ORNL/TM-6111

Small Radius Start-up of Tokamak Plasmas with a Moving Limiter

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FUSION ENERGY DIVISION

SMALL RADIUS START-UP OF TOKAMAK PLASMAS WITH A MOVING LIMITER

T. Uckan

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Prepared by the
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ABSTRACT

The problem of start-up for a large size tokamak plasma is studied with a moving limiter. The plasma transport with the presence of the electric field diffusion and heat conduction losses is investigated analytically by the separation of variables during this early phase of the discharge. The results are then applied to a TNS-size plasma. It is shown that a moving limiter may help ameliorate the possible problem of skin effects on the current profile.

1. INTRODUCTION

In order to avoid the skin effect on the current profiles in a large, ohmically heated tokamak plasma during the early phase of the discharge, a moving limiter is one of the proposed[1] alternatives to the solution of the problem. Since the plasma column expands by the controlled moving limiter, a desirable current profile may be obtainable. The plasma transport during this expansion phase is studied analytically by means of separation of variables[2] which are time, t, and $\rho = r^2 h(t)$, where h(t) is only a function of time. This approach allows one to investigate the plasma discharge parameters in terms of the limiter motion as well as the plasma current rise. Furthermore, the plasma parameters such as poloidal beta, safety factor, flux function, etc., are obtainable by making use of the analytical solutions of the plasma temperature and the current density.

This problem was first studied extensively by Bardotti et al.[2] in the case of pseudoclassical type losses assumed for the electron heat conduction. In this paper, we extend their approach by introducing a model heat conductivity coefficient which in turn provides a general view of the problem of separability. We also observe other possible cases.

In this report, Sect. 2 describes the plasma model and the basic equations, Sect. 3 outlines system equations and Sect. 4 gives the evaluation of the plasma discharge parameters. General discussions and an application of the results are included in Sect. 5.

2. PLASMA MODEL AND THE BASIC EQUATIONS

As was done previously,[2,3] a cylindrical plasma column is adopted so that the computational complexities due to toroidal geometry are avoided. Furthermore, we assume:

1) The plasma density is constant and uniform, and the ion density, n_i, is equal to the electron density, n_e; $n = n_e = n_i$.

2) The species have the same temperature, T. On the border of the plasma which is defined by the limiter position, $r_L(t)$, the temperature is T_o and constant.

3) Except for the heat conduction losses, all other losses are ignored.

4) The electrical conductivity, σ, is classical and vanishes outside the limiter.

In the model it is assumed that the plasma radius is being increased from zero to r_L $(t = \tau) = a$ during $t = \tau$ (see Fig. 1). Thus the basic equations for $r < r_L(t)$ are as follows (mks units are used):

$$\frac{\partial E}{\partial r} = \frac{\partial B_p}{\partial t}, \; J = \sigma E, \; \sigma = kT^{3/2}$$

$$\mu J = \frac{1}{r}\frac{\partial}{\partial r}(rB_p), \; 3n\frac{\partial T}{\partial t} = \frac{J^2}{\sigma} - \frac{1}{r}\frac{\partial}{\partial r}(rq_r) \tag{1}$$

where $q_r = -n\chi\frac{\partial T}{\partial r}$ is the radial heat conduction flux of the electrons. Here E is the toroidal electric field, $B_p(r, t) = \mu I(r, t)/2\pi r$ is the induced poloidal magnetic field due to the plasma current $I(r, t) = 2\pi \int_0^r dr'r' J(r', t)$, $(\mu = 4\pi \times 10^{-7}$ H/m), and $J(r, t)$ is the toroidal current density. For the heat conductivity coefficient, χ, we introduce the following general form:

$$\chi(r,\ t) = Cn^{\gamma} r^{2s} / I^{p} T^{q/2}.$$

Here C is a dimensional numerical factor that depends on the plasma parameters such as toroidal magnetic field, major and minor radii, etc. The values of s, p, and q are determined later on.

The analytical solutions for the current density and the temperature are sought by introducing two variables, t and $\rho = r^2 h(t)$. In the following section, the separability condition and the resulting system equations will be discussed.

3. SYSTEM EQUATIONS

Let us start with assuming current density profiles of the form

$$J(r,\ t) = J_f \left(\frac{t}{\tau}\right)^{\alpha} F(\rho)$$

with an arbitrary constant, α. Here, at time, τ, the limiter reaches the final plasma radius, a; thus the plasma current on the magnetic axis is $J_f \equiv J(r = 0,\ t = \tau)$ since $F(\rho = 0) = 1$. With this in mind, the system equations are obtained by making use of the variable transformation as well as imposing the separability in t and ρ on Eq. (1). The resulting equations are then as follows:[3]

$$T(r,\ t) = T_f \left(\frac{t}{\tau}\right)^{2(1+2\alpha)/5} G(\rho)$$

$$I(r,\ t) = I_f \left(\frac{t}{\tau}\right)^{(2-\alpha)/5} \frac{Z(\rho)}{Z_f}$$

$$\gamma(r,\ t) = \frac{Cn^{\gamma}}{(\pi J_f)^p} \frac{h_f^{(p-s)}}{T_f^{q/2}} \left(\frac{t}{\tau}\right)^{-3(1+2\alpha)/5} P(\rho)$$

$$h(t) = h_f \left(\frac{t}{\tau}\right)^{-2(1-3\alpha)/5} .$$

The functions F, G, Z, and P must satisfy the following set of nonlinear differential equations:[3]

$$\frac{dF}{d\rho} = \frac{3}{2} FSG^{(q/2-1)} \frac{Z^p}{\rho^{s+1}} + \frac{G^{3/2}}{2} \left[\left(\frac{2 - \alpha}{10\alpha}\right) \frac{Z}{\rho} - \left(\frac{1 - 7\alpha}{5\alpha}\right) F\right]$$

$$\frac{dG}{d\rho} = SG^{q/2} \frac{Z^p}{\rho^{s+1}} \tag{2}$$

$$\frac{dZ}{d\rho} = F$$

$$\frac{dS}{d\rho} = \left[DG - F^2G^{-3/2} - D\left(\frac{1 - 3\alpha}{1 + 2\alpha}\right) SG^{q/2} \frac{Z^p}{\rho^s}\right] \Big/ A ,$$

