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# EFFECTS OF FUELING PROFILES ON PARTICLE TRANSPORT AND HELIUM ASH ACCUMULATION

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# Effects of Fueling Profiles on Particle Transport and Helium Ash Accumulation

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Parameteric surveys are conducted to investigate the effects of particle source profiles in the steady state of an ignited D-T tokamak plasma on the particle confinement time, the helium ash accumulation and the particle flux. The reference reactor envisaged is the INTOR-J having poloidal divertors with major axis of 5 m and minor radius of 1.2 m. The helium ash accumulation increases gradually for the helium recycling fraction $R_\alpha$ less than about 0.8 and rapidly for $R_\alpha > 0.8$. It is possible to reduce considereably the required pumping speed by raising the recycling fraction to about 0.8 without an appreciable enhancement in $\beta$-value.

Keywords: Tokamak Fusion Reactor, INTOR, Fueling, Density Profile, Confinement Time, Ash Accumulation, One-dimensional Transport, Recycling Fraction

# プラズマ内の燃料源分布が粒子輸送とヘリウム灰の蓄積に及ぼす効果

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DTトカマク・プラズマの定常状態において，燃料粒子源の空間分布が粒子閉込め時間，ヘリウム灰の蓄積と粒子束に及ぼす効果について検討を行った。解析は1次元輸送モデルに基づいてINTOR（国際トカマク炉）程度のプラズマの大きさを対象として行っている。特にヘリウム粒子のリサイクリング効果について検討を行い，リサイクリングが0.8程度までは炉心プラズマ内のヘリウム蓄積即ちベータ値の増大をあまり大きくすることなしに，必要排気速度を相当に減少させ得ることが明らかになった。

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# 1. Introduction

Particle source profiles affect the particle transport characteristics, the particle flux escaping from the plasma and the scrape-off layer plasma. The particle source is provided by an external injection (gas puffing, pellet injection), recycled neutrals and the fusion reaction for an ignited plasma. We should note differences in particle source profile between fuel and helium particles. Fuel particles are refueled from outside, while helium particles are generated in a main plasma and the source profile is centrally peaked. The fuel source profile strongly depends on the fueling method. The fuel penetration for gas puffing is very shallow, while pellet injection provides deep penetration. Another important consideration is the particle recycling which yields a shallow particle source profile. The density profile for a shallow source profile is nearly flat and that for deep fuel penetration a more centrally peaked profile.

The required pumping speed is closely related to the particle flux and the recycling fraction. The accumulation of helium in a main plasma would be influenced by the recycling fraction. In an equilibrium burn state the ash exhaust rate is equal to the generation rate of helium in the plasma and the amount of additionally refueled particles is the loss by burn and pumping out.

In this paper we will concentrate on the investigation into the effects of particle source profile in the steady state of an ignited D-T tokamak plasma on the density profiles, the particle confinement time, the helium ash accumulation and the particle flux to wall materials. Parametric surveys have been conducted by varying the boundary conditions which cover the scrape-off plasma parameters for the operational conditions considered. The reference reactor envisaged is the INTOR-J [1] having poloidal divertors with major radius (R) of 5 m and minor radius (a) of 1.2 m. The plasma is treated as having a circular cross section for simplicity.

## 2. Model

The plasma boundary conditions and the particle recycling fraction are interrelated with the transport model in the main plasma and the behavior of the scrape-off plasma including the particle motion in a divertor chamber. The parameters of the scrape-off plasma are given by the empirical scaling laws obtained in DIVA [2].

$$\bar{T}_b = \frac{P_\alpha - P_{cx} - P_R}{\gamma \Gamma_{es}} = 1.56 \times 10^{21} \frac{P_w^n (1 - f_w)}{\gamma \Gamma_f} \qquad (1)$$

$$f_w = (P_{cx} + P_R)/P_\alpha \qquad (2)$$

$$\bar{n}_b d = \frac{L}{4\pi^2 R_a} \frac{\Gamma_{es}}{v_f} \qquad (3)$$

$$L = \frac{\pi a}{y} \frac{\sqrt{B_t^2 + B_\theta^2}}{B_\theta} \qquad (4)$$

where $\bar{T}_b$(keV) is the mean temperature of the scrape-off plasma, $\gamma$ the heat transport rate to the neutralizer plate, $P_\alpha$ the $\alpha$-particle heating power, $P_{cx}$ the charge-exchange loss, $P_R$ the radiation loss, $\Gamma_{es}$ is the total particle flux ( $= 4\pi^2 R_a \Gamma_f$ ), $\Gamma_f$ the particle flux ($m^{-2} \cdot s^{-1}$), $P_w^n$ the neutron wall loading ($MW/m^2$), $v_f$ the particle flow velocity, conditions considered. The reference reactor envisaged is the INTOR-J[1] having poloidal divertors with major radius (R) of 5 m and minor radius (a) of 1.2 m. The plasma is treated as having a circular cross section for simplicity.

