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ABSTRACT

The zero-dimensional code SCORCH determines number density and temperature evolution in plasmas using concepts derived from the Hinton and Hazeltine transport theory. The code uses the previously reported ADL-1 data library.

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CHARGED-PARTICLE TRANSPORT THE; ELECTRON DENSITY; ELECTRON TEMPERATURE; ENERGY LOSSES; IMPURITIES; ION DENSITY; ION TEMPERATURE; PLASMA; S CODES; TOKAMAK DEVICES

CONTENTS

1. INTRODUCTION

Since the early 1970s, the tokamak has shown increasingly better performance in plasma confinement than other fusion devices, hence it is attracting effort in both experiment and conceptual design studies. Before the advent of neutral beam injection heating in the Princeton large torus (PLT), a great deal of interest was directed at the maximum plasma core temperatures attainable with ohmic heating alone. Hugill and Sheffield [1978] reviewed various machine parameters in an effort to find scaling laws for energy confinement times so that extrapolation to larger dimensions and confinement times could be carried out. Their survey provides a useful set of benchmark data against which to check zero and one-dimensional code predictions for hydrogen and deuterium plasmas.

In the first comprehensive review of conceptual D-T design studies, Ribé [1975] considered in depth the power balance problem arising from alpha particle and ohmic heating, bremsstrahlung, ion and electron heat transport, and synchrotron losses. He predicted an ignition temperature of the order of 7 keV from D-T fusion. Ribé also gave an elementary treatment of neoclassical theory, but neglected impurity problems.

A year later, Hinton and Hazeltine [1976] presented their famous review of plasma transport theory for ions and electrons in toroidal systems. In a comprehensive analysis of previous theories, they gave the diffusion coefficients for the three well-established 'banana' (or collisionless), plateau and Pfirsch-Schlüter regimes for the collision frequency. They also gave the heat transport coefficients, *e.g.* the thermal and electrical conductivities of electrons and ions. It is quite apparent, from their two-ion species theory, that impurities such as oxygen, iron, molybdenum or tungsten could make the multiple species problem immensely complex.

Watkins *et al.* [1976] gave details of ICARUS, a one-dimensional plasma diffusion code, and reported on the difficulties experienced by previous authors in obtaining agreement with measured electron and ion number density profiles and, similarly, with temperature profiles. Watkins *et al.* and Hinton and Hazeltine both gave smoothing functions for the effective collision frequency. The former also solved the coupled radial and time-dependent equations using finite difference schemes.

Many such one dimensional codes followed, and Ortolani [1980] put forward the concept of a zero-dimensional plasma model based on the analogous time-dependent neutron transport theory. Principally, the buckling factor B [Glasstone and Edlund 1958] is introduced by assuming that the electron and ion number density profiles obey the diffusion equation: the leakages of ions and electrons at the edge of the profiles are $D_e B^2$ and $D_i B^2$, respectively, where D is the diffusion coefficient. The same assumption is made for the temperature profiles which obey heat diffusion equations. There are many empirical formulas for fits to such measured profiles and, in principle, the buckling can be varied, as is done in reactor physics, with the geometry of the system. Ortolani does not actually use this method, but introduces the effective charge Z_{eff} measured by the ratio of the observed electron conductivity over the classical theoretical conductivity [Spitzer 1956].

2. SCORCH DEVELOPMENT

Our studies of tokamak behaviour began with a simple corona model for hydrogen isotope plasmas, using data presented at the Atomic and Molecular Data for Fusion Conference [Lorentz 1977]; we also took account of oxygen, iron, molybdenum and tungsten impurity radiation using an average ion impurity model. A data library [Clancy *et al.* 1981] was developed using power rate coefficients and Z_{eff} values calculated by Post *et al.* [1977]. Since the work of Ashby and Hughes [1981], it has become increasingly apparent that these impurity data are crucial to the temperature stability of such large projected systems as INTOR (international torus concept), owing to line radiation, recombination radiation and bremsstrahlung losses from the cool plasma edge. A extensive review of neoclassical transport of impurities in tokamak plasmas was made by Hirshman and Sigmar [1981], but as yet there is no code which employs their rigorous treatment of the problem.

The widespread interest in such studies, on small and large machines, and our interest in participating in such work, has led to the development of a zero-dimensional, time-dependent code SCORCH. The whole code uses SI units.

After reviewing the Hinton and Hazeltine transport coefficients, the transport equations and the use of buckling to represent the special number density and temperature profiles are discussed. The solution of the time-dependent rate equations for particle number and power losses and gains is dealt with in Section 4; Section 5 gives a detailed description of how losses and gains can be computed from various theories or simply read in from the ADL-1 data library [Cook *et al.* 1981]. Finally the code input parameters for the toroidal configuration are discussed, together with the starting values of number densities and temperatures for electrons and ions. The sequence of operations of SCORCH follows from Sections 3, 4 and 5.

Appendix A contains a sample listing of input and output for Ribé's reactor at an arbitrary initial time t = 0. The negative electron thermal conductivity of Hinton and Hazeltine [1976] is due to a fault in their equation (17) and represents the contribution from the second term on the left of equation 1(ii). When the losses are summarised, the net loss is positive. It must be recalled that in Ribé's predictions, the electron thermal conduction is anomalous and ought to be about the same size as the ion thermal conduction loss. As yet, there is no rigorous theory for this anomaly.

Although much research is under way to determine how to scale the appropriate transport coefficient, the best that can be said [Hugill 1981] is that if the electron thermal conductivity is taken to be approximately equal to the ion thermal conductivity (which classically is 43 times larger), this at least gives an estimate of its value. Recently, Hirshman and Molvig [1981] gave a useful temperature-dependent law which states that the electron thermal conductivity is given by

$$\chi_e = \frac{T_e^{1/2}}{n_e a} G\ (T_i/T_e)$$

where $G(x) = \frac{x^{3/2}}{(1+x)^4}$.

This law is at least consistent with the Hugill [1981] correction.

