^4 E}{T_e}\right) \text{ erg cm}^{-3} \text{ sec}^{-1}$$

T_e in °K

or

$$P = n_e n_i \frac{5.05 \times 10^{-18} f}{T_e^{1/2}} \exp\left(-\frac{E}{T_e}\right) \text{ erg cm}^{-3} \text{ sec}^{-1}$$

T_e in eV

In these equations f and E are the oscillator strength and excitation potential of the individual resonance lines, respectively. For the computer code two "averaged" resonance lines per ionization stage are used, with average f and E values taken from calculations of Group T-4, courtesy Al Merts. The actual values used can be gotten from the program listing at the beginning of Subroutine FSETUP, OS(1,1) through OS(8,2) for oscillator strengths and DE(1,1) through DE(8,2) for averaged excitation potentials.

In addition, an empirical correction factor multiplier (= 5) was originally put into the calculation in an attempt to approximate better more recent detailed calculations on individual lines and fragmentary experimental results, based on private communications from the University of Maryland. Subsequently an article by H. Griem on "Atomic Rate Coefficients for Tokamak Plasmas" has appeared in the Proceedings on Plasma-Wall Interactions, Jülich, West Germany, Oct. 1976. Comparison of the values given there with those in the present code after inclusion of the factor 5, indicates that our values are about a factor 2 high (except for the lithium-like ion OVI, in which our value is about 50% low). Since Griem is the world authority in this matter and also the source of the original factor 5, his values must be regarded as better. (In rereading McWhirter it appears he had already increased the Seaton estimate of effective Gaunt factor). However, the factor 5 has been retained for the following reason: uncertainties remain in what the best Seaton approximation is and the code should be on the conservative side, i.e., overestimate rather than underestimate the cooling effect of impurities.

Furthermore, whenever heating dominates, changing the loss terms causes only small differences in the results. The results can be characterized as exhibiting a critical impurity concentration below which heating proceeds almost unimpeded and above which the temperature is clamped in a balance of heating and loss terms.

The actual value of n_e changes in time as the impurity content passes through successive ionization stages. This correction is included in the calculation.

C. Continuum Radiation

The continuum radiation term consists of bremsstrahlung and recombination radiation for both the deuterium and the various oxygen ionization stages.

From, e.g., Glasstone and Lovberg, "Controlled Thermonuclear Reactions," Van Nostrand, 1960, Eq. 2.25, p. 31,

$$P_{br} = 1.57 \times 10^{-27} n_e \sum (n_i Z^2) T_e^{1/2} \text{ ergs/cm}^3 \text{sec}$$

with T_e in $^{\circ}\text{K}$

while from Griem, Plasma Spectroscopy McGraw-Hill, 1964, p. 195, the recombination radiation can be approximated by a factor χ/kT larger than bremsstrahlung, where χ is the ionization potential of the recombined ion.

D. Electron-Ion Equilibration

The electron-ion energy exchange term is taken from Eq. 9-60 in Longmire, "Elementary Plasma Physics," John Wiley and Sons, Inc.

$$\frac{d(\frac{3}{2} n k T_e)}{dt} = n_e n_D 4(2\pi)^{1/2} e^4 \ln \Lambda \frac{m_e^{1/2} (k T_i - k T_e)}{m_D (k T_e)^{3/2}}$$

Subscript D refers to deuterium, and $\ln \Lambda$ is the Coulomb logarithm, where

$$\Lambda = \frac{3}{2 e^3} \left(\frac{k^3 T^3}{\pi n_e} \right)^{1/2} \quad \text{for } T < 4.2 \times 10^5 \text{ } ^\circ\text{K}$$

$$\text{and multiplied by } \left(\frac{4.2 \times 10^5}{T} \right)^{1/2} \quad \text{when } T > 4.2 \times 10^5 \text{ } ^\circ\text{K}$$

(Spitzer, "Physics of Fully Ionized Gases," Interscience, 1962.)

The correction to the exchange term due to the impurity ions is small and has been ignored.

E. Ohmic Heating

Classical resistivity (F. Chen, "Introduction to Plasma Physics," Plenum Press, 1974) is given by

$$\eta_{\parallel} \approx 5.2 \times 10^{-3} Z_{\text{eff}} \ln \Lambda / T^{3/2} \quad \text{ohm-cm}$$

(T in eV)

$$Z_{\text{eff}} = \frac{\sum_z n_z Z^2}{\sum_z n_z Z} \approx 1 + \frac{\sum_i n_i Z_i^2}{n_e}$$

Energy addition per unit volume is ηJ^2 , in units of joules/m³ - sec if η is ohm - m and J is amps/m². For energy in units of ergs/cm³-sec and J in kA/cm², proper unit conversion gives

$$P_{\text{ohmic}} = 5.2 \times 10^{10} \frac{Z_{\text{eff}} \ln \Lambda}{T_{\text{ev}}^{3/2}} J^2 \quad \text{ergs/cm}^3\text{-sec}$$

F. Other Loss Processes

As previously mentioned, time constants for additional arbitrary energy loss terms for both electrons and ions may be entered by the user.

G. Model Limitations

Obviously, due to approximations and lack of precise knowledge of atomic rates and neglect of certain detail, the code results are indicative of trends rather than accurate predictions. The biggest limitation is the assumption of spatial uniformity.

PROGRAM CODE

Execution proceeds via a command file

```
EX @OXYALU.CMD (= EX OXYALU, RATESB, SUMMER, PUB:CTR6/LIB, PUB: PLOT
1G/LIB)
```

where the file OXYALU is the main program described in this report and the file RATESB, which in turn calls SUMMER, is invoked only when the requested density differs from the density used during the last execution of the program, in order to compute a new table of recombination coefficients. OXYALU and RATESB themselves call files IONROA.DAT, RECSUM.DAT, and OA.DAT, containing ionization and recombination rates and the most recent density value, respectively, and which must originally have been copied into the user directory (once and for all). Each time new recombination coefficients are computed they are placed in a file called RATBO.DAT.

RATESB and SUMMER, themselves, are modifications of a general program, IONREC, written by Ed Fenimore, P-4, that generates the coefficients for many elements up to atomic number 30 from the Summers tables. (IONREC has been adapted to run on the PDP-10 and is also available. It was used also to generate the ionization rates in IONROA.DAT.).

During the initialization of every problem the coefficient tables are read (SUBROUTINE SETF) from IONROA.DAT and RATBO.DAT multiplied by 10^{-6} for conversion to μsec^{-1} , and retained in a COMMON block location. (Two particular values are printed out as a diagnostic check that all the subsidiary files have been available and properly accessed.)

Also during the initialization a call to SUBROUTINE FSETUP loads the oxygen ionization potentials, oscillator strengths, average resonance line excitation potentials, and a few constants that will be used in the energy equations.

The differential equation solver is the PDP-Public Library routine ODE, with equations set up in subroutine G. The differential equations themselves appear according to the terms described in the physics section above. Only five oxygen (and five aluminum) rate equations are used, picked automatically each new time cycle to be optimally centered about the ionization stages with maximum population. The constants follow from the fact that temperatures are now in units of eV, time is in microseconds, and all terms of the two energy equations have been divided by the factor $3/2nk$, where n is the density variable and k is the Boltzmann constant 1.6×10^{-12} ergs/eV. The rate coefficients are determined by linear interpolation (SUBROUTINE OXY) for current value of electron temperature from the tables.

