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Current Tokamak theory is extrapolated to predict the characteristics of future reactor regimes and to examine certain transport effects in those regimes.

Theoretical models of radial transport in Tokamaks have met with some success in fitting present-day experiments.[1,2] This success encourages the extrapolation of current Tokamak theory to the prediction of operating regimes for power reactors, which is the main purpose of this paper. A secondary purpose is to examine the effect of certain transport phenomena upon the determination of the operating regime.

The calculational model consists of: (1) a particle balance between a uniform injected source of ions (a single species is treated with parameters adjusted to represent a 50-50 D-T mixture) and losses due to radial transport and fusion; (2) an ion energy balance between alpha heating and losses due to radial energy transport and heat conduction, work done against the confining poloidal field by the outward moving ions, and Coulomb energy exchange with the electrons; (3) an electron energy balance between alpha and ohmic heating and Coulomb energy exchange with the ions and losses due to radial energy transport and heat conduction, work done against the confining poloidal field, and bremsstrahlung and cyclotron radiation losses; and (4) a calculation of the poloidal magnetic field distribution and the toroidal current distribution. The ion and electron spectral distributions are assumed to be Maxwellian. Alpha heating of ions and electrons, radiation losses and electron-ion energy exchange are modeled as in Refs. 3 and 4. The radial plasma velocity, and hence the radial transport of particles and heat energy and the work done against the confining poloidal field, is based upon Ref. 5 with the inclusion of a term to account for the trapped particle pinch effect[6] in the banana regime. Heat conduction is modeled after Ref. 7 in the banana regime and otherwise described in Ref. 1. The diffusion coefficient and thermal conductivities at each radial location are computed from expressions for the banana, plateau, or classical regimes, based upon the selection criteria given in Ref. 5.

In radial geometry, with corrections for toroidal effects, the basic equations are:

Transport Equations

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\, nV_r\right) = S - \frac{1}{2}\,\sigma v\langle n^2\rangle ,$$

$$\frac{\partial n(0)}{\partial r} = n(a) = 0 . \qquad (1)$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{3}{2}\,nT_\xi V_r\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(rq_\xi\right) + nT_\xi\frac{1}{r}\frac{\partial}{\partial r}\left(rV_r\right) = Q_\xi ,$$

$$\frac{\partial T_\xi(0)}{\partial r} = T_\xi(a) = 0 ;$$

$$\xi = e,i . \qquad (2)$$

$$\frac{\partial}{\partial r}\left[\frac{n}{1 - 1.95(r/R)^{1/2}}\,\frac{1}{r}\,\frac{\partial\left(rB_\theta\right)}{\partial r}\right] = 0 ,$$

$$B_\theta(0) = 0 ,$$

$$B_\theta(a) = \frac{\mu J_z}{2\pi a} . \qquad (3)$$

Velocity

$$V_r = -D\left[\frac{1}{n}\frac{\partial n}{\partial r} + \frac{1.5}{T_i + T_e}\left(\frac{\partial T_i}{\partial r} + \frac{\partial T_e}{\partial r}\right)\right] - \frac{2.44E_z}{B_\theta}\left(\frac{r}{R}\right)^{1/2} . \qquad (4)$$

Heat Fluxes

$$q_i = -K_i\frac{\partial T_i}{\partial r} , \qquad (5)$$

$$q_e = -K_{ee}\frac{\partial T_e}{\partial r} - K_{ei}\frac{\partial T_i}{\partial r} - K_{en}\frac{\partial n}{\partial r} + \frac{1.75nT_eE_z}{B_\theta}\left(\frac{r}{R}\right)^{1/2} . \qquad (6)$$

Ampere's Law

$$\mu j_z = \frac{1}{r}\frac{\partial\left(rB_\theta\right)}{\partial r} . \qquad (7)$$

Ohm's Law

$$E_z = \eta j_z . \qquad (8)$$

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In these equations, a is the plasma radius, R is the major radius of the torus, n is the ion density, S is the injected source of ions, T_i and T_e are ion and electron temperature, Q_i and Q_e are the net ion and electron heat sources, B_θ is the poloidal magnetic field, η is the plasma resistivity, E_z is the toroidal electric field and j_z is the resulting current, and D and K are the diffusion and conductivity coefficients.