3. TRANSPORT COEFFICIENTS

In their notation, Hinton and Hazeltine [1976] define the inner products for electron transport at given points in space and time:

$$\text{(i)} \quad -(\alpha_1, g_{1e}) = n_e\, \varepsilon^{1/2}\, \rho_{e\theta}^2\, K_{11}$$

$$\text{(ii)} \quad -(\alpha_1, g_{2e}) - \frac{5}{2}(\alpha_1, g_{1e}) = n_e\, \varepsilon^{1/2}\, (\rho_{e\theta}^2/\tau_e)\, K_{12}$$

$$\text{(iii)} \quad -(\alpha_2, g_{2e}) - 5(\alpha_1, g_{ie}) - \frac{25}{4}(\alpha_1, g_{ie}) = n_e\, \varepsilon^{1/2}(\rho_{e\theta}^2/\tau_e)\, K_{22}\ ,$$

$$\text{(iv)} \quad -(\alpha_1, g_{3e}) = \varepsilon^{1/2}(n_e/B_{po})\, K_{13}$$

$$\text{(v)} \quad -(\alpha_2, g_{3e}) - \frac{5}{2}(\alpha_1, g_{3e}) = \varepsilon^{1/2}(n_e/B_{po})\, K_{23}\ ,$$

$$\text{(vi)} \quad -(\alpha_2, g_{3e}) = \varepsilon^{1/2}\left(\frac{\sigma_{11}}{k\ Te}\right) K_{33} \qquad (1)$$

where $\varepsilon = r_o/R$ is the inverse aspect ratio, r_{ot} is the minor radius, and R is the major radius;

$$\rho_{e\theta}^2 = \frac{2\ m_e k\ Te}{e^2 B_{po}^2}\ ,$$

where $\rho_e\theta$ is the gyroradius of the electron in the poloidal field (m), k is Boltzmann's constant, m_e is the electron mass (kg), T_e is the electron temperature (K), e is the electric charge in SI units (C), B_{po} is the poloidal magnetic field (T);

$$\frac{1}{\tau_e} = \frac{4}{3}\sqrt{(2\pi)}\,(n_i\, Z_{eff}^2\, e^4\, ln\Lambda/(m_e^{1/2}[k\ T_e]^{3/2}) \qquad (3)$$

where τ_e is the electron-ion collision time, n_e is the electron number density m^{-3}, and n_i is the total ion number density (m^{-3}); and

$$Z_{eff} = \sum_{j=1}^{N} Z_j^2 n_j / \sum_{j=1}^{N} Z_j n_j \quad (4)$$

the effective ionic charge.

The derivations and meanings of these coefficients are fully discussed in Hinton and Hazeltine's review article.

The ADL-1 data library contains the tabulations of Z_j; the ionic charge, as a function of temperature n_j (T_j), is the number density of ion species , and T_j the temperature of the ion species. The coulomb logarithm $ln\Lambda$ is taken as 20 [Glasstone and Loveberg 1960] to which the code applies the Braginski [1965] correction. Local charge balance is assumed throughout the code, *i.e.*

$$\sum_{j=1}^{N} n_j Z_j = n_e , \quad \overline{Z}_i = \sum_{j=1}^{N} n_j Z_j^2 = Z_{eff} \quad (5)$$

for N species.

In equation 1(vi) electron conductivity is parallel to the current, and related to Spitzer's classical conductivity theory by

$$\text{(i)} \quad \sigma_{11} = \frac{n_e e^2 \tau_e}{m_e} f(\overline{Z}_i),$$

$$\text{(ii)} \quad f(\overline{Z}_i) = \left[0.29 + \frac{0.46}{1.08 + Z_i} \right]^{-1} \quad (6)$$

The values of transport coefficient matrix K_{mn} were generalised by Hinton and Hazeltine [1976] to define the three electron regimes by the relations

$$K_{mn} = K_{mn}^{(o)} \frac{1}{1 + a_{mn} \upsilon_{*e}^{1/2} + b_{mn} \upsilon_{*e}} + \frac{\varepsilon^{1/2} (c_{mn}^2 / b_{mn}) \upsilon_{*e} \varepsilon^{1/2}}{1 + c_{mn} \upsilon_{*e} \varepsilon^{3/2}} \quad m,n = 1, 2 \quad (7)$$

$$K_{m3} = K_{m3}^{(o)} [1 + a_{m3} \upsilon_{*e}^{1/2} + b_{m3} \upsilon_{*e}]^{-1} [1 + c_{m3} \upsilon_{*e} \varepsilon^{3/2}]^{-1} \quad (8)$$

where $K_{mn}^{(o)}$, a_{mn}, b_{mn} and c_{mn} are the constants tabulated by Hinton and Hazeltine for values of Z_i of 1, 2 and 4 by fits to the total electron-ion collision frequency υ_{*e}. This is defined by the equation

$$\upsilon_{*e} = \frac{\sqrt{(2)}\, r_o B_o}{B_{po} v_{the} \tau_e \varepsilon^{3/2}} \quad (9)$$

where $B_o \cong [\langle B^2 \rangle]^{1/2}$, the average toroidal magnetic field, taken as input values and

$$v_{the} = \sqrt{(2kT_e/m_e)}$$

the thermal velocity of the electron.

The coefficients K_{ln} (Z_i), K_{2n} (Z_i) are fitted to Z_i by the relationships obtained from SUPERFIT [Clancy 1977]:

$$\text{(i)} \quad K_{11}^{(o)} = 0.67 + \frac{0.37}{Z_i} \qquad \text{(ii)} \quad K_{12}^{(o)} = 0.71 + \frac{0.49}{Z_i}$$

$$\text{(iii)} \quad K_{22}^{(o)} = 1.43 + \frac{1.12}{Z_i} \qquad \text{(iv)} \quad a_{11} = 2.30 - \frac{0.38}{Z_i}$$

$$\text{(v)} \quad a_{12} = 0.81 - \frac{0.05}{Z_i} \qquad \text{(vi)} \quad a_{22} = 0.47 - \frac{0.01}{Z_i}$$

$$\text{(vii)} \quad b_{11} = 0.80 - \frac{0.73}{Z_i} \qquad \text{(viii)} \quad b_{12} = 0.34 + \frac{0.33}{Z_i}$$

$$\text{(ix)} \quad b_{22} = 0.13 + \frac{0.29}{Z_i} \qquad \text{(x)} \quad c_{11} = 0.69 + \frac{0.2}{Z_i}$$

$$\text{(xi)} \quad c_{12} = 0.45 + \frac{0.11}{Z_i} \qquad \text{(xii)} \quad c_{22} = 0.25 + \frac{0.17}{Z_i} \tag{10}$$