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$\bar{n}_b$ the mean density of the scrape-off plasma, d the thickness of the scrape-off layer, $B_t$ the totroidal magnetic field, $B_\theta$ the poloidal magnetic field, L the length of magnetic field lines to a material surface and y the number of divertor null-point.

In a reactor design the neutron wall loading is a key design parameter. Its value expected in a near future reactor like the INTOR-size[3] considered here is around 1 $MW/m^2$. The neutron wall loading of 1 $MW/m^2$ corresponds to a fusion power of 300 MW for a circular plasma. In Fig.1 are shown relations among the parameters in Eqs.(1) ~ (3) for typical values covered in this study assuming $B_t/B_\theta$ = 10, y = 2 and $v_f = 0.3\ v_s$[2] ($v_s$: sound velocity). The value of d varies from a few centimeters to a few tens of centimeters and is influenced by ergodic layer, by diffusion effect and by mirror effect[4]. The relations in Fig.1 are helpful to the consideration of the plasma edge condition. For instance, a set of $\bar{T}_b \sim 0.5$ keV, $\Gamma_f \sim 1 \times 10^{20}\ m^{-2}\cdot s^{-1}$, d ~ 0.15 m, $\bar{n}_b \sim 3 \times 10^{18}\ m^{-3}$, $f_w \sim 0.5$ and $P_w^n \sim 1\ MW/m^2$ yields consistent solutions. These values for $\bar{T}_b$ and $\bar{n}_b$ are apllied as reference boundary conditions. The DT particles are treated as haveing an effective mass number of 2.5 in this study.

One-dimensional equations for the particle balance for cylindrical geometry are solved.

$$-\frac{1}{r}\frac{d}{dr}(r\Gamma) + S(r) = 0 \qquad (5)$$

$$S(r) = S_g(r) + S_p(r) - \frac{1}{2} n_i^2 < \sigma v >_f \quad \text{for fuel particles} \qquad (6)$$

$$S(r) = S_g(r) + \frac{1}{4} n_i^2 < \sigma v >_f \quad \text{for helium particles} \qquad (7)$$

where $S_g(r)$ represents the particle source profile by neutral gas (gas puffing, recycling), $S_p(r)$ the particle source profile by pellet injection,

$n_i$ the fuel density and $<\sigma v>_f$ the fusion reaction rate. The source profile $S_p(r)$ used linearly varies in intensity:

$$S_p(r) = \frac{h_p - h_\ell}{\ell}\left(\frac{r}{a} - 1\right) + h_p \quad \text{for } \frac{r}{a} \geq 1 - \ell$$
$$= 0 \quad \text{for } \frac{r}{a} < 1 - \ell \tag{8}$$

where $a\ell$ is the maximum penetration depth of the source measured from the plasma edge, and $h_p$ and $h_\ell$ are the source intensity at the plasma edge and $r = a - a\ell$, respectively. The profile $S_g(r)$ is obtained by solving the Boltzmann neutral transport equation for cylindrical geometry which is consistently coupled with Eq.(5). For fuel particles the ionization rate coefficients formulated by Freeman and Jones(5) and the charge exchange rate coefficients by Riviere(6) are used. The ionization rate coefficients for helium particles are those given by Lotz(7).

The particle flux may be given by a combination of the Ware pinch flux $\Gamma_w$(8) and the diffusion coefficient D related to the empirical electron thermal diffusivity $\chi_e$(3):

$$\Gamma = -D\frac{dn}{dr} + n\,\Gamma_w \tag{9}$$

where

$$D = \chi_e/C_D \quad (m^2/s)$$
$$\chi_e = \frac{5 \times 10^{19}}{n_e} \quad (m^2/s) \tag{10}$$

$$\Gamma_w(r) = -\frac{2.44}{1 + 0.85\,\nu_e^*} \cdot \frac{(r/R)^{1/2}\,E_Z(r)}{B_\theta(r)}\,n(r) \tag{11}$$

$$\nu_e^* = \nu_{ei}/\nu_{e1}$$
$$\nu_{e1} = (r/R)^{3/2}\,V_T/Rq$$

$q$ : safety factor

$V_T$ : thermal velocity

$E_Z$ : toroidal electric field.