where

$$S = \rho P \frac{dG}{d\rho} \text{ with } P = \rho^s/Z^pG^{q/2} .$$

Here, T_f denotes the final value of the temperature on the magnetic axis, i.e., $T_f \equiv T(r = 0,\ t = \tau)$; ρ_f is the final value of ρ at the edge, i.e., $\rho_f \equiv \rho(r = a,\ t = \tau) = a^2 h_f$ and $Z_f \equiv Z(\rho_f)$. The constants A, D, and τ are given by

$$D = \frac{6}{5} \left(\frac{1 + 2\alpha}{\alpha}\right) nT_f h_f/\mu J_f^2$$

$$A = (4C\sigma_f T_f n^{\gamma}/J_f^{\,2}) \quad \frac{h_f^{\,(p-s+1)}}{(\pi J_f)^p T_f^{\,q/2}}$$

$$\tau = \mu\sigma_f a^2\alpha/\rho_f, \text{ with}$$

$$\sigma_f = kT_f^{\,3/2} .$$

The separability requires that α, p, q, and s must satisfy

$$\alpha(6 - 6s + p - 2q) + 3 - 2p + 2s - q = 0 . \tag{3}$$

This relation gives us some of the acceptable scaling laws for $\chi(\mathbf{r}, t)$, which are listed in Table 1. As we see from the table, the pseudo-classical scaling is

$$\chi^{PS} \equiv \chi(s = 1,\ q = 1,\ p = 2) = C_o^{PS}\ \rho_p^2\ \nu_e ,$$

where ρ_p is the poloidal Larmor radius, ν_e is the collision frequency of the electrons, and C_o^{PS} is an enhancement factor. In this case the constant C becomes

$$C^{PS} = C_o^{PS} \left(\frac{4\pi}{\mu}\right)^2 \frac{n}{k} ,$$

with $C_o^{PS} \sim 1 - 10$. Moreover the system constants D and A have the expressions

$$D = \left(\frac{\epsilon n}{\mu a^2}\right) \frac{T_f \rho_f}{5J_f^2} \left(\frac{\alpha}{1 + 2\alpha}\right) \text{ and } A = C_o^{PS}\left(\frac{10}{3}\, D\, \frac{\alpha}{1 + 2\alpha}\right)^2 .$$

Here, we have made use of the fact that the toroidal conductivity is given by $\sigma = 2ne^2/m_e\nu_e$, where m_e and e are the mass and the charge of the electron, respectively. The divergent nature of χ^{PS} on the magnetic axis can be avoided by introducing

$$\chi^M \equiv \left(\frac{r}{a}\right)^2 \chi^{PS} = \chi(s = 2,\ q = 1,\ p = 2) \ ,$$

which is called the Mercier scaling.[4] We are, on the other hand, limited by the value of α, which is 1/3.[5] The enhancement factor and the system constants in this case become

$$C^M \equiv C^{PS}/a^2 \text{ and}$$

$$\Lambda = C_o^M \left(\frac{2}{3} D\right)^2/\rho_f \ .$$

Here, C_o^M depends on the inverse aspect ratio, $\varepsilon = a/R_o$ by the relation

$$C_o^M = \begin{cases} 2000, & \varepsilon \leq 0.2 \\ 2000 \left(\frac{0.2}{\varepsilon}\right)^2, & \varepsilon > 0.2 \end{cases}$$

where R_o is the major radius of the torus.

Table 1. The heat conductivity coefficient,

$$\chi = Cn^\gamma r^{2s}/I^p T^{q/2}.$$

α	s	q	p	χ
Arbitrary	0	3	0	$1/T^{3/2}$, neoclassical
Arbitrary	1	1	2	$r^2/I^2T^{1/2}$, pseudoclassical
1/3	2	1	2	$r^4/I^2T^{1/2}$, Mercier's like

In the case of neoclassical scaling, we have

$$\chi^{NC} \equiv \chi(s = 0,\ q = 3,\ p = 0) = C^{NC}/T^{3/2} .$$

Assuming that $\chi^{NC} = C_o^{NC} a^2 \nu_e$, then $C^{NC} = C_o^{NC} K a^2$ where $K = \nu_e T^{3/2}$. The system constant A then has the form

$$A = \frac{10}{3} C_o^{NC} \mu k K D \frac{\alpha a^2}{(1 + 2\alpha)} ,$$

where $kK = 2\ ne^2/m_e$.

We should note that the enhancement factor, i.e., C_o^{NC}, C_o^{PS}, C_o^{M}, has to be chosen so that the plasma temperature becomes T_o on the limiter at any time. Furthermore, it is clear that Table 1 may be extended to account for some other possible empirical scaling laws as long as the choice of α, p, q, and s satisfy the separability condition, Eq. (3).

In order to complete the scheme of obtaining the functions F, G, Z, and S from the set of differential equations given earlier, the boundary and the initial conditions must be stated. For r = 0 we should have $F(0) = G(0) = 1$ and $Z(0) = S(0) = 0$.

For a moment let us discuss the time evolution of the limiter. The limiter motion may be found by imposing the condition that there will be no temperature discontinuity on the border of the plasma at any time. This condition is satisfied by the temperature equation as

$$T(r = r_L,\ t) = \text{constant} = T_o ,$$

which implies that

$$G(\rho_L) = \frac{T_o}{T_f}\left(\frac{t}{\tau}\right)^{-2(1+2\alpha)/5} .$$

Here $\rho_L = r_L^2(t)\ h(t)$, which defines the evolution of the limiter position, $r_L(t)$. This, in turn, gives us the initial time, t_o, which sets the limiter on the magnetic axis, $r_L(t_o) = 0$. Since $G(0) = 1$,

$$\frac{t_o}{\tau} = \left(\frac{T_o}{T_f}\right)^{5/2(1+2\alpha)}$$

which defines t_o.