With regard to the ion particle transport, charge balance ensures that the total ion number density can be found from equation (5); this is not the case for ion thermal transport. Using Hinton and Hazeltine's notation, ion thermal conductivity is given by

$$-(\beta_2 g_{2i}) = n_i \, \varepsilon^{1/2} (\rho_{i\theta}^2/\tau_i) K_2 \tag{11}$$

$$\text{where} \quad \rho_{i\theta}^2 = \frac{2\bar{m}_i \, kT_i}{\bar{Z}_i^2 \, e^2 \, B_{po}^2}$$

the ion gyroradius squared, T_i is the ion temperature (K), all ions are assumed to be at an averaged temperature T_i, $\bar{m}_i$ is an effective ion mass (to be defined by equation (24)

$$K_2 = K_2^{(o)} \frac{1}{1+a_2 \, \upsilon_{*i}^{1/2} + b_2 \, \upsilon_{*i}} + \frac{\varepsilon^{1/2}(c_2^2/b_2) \, \upsilon_{*i} \, \varepsilon^{3/2}}{1+C_2 \, \upsilon_{*i} \, \varepsilon^{3/2}} \tag{12}$$

$$\upsilon_{*i} = \frac{\sqrt{(2)} \, r_o B_o}{B_{po} \, v_{thi} \, \tau_i \, \varepsilon^{3/2}} \tag{13}$$

the effective ion-ion collision frequency,

$$\frac{1}{\tau_i} = \frac{4}{3}\sqrt{(\pi)} \, \frac{n_i Z_i^4 e^4 ln \Lambda}{m_i^{1/2}(kT_i)^{3/2}} \quad \text{and} \tag{14(i)}$$

$$v_{thi} = \left(\frac{2kT_i}{m_i}\right)^{1/2} \tag{14(ii)}$$

the averaged ion thermal velocity.

All ions are assumed to be at the same local temperature. The constants in equation (12) are

$K_2^{(o)} = 0.66$, $a_2 = 1.03$, $b_2 = 0.31$, $c_2 = 0.74$

4. TREATMENT OF TRANSPORT EQUATIONS

In terms of the transport coefficients K_{mn} in equation (7), the electron particle current can be written, according to Hinton and Hazeltine [1976], as

$$\Gamma_e = -n_e \varepsilon^{1/2}(\rho_{e\theta}^2/\tau_e) K_{11} \, A'_{1e} + K_{12} \frac{\partial}{\partial r} (ln \; T_e) - \frac{K_{13} \, n_e \; \varepsilon^{1/2} \langle E_{\parallel}/h \rangle}{B_{po}} \tag{15}$$

The last term involves the electric field $E_{\parallel}$ in the direction of the plasma current. This term is usually quite small and requires a knowledge of the current density profile $\underset{\sim}{J}(r)$, through Ohm's law

$$\underset{\sim}{E}_{\parallel} = \underset{\sim}{J}/\sigma_{\parallel}$$

Either a measured current density profile or, as is done in the code, Ampere's law from B_{Pol}, can be used to determine the current

$$I = \underset{\sim}{J}.dA$$

where dA is the cross-sectional area of the toroidal column. In its present form the code uses the latter option, but it can be modified to produce the former. The force A'_{1e} is

$$A'_{1e} = \frac{\partial}{\partial r}(ln\ p_e) - \frac{5}{2}\frac{\partial}{\partial r}(ln\ T_e) + \frac{T_i}{Z_i T_e}\left[\frac{\partial}{\partial r}(ln\ p_i) - \frac{(\beta_{\|} g_{2i})}{1+\upsilon_{*e}^2 \varepsilon^2}\right] \tag{16}$$

where p_e is the electron plasma pressure, p_i is the ion plasma pressure, and

$$(\beta_1 , g_{2i}) \quad \frac{\frac{5}{2} - y - 2.1\ \upsilon_{*i}^2 \varepsilon^3}{1 + \upsilon_{*i}^2\ \varepsilon^3} ,$$

$$\text{where} \quad \frac{5}{2} - y = \frac{1.17 - 0.35\ \upsilon_{*i}^{1/2}}{1 + 0.7\ \upsilon_{*i}^{1/2}}$$

The electron heat conduction q_e is given by

$$q_e + \frac{5}{2} k\ T_e\ \Gamma_e = -\ n_e\ kT_e\ \varepsilon^{1/2}(\varepsilon_{c\theta}^2/\tau_e)\left\{K_{12}A'_{12} + K_{22}\frac{\partial}{\partial r}(\ ln\ T_e)\right\} \tag{17}$$

where the electric field term is again excluded. A one-dimensional code integrates these two equations over the radial distance r, recognising as a starting value all coefficients as a function of r at time t_o. Now the ideal gas laws

$$\text{(i)} \quad p_e = n_e kT_e$$

$$\text{(ii)} \quad p_i = n_i kT_i \tag{18}$$

apply locally; therefore

$$\frac{\partial\ ln\ p_e}{\partial r} = \frac{\partial\ ln\ n_e}{\partial r} + \frac{\partial\ ln\ T_e}{\partial r} , \tag{19}$$

from which the number density derivative can be found by substituting equation (19) into equations 15 and 17 and solving for

$$\frac{\partial\ ln\ n_e}{\partial r}, \frac{\partial\ ln\ T_e}{\partial r} .$$

The same procedure holds for the effective ion equations. This assumption is not used in the code but, when used to solve the transport equations in zero dimensions, it is always approximately correct.

The next problem is how to construct a zero-dimensional model so that numerical integration over time t can be performed more readily. If the coefficient of $\partial n_e/\partial r$ is regarded as a diffusion coefficient $D_e(r)$, the buckling could be defined by

$$B^2 = \frac{A\ D_e(r_o)(\partial n_e/\partial r)r_o}{D(r_1)n_e(r_1)V}$$

where A is the surface area of the plasma torus, r_o is the distance to the limiter, and r_1 is any reference point, such as $r = 0$. To use this notion, profiles for $n_e(r)$, $T_e(r)$ and $R_e(r)$ must be postulated. The present version of the code uses

$$\text{(i)} \quad n_e(r) = n_e(o)\left\{1 - c_n\ (r/r_o)^2\right\}$$

$$\text{(ii)} \quad T_e(r) = T_e(o)\left\{1 - c_e\ (r/r_o)^2\right\} \quad \text{and} \tag{21}$$

$$\text{(iii)} \quad T_i(r) = T_i(o)\left\{1 - c_i\ (r/r_o)^2\right\}$$

where the constants c_n and c_i are known as 'pedestals'. To make the best use of these formulas, the pedestals should be given in terms of their values at the limiter, because introduction of impurities from outgassing and sputtering are strong functions of n_i and T_i at this limit; if the limiter is not present the values at the wall should be used. If profiles 21 are inadequate, other types of profile can be used and the leakage rates as losses are obtained in the forms

$$L_n = D\, B_n^2\, n(r_1)\, V = \text{particle leakage rate,}$$

$$H = \kappa\, B_T^2\, (kT(r_1))\, V = \text{energy leakage rate or power loss by thermal transport, and}$$

$$\kappa = \text{an effective thermal conductivity.}$$

Profiles 21, evaluated at, say, r_1 and r_0 and Γ_e, Γ_i, q_e, q_i from the derivatives of ln $n_e(r)$ and $T_e(r)$ are then substitutes. The classical collision terms τ_e and τ_i can be obtained from the coulomb scattering rate coefficient σv [Glasstone and Loveberg 1960]:

$$\tau_e = \frac{1}{n_i \sigma_{ei} v_e}, \quad \tau_i = \frac{1}{n_i \sigma_{ii} v_i}$$