Input is requested from the user in easily interpretable terminal dialogue form. If a nonconstant ohmic heating current is chosen, a sinusoidal rise time t_r and an exponential decay time t_d are requested for the analytic expression $J = J_{\max} \sin(\pi/2 t/t_r) \exp(-t/t_d)$ for $t < t_r$, and $J = J_{\max} \exp(-t/t_d)$, for $t > t_r$.

Time steps for print-out also determine the time interval specified on each call to the differential equation solver routine. After the specified total time is reached an option is given to extend the time with a new choice of time step. Experimentation with small initial steps, watching progress, is advised. The print-out gives time, T_i , relative population of oxygen and aluminum ionization states, T_e , and a check-sum on relative populations that must remain very nearly equal to 1. A plot request instead of a time extension ends the problem with an auto-scaled graph of electron and ion temperatures versus time with linear interpolation between all previously called-out time steps.

Two additional convenient features have been incorporated:

- a) At the end of each run an option may be exercised (up to 4 times total) to defer plotting, permitting multiple plots for purposes of comparison. All T_e curves (up to 4) are plotted, but only the T_i curve corresponding to the last case calculated is shown. The

various curves can be identified from a legend identifying the various plotting characters, and all input parameters are printed out.

- b) An additional option during the input dialogue can include a linearly increasing impurity content during a chosen time interval by specifying the desired time constant to double the initial impurity concentration. (This option is implemented for oxygen only, by the inclusion of a constant term on the right side of the lowest active oxygen ion rate equation.) Proper execution of this option can be monitored by observing if the check-sum on relative population increases at the expected rate.

ACKNOWLEDGMENTS

A simple initial version of this code was written by S. Ortolani. E. Fenimore provided his CCF code for rate coefficients and helped with its conversion to PDP-10. A. Merts provided averaged oscillator strengths and energy levels. L. Mann has helped throughout the progressive code development.

LISTING OF THE CODE

```

C*****
C
C      S.ORTOLANI, ZERO-DIMENSIONAL PLASMA MODEL, OCTOBER 1979
C
C      THIS CODE HAS BEEN WRITTEN BY ADDING TO THE OXYALU CODE, DEVELOPED
C      BY F. JAHODA, THE ELECTRON DENSITY EQUATION AND THE CIRCUIT EQS.
C      IN THIS WAY 15 EQS. ARE SIMULTANEOUSLY SOLVED SO THAT THE DENSITY
C      GROWTH AND THE PLASMA CURRENT TIME VARIATION ARE CONSISTENTLY
C      TREATED WITH THE ELECTRON AND ION TEMPERATURE EVOLUTION.
C
C      OTHER FEATURES ADDED TO THE MODEL ARE:
C      RESISTANCE FORM FACTOR
C      VARIABLE PLASMA INDUCTANCE
C      LOSSES DUE TO THE IONIZ. AND RECOMB. OF THE MAIN GAS (DEUTERIUM)
C      LOSSES DUE TO THE IONIZATION OF THE IMPURITIES (O AND AL)
C      RADIATION LOSSES DUE TO IRON IMPURITIES
C      CLASSICAL THERMAL CONDUCTION LOSSES
C      ENHANCED TRANSPORT LOSSES ASSOCIATED WITH MAGNETIC FIELD FLUCT.
C
C*****
C      AUG 79 VERSION OF IMPURITY RADIATION CODE. ACCEPTS BOTH O AND AL IMP.
C      LINE RADIATION IS BASED ON TWO STRONGEST LINES OF EACH SPECIES TIMES
C      EMPIRICAL FACTOR 3 ON SEATON FORMULA.
C      IMPURITY INFLUX OPTION AT CONSTANT RATE APPLIES ONLY TO OIV.
C      UP TO 4 PLOTS MAY BE SAVED FOR COMMON GRAPH.
C      COMMON/RI/R12, TOUT, IMAX, IMAXA, Y(30)
C      COMMON /F1/ CH1(25), OS(25,2), DE(25,2)
C      COMMON /F2/ S2, FI, FIA, ZION, ETA, ETB, TCONS, ETC, DB, ITRLOS, ICD, FIIR
C      COMMON/BLK 1/ ANEF, ALNNE, COR, ANEE, KTIME
C      COMMON/CURR/RECYC, ICUR, TRISE, TDECAY, IEXTRA, ELOSS, DLOSS
C*****
C
C      COMMON AREA FOR CIRCUIT QUANTITIES
C      COMMON/CIRC/VC01, ANTR, C, ALE, RE, ALM, ALP0, VC0, AL, S, RMA, RMI, BZ0, VC
C      1 , VP, VRP, THETA, RFORME, ALP, TCB
C
C*****
C      COMMON /INTG/ RP, DLP, FME
C      DIMENSION   TAU(100), TEMP(100), TEMPI(100)
C      DIMENSION   TAU1(100), TAU2(100), TAU3(100), JMAXG(3)
C      DIMENSION   TEMP1(100), TEMP2(100), TEMP3(100)
C      DIMENSION   ANEG(4), FIIRG(4), FIG(4), FIAG(4), TRECG(4), ICDG(4)
C      DIMENSION   BZ0G(4), TCBG(4), DBG(4), ITRLG(4), ETIMEG(4), DTIMEG(4)
C      DIMENSION   ANEFG(4), VC01G(4), ANTRG(4)
C      DIMENSION   WORK(415), IWORK(5)
C      DIMENSION   YP(15), YD(15)
C      EXTERNAL G
C      OPEN(UNIT=31, DEVICE='DSK', ACCESS='SEQUINOUT', MODE='ASCII')
C      OPEN(UNIT=32, DEVICE='DSK', ACCESS='SEQUINOUT', MODE='ASCII')
C      OPEN(UNIT=33, DEVICE='DSK', ACCESS='SEQUINOUT', MODE='ASCII')
C      ANEE=1.
C      KTIME=1
400  CONTINUE
C      CALL INITT(120)
C      NP=0
C      BMIN=1000.
C      BMAX=1.
C      TMAX=1.
444  CONTINUE
C      NL=NP+1

```

```

      INDEX=0
      CKSUM=1.
      CALL NEUPAG
      TYPE 403
403  FORMAT(' FILLING DENSITY IN UNITS OF 10**14')
      ACCEPT 402,ANEF
      RLNE=ALOG(ANEF*1.E2)
      ANEF =ANEF*1.E14
      ANEFG(NL)=ANEF
C
C  LOAD IONIZATION RATE COEFFS 1ST TIME AND RECOMBINATION COEFFS AFTER
C  EVERY CHANGE OF DENSITY
C
      OPEN(UNIT=22,FILE='DA.DAT')
      READ(22,39)OLDANE
29  FORMAT(E8.3)
      QUO=OLDANE/ANEF
      IF(QUO.GT.0.98.AND.QUO.LT.1.01)GO TO 333
      TYPE 335
335  FORMAT(' BECAUSE THIS IS A CHANGE OF DENSITY
1  EXPECT LONG WAIT WHILE COEFFS ARE COMPUTED')
      CALL RATESB
      CALL XXX
C      TYPE 339
C999  FORMAT(' LINE 30 CALL TO RATESB COMMENTED OUT
C      1  AT 2.E14 THIS MESSAGE LINES 47-49')
      ANEE=ANEF
      KTIME=2
333  CONTINUE
407  FORMAT(I1)
      KKK=1
3  CONTINUE
      TYPE 401
401  FORMAT(' OXYGEN IMPURITY FRACTION')
      ACCEPT 402,FI
      TYPE 399
399  FORMAT(' ALUMINUM IMPURITY FRACTION')
      ACCEPT 402,FIA
      TYPE 363
363  FORMAT(' IRON IMPURITY FRACTION ')
      ACCEPT 402,FIIR
402  FORMAT(F)
      FIG(NL)=FI*ANEF
      FIAG(NL)=FIA*ANEF
      FIIRG(NL)=FIIR*ANEF
      RECYC=0.
      TRECG(NL)=1.E16
      TYPE 4003
4003  FORMAT(' 1=CONSTANT IMPURITY 2=ADDITIONAL IMP INFLUX(OIV)')
      ACCEPT 407,INFL
      IF(INFL.EQ.1)GO TO 4002
      TYPE 4001
4001  FORMAT(' ADDITIONAL OXYGEN DOUBLING TIME(MICROSEC)')
      ACCEPT 402,TREC
      RECYC=1./TREC
      TYPE 4010
4010  FORMAT(' START TIME ADDITIONAL IMPURITY')
      ACCEPT 402,TRISE
      TYPE 4012
4012  FORMAT(' END TIME ADDITIONAL IMPURITY')