In the coming section, we take up the problem of relating the system parameters, i.e., α, ρ_f, and D to the plasma discharge parameters.

4. PLASMA DISCHARGE PARAMETERS

Knowing the time evolution of the current profile and temperature, the following plasma discharge parameters can be computed in a straightforward manner.

1) The plasma current, $I_p(t)$:

$$I_p(t)/I_f = \left(\frac{t}{\tau}\right)^{(2-\alpha)/5} \frac{Z(\rho_L)}{Z_f} \quad ,$$

with $I_f \equiv I(r = a,\ t = \tau) = \pi J_f Z_f / h_f$.

2) The normalized safety factor, $q_s(r,\ t)/q_s(0,\ t)$:

From the definition of the safety factor $q_s(r,\ t)$, we find

$$\frac{q_s(r,\ t)}{q_s(0,\ t)} = \frac{\rho}{Z}\left(\frac{t}{\tau}\right)^{-\alpha} \quad .$$

For $t = \tau$, this yields

$$q_b \equiv \frac{q_s(a,\ \tau)}{q_s(0,\ \tau)} = \frac{\rho_f}{Z_f} \quad .$$

3) The poloidal flux function, ψ:

Since $\psi = R_o \int_0^r dr' B_p(r', t)$, and from the definition of $B_p(r, t)$, we get

$$\psi(r, t) = \mu \frac{R_o J_f}{4h_f}\left(\frac{t}{\tau}\right)^{(2-\alpha)} \int_0^{\rho} d\rho' Z/\rho' .$$

4) The skin time, $\tau_s(r, t)$:

We find

$$\frac{\tau}{\tau_s} = \frac{2\tau}{5t}(1 - 3\alpha) \left[\left(\frac{2 - \alpha}{1 - 3\alpha}\right) - \frac{Z(\rho)}{\int_0^{\rho} d\rho' Z/\rho'}\right]$$

since $1/\tau_s \equiv \frac{1}{\psi}\frac{\partial\psi}{\partial t}$.

5) The averaged poloidal beta, $\bar{\beta}_p$:

$$\bar{\beta}_p \equiv \frac{2n \int_0^a dr 2\pi r T(r, \tau)}{(B_f^{\,2}/2\mu)\pi a^2} \quad \text{or}$$

$$\bar{\beta}_p/\beta_{p_o} = \int_0^{\rho_f} d\rho G(\rho)/\rho_f G_f ,$$

where

$$\beta_{p_o} \equiv \frac{2nT_o}{B_f^{\,2}/2\mu} = \frac{T_o}{T_B} \text{ and}$$

$$G_f \equiv G(r = a, t = \tau) = T_o/T_f .$$

Here we have used $B_f \equiv \mu I_f/2\pi a$ and $T_B \equiv B_f^2/4\mu n$.

6) The electron energy lifetime, τ_E:

$$\tau_E(r) = \frac{\frac{3}{2} n \int_0^r dr' r' \; T(r', \tau)}{\int_0^r dr' r' E(r', \tau) \; J(r', \tau)} \quad \text{or}$$

$$\tau_E(r)/\tau_{E_f} = \frac{\int_0^\rho d\rho'\ G}{\int_0^\rho d\rho'\ F^2/G^{3/2}} \quad \text{with } \tau_{E_f} \equiv \frac{3}{2} n\ T_f/J_f^2/\sigma_f \ .$$

7) The transformer flux, ψ_{tr}:

Assuming that the transformer coil is located at $r = b$, the electric field at that point is

$$E(r = b,\ t) = \frac{1}{2\pi R_o} \frac{\partial \psi_{tr}}{\partial t} \ .$$

From this, we compute ψ_{tr} for $t = \tau$, which takes the form

$$\frac{\psi_{tr}}{\mu R_o I_f} = \frac{10\alpha}{(2 - \alpha) Z_f} \left[1 - G_f^{(1-\alpha/2)/(1+2\alpha)}\right] + \left[\ell n(b/a) + \frac{1}{2Z_f} \int_0^{\rho_f} d\rho Z/\rho\right] .$$

5. APPLICATION AND DISCUSSION

Before the results are demonstrated on an example, it is convenient to carry out the computation in terms of β_{p_o}, q_b, and η, which is defined by

$$\eta = \Delta t/\tau_B \text{ with } \tau_B = \tau (T_B/T_f)^{1.5} \rho_f/\alpha \ .$$

Here $\Delta t = \tau - t_o$ may be called an opening time of the limiter. For most cases, it is reasonable to assume $t_o/\tau << 1$, so that the system parameters become

$$\rho_f = \left[\frac{\alpha}{\eta} \left(\frac{40}{3} \frac{\alpha}{1 + 2\alpha} D\right)^{1.5} q_b^3\right]^{0.4} ,$$

$$G_f = \frac{3}{40} \beta_{p_o} \left(\frac{1 + 2\alpha}{\alpha} \frac{\rho_f}{D q_b^2}\right), \text{ and}$$

$$\beta_{p_o}/G_f = T_f/T_B \; .$$

The last relation gives us the value of the final temperature, T_f, on the magnetic axis.

We illustrate the results on a TNS-size plasma with a moving limiter that starts from the magnetic axis and reaches the full-size radius at the end of discharge. The Mercier-like scaling is assumed for χ during the computation, since the pseudoclassical scaling case is vastly explored in Ref. 2.

The typical device parameters are: $R_o = 6$ m, $a = 1.25$ m, $b = 1.5$ m, $q_s(r = a, t = \tau) = 4$, $n = 6 \times 10^{19}$ m^{-3}, and the toroidal magnetic field is 8 T. The system parameters used for the computation are $\beta_{p_o} = 1.8 \times 10^{-2}$ and $\eta = 5 \times 10^{-3}$, which yield $T_f = 2.3$ keV, $I_f = 2.6$ MA, and $T_o = 64$ eV. After having solved Eq. (2) numerically, the findings are presented in Figs. 2-9 for $J(r, t)/J_f$, $T(r, t)/T_f$, $q_s(r, t)/q_s(0, t)$, $\chi(r, t)$, $I_p(t)/I_f$, $\tau/\tau_s(r = a, t)$, $\psi(r = a, t)$ and $r_L(t)/a$. For this particular case the limiter opening time is set to $\Delta t \simeq \tau = 2.3$ sec, and the other plasma parameters found from the computation are $\bar{\beta}_p = 0.122$, $\bar{\chi} = 16.5$ m^2/sec, $\psi_{tr} = 29.5$ volt-sec, and $\tau_E(r = a) = 0.284$ sec.