The transport coefficients in the banana regime, which obtained for all calculations in this paper, are:

Banana Transport Coefficients

$$D = \frac{1.1\left(1 + T_i/T_e\right)}{\tau_e} \rho^2_{e,\theta} \left(\frac{r}{R}\right)^{1/2} , \tag{9}$$

$$K_i = \frac{0.68 n \rho^2_{i,\theta}}{\tau_i} \left(\frac{r}{R}\right)^{1/2} , \tag{10}$$

$$K_{ee} = \frac{1.81 n \rho^2_{e,\theta}}{\tau_e} \left(\frac{r}{R}\right)^{1/2} , \tag{11}$$

$$K_{ei} = \frac{0.27 n \rho^2_{e,\theta}}{\tau_e} \left(\frac{T_e}{T_i}\right) \left(\frac{r}{R}\right)^{1/2} , \tag{12}$$

$$K_{en} = - \frac{1.53\left(T_i + T_e\right) \rho^2_{e,\theta}}{\tau_e} \left(\frac{r}{R}\right)^{1/2} . \tag{13}$$

ρ_θ is the Larmor radius in the poloidal field, and τ_e and τ_i are the electron-ion and ion-ion collision times, respectively.

A reactor model with a major radius of 5 m, a plasma radius of 1 m, and a toroidal field of 5 Wb/m^2 was chosen for the study. As shown in Table I, an equilibrium regime was found with n_{max} = 2.8-3.2 × 10^{20}/m^3, T_{max} = 20-100 keV, and particle and energy escape $n\tau$ in the range 2-8 × 10^{20} sec/m^3. $n\tau$'s were computed by integrating the LHS of Eqs. (1) and (2) over the plasma radius, once the solution was obtained. Particle $n\tau$'s are shown in the tables. This regime had 2-11% fractional fuel burnup and linear radiation and neutron power production rates of 0.2-0.8 and 8-37 MW/m, respectively. Radial density and temperature profiles were found to be rather flat, and there was no evidence of a skin effect. The safety parameter, q, was ~2 on the axis and increased to ~10 at the plasma radius, indicating an ample margin of stability against kink modes. However, β_θ was orders of magnitude greater than the aspect ratio, implying instability against balloon modes. β_θ was computed as the ratio of the thermal pressure at the plasma centerline to the poloidal magnetic pressure at the plasma radius. Increasing the toroidal current to increase the poloidal field, thereby reducing β_θ, led to high temperatures which offset the reduction in β_θ, from which it may be concluded that the purely classical formulas predict too great an energy and particle confinement for operation in the reactor regime. More realistic calculations are in progress in which bremsstrahlung losses are enhanced to account for the presence of impurities, and radial transport and heat conductivity are enhanced to account for the presence of microinstabilities.

Additional calculations were performed to assess the effect of various terms in the description of the radial transport and heat conduction phenomena, and the results are summarized in Table II. The trapped particle pinch effect was found to be negligible. The omission of heat transport due to radial plasma flow increased the electron temperature, as expected, but decreased the ion temperature—heat transport is small relative to heat conduction for the ions; and the increased alpha heating of the ions, which results from the increased electron temperature, is a more important effect. A similar result was obtained when work done against the confining poloidal field was omitted, for similar reasons.

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TABLE I. Operating Characteristics

($R = 5$ m, $a = 1$ m, $B_z = 5$ Wb/m^2, $S = 10^{20}$ m^{-3}-sec^{-1})

J_z (10^6 A)	f_b (%)	n_0 (10^{20}/m^3)	T_{e0} (keV)	T_{i0} (keV)	P_n (MW/m)	q_{min}	β_0	$n\tau$ (10^{20} sec/m^3)
0.37	2.3	2.8	25.8	17.0	8.1	2.0	$\sim 10^3$	3.5
0.38	6.3	2.9	55.2	36.7	21.9	2.1	$>10^3$	3.8
0.39	9.0	2.9	75.5	82.1	31.3	2.2	$>10^3$	4.2
0.40	9.3	2.9	77.4	87.4	32.3	2.1	$>10^3$	4.3
0.45	10.7	3.2	84.5	107.3	37.1	1.9	$>10^3$	5.4

TABLE II. Sensitivity to Transport Model

($R = 5$ m, $a = 1$ m, $B_z = 5$ Wb/m^2, $S = 10^{20}$ m^{-3}-sec^{-1}, $J_z = 0.4 \times 10^6$ A)

Comment	f_b (%)	n (10^{20}/m^3)	T_{e0} (keV)	T_{i0} (keV)	P_n (MW/m)	q_{min}	β_0	$n\tau$ (10^{20} sec/m^3)
Base case	9.3	2.9	77.4	87.4	32.3	2.1	$>10^3$	4.3
No pinch effect	9.3	2.9	77.4	87.2	32.3	2.1	$>10^3$	4.3
$K_{ei} = K_{en} = 0$	9.3	2.9	74.1	87.5	32.2	2.1	$>10^3$	4.3
$nT \frac{1}{r}\frac{\partial}{\partial r}\left(rV_r\right) = 0$	11.4	3.2	86.5	55.9	39.6	2.4	$>10^3$	5.9
$\frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{3}{2} nT V_r\right) = 0$	6.1	2.8	91.3	76.0	21.0	1.6	$>10^3$	2.7