```

```

ACCEPT 402,TDEDAY
TREG(NL)=TREC
4002 CONTINUE
TYPE 404
404 FORMAT(' ION TEMP IN EV')
ACCEPT 402,TI
TIINIT=TI
TYPE 405
405 FORMAT(' ELECTRON TEMP IN EV')
ACCEPT 402,TE
TEINIT=TE
TYPE 506
506 FORMAT(' INITIAL ELECTRON DENSITY ( 10E14 cmE-3) ')
ACCEPT 402,ANE
ANE=ANE*1.E+14
ANEG(NL)=ANE
TYPE 507
507 FORMAT(' BANK VOLTAGE(KV) TRANS. RATIO TOROID. BIAS FIELD(T)
1 AND CROW=BAR TIME(MICROSEC)')
ACCEPT 517,VC01,ANTR,BZ0,TCB
517 FORMAT(4F)
VC01G(NL)=VC01
VC01=VC01*1.E+3
ANTRG(NL)=ANTR
CALL CIRPAM
TYPE 508
508 FORMAT(' IPRINT:=1,IMPUR POUT:=2,CIRC POUT:=3,FLUX & EN. POUT')
ACCEPT 407,IPRINT
TYPE 511
511 FORMAT(' FIELD FLUCT. RELATIVE AMPL. ')
ACCEPT 402,DB
TYPE 512
512 FORMAT(' ITRLOS:=1,NO SCALING; =2,S*%-5 SCALING ')
ACCEPT 407,ITRLOS
TYPE 513
513 FORMAT(' ICD=1,CLASS. DIFF. TERM INCL.; ICD=0,NOT INCL. ')
ACCEPT 407,ICD
BZ0G(NL)=BZ0
TCBG(NL)=TCB
DBG(NL)=DB
ITRLOG(NL)=ITRLOS
ICDG(NL)=ICD
TYPE 523
523 FORMAT(' DO YOU WANT NON-RADIATIVE LOSS TERMS?
1 1=NO 2=ELECTRONS+IONS 3=ELECTRONS ONLY 4=IONS ONLY')
ACCEPT 407,IEXTRA
ELOSS=0.
DLOSS=0.
ETIMEG(NL)=1.E16
DTIMEG(NL)=1.E16
IF(IEXTRA.EQ.1)GO TO 529
IF(IEXTRA.EQ.4)GO TO 527
TYPE 524
524 FORMAT(' ELECTRON LOSS TIME CONSTANT(MICROSEC)')
ACCEPT 402,ETIME
ELOSS=1./ETIME
ETIMEG(NL)=ETIME
IF(IEXTRA.EQ.3)GO TO 529
TYPE 526
526 FORMAT(' ION LOSS TIME CONSTANT(MICROSEC)')

```

```

      ACCEPT 402,DTIME
      DLOSS=1./DTIME
      DTIMEG(NL)=DTIME
529    CONTINUE
      WRITE(31,9005)
      WRITE(31,9333),ANEFG(NL),ANEG(NL),FIG(NL),FIAG(NL),FIIRG(NL),
      1ITRECG(NL),VC01G(NL),BZ0G(NL),TCBG(NL),DBG(NL),ITRLSG(NL),
      1ICDG(NL),ETIMEG(NL),DTIMEG(NL),ANTRG(NL)
      WRITE(31,411)
      WRITE(32,9005)
      WRITE(32,9333),ANEFG(NL),ANEG(NL),FIG(NL),FIAG(NL),FIIRG(NL),
      1ITRECG(NL),VC01G(NL),BZ0G(NL),TCBG(NL),DBG(NL),ITRLSG(NL),
      1ICDG(NL),ETIMEG(NL),DTIMEG(NL),ANTRG(NL)
      WRITE(32,1002)
      WRITE(33,9005)
      WRITE(33,9333),ANEFG(NL),ANEG(NL),FIG(NL),FIAG(NL),FIIRG(NL),
      1ITRECG(NL),VC01G(NL),BZ0G(NL),TCBG(NL),DBG(NL),ITRLSG(NL),
      1ICDG(NL),ETIMEG(NL),DTIMEG(NL),ANTRG(NL)
      WRITE(33,1998)
      TYPE 509
509    FORMAT(' TIME STEP FOR PRINTOUT')
      ACCEPT 402,TOUT
      TSTEP=TOUT
      TYPE 519
519    FORMAT(' TOTAL TIME')
      ACCEPT 402,TEND
      CALL SETF
      TYPE 9000,ANEF
9000    FORMAT(' FILLING DENSITY = '1PE15.5)
      NEQN=15
      Y(1)=TE
      Y(10)=TI
      Y(1) = 0.
      Y(2) = 0.
      Y(3) = 0.
      Y(4) = 0.
      Y(5) = 0.
      Y(6) = 0.
      Y(7) = 0.
      Y(8) = 0.
      Y(9) = 0.
      Y(KKK)=1.
      DO 398 I=12,25
398    Y(1)=0.
      Y(KKK+11)=1.
      Y(26)=ANE
      Y(27)=0.
      Y(28)=0.
      T=0.0
      RELERR = 1.0E-4
      ABSERR = 1.0E-4
      NEQN1 = 9
      TYPE 100,T,TI,(Y(JJ),JJ=1,NEQN1),TE
100    FORMAT(F7.1,F6.1,9(1X,F4.2),26X,F6.1,24X,F8.2,4X,12)
101    FORMAT(13X,14(1X,F4.2),7X,3E8.2,F8.2)
      J = 0
      CALL FSETUP
      VCOLD=VC01/ANTR
      VPOLD=0.
      TOLD=0.