Since we have a current profile peaked off-axis, we can demonstrate the effect of the moving limiter by adjusting the opening time. Fig. 10 (a, b) shows the final forms of the current density profiles for the opening times $\tau = 2.3$ sec and $\tau = 4.77$ sec, respectively. We see that the slower motion of the limiter has a tendency to give rise to a profile peaked farther out. That is simply a result of gaining more time for the plasma temperature to grow appreciably in the central part of the discharge. We should also note that the transformer flux for $\tau = 4.77$ sec is about 36.5 volt-sec compared to 29.5 volt-sec for the previous case. This also indicates that having a moving limiter may prevent the system from the deposition of an excessive amount of magnetic energy and reduce current density skin effects.

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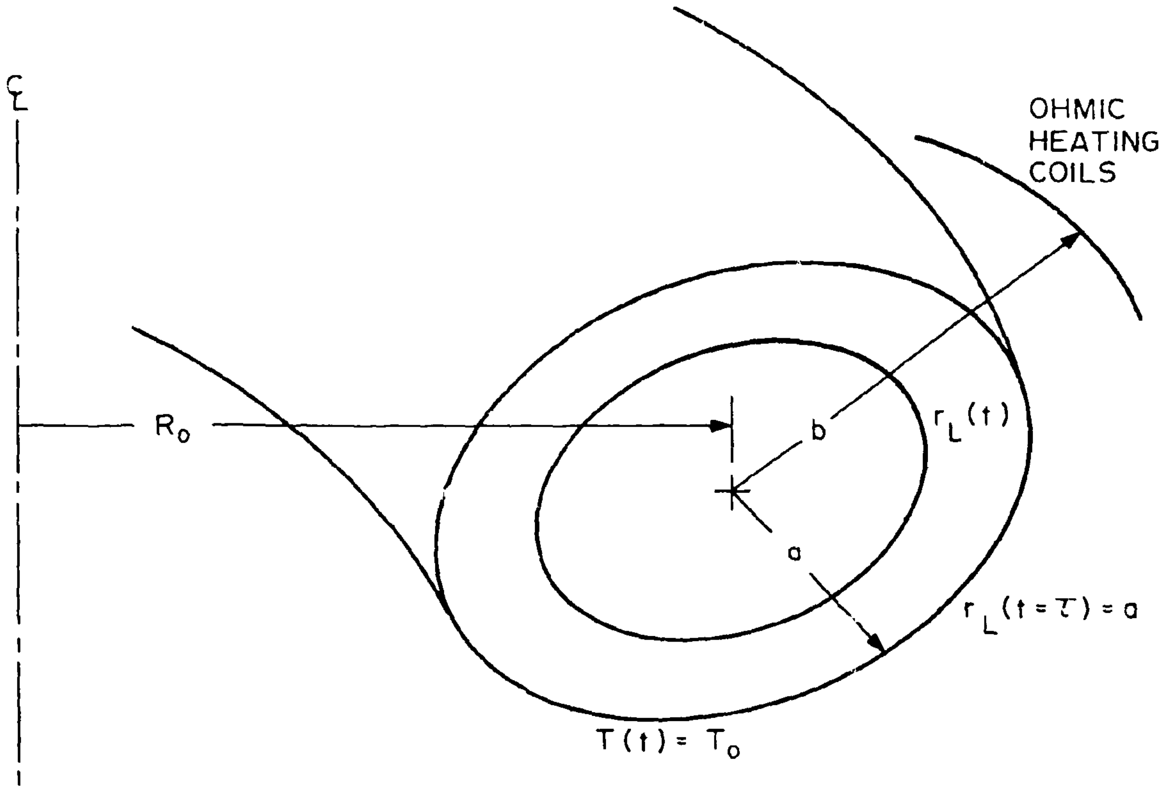

Fig. 1. The geometry of the problem.