SCORCH then uses the appropriate rate coefficients in ADL-1 with $ln\Lambda$ set equal to 20. The buckling concept actually finds that representative point in a profile where the average of the specified quantity is the same function evaluated at the averaged point. This subject is discussed extensively in reactor physics literature (for example, the classic work of Weinberg and Wigner [1958]).

5. TIME-DEPENDENCE

In their work on the ADL-1 library, Clancy et al. [1981] gave the rate equations for number densities. To generalise these, we write for all species

$$\frac{dn_j}{dt} = \sum_i \lambda_{ij}\, n_i - (\sum_j \lambda_{ji} n_j) - L_j + S_j n_j \tag{22}$$

where L_j is the particle leakage rate, S_j is the source injection rate, and the λ_{ij} are the loss or gain rate coefficients discussed in the text. For the power loss and gain rates, where $T_j = F_e$, $T_j = T_i$, species by species

$$k\,\frac{dT_j}{dt} = -\sum_k n_e n_k\, P_{ek} - H_j + P_\Omega + P_\alpha n_D n_T$$

$$- n_e n_i P_{br} - P_{sy} + P_{eq} + P_L + S_{RF}\,,\ etc. \quad (\text{W m}^{-3}) \tag{23}$$

where P_{ek} is the power rate coefficient for radiative losses of all varieties; P_Ω is the ohmic heating term going directly to the electrons P_α is the fusion alpha-particle heating power rate coefficient in D-T plasma if required, 13/14 of which goes to heating the electrons directly; P_{br} is the bremsstrahlung loss for the electron equation only; S_j is a source of particles such as neutral or ion beam injection; S_{RF} is a source heating rate such as RF heating (or particle injection heating); H_j is a heat loss term due to particle loss; P_{eq} is an equilibration exchange term defined in Section 5, and P_{sy} is the electron synchrotron radiation loss.

SCORCH assumes that the current discharge into the plasma has attained a steady-state plasma current and from an initial arbitrary time, possibly quite early in the shot, all transport equations described in Section 3 apply. Use is then made of an Argonne Code Center standard code GEAR, which requires the function values η_e, T_e, T_i and their derivatives $\partial n_e/\partial t$, $\partial T_e/\partial t$, $\partial T_i/\partial t$, and integrates Equations (22) and (23) over time from specified input values. Equations (22) and (23) are 'stiff', which means that large variations in variables have a small effect, and ordinary difference schemes often do not function correctly; GEAR takes this into account. Species by species solutions of the rate equations are then group-collapsed using an effective mass for the ions

$$m_i = \frac{\sum_{j=1}^{N} \eta_j\, m_j}{\sum_{j=1}^{N} \eta_j} \tag{24}$$

where $\bar{\upsilon}_{ej}$ is the average electron-ion collision frequency. Equations (5) are then used to give the net Z_{eff}. $\bar{m}_i$ and $\bar{Z}_i$ are the ionic mass and charge seen by the electron.

6. POWER LOSSES AND GAINS

6.1 Bremsstrahlung

The code calculates the bremsstrahlung power rate coefficient from Spitzer's formula

$$P_{br} = (2\pi k T_e/3m_e)^{1/2} \times \frac{2^5 \pi e^6}{3hm_e} (\bar{Z}_i)^2 f_G \tag{25}$$

where h is Planck's constant. As the data of Post et al. [1977] contain this contribution added to the line radiation contribution, in ADL-1, the rate coefficients (25) are subtracted from them. SCORCH also evaluates the Gaunt factor f_G, which modifies the low-temperature behaviour by an empirical fit to the curve reported by Harzas and Latter [1960]. This curve gives f_G as a function of γ_i^2, where

$$\gamma_i^2 = \frac{Z^2 Ry}{kT_e} \tag{26}$$

and Ry is Ryberg's constant. The fit gives

$$f_G(Z_i, T_e) = \frac{6.35+z\,(0.582+z\,)}{(4.33+z\,[0.432+z\,])(1+0.025\,exp\,(z\,))}$$

$$z = log_{10}\,\gamma_i^2$$

The upper end of the temperature range is not sufficiently high to warrant relativistic corrections.

6.2 Synchrotron Radiation

Ribé [1975] reported the following formula for the power density

$$P_{sy} \approx \frac{2.9 \times 10^{-19}\, \eta_e^{1/2}\, T_e^{11/4}\, B_o^{5/2}}{\sqrt{r_1}} (1-R_r)\ (\mathrm{W\ m^{-3}}) \tag{27}$$

where R_r is the reflection coefficient of the well and T_e is in electron volts. The origin of this formula is obscure and, despite literature searches, we have not been able to locate its derivation. The classical mechanical formula is [Glasstone and Loveberg 1960]

$$P_{sy} = \frac{4e^4 k}{3\pi\varepsilon_o m_e^3 c^3} B_o^2\, \eta_e\, T_e\,, \quad (\mathrm{W\ m^{-3}}) \tag{28}$$

Where ε_o is the permittivity of free space in SI units and, c is the velocity of light in SI units. Equation (28) is used in the present version of the code with an optional input correction for wall reflection. In fact, all losses and gains contain a correction factor which is part of the input.

6.3 Ohmic Heating

The rate of ohmic heating is given by the power density

$$P_\Omega = \frac{1}{\sigma_{||}} J^2 \quad (\mathrm{W\ m^{-3}}) \tag{29}$$

where J is the current density. Ribé also quotes the relationship

$$P_\Omega = \frac{0.5\, J^2\, \chi\, ln\, \Lambda}{T_e} \quad (\mathrm{W\ m^{-3}}) \tag{30}$$

where χ is a correction factor and T_e is again in eV.