```

```

PGOLD=0.
PPOLD=0.
PDCOLD=0.
PDPOLD=0.
PMEOLD=0.
WMCOLD=0.
WMPOLD=0.
FFOLD=0.
VSG=0.
VSP=0.
UG=0.
UP=0.
WDC=0.
WDP=0.
WME=0.
5 CONTINUE
YMAX=0.
YMAXA=0.
IF (TEMP(J).LT.1..AND.J.GT.1)GO TO 429
J=J+1
10 CONTINUE
DO 39 I=1,9
IF (YMAX.GT.Y(I))GO TO 39
YMAX=Y(I)
IMAX=I
39 CONTINUE
IF (IMAX.GT.7) IMAX=7
IF (IMAX.LT.3) IMAX=3
YD(1)=Y(IMAX-2)
YD(2)=Y(IMAX-1)
YD(3)=Y(IMAX)
YD(4)=Y(IMAX+1)
YD(5)=Y(IMAX+2)
YD(6)=Y(10)
YD(7)=Y(11)
DO 390 I=12,25
IF (YMAXA.GT.Y(I))GO TO 390
YMAXA=Y(I)
IMAXA=I
390 CONTINUE
IF (IMAXA.GT.23) IMAXA=23
IF (IMAXA.LT.14) IMAXA=14
YD(8)=Y(IMAXA-2)
YD(9)=Y(IMAXA-1)
YD(10)=Y(IMAXA)
YD(11)=Y(IMAXA+1)
YD(12)=Y(IMAXA+2)
YD(13)=Y(26)
YD(14)=Y(27)
YD(15)=Y(28)
IFLAG=1
CALL ODE (G,NEQN,YD,T,TOUT,RELERR,ABSERR,IFLAG,WORK,IWORK)
TNEW=TOUT
TOUT=TOUT+TSTEP
PG=VC*Y(28)
PP=VP*Y(28)
PDC=RE*Y(28)*Y(28)
WMC=0.5*ALE*Y(28)*Y(28)
WMP=0.5*ALP*Y(28)*Y(28)
PDP=RP*Y(28)*Y(28)

```

```

PME=0.5*THETA*FME*Y(28)*1.E+05
DT=(TNEW-TOLD)*1.E-05
VSG=(VC+VCOLD)/2.*DT+VSG
VSP=(VP+VPOLD)/2.*DT+VSP
FP=ALP*Y(28)
UMC=(UMCOLD+UMC)/2.
UMP=(UMPOLD+UMP)/2.
FP=(FPOLD+FP)/2.
WG=(PG+PGOLD)/2.*DT+WG
WP=(PP+PPOLD)/2.*DT+WP
WDC=(PDC+PDCOLD)/2.*DT+WDC
WDP=(PIP+PIPOLD)/2.*DT+WDP
UME=(PME+PMEOLD)/2.*DT+UME
VCOLD=VC
VPOLD=VP
TOLD=TNEW
UMCOLD=0.5*SCALE*Y(28)*Y(28)
UMPOLD=0.5*ALP*Y(28)*Y(28)
FPOLD=ALP*Y(28)
PGOLD=VCOLD*Y(28)
PPOLD=VPOLD*Y(28)
PDCOLD=RE*Y(28)*Y(28)
PDPOLD=PP*Y(28)*Y(28)
PMEOLD=0.5*THETA*FME*Y(28)*1.E+05
WRITE(31,106),T,Y(10),(Y(JJ),JJ=1,9),Y(11),CHKSUM,IFLAG
WRITE(31,101),(Y(JJ),JJ=12,28),CHKSUM
WRITE(32,1003),T,Y(10),Y(11),Y(26),Y(27),Y(28),VC,VP,VRP,
1 THETA,RFORMF,ALP
WRITE(33,1996),T,Y(11),Y(26),Y(28),VSG,VSP,FP,WG,UMC,WDC,WP,UMP
1 WDP,UME
IF(INDEX.NE.0)GO TO 408
CALL NEMPAG
WRITE(5,5095)
WRITE(5,5333),ANEFG(NL),ANEG(NL),FIG(NL),FIAG(NL),FIIRG(NL),
1TREG(NL),VORG(NL),BZOG(NL),TCBG(NL),DBG(NL),ITRLSG(NL),
1ICDG(NL),ETIMEG(NL),DTIMEG(NL),ANTRG(NL)
408 CONTINUE
IF(IPRINT.EQ.3) GO TO 1999
IF(IPRINT.EQ.2) GO TO 1001
IF(INDEX.NE.0) GO TO 415
TYPE 411
411 FORMAT(6X'T'4X'TI'4X'I'3X'II'2X'III'3X'IV'4X'V'3X'VI'2X'VII'
1X'VIII'3X'IX'4X'X'3X'XI'2X'XII'X'XIII'2X'XIV'4X'TE'4X'ANE'7X'
10'5X'I'5X'CHKSUM')
INDEX=1
415 CONTINUE
CHKSUM=0.
DO 443 L=1,9
443 CHKSUM=CHKSUM+Y(L)
TYPE 100,T,Y(10),(Y(JJ),JJ=1,9),Y(11),CHKSUM,IFLAG
CHKSUM=0.
DO 445 L=12,25
445 CHKSUM=CHKSUM+Y(L)
TYPE 101,(Y(JJ),JJ=12,28),CHKSUM
GO TO 1004
1001 IF(INDEX.NE.0) GO TO 1005
TYPE 1002
1002 FORMAT(6X'T'8X'TI'8X'TE'8X'ANE'8X'Q'8X'I'8X'VC'8X'VP'8X'VRP'
1 5X'THETA'5X'RFORMF'5X'ALP')
INDEX=1

```



```

1005 TYPE 1003,T,Y(10),Y(11),Y(26),Y(27),Y(28),VC,VP,VRP,
1 THETA,RFORMF,ALP
1003 FORMAT (1P12E10.2)
GO TO 1004
1999 IF(INDEX.NE.0) GO TO 1997
TYPE 1998
1998 FORMAT(6X'T'7X'TE'7X'NE'7X'I'7X'VSG'7X'VSP'6X'FP'6X'WG'
1 7X'WMC'6X'WDC'6X'WP'7X'WMP'7X'WDP'6X'WME')
INDEX=1
1997 TYPE 1999,G,T,Y(11),Y(26),Y(28),VSG,VSP,FP,WG,WMC,WDC,WP,WMP,WDP
1 WME
1996 FORMAT (1P14E9.2)
1004 TAU(J)=T
TEMP(J)=Y(11)
TEMPI(J) = Y(28)*1.E-4
IF(BMIN.GT.TEMP(J))BMIN=TEMP(J)
IF(BMAX.LT.TEMP(J))BMAX=TEMP(J)
IF(BMIN.GT.TEMPI(J))BMIN=TEMPI(J)
IF(BMAX.LT.TEMPI(J))BMAX=TEMPI(J)
IF(J.EQ.1) GO TO 5
IF(TOUT.LE.TEND) GO TO 5
DO 666 K=1,J
M=J+1-K
TAU(M+1)=TAU(M)
TEMP(M+1)=TEMP(M)
666 TEMPI(M+1)=TEMPI(M)
TAU(1)=0.
TEMP(1)=TEINIT
TEMPI(1)=TIINIT
777 CONTINUE
TYPE 541
541 FORMAT(' 1=PLOT 2=NO PLOT 3=EXTEND TIME 4=SAVE FOR LATER PLOT')
429 JMAX=J+1
ACCEPT 407,IPL0T
IF(IPL0T.EQ.2)GO TO 8001
IF(IPL0T.EQ.3)GO TO 569
IF(IPL0T.EQ.1)GO TO 567
IF(IPL0T.EQ.4)GO TO 778
GO TO 777
778 NP=NP+1
GO TO (581,582,583,567)NP
581 DO 591 I=1,JMAX
TAU1(I)=TAU(I)
591 TEMP1(I)=TEMP(I)
JMAXG(1)=JMAX
GO TO 444
582 DO 592 I=1,JMAX
TAU2(I)=TAU(I)
592 TEMP2(I)=TEMP(I)
JMAXG(2)=JMAX
GO TO 444
583 DO 593 I=1,JMAX
TAU3(I)=TAU(I)
593 TEMP3(I)=TEMP(I)
JMAXG(3)=JMAX
GO TO 444
569 CONTINUE
TOUT=TOUT-TSTEP
TYPE 509
ACCEPT 432,TSTEP