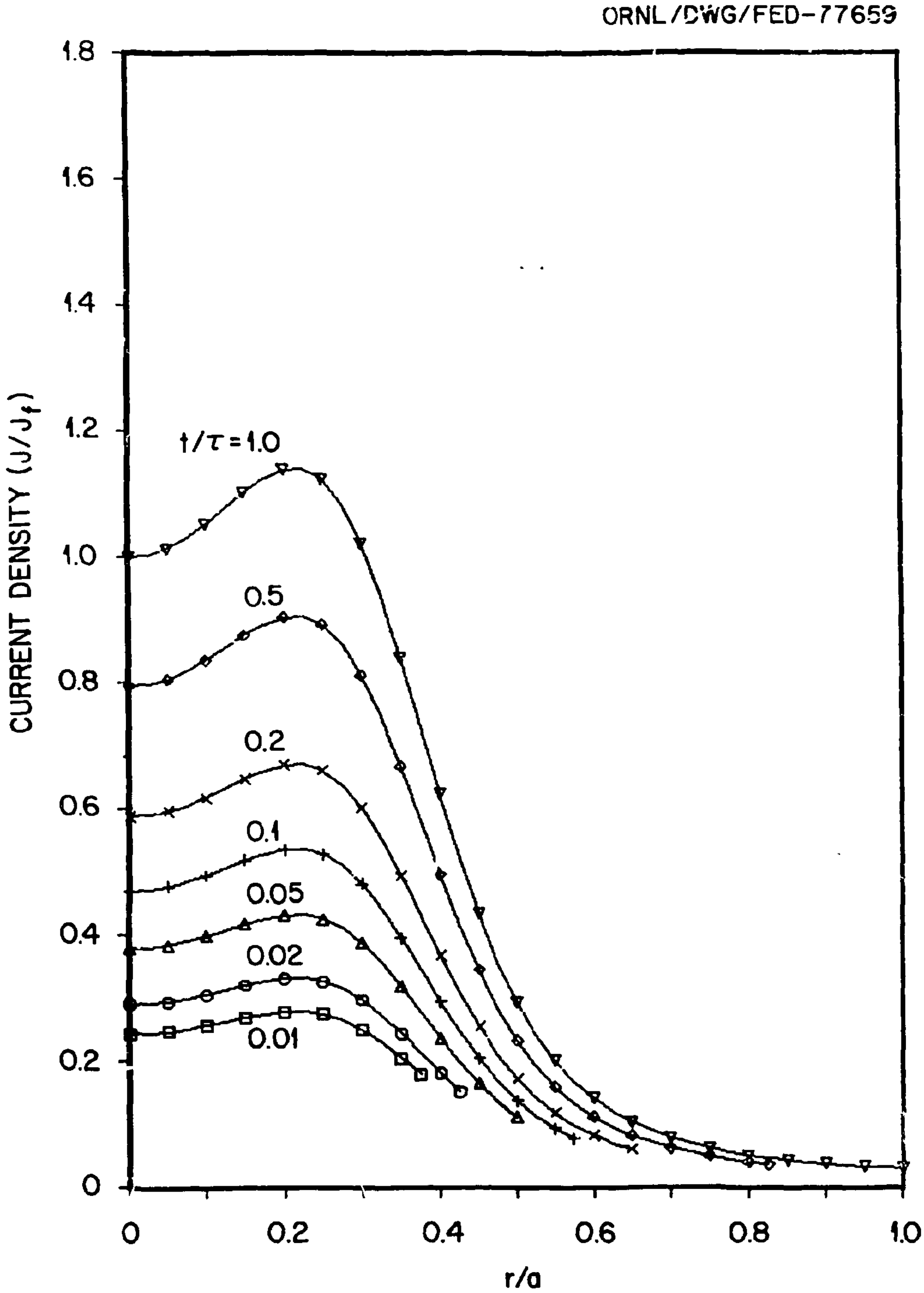

Fig. 2. Time evolution of the radial profiles of the current density.

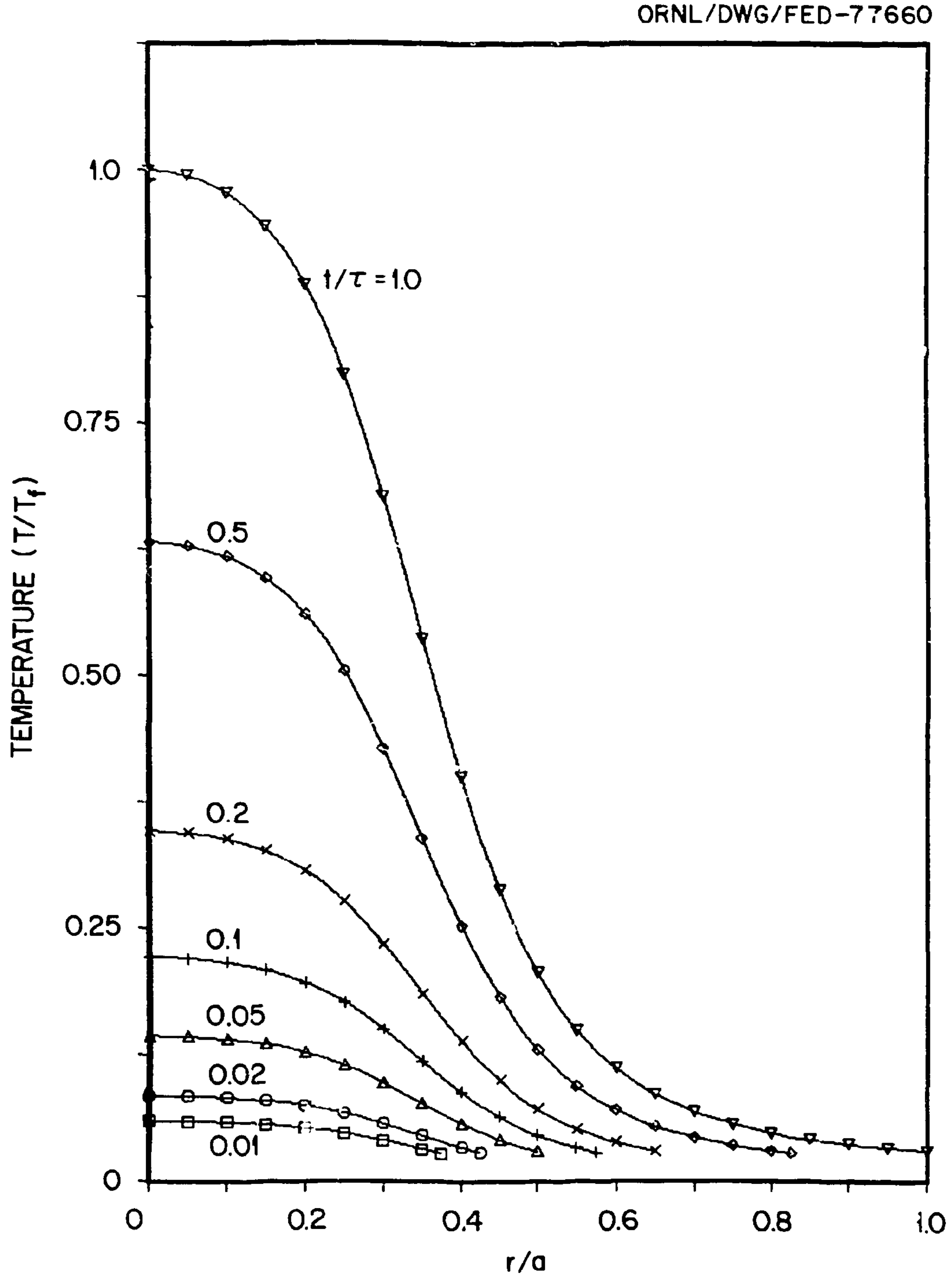

Fig. 3. Time evolution of the temperature profiles.