6.4 Fusion Alpha Heating

Fusion alpha heating is obtained from the ADL-1 rate coefficient for D-T fusion and is simply

$$P_\alpha = \eta_D\, \eta_T\, \sigma_i v_i\, E_\alpha \quad (\mathrm{W\ m^{-3}}) \tag{31}$$

where E_α is the emitted α-energy. The electron heat transport and ion heat transport losses are obtained in the way discussed in Section 4.

6.5 Equilibration Exchanges

The hotter species, usually the electrons, will undergo energy losses by coulomb collisions with ions. This equilibration loss for electrons and gain for ions was given by Spitzer [1956] as

$$P_{eq} = \frac{k(T_i - T_e)}{\tau_{eq}} \tag{32}$$

where

$$\tau_{eq} = \frac{3 m_e m_i \, k^{3/2}}{8\sqrt{(2\pi)}\eta_i \, Z_i^2 \, ln\Lambda} \left\{\frac{T_e}{m_e} + \frac{T_i}{m_i}\right\}^{3/2} \tag{33}$$

This can be related to τ_e by the equation

$$\tau_{eq} \approx \frac{1}{2}(m_i/m_e)\,\tau_e \tag{34}$$

since $m_i/m_e > 1800$.

The only loss that has not been taken into account is charge exchange, which could be quite important. The rate coefficients for this process are being evaluated.

7. CODE INPUT AND OUTPUT

Appendix A contains a listing of the input data for the parameters of the Ribé [1956] conceptual reactor. The AAEC program SCAN provides a free format input which ignores lettering; only the sequence of numbers has to be correct. Experimentalists normally do not give values of B_{po}, but measure a safety factor

$$q = \frac{r}{R}\frac{B_o}{B_{po}} = \varepsilon\frac{B_o}{B_{po}} \tag{35}$$

This usually takes a value of about 2 or 3. The code uses Equation (35) to compute B_{po}. Other parameters quoted in design characteristics are the ratios of the plasma pressure to the magnetic pressure

$$\text{(i)} \quad \beta_o = \frac{p}{B_o^2/2\,\mu_o} \tag{36}$$

$$\text{(ii)} \quad \beta_{po} = \frac{p}{B_{po}^2/2\,\mu_o}$$

where μ_o is the magnetic permeability of free space, in SI units, which are usually such that $\beta_o \sim 0.5$ per cent or so in tokamaks. The current can be used, *via* Ampere's law, to determine $q(r_e)$, where r_e is the plasma edge. On average, the current density is just

$$J = \frac{I}{A} \quad (A\ m^{-2}) \tag{37}$$

and the loop voltage is as used to measure Z_{eff},

$$V_o = \frac{1}{\sigma_{\parallel}} I \frac{L}{A} \tag{38}$$

where L is the length around the torus, and A is the cross-sectional area.

In Appendix A is also a listing of the code output for the Ribé [1956] reactor. The energy confinement time, where a simplistic exponential decay of power with time was assumed, is also shown. As the time integration steps are taken by GEAR, output at various times is given and $1/\tau_e$ is plotted against temperature to give a power balance for the reactor, as well as an ignition temperature of about 6 keV.

8. CONCLUSIONS

All aspects of tokamak behaviour relating to power balance and time evolution can be dealt with satisfactorily in zero dimensions, except for the anomalous electron thermal conduction which is, as yet, something of a mystery, and about an order of magnitude greater than the classical predictions. Unless this contribution is included in SCORCH, the code will yield 'runaway' solutions to the time-dependent problem, in which the electrons continue to accumulate heat but the ions stay at the same temperature during the evolution of a discharge.

A review of a range of tokamak parameters was undertaken with successful prediction of the energy confinement time in all cases. Neutral beam injection experiments, however, need to be considered in greater detail to take account of the relationship of beam attenuation, and that of parallel and antiparallel injection, to the current. The only problem not dealt with by SCORCH is radiofrequency heating, an aspect of much interest, although a source term for the input power is available. This, of course, neglects such effects as current drive and anomalous resistivity, both of which are promising fields for future research.