```

```

      TOUT=TOUT+TSTEP
      TYPE 519
      ACCEPT 402,TEND
      GO TO 5
567    CONTINUE
      CALL NEWPAG
      CALL BINITT
      CALL NPTS(JMAX)
      CALL SLIMY(260,750)
      CALL LINE(1)
      CALL DLIMY(BMIN,BMAX)
      CALL CHECK(TAU,TEMP)
      CALL DSPLAY(TAU,TEMP1)
      CALL LINE(0)
      CALL CPLOT(TAU,TEMP)
      JMAXN=JMAXG(1)
      CALL LINE(2)
      CALL NPTS(JMAXN)
      IF(NP.GE.1)CALL CPLOT(TAU1,TEMP1)
      JMAXN=JMAXG(2)
      CALL LINE(3)
      CALL NPTS(JMAXN)
      IF(NP.GE.2)CALL CPLOT(TAU2,TEMP2)
      JMAXN=JMAXG(3)
      CALL LINE(4)
      CALL NPTS(JMAXN)
      IF(NP.GE.3)CALL CPLOT(TAU3,TEMP3)
      CALL FINITT(0,150)
      TYPE 467
467    FORMAT(99X,'MICROSECONDS')
      TYPE 9005
9005   FORMAT(' FINAL NE START NE OXYGEN ALUMINUM'
13X' IRON DOUBLING KV BIAS CB TIME FLUC SCAL DIFF ELOSS'
11X' ILOSS TR RATIO')
      DO 9444 I=1,NL
9444   TYPE 9333,ANEFG(I),ANEG(I),FIG(I),FIAG(I),FIIRG(I),TREGG(I),
1VCOIG(I),BZOG(I),TCBG(I),DBG(I),ITRLSG(I),ICDG(I),
1ETIMEG(I),DTIMEG(I),ANTRG(I)
9333   FORMAT(1P5E9,2,0PF6,1,2X,F5,1,F5,2,2X,F5,1,X,F4,2,4X,11,4X,11,
12X,2F6,1,F8,2)
      TYPE 9500
9500   FORMAT(' CASE 1:TE-DOT,DASH CASE 2:TE-DASH CASE 3:TE-LONG DASH
1 LAST CASE:TE-SOLID,I-DOT(IN UNITS OF 10 KA)')
8001   TYPE 8000
8000   FORMAT(' 1=NEW CASE 2=STOP')
      TYPE 8009
8009   FORMAT(' *****')
      TYPE 8010
8010   FORMAT(' LATEST IMPURITY PRINTOUT STORED IN FOR31.DAT')
      TYPE 8011
8011   FORMAT(' LATEST CIRCUIT PRINTOUT STORED IN FOR32.DAT')
      TYPE 8012
8012   FORMAT(' LATEST FLUX + EN. PRINTOUT STORED IN FOR33.DAT')
      TYPE 8009
      ACCEPT 407,NEXT
      IF(NEXT.EQ.1)GO TO 400
      IF(NEXT.NE.2)GO TO 8001
      STOP
END
SUBROUTINE FSETUP

```

```

COMMON /A1/A12, TOUT, IM9X, IM9X9, Y(30)
COMMON /F1/ CH(25), OS(25,2), DE(25,2)
COMMON /F2/ S2, F1, F1N, Z10N, ETR, ETR, TCONS, ETC, DB, ITRLOS, ICD, F1IR

CH(1)=13.017
CH(2)=35.145
CH(3)=54.934
CH(4)=77.394
CH(5)=118.873
CH(6)=150.090
CH(7)=735.114
CH(8)=871.
CH(12)=5.906
CH(13)=10.828
CH(14)=20.447
CH(15)=119.99
CH(16)=157.71
CH(17)=150.47
CH(18)=241.43
CH(19)=204.59
CH(20)=330.21
CH(21)=393.57
CH(22)=442.07
CH(23)=2086.
CH(24)=2304.
OS(1,1)=0.105
OS(2,1)=0.551
OS(3,1)=0.628
OS(4,1)=0.657
OS(5,1)=.53
OS(6,1)=.196
OS(7,1)=0.013
OS(8,1)=.416
OS(12,1)=0.12
OS(13,1)=2.7
OS(14,1)=0.88
OS(15,1)=0.48
OS(16,1)=.12
OS(17,1)=.196
OS(18,1)=0.294
OS(19,1)=.339
OS(20,1)=.360
OS(21,1)=.356
OS(22,1)=.115
OS(23,1)=.75
OS(24,1)=.42
DE(1,1)=10.7
DE(2,1)=15.91
DE(3,1)=16.03
DE(4,1)=14.65
DE(5,1)=12.56
DE(6,1)=11.99
DE(7,1)=561.
DE(8,1)=653.
DE(12,1)=4.02
DE(13,1)=7.34
DE(14,1)=6.66
DE(15,1)=95.0
DE(16,1)=44.3
DE(17,1)=39.0
DE(18,1)=38.48

```

```

DE(19,1)=33.22
DE(20,1)=27.23
DE(21,1)=20.58
DE(22,1)=22.47
DE(23,1)=1599.
DE(24,1)=1724.
OS(1,2)=0.42
OS(2,2)=0.389
OS(3,2)=0.652
OS(4,2)=0.466
OS(5,2) = .59
OS(6,2) = .262
OS(7,2)=0.0
OS(8,2) = .0
OS(12,2)=0.12
OS(13,2)=2.7
OS(14,2)=0.88
OS(15,2)=0.48
OS(16,2) = .12
OS(17,2) = .196
OS(18,2)=1.415
OS(19,2) = 1.096
OS(20,2) = .591
OS(21,2) = .670
OS(22,2) = .354
OS(23,2) = .75
OS(24,2) = .42
DE(1,2)=16.7
DE(2,2)=25.05
DE(3,2)=39.37
DE(4,2)=51.98
DE(5,2)=72.22
DE(6,2)=82.60
DE(7,2)=561.
DE(8,2)=653.
DE(12,2)=4.02
DE(13,2)=7.34
DE(14,2)=6.66
DE(15,2)=95.0
DE(16,2)=44.3
DE(17,2)=39.8
DE(18,2)=159.6
DE(19,2)=101.9
DE(20,2)=204.5
DE(21,2)=236.1
DE(22,2)=257.3
DE(23,2)=1599.
DE(24,2)=1724.
C BASED ON P(OHM)=5.2E17*J**2(KA/CM**2)**2*E-6 ERGS/MICROSECOND
C USING COULOMB LOG = 10
ETC=5.2E-4
ETB=ETC*1.E+14*10.*1.E-06/1.6E-12
PI = 3.1415927
XME = 9.1E-28
XMI = 3.34E-24
E = 4.81E-10
XLNLA = 10.
C TIONS BASED ON EQ 9-60 IN LONGMIRE WITH LN TERM = 10 AND TIME IN
C MICROSECONDS. TEMP IN EV. MULTIPLIER IN ION-ELECTRON EXCHANGE TERM
C LOG TERM CORRECTED LATER FOR DENS. TEMP VARIATION