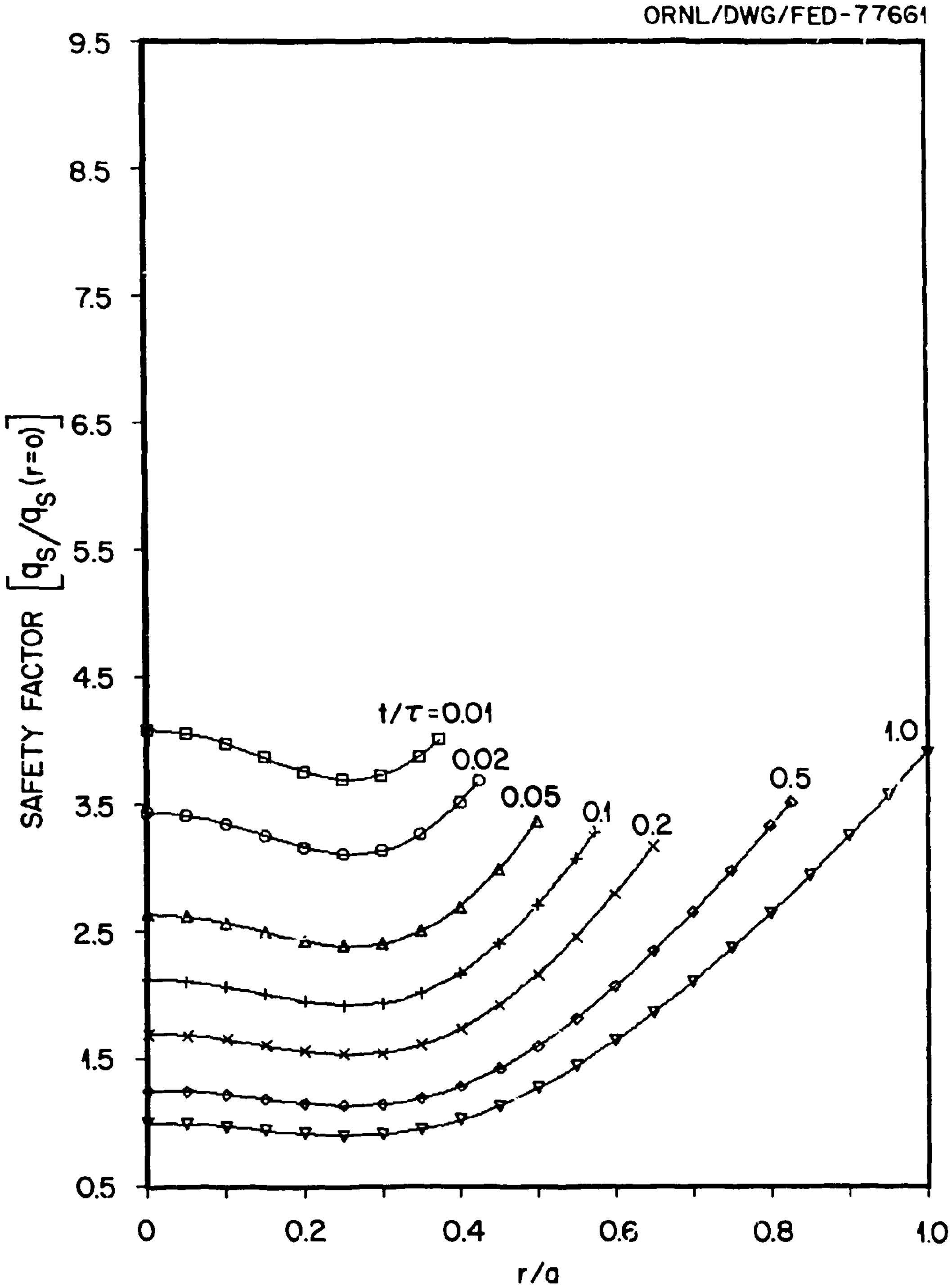

Fig. 4. Time evolution of the normalized safety factor.