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APPENDIX A

SAMPLE DESCRIPTIVE OUTPUT FROM SCORCH

```
SCANNING CARD INPUT -----------------------------------------------------
        *RIBE'S REACTOR ???
        SPECIES 9 SPECIAL (OXYGEN)
        LIBPRT ETC 0 0 0 10  MINIMUM PRINTOUT
        COEFFICIENT MODIFIERS 4*1 1.E-6 3*1 .003 3*1 LIMITED SYNCHROTRON RADN
        RMINOR 1.5 RMAJOR 7.5 TI -5000 TE -5000
        BPED 0.4 CPED 0.4
        SCE 9*0
        EN 1.E+10 5.E1 1.5E20 7.E11 1.5E20 7.E11 1.E10 1.E10 1.E10
         BEE TOR 12.0 T  AMPS 6.0E6 ZEFF 1.01
        SCE 8*0 9.86E14     OXYGEN INCOMING
--------------------------------------------------------------------------------
ZEFF SET TO                            1.0100
AT R           =       1.06066D+00               1.50000D+00
ION TEMP       =       5.80261D+07               4.35196D+07
ELECT TEMP     =       5.80261D+07               4.35196D+07
ION CONDY      =       1.22419D+19               7.96317D+18
ELECT CONDY    =     -5.63177D+10              -3.59469D+10
SPECIES        EN           D            EN           D            BUCKLING        SPECIES
               /CU.M        M**2/SEC     /CU.M        M**2/SEC     /SQ.M
H+             1.00000D+10  1.59207D-03  7.50000D+09  1.37505D-03  7.67722D-01     H+
HO             5.00000D+01  2.35910D+03  3.75000D+01  1.89727D+03  7.14873D-01     HO
D+             1.50000D+20  1.59207D-03  1.12500D+20  1.37505D-03  7.67722D-01     D+
DO             7.00000D+11  1.17955D+03  5.25000D+11  9.48633D+02  7.14873D-01     DO
T+             1.50000D+20  1.59207D-03  1.12500D+20  1.37505D-03  7.67722D-01     T+
TO             7.00000D+11  7.86367D+02  5.25000D+11  6.32422D+02  7.14873D-01     TO
HELIUM3        1.00000D+10  3.18415D-03  7.50000D+09  2.75011D-03  7.67722D-01     HELIUM3
HELIUM4        1.00000D+10  3.18415D-03  7.50000D+09  2.75011D-03  7.67722D-01     HELIUM4
OXYGEN         5.36768D+16  1.27334D-02  4.02576D+16  1.09977D-02  7.67722D-01     OXYGEN

                                                                   1.39262D+00     ELECTRON TEMPERATURE
                                                                   1.36651D+00          ION TEMPERATURE
PROFAC(1)=     7.5000D-01 AVERAGES ENERGY LEAKING WITH ELECTRONS
PROFAC(2)=     7.5000D-01 AVERAGES ENERGY LEAKING WITH "IONS"
PROFAC(3)=     1.0208D+00 AVERAGES ALL COULOMB REACTION RATES
PROFAC(4)=     1.0208D+00 AVERAGES "LINE" RADIATION
PROFAC(5)=     1.0390D+00 AVERAGES BREMSSTRAHLUNG POWER DENSITY
PROFAC(6)=     1.0078D+00 AVERAGES ELECTRICAL CONDUCTIVITY
PROFAC(7)=     1.0078D+00 AVERAGES EQUILIBRATION ENERGY
PROFAC(8)=     1.0208D+00 AVERAGES PRESSURES AND ENERGY DENSITIES

*RIBE'S REACTOR ???
   9 SPECIES CALCULATION:-:KPRT,JDUMP,LPRT,KITMAX =  0  0  0 10
COEFFICIENT MODIFIERS
 1  * SIJK(I,J,K) ....................  1.000D+00  2  * SOIJ(I,J) ............................  1.000D+00
 3  * DI(I) ..........................  1.000D+00  4  * ION      THERMAL  CONDUCTIVITY ..........  1.000D+00
 5  * ELECTRON THERMAL  CONDUCTIVITY ..  1.000D-06  6  * ELECTRICAL CONDUCTIVITY ...............  1.000D+00
 7  * BREMSSTRAHLUNG POWER ...........  1.000D+00  8  * LINE RADIATION POWERS .................  1.000D+00
 9  * SYNCHROTRON POWER ..............  3.000D-03 10  FRACTION OF CHARGED FUSION FRAGMENTS RETAINED  1.000D+00
11  * IONIZATION ENERGY ..............  1.000D+00 12  LT.EQ.GT 0. CLASSICAL,NEO-CLASS,BOTH COEFFTS    1.000D+00
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MINOR RADIUS .................    1.500D+00 M. HALF-HEIGHT =   1.500D+00 M.
MAJOR RADIUS .................    7.500D+00 M.
ASPECT RATIO & INVERSE .......    5.000D+00          2.000D-01
VOLUME .......................    3.331D+02 M**3
CROSS.SECTIONAL AREA .........    7.069D+00 M**2
SURFACE AREA .................    4.441D+02 M**2
   PARTICLE PEDESTAL (BPED) ..    4.000D-01 =1-N(EDGE)/N(CENTRE)
TEMPERATURE PEDESTAL (CPED) ..    4.000D-01 =1-T(EDGE)/T(CENTRE)
SPEC        MASS         ZNOMNL        Z             SOURCE        VEL            GYRO-RAD     START.VAL
            (AMU)                                  ( /CU.M/S)      (M/S)          (M)  (TOR)   (/CU.M)
H+         1.00000D+00  1.00000D+00  1.00000D+00  0.0            9.82224D+05  8.48414D-04  1.00000D+10
HO         1.00000D+00  0.0          0.0          0.0            9.82224D+05  0.0          5.00000D+01
D+         2.00000D+00  1.00000D+00  1.00000D+00  0.0            6.94538D+05  1.19984D-03  1.50000D+20
DO         2.00000D+00  0.0          0.0          0.0            6.94538D+05  0.0          7.00000D+11
T+         3.00000D+00  1.00000D+00  1.00000D+00  0.0            5.67088D+05  1.46950D-03  1.50000D+20
TO         3.00000D+00  0.0          0.0          0.0            5.67088D+05  0.0          7.00000D+11
HELIUM3    3.00000D+00  2.00000D+00  2.00000D+00  0.0            5.67088D+05  7.34748D-04  1.00000D+10
HELIUM4    4.00000D+00  2.00000D+00  2.00000D+00  0.0            4.91112D+05  8.48414D-04  1.00000D+10
OXYGEN     1.60000D+01  8.00000D+00  7.99800D+00  0.0            2.45556D+05  4.24313D-04  5.36768D+16
ELECTRON                                                         4.19379D+07  1.98706D-05  3.00429D+20
EXTERNAL POWER DENSITY GAINS
TO ELECTRONS                      0.0       WATTS/CU.M
TO IONS                           0.0       WATTS/CU.M
REACTION (  3) ON (  5) GIVING (  8) DEPOSITS  5.640D-13 J ON IONS, 2.260D-12 J ON NEUTRONS
REACTION (  3) ON (  3) GIVING (  7) DEPOSITS  1.314D-13 J ON IONS, 3.925D-13 J ON NEUTRONS
REACTION (  3) ON (  3) GIVING (  1) DEPOSITS  6.456D-13 J ON IONS, 0.0       J ON NEUTRONS
-------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------
------------------------------------- LEAKAGE EDIT ----------------------
ELECTRON  ION          EFFZED     EFF.MASS  LOG-LAMBDA     LARMOR & PLASMA FREQUENCIES
REGIME    REGIME                                           RAD/SEC   RAD/SEC
 BANANA    BANANA       1.01       2.65       17.16        2.115D+12 3.466D+12
NU(E,I)      NU(I,I)      NU(*,E)      NU(*,I)      TEQ(ELECT)   TEQ(N+ION)   TAU(ENERGY)  TAU(PTCLE)
/SEC.        /SEC.                                  SEC.         SEC.         SEC.         SEC.
 4.27922D+04  6.27707D+02  4.68913D-01  4.78338D-01  5.65074D-02  5.64368D-02  2.15587D+01  8.14943D+02
-------------------------------------------------------------------------------------------------------
SPECIES   NUMB.DENS    LEAK.RATE    DI           LINE.POWER   DN/DT        D(TEMP)/DT   IONIZATION    Z
          /CU.M        /CU.M/SEC    M**2/SEC     W            /CU.M/SEC    DEGK/SEC.    ENERGY(J)
H+        1.00000D+10  1.22227D+07  1.59207D-03  0.0           7.86838D+14 -4.90560D+05  0.0          1.000
HO        5.00000D+01  8.43229D+04  2.35910D+03  7.38075D-15  -1.00997D+07 -4.90560D+05  0.0          0.0
D+        1.50000D+20  1.83341D+17  1.59207D-03  0.0          -4.26645D+17 -4.90560D+05  0.0          1.000
DO        7.00000D+11  5.90260D+14  1.17955D+03  1.03331D-04  -8.87202D+15 -4.90560D+05  0.0          0.0
T+        1.50000D+20  1.83341D+17  1.59207D-03  0.0          -4.23498D+17 -4.90560D+05  0.0          1.000
TO        7.00000D+11  3.93507D+14  7.86367D+02  1.03331D-04  -8.67526D+15 -4.90560D+05  0.0          0.0
HELIUM3   1.00000D+10  2.44454D+07  3.18415D-03  1.47004D-04   7.86838D+14 -4.90560D+05  8.70261D-18  2.000
HELIUM4   1.00000D+10  2.44454D+07  3.18415D-03  1.47004D-04   2.49226D+17 -4.90560D+05  8.70261D-18  2.000
OXYGEN    5.36768D+16  5.24730D+14  1.27334D-02  2.11331D+05  -5.24730D+14 -4.90560D+05  1.39172D-16  7.998
ELECTRON  3.00429D+20  3.70878D+17  1.60799D-03               -3.53527D+17  6.82816D+04
-------------------------------------------------------------------------------------------------------
```