```

```

TICONS=4.0E-6*SQRT(2.*PI)*2./3.*LNLA*
1 ((E**2)*(E**2/XMI)*(SQRT(XME)/((1.6E-12)**1.5)))
RETURN
END
SUBROUTINE G(T,YD,YP)
COMMON/A1/A12,TOUT,IMAX,IMAXA,Y(30)
COMMON /F1/ CHI(25),OS(25,2),DE(25,2)
COMMON /F2/ S2,F1,FIA,ZION,ETA,ETB,TICONS,ETC,DB,ITRLOS,ICD,FIIR
COMMON/BLK 1/ANEF,ALNNE,COR,ANEE,KTIME
COMMON/CURR/RECYC,ICUR,TRISE,TDECAY,IEXTRA,ELOSS,DLOSS
C*****
C
C      COMMON AREA FOR CIRCUIT QUANTITIES
COMMON/CIRC/VC01,ANTR,C,ALE,RE,ALM,ALP0,VC0,AL,S,RMA,RMI,BZ0,VC
1 ,VP,VRP,THEFA,RFORMF,ALP,TCD
C
C*****
COMMON /INTG/ RP,DLP,FME
DIMENSION EXCITX(25),RECOMX(25)
DIMENSION YD(1),YP(1)
REAL MBSJ1
YEV=YD(7)
CALL DXY(YEV,RECOMX,EXCITX,RECKX)
C COULOMB LOG CORRECTION FOR DENS AND TEMP
ARGLNE=YD(13)*1.E-16
ALNNE=ALOG(ARGLNE)
ALNTE=ALOG(YD(7))
CORR=5.02-0.5*ALNNE+1.5*ALNTE
IF(YD(7).GT.37.)CORR=CORR+1.00-0.5*ALNTE
COR=CORR/10.
IONE=1
IF(IMAX.GT.3) IONE=IMAX-2
IF(IMAX.GT.7) IONE=5
IONE=12
IF(IMAXA.GT.14) IONEA=IMAXA-2
IF(IMAXA.GT.23) IONEA=21
ITWOA=IONE+1
ITHREA=IONE+2
IFOURA=IONE+3
IFIVEA=IONE+4
ITWO=IONE+1
ITHREE=IONE+2
IFOUR=IONE+3
IFIVE=IONE+4
SUM=0.
SUMA=0.
SUBSUM=1.
ANI=0.
DO 554 K=1,8
SUBSUM=SUBSUM+Y(K+1)*K**2*FI
ANI=ANI+Y(K+1)*K*FI*YD(13)
DO 554 J=1,2
SUM=SUM+Y(K)*OS(K,J)*EXP(-DE(K,J)/Y(11))
DO 555 K=12,24
SUBSUM=SUBSUM+Y(K+1)*(K-11)**2*FIA
ANI=ANI+Y(K+1)*(K-11)*FIA*YD(13)
DO 555 J=1,2
SUMA=SUMA+Y(K)*OS(K,J)*EXP(-DE(K,J)/Y(11))
PLIRON=0.
IF(FIIR.EQ.0) GO TO 1111

```

```

      CALL AIFON(YD(7),FP,FZ,FZ2)
      PLIRON=FP**YD(15)**F1IR**1.E+06/1.6
1111  CONTINUE
      SUBSUM=SUBSUM+F1IR*FZ2
      THETA=2.8-7**YD(15)/(RMI*8ZC)
      THETA2=THETA**2.
      AJ1=MMESJ1*THETA2,IER)
      RFORMF=(THETA+.001)/(CJ1+.001)
      IF(THETA.LT.1.E-2) RFORMF=1
      IF(THETA.GT.1.45) RFORMF=4
      PR=ETC*SUBSUM*COR/YD(7)**1.5*AL/S*RFORMF
      R12=YD(15)*YD(15)/(S**S)*1.E-14
C     CONTINUUM RADIATION TERM
      BRFB = YD(13)
      DO 51 K=2,9
51    BRFB = BRFB + F1*YD(13)*Y(K)*((K-1)**2)
      DO 52 K=13,25
52    BRFB=BRFB+F1*YD(13)*Y(K)*((K-12)**2)
      RAD=7.04E-24*YD(7)**0.5*BRFB
C     RAD IS SUBTRACTED ON RHS OF YP(7)
      ANEI=YD(13)*ANI
      ANEI=ANEI+F1IR*YD(13)*FZ
      ADDIMP=0.
      IF(CT,GE,TRISE,AND,T.LE,TDECAY)ADDIMP=RECYC
      YP(6)=-TICONS*COR*YD(15)*(YD(6)-YD(7))/(YD(7)**1.5)
1    -DLOSS*YD(6)-1./YD(13)*YD(6)*YP(13)
      YP(1)=-ANEI*YD(1)*EXCITX(IONE)+ANEI*YD(2)*RECOMX(IONE)+ADDIMP
      YP(2)=ANEI*YD(1)*EXCITX(IONE)-ANEI*YD(2)*(EXCITX(ITWO))
1    +RECOMX(IONE))+ANEI*YD(3)*RECOMX(ITWO)
      YP(3)=ANEI*YD(2)*EXCITX(ITWO)-ANEI*YD(3)*(EXCITX(ITHREE))
1    +RECOMX(ITWO))+ANEI*YD(4)*RECOMX(ITHREE)
      YP(4)=ANEI*YD(3)*EXCITX(ITHREE)-ANEI*YD(4)*(EXCITX(IFOUR))
1    +RECOMX(ITHREE))+ANEI*YD(5)*RECOMX(IFOUR)
      YP(5) = ANEI*YD(4)*EXCITX(IFOUR) -
1ANEI*RECOMX(IFOUR)*YD(5)
C     MARYLAND FACTOR IS IN THE SECOND TERM
      ETA=ETB*COR*SUBSUM*RFORMF
      XMI=3.34E-24
      STHETA=(4.*3.14E-7)**1.5*YD(15)/(RP*S*AL*2.*3.14*SQR(YD(13)
1    *XMI*1.E+3))
      IF(ITRLOS.EQ.1) GO TO 1009
      DLOSS=.65*YD(7)/YD(13)**0.5*DB*SQR(1000./STHETA)*YD(15)/
1    (RMI*RMI)
      GO TO 1009
1008  DLOSS=.65*YD(7)/YD(13)**0.5*DB*YD(15)/(RMI*RMI)
1009  CONTINUE
      SIONH=7.8E-11*(YD(7)**11600)**0.5*EXP(-13.6/YD(7))
      SIONH=SIONH**1.E-06
      PIO=0.
      PIA=0.
      DO 77 I=1,4
      J=IONE+I-1
      K=IONE+I-1
      L=7+I
      PIO=PIO+YD(I)*EXCITX(J)*CHI(J)
      PIA=PIA+YD(L)*EXCITX(K)*CHI(K)
77    CONTINUE
      PIO=PIO*F1*YD(13)
      PIA=PIA*F1*YD(13)
      YP(7)=(ETA*R12/(ANEI*YD(7)**1.5)-(ANEI*5/1.6E-12)*