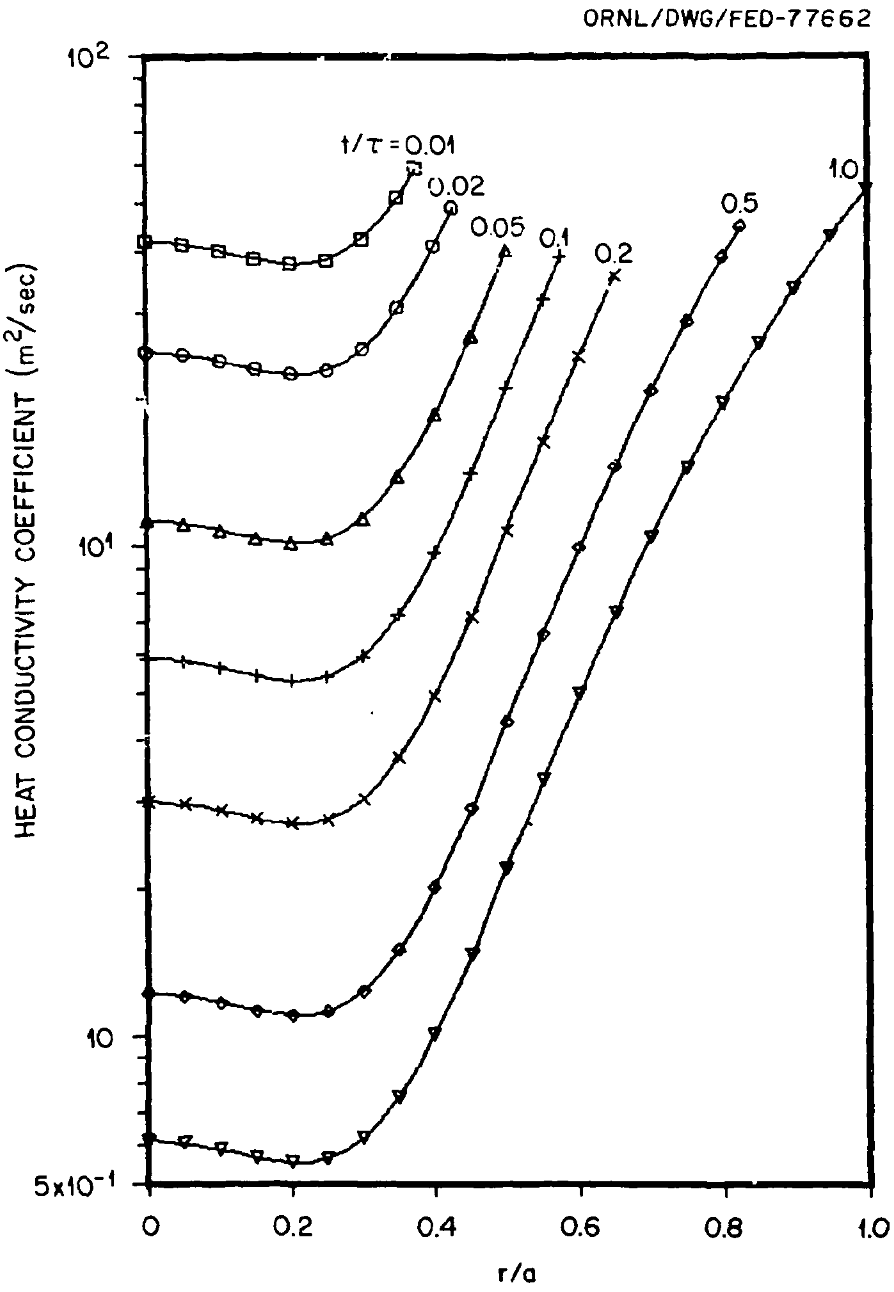

Fig. 5. Evolution of the heat conductivity coefficient.

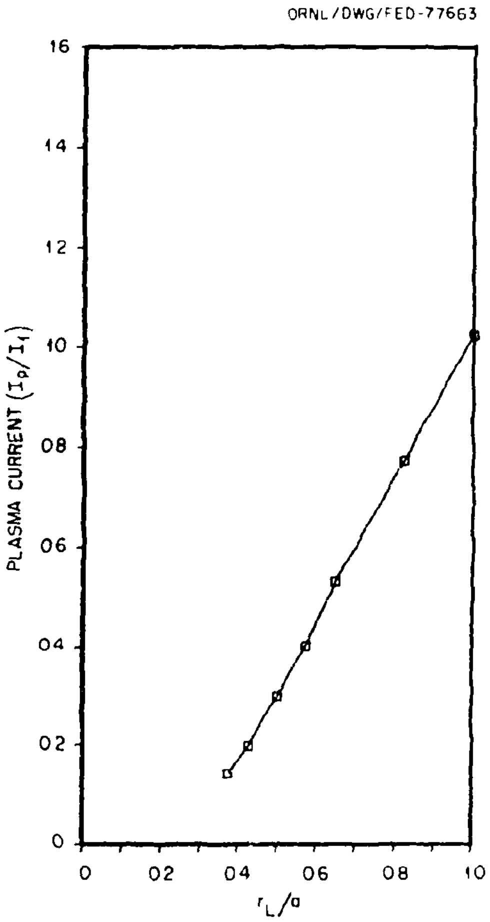

Fig. 6. The plasma current as a function of limiter position.

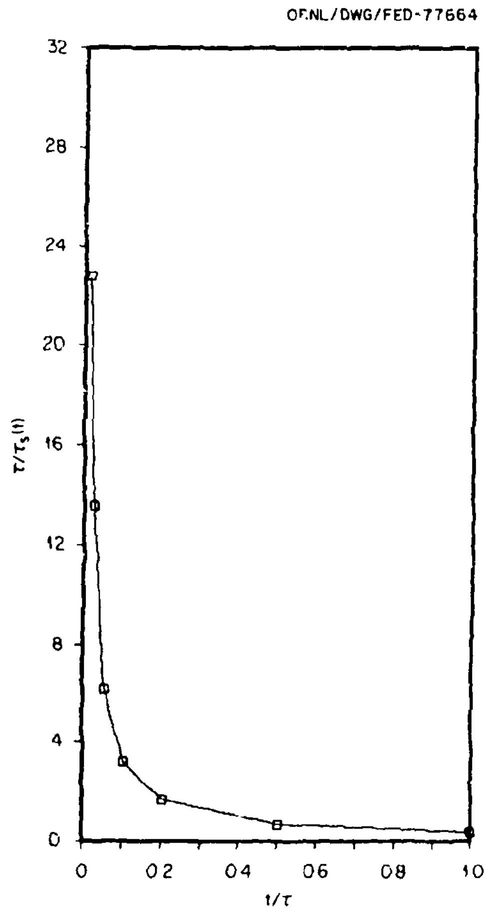

Fig. 7. Evolution of the skin time at the edge.

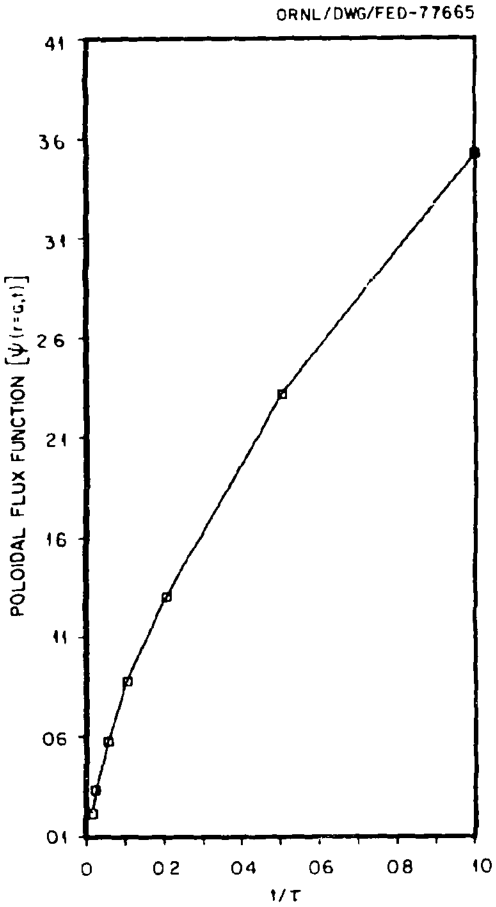

Fig. 8. Evolution of the poloidal flux function at the edge.