ELECTRON TEMPERATURE..................	5.80261D+07	(K)	= 5.00000D+03 E.V. = 8.01050D-16 J
ION TEMPERATURE..................	5.80261D+07	(K)	= 5.00000D+03 E.V. = 8.01050D-16 J
KINETIC PRESSURE (NEUTRALS)....(AVG.)	1.14483D-03	(PA)	
KINETIC PRESSURE (IONS +E)....(AVG.)	4.91038D+05	(PA)	
TOROIDAL FIELD	1.20000D+01	(T)	
TOROIDAL MAGNETIC PRESSURE...........	5.72958D+07	(PA)	
TOROIDAL BETA.......................	8.57023D-03		
POLOIDAL FIELD .... (EDGE)	8.00000D-01	(T)	
POLOIDAL FIELD .... (REF)	7.36487D-01	(T)	
POLOIDAL MAGNETIC PRESSURE.... (REF)	2.15819D+05	(PA)	
POLOIDAL BETA................. (REF)	2.27523D+00		
TOTAL BETA.................... (REF)	8.53807D-03		
TOTAL BETA.................... (EDGE)	4.79942D-03		
AVG. TOROIDAL CURRENT DENSITY........	8.48826D+05	(A/SQ.M)	
TOTAL TOROIDAL CURRENT..............	6.00000D+06	(A)	
CENTRE SAFETY FACTOR Q(0)	1.78433D+00		
REFERENCE SAFETY FACTOR Q(R)	2.30426D+00		
EDGE SAFETY FACTOR Q(A)	3.00000D+00		
LOOP FIELD	2.17171D-03	(V/M)	
LOOP VOLTAGE (VOLTS/TURN)............	1.02339D-01	(V)	
ION THERMAL CONDUCTIVITY.............	1.22419D+19	(/M.SEC)	
ELECTRON THERMAL CONDUCTIVITY........	-5.63177D+10	(/M.SEC)	
ELECTRICAL CONDUCTIVITY.............	3.87820D+08	(/OHM.M)	

PLASMA	POWER DENSITY W/CU.M	REACTOR POWER W	WALL LOADING W/SQ.M
LOSS BY ION+NEUT LEAKAGE	5.53009D+02	1.84207D+05	4.14757D+02
+ LOSS BY ELECTRON LEAKAGE	5.57047D+02	1.85552D+05	4.17785D+02
= LOSS BY PARTICLE LEAKAGE	1.11006D+03	3.69759D+05	8.32542D+02
LOSS BY BREMSSTRAHLUNG	1.19892D+05	3.99360D+07	8.99191D+04
LOSS BY LINE RADIATION	6.34439D+02	2.11331D+05	4.75829D+02
LOSS BY SYNCHROTRON RADN.	4.03029D+04	1.34248D+07	3.02271D+04
LOSS BY ION CONDUCTION	1.34005D+04	4.46370D+06	1.00504D+04
LOSS BY ELECTRON CONDUCTION	-6.28254D-05	-2.09271D-02	-4.71191D-05
LOSS BY ELECTRON IONIZATION	9.59326D-05	3.19551D-02	
LOSS TOTAL	1.75340D+05	5.84056D+07	
GAIN BY OHMIC HEATING	1.84340D+03	6.14035D+05	
GAIN BY FUSION IONS RETAINED	1.41175D+05	4.70252D+07	
GAIN FROM SOURCE PARTICLES	0.0	0.0	
GAIN (EXTERNAL TO ELECTRONS)	0.0	0.0	
GAIN (EXTERNAL TO IONS)	0.0	0.0	
GAIN TOTAL	1.43018D+05	4.76392D+07	
EXCHANGE POWER TO ELECTRONS	0.0		
NEUTRON POWER		1.87721D+08	4.22669D+05
TOTAL TO WALL			5.54174D+05

NEUTRON	SOURCE DENSITY N/CU.M/SEC	SOURCE N/SEC	WALL CURRENT N/SQ.M/SEC
	2.50013D+17	8.32790D+19	1.87510D+17

TIME	T(ELECT)	T(ION)	N(ELECT)	N(ION)	N(NEUT)	TAU-ENGY	TAU-PTCL	ENERGYDN	AMPS
1.5001D-03	5.8026D+07	5.8025D+07	3.0043D+20	3.0005D+20	1.3938D+12	2.1554D+01	8.1496D+02	7.3655D+05	6.0000D+06
2.2503D-03	5.8026D+07	5.8025D+07	3.0043D+20	3.0005D+20	1.3938D+12	2.1552D+01	8.1496D+02	7.3655D+05	6.0000D+06
3.3756D-03	5.8026D+07	5.8025D+07	3.0043D+20	3.0005D+20	1.3938D+12	2.1549D+01	8.1497D+02	7.3654D+05	6.0000D+06
5.0636D-03	5.8026D+07	5.8024D+07	3.0043D+20	3.0005D+20	1.3938D+12	2.1544D+01	8.1497D+02	7.3654D+05	6.0000D+06
7.5959D-03	5.8027D+07	5.8023D+07	3.0043D+20	3.0005D+20	1.3938D+12	2.1537D+01	8.1498D+02	7.3653D+05	6.0000D+06
1.0000D-02	5.8027D+07	5.8022D+07	3.0043D+20	3.0005D+20	1.3938D+12	2.1531D+01	8.1499D+02	7.3652D+05	6.0000D+06