```

```

1(5.05E-24/YD(7))*2.5)*(FI*SUM+PIA*SUMA))*2./3.
1-YP(6)-ELOSS*YD(7)
1  - RAD
1  -1./ANEI*YD(7)*YP(13)
1  -20.*(ANEF-YD(13))*SIONH
1  -1./2.*(ETA*AI2/(ANEI*YD(7))*1.5))*2./3.*ICD
1  -DELOSS
1  -YD(7)*YD(13)*RECHX
1  -PI0-PIA-PLIRON
    YP(8)=-ANEI*YD(8)*EXCITX(IONE)+ANEI*YD(9)*RECOMX(IONE)
    YP(9)=ANEI*YD(8)*EXCITX(IONE)-ANEI*YD(9)*(EXCITX(ITWOA)
1  +RECOMX(IONE))+ANEI*YD(10)*RECOMX(ITWOA)
    YP(10)=ANEI*YD(9)*EXCITX(ITWOA)-ANEI*YD(10)*(EXCITX(ITHREA)
1  +RECOMX(ITWOA))+ANEI*YD(11)*RECOMX(ITHREA)
    YP(11)=ANEI*YD(10)*EXCITX(ITHREA)-ANEI*YD(11)*(EXCITX(IFOURA)
1  +RECOMX(ITHREA))+ANEI*YD(12)*RECOMX(IFOURA)
    YP(12) = ANEI*YD(11)*EXCITX(IFOURA) -
1ANEI*RECOMX(IFOURA)*YD(12)
    YP(13)=(ANEF-YD(13))*ANEI*SIONH-YD(13)*ANEI*RECHX
    IF(THETA.LT.0.4) ALP=ALP0*0.5
    IF(THETA.GT.1.5) ALP=ALP0*1.5
    DLP=0.
    IF(THETA.GE.0.4.AND.THETA.LE.1.5)GO TO 777
    GO TO 778
777  ARG=3.14*(THETA-0.4)*.625
    ALP=ALP0*0.5*(2.29-1.29*COS(ARG))
    DLP=ALP0*0.5*(1.29*.3.14*0.625*SIN(ARG))
778  CONTINUE
    VC=VC0-YD(14)/C
    VP=(ALP+THETA*DLP)*YP(15)*1.E+06+RP*YD(15)
    FME=DLP*YP(15)
    VRP=RP*YD(15)
    IF(VC.GT.0..AND.T.LT.TCB) GO TO 111
    VC=0.
    RE1=147.E-06
    ALE1=4.E-09
    ANTR2=ANTR*ANTR
    RE=RE1/ANTR2
    ALE=ALE1/ANTR2
111  CONTINUE
    YP(14)=1.E-6*YD(15)
    YP(15)=1.E-6/(ALE+ALP+THETA*DLP)*(VC-(RE+RP)*YD(15))
    Y(IMAX-2)=YD(1)
    Y(IMAX-1)=YD(2)
    Y(IMAX)=YD(3)
    Y(IMAX+1)=YD(4)
    Y(IMAX+2)=YD(5)
    Y(IMAXA-2)=YD(8)
    Y(IMAXA-1)=YD(9)
    Y(IMAXA)=YD(10)
    Y(IMAXA+1)=YD(11)
    Y(IMAXA+2)=YD(12)
    Y(10)=YD(6)
    Y(11)=YD(7)
    Y(26)=YD(13)
    Y(27)=YD(14)
    Y(29)=YD(15)
    RETURN
    END
    SUBROUTINE SETF

```

```

COMMON/A1/A12,TOUT,IMAX,IMAXA,Y(30)
COMMON /FIT/RECOM,EXCIT,TEMP,RECOMH
DIMENSION TEMP(100),RECOM(25,100),EXCIT(25,100)
DIMENSION RECOMH(10,100)
OPEN(UNIT=21,FILE='RATE0.DAT')
OPEN(FILE='IONR00.DAT',UNIT=20)
READ(21,121)(TEMP(I),(RECOM(J,I),J=1,8),I=1,41)
READ(20,121)(TEMP(I),(EXCIT(J,I),J=1,8),I=1,41)
READ(21,122)(TEMP(I),(RECOM(J,I),J=12,24),I=1,41)
READ(20,122)(TEMP(I),(EXCIT(J,I),J=12,24),I=1,41)
CLOSE(FILE='IONR00.DAT',UNIT=20)
OPEN(UNIT=24,FILE='XXXOUT.DAT')
READ(24,124)(TEMP(I),(RECOMH(J,I),J=1,1),I=1,41)
124  FORMAT(9P9.2,1P8.1)
DO 159 J=1,1
DO 159 I=1,41
159  RECOMH(J,I)=RECOMH(J,I)*1.E-06
121  FORMAT(9P9.2,1P8.1)
122  FORMAT(9P9.2,1P13.1)
DO 150 J=1,8
DO 150 I=1,41
RECOM(J,I) = RECOM(J,I)*1.0E-6
EXCIT(J,I) = EXCIT(J,I)*1.0E-6
150  CONTINUE
DO 151 J=12,24
DO 151 I=1,41
RECOM(J,I) = RECOM(J,I)*1.0E-6
EXCIT(J,I) = EXCIT(J,I)*1.0E-6
151  CONTINUE
TYPE 8000,RECOM(4,20),EXCIT(4,20)
8000  FORMAT(2E12.3)
RETURN
END
SUBROUTINE OXY(T,RECOMX,EXCITX,RECHX)
C      REMEMBER TO PUT FIRST DIMENSION STATEMENT IN CALLING ROUTINE
DIMENSION EXCITX(25),RECOMX(25)
DIMENSION TEMP(100),RECOM(25,100),EXCIT(25,100)
COMMON /FIT/ RECOM,EXCIT,TEMP,RECOMH
DIMENSION RECOMH(10,100)
DO 10 I=1,41
ISAV = I
10  IF(T.LT.TEMP(I)) GO TO 20
C  THIS IS LINEAR INTERPOLATION REPLACE WITH THE SPLINE
20  FACTOR = (T-TEMP(ISAV-1))/(TEMP(ISAV)-TEMP(ISAV-1))
DO 30 J=1,8
EXCITX(J) = FACTOR*(EXCIT(J,ISAV)-EXCIT(J,ISAV-1))
1 + EXCIT(J,ISAV-1)
30  RECOMX(J) = FACTOR*(RECOM(J,ISAV)-RECOM(J,ISAV-1))
1 + RECOM(J,ISAV-1)
DO 31 J=12,24
EXCITX(J) = FACTOR*(EXCIT(J,ISAV)-EXCIT(J,ISAV-1))
1 + EXCIT(J,ISAV-1)
31  RECOMX(J) = FACTOR*(RECOM(J,ISAV)-RECOM(J,ISAV-1))
1 + RECOM(J,ISAV-1)
DO 99 J=1,1
RECHX=FACTOR*(RECOMH(J,ISAV)-RECOMH(J,ISAV-1))
1 +RECOMH(J,ISAV-1)
99  CONTINUE
RETURN
END

```



```

SUBROUTINE CIRPAM
C*****
C
C      COMMON AREA FOR CIRCUIT QUANTITIES
      COMMON/CIRC/VC01,ANTR,C,ALE,RE,ALM,ALP0,VC0,AL,S,RMA,RMI,BZ0,VC
1    ,VP,VRP,THETA,RFORM,ALP,TCB
C
C*****
      C1=30600.E-06
      ALE1=0.097E-06
      RE1=1.567E-05
      ALM=10.E-06
      RMA=1.14
      FACTOR=1.
      ALP0=2.*3.14E-7*RMA*FACTOR
      RMI=.2
      AL=2.*3.14*RMA
      S=3.14*RMI*RMI
C  CIRCUIT PARAMETERS ARE TRANSFORMED TO THE SECONDARY
      ANTR2=ANTR*ANTR
      C=C1*ANTR2
      VC0=VC01/ANTR
      ALE=ALE1/ANTR2
      RE=RE1/ANTR2
      RETURN
      END
      SUBROUTINE AIRON(TEV,FP,FZ,FZ2)
      TKEV=TEV*.1E-3
      IF(TKEV.LT.2.E-2) GO TO 1
      IF(TKEV.GT.20.) GO TO 2
      IF(TKEV.GT.2.E-2.AND.TKEV.LT.2.E-1) GO TO 3
      IF(TKEV.GT.2.E-1.AND.TKEV.LT.2.) GO TO 4
      A0=-16.71042
      A1=-16.46143
      A2=37.66238
      A3=-39.44080
      A4=19.18529
      A5=-3.509238
      B0=14.78150
      B1=69.45311
      B2=-199.1202
      B3=265.3804
      B4=-163.1423
      B5=37.70026
      C0=118.1937
      C1=3464.816
      C2=-9953.434
      C3=13280.83
      C4=-8173.660
      C5=1891.447
      GO TO 5
4    A0=-18.34973
      A1=-1.252028
      A2=-7.533115
      A3=-3.289693
      A4=28.66739
      A5=28.30249
      B0=19.59496
      B1=19.97852
      B2=9.593373