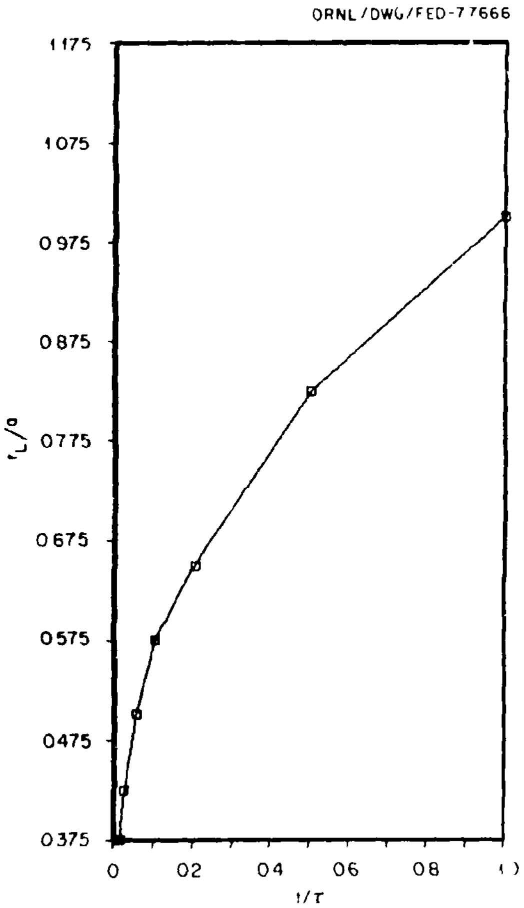

Fig. 9. Evolution of the limiter position.

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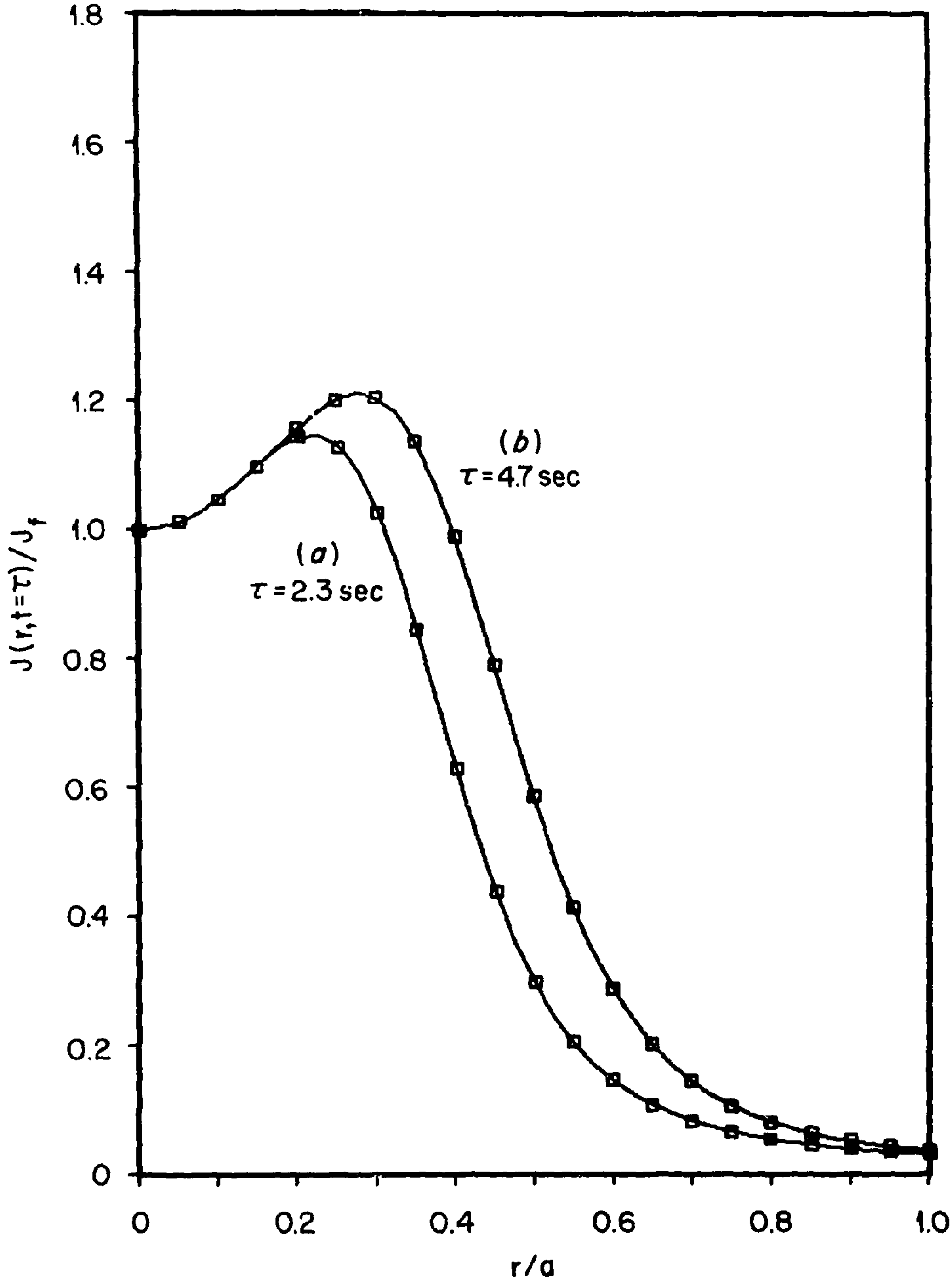

Fig. 10. Final current density profiles for (a) $\tau = 2.3$ sec, (b) $\tau = 4.7$ sec.

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