ELECTRON REGIME	ION REGIME	EFFZED	EFF.MASS	LOG-LAMBDA	LARMOR & RAD/SEC	PLASMA FREQUENCIES RAD/SEC
BANANA	BANANA	1.01	2.65	17.16	2.115D+12	3.466D+12

NU(E,I) /SEC.	NU(I,I) /SEC.	NU(*,E)	NU(*,I)	TEQ(ELECT) SEC.	TEQ(N+ION) SEC.	TAU(ENERGY) SEC.	TAU(PTCLE) SEC.
4.27916D+04	6.27798D+02	4.68903D-01	4.78428D-01	5.65090D-02	5.64378D-02	2.15309D+01	8.14990D+02

SPECIES	NUMB.DENS /CU.M	LEAK.RATE /CU.M/SEC	DI M**2/SEC	LINE.POWER W	DN/DT /CU.M/SEC	D(TEMP)/DT DEGK/SEC.	IONIZATION ENERGY(J)	Z
H+	7.87772D+12	9.62819D+09	1.59199D-03	0.0	7.86598D+14	-4.00623D+05	0.0	1.000
HO	3.65861D+04	6.16[illegible]39D+07	2.35883D+03	5.40053D-12	3.65323D+06	-4.00623D+05	0.0	0.0
D+	1.49996D+20	1.83325D+17	1.59199D-03	0.0	-4.35421D+17	-4.00623D+05	0.0	1.000
DO	6.96848D+11	5.87536D+14	1.17942D+03	1.02863D-04	-2.74202D+09	-4.00623D+05	0.0	0.0
T+	1.49996D+20	1.83325D+17	1.59199D-03	0.0	-4.32079D+17	-4.00623D+05	0.0	1.000
TO	6.96918D+11	3.91730D+14	7.86277D+02	1.02873D-04	-2.72734D+09	-4.00623D+05	0.0	0.0
HELIUM3	7.87768D+12	1.92563D+10	3.18398D-03	1.15803D-01	7.86589D+14	-4.00623D+05	8.70261D-18	2.000
HELIUM4	2.49203D+15	6.09155D+12	3.18398D-03	3.66332D+01	2.49142D+17	-4.00623D+05	8.70261D-18	2.000
OXYGEN	5.36716D+16	5.24650D+14	1.27327D-02	2.11306D+05	-5.24650D+14	-4.00623D+05	1.39172D-16	7.998
ELECTRON	3.00426D+20	3.70859D+17	1.60793D-03		-3.71051D+17	7.16681D+04		

ELECTRON TEMPERATURE..................	5.80268D+07	(K) = 5.00006D+03 E.V. = 8.01060D-16 J
ION TEMPERATURE..................	5.80217D+07	(K) = 4.99962D+03 E.V. = 8.00989D-16 J
KINETIC PRESSURE (NEUTRALS)....(AVG.)	1.13965D-03	(PA)
KINETIC PRESSURE (IONS +E)....(AVG.)	4.91014D+05	(PA)
TOROIDAL FIELD	1.20000D+01	(T)
TOROIDAL MAGNETIC PRESSURE...........	5.72958D+07	(PA)
TOROIDAL BETA........................	8.56982D-03	
POLOIDAL FIELD .... (EDGE)	8.00000D-01	(T)
POLOIDAL FIELD .... (REF)	7.36487D-01	(T)
POLOIDAL MAGNETIC PRESSURE.... (REF)	2.15819D+05	(PA)
POLOIDAL BETA................. (REF)	2.27512D+00	
TOTAL BETA.................... (REF)	8.53766D-03	
TOTAL BETA.................... (EDGE)	4.79919D-03	
AVG. TOROIDAL CURRENT DENSITY........	8.48826D+05	(A/SQ.M)
TOTAL TOROIDAL CURRENT...............	6.00000D+06	(A)
CENTRE SAFETY FACTOR Q(0)	1.78433D+00	
REFERENCE SAFETY FACTOR Q(R)	2.30426D+00	
EDGE SAFETY FACTOR Q(A)	3.00000D+00	
LOOP FIELD	2.17169D-03	(V/M)
LOOP VOLTAGE (VOLTS/TURN)............	1.02339D-01	(V)
ION THERMAL CONDUCTIVITY.............	1.22417D+19	(/M.SEC)
ELECTRON THERMAL CONDUCTIVITY........	-5.63094D+10	(/M.SEC)
ELECTRICAL CONDUCTIVITY..............	3.87822D+08	(/OHM.M)

PLASMA	POWER DENSITY W/CU.M	REACTOR POWER W	WALL LOADING W/SQ.M
LOSS BY ION+NEUT LEAKAGE	5.52924D+02	1.84178D+05	4.14693D+02
+ LOSS BY ELECTRON LEAKAGE	5.57026D+02	1.85545D+05	4.17769D+02
= LOSS BY PARTICLE LEAKAGE	1.10995D+03	3.69723D+05	8.32462D+02
LOSS BY BREMSSTRAHLUNG	1.19892D+05	3.99359D+07	8.99189D+04
LOSS BY LINE RADIATION	6.34474D+02	2.11343D+05	4.75855D+02
LOSS BY SYNCHROTRON RADN.	4.03030D+04	1.34249D+07	3.02272D+04
LOSS BY ION CONDUCTION	1.33992D+04	4.46327D+06	1.00494D+04
LOSS BY ELECTRON CONDUCTION	-6.28169D-05	-2.09243D-02	-4.71127D-05
LOSS BY ELECTRON IONIZATION	1.00679D-04	3.35362D-02	
LOSS TOTAL	1.75338D+05	5.84051D+07	
GAIN BY OHMIC HEATING	1.84339D+03	6.14032D+05	
GAIN BY FUSION IONS RETAINED	1.41131D+05	4.70106D+07	
GAIN FROM SOURCE PARTICLES	0.0	0.0	
GAIN (EXTERNAL TO ELECTRONS)	0.0	0.0	
GAIN (EXTERNAL TO IONS)	0.0	0.0	
GAIN TOTAL	1.42974D+05	4.76246D+07	
EXCHANGE POWER TO ELECTRONS	-5.72457D+02		
NEUTRON POWER		1.87663D+08	4.22538D+05
TOTAL TO WALL			5.54042D+05

NEUTRON	SOURCE DENSITY N/CU.M/SEC	SOURCE N/SEC	WALL CURRENT N/SQ.M/SEC
	2.49935D+17	8.32532D+19	1.87451D+17