```

```

B3=-76.09962
B4=-100.7190
B5=-11.44948
C0=380.5212
C1=790.9700
C2=607.7125
C3=-2903.599
C4=-5150.387
C5=-1053.747
GO TO 5
3  H0=-27.52599
    A1=-39.00220
    A2=-64.69423
    A3=-55.55648
    A4=-24.05568
    A5=-4.093160
    B0=8.770316
    B1=-55.81412
    B2=-122.5124
    B3=-161.3985
    B4=-39.14244
    B5=-5.851445
    C0=-1.629057
    C1=-2030.262
    C2=-4720.863
    C3=-4299.215
    C4=-1797.781
    C5=-287.9963
5   AAA=A0+A1**ALOG10(TKEV)+A2*(ALOG10(TKEV))**2+
1   A3*(ALOG10(TKEV))**3+A4*(ALOG10(TKEV))**4+
1   A5*(ALOG10(TKEV))**5
    FP=10.**AAA
    FZ=B0+B1*ALOG10(TKEV)+B2*(ALOG10(TKEV))**2+
1   B3*(ALOG10(TKEV))**3+B4*(ALOG10(TKEV))**4+
1   B5*(ALOG10(TKEV))**5
    FZ2=C0+C1*ALOG10(TKEV)+C2*(ALOG10(TKEV))**2+
1   C3*(ALOG10(TKEV))**3+C4*(ALOG10(TKEV))**4+
1   C5*(ALOG10(TKEV))**5
    GO TO 100
2   FP=0.
    FZ=26.
    FZ2=676.
    GO TO 100
1   CONTINUE
    FZ=1.
    FZ2=1.
100  CONTINUE
      RETURN
      END

```

APPENDIX III

INPUT DIALOG

```
FILLING DENSITY IN UNITS OF  $10^{21}$ 
3.5
OXYGEN IMPURITY FRACTION
0.0
ALUMINUM IMPURITY FRACTION
0.0
IRON IMPURITY FRACTION
0.0
1=CONSTANT IMPURITY 2=ADDITIONAL IMP INFLUX(OIV)
1
ION TEMP IN EV
1
ELECTRON TEMP IN EV
1
INITIAL ELECTRON DENSITY (  $10^{21}$  cm-3)
0.035
BANK VOLTAGE(KV) TRANS. RATIO TOROID. BIAS FIELD(T) AND CROW-BAR TIME(MICROSEC)
8.,.25,.25,100.
:PRINT:=1,IMPUR POUT;-2,CIRC POUT;-3,FLUX & EN. POUT
1
FIELD FLUCT. RELATIVE AMPL.
0.0
ITRLOS1=1,NO SCALING; -2,5%-.5 SCALING
1
ICD=1,CLASS. DIFF. TERM INCL.; ICD=0,NOT INCL.
1
DO YOU WANT NON-RADIATIVE LOSS TERMS? 1=NO 2=ELECTRONS+IONS 3=ELECTRONS ONLY 4=IONS ONLY
1
TIME STEP FOR PRINTOUT
1
TOTAL TIME
10
```

APPENDIX IV

EXAMPLE OF THE THREE PRINTOUTS

TYPE FOR31.DAT														
FINAL NE START	NE	OXYGEN	ALUMINUM	IRON	DOUBLING	KU	BIAS CB	TIME	FLUC	SCAL	DIFF	ELOSS	ILOSS	TR RATIO
3.50E+14	3.50E+12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.0	0.25	100.0	.00	1	1	1	1	0.25
TE	TI	II	III	IV	UI	UII	UIII	UC	UD	UE	UF	UG	UH	UI
1.0	1.0	1.00	0.00	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
2.0	1.0	1.00	0.00	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
3.0	0.8	.99	.01	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
4.0	0.7	.98	.02	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
5.0	0.6	.96	.04	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
6.0	0.5	.93	.07	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
7.0	0.4	.89	.11	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
8.0	0.4	.85	.15	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
9.0	0.5	.79	.21	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
10.0	0.5	.72	.28	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
		.14	.85	.01	0.00	0.00	.00	.00	.00	.00	.00	.00	.00	.00
.TYPE FOR32.DAT														
FINAL NE START	NE	OXYGEN	ALUMINUM	IRON	DOUBLING	KU	BIAS CB	TIME	FLUC	SCAL	DIFF	ELOSS	ILOSS	TR RATIO
3.50E+14	3.50E+12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.0	0.25	100.0	.00	1	1	1	1	0.25
TE	TI	II	III	IV	UI	UII	UIII	UC	UD	UE	UF	UG	UH	UI
1.00E+00	1.01E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00	1.07E+00
2.00E+00	9.84E-01	3.51E+00	3.68E+12	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02
3.00E+00	8.49E-01	4.11E+00	4.43E+12	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02
4.00E+00	6.06E-01	4.30E+00	5.68E+12	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01
5.00E+00	5.61E-01	4.52E+00	7.63E+12	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01
6.00E+00	4.67E-01	4.57E+00	1.05E+13	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01
7.00E+00	4.19E-01	4.56E+00	1.45E+13	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01
8.00E+00	4.18E-01	4.53E+00	2.00E+13	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01
9.00E+00	4.59E-01	4.48E+00	2.67E+13	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01
1.00E+01	5.40E-01	4.42E+00	3.50E+13	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01
.TYPE FOR33.DAT														
FINAL NE START	NE	OXYGEN	ALUMINUM	IRON	DOUBLING	KU	BIAS CB	TIME	FLUC	SCAL	DIFF	ELOSS	ILOSS	TR RATIO
3.50E+14	3.50E+12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.0	0.25	100.0	.00	1	1	1	1	0.25
TE	TI	II	III	IV	UI	UII	UIII	UC	UD	UE	UF	UG	UH	UI
1.00E+00	1.97E+00	3.50E+12	1.68E+04	3.20E-02	3.20E-02	3.20E-02	3.20E-02	3.20E-02	3.20E-02	3.20E-02	3.20E-02	3.20E-02	3.20E-02	3.20E-02
2.00E+00	3.51E+00	3.68E+12	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02	3.37E-02
3.00E+00	4.11E+00	4.43E+12	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02	7.98E-02
4.00E+00	4.30E+00	5.68E+12	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.39E-01
5.00E+00	4.52E+00	7.63E+12	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01	2.15E-01
6.00E+00	4.57E+00	1.05E+13	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01	3.09E-01
7.00E+00	4.57E+00	1.45E+13	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01	4.20E-01
8.00E+00	4.57E+00	2.00E+13	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01	5.52E-01
9.00E+00	4.59E+00	2.67E+13	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01	6.91E-01
1.00E+01	4.42E+00	3.50E+13	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01	8.44E-01