According to the reference transport model formulated at the INTOR Workshop(3) the constants $C_D$ = 12 and 4 are assumed.

The analytical temperature profile used is given by

$$T(r) = [T(o) - T(a)]\ [1 - (\frac{r}{a})^m]^n + T(a) \tag{12}$$

The profile of m = 4 and n = 2.5 has been employed, which is fitted to the typical profile obtained by one-dimensional time-dependent transport code considering the particle and energy balances. The results for the particle transport behavior are not so sensitive to the temperature profile. The peak temperature T(o) is determined to give an average temperature of $\bar{T}$ = 10 keV. Steady state solutions for the desity profile that satisfy a fixed neutron wall loading are sought.

## 3. Results and discussion

Figure 2 shows the solutions when $S_g(r)$ is provided by neutral gas fueling with incident energy $T_n$. The plasma edge temperature is assumed to be equal to $T_n$. The results for fairly low density boundaries are illustrated for comparison. For the case of $C_D$ = 12 without helium recycling the helium conceneration is 5 ~ 6 % and the helium confinement time is larger approximately one order of magnitude than the fuel confinement time. The helium confinement time and the helium density concentration are not so sensitive to $T_n$, while the fuel ion flux and the fuel confinement time relatively depend on $T_n$ and the

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In the followsing the case treating pellet fueling and helium recycling are discussed. The respective fractions are defined as

$$C_p = \frac{\text{pellet fueling}}{\text{total fueling including recycling}}$$

$$R_\alpha = \frac{\text{recycled helium into the plasma}}{\text{helium escaping from the plasma}} \quad .$$

The difference in particle flow between the denominator and the numerator in the $R_\alpha$-definition is exhausted, which is equal to the helium production rate by the fusion reaction. The $R_\alpha$ corresponds to the back flow fraction to the main plasma in Ref.(9). According to their numerical simulation for the particle motion in a divertor chamber the back flow fraction of helium particles determined from the effective pumping speed of $5 \times 10^5$ litre $\cdot$ $s^{-1}$ is less than that of fuel particles by 0.1 ~ 0.2 and exceeds about 0.3 for most of conceivable conditions, though the pumping speed required for the steady state is not self-consistently determined with the back flow fraction. However, relations between helium and fuel particle recycling would be dependent on a model used. The problem of particle recycling should be solved on the basis of a consistent model for the particle and energy transport in a main plasma, the scrape-off plasma, the particle reflection and density in a divertor chamber and the pumping speed. In this paper the value of $R_\alpha$ is parametrically varied independent of fuel particle recycling in order to find the effect on helium accumulation and confinement time.

The penetration depth $\ell$ of pellet injection with the velocity as high as $10^4$ m·s$^{-1}$ may be at most 0.5 for the present plasma parameters[3]. With considerable recycled particles the source profile becomes relatively shallow as a whole. The reference boundary parameters previously mentioned, $n_i(a) = \bar{n}_b = 3 \times 10^{18}$ m$^{-3}$, $T(a) = \bar{T}_b = 0.5$ keV, correspond roughly to those for the pellet injection of $\ell = 0.5$, $h_\ell = 0$ and $C_p = 0.5$ with recycling. In Fig.3 effects of the helium recycling on the particle parameters (average density, flux, confinement time) are shown for different boundary conditions. The energy of recycled particles is assumed to be $\bar{T}_b$. All the particle parameters envisaged were found to be quite insensitive to the energy of recycled helium particles. The parameters of the scrate-off layer plasma are greatly influenced by the main-plasma parameters, as seen in Fig.1. On the other hand, the particle parameters of the main-plasma are not so much sensitive to the boundary parameters, as seen in Fig.2 and 3. Figure 3 illustrates large differences in helium concentration between density and particle flux in the range of $R_\alpha \lesssim 0.8$. It is because the flux $\Gamma_\alpha$ increases in proportion to $(1 - R_\alpha)^{-1}$ and the $\Gamma_f$ is almost constant over the change of $R_\alpha$. The results suggest that helium pumping can be alleviated without an appreciable enhancement of helium accumulation.

In Fig.4 the neutron wall loading $P_w^n$ is varied. The helium density concentration increase nearly in proportion to an increase of $P_w^n$. The increase of the confinement time of helium for a change from $P_w^n = 1$ MW/m$^2$ to 2 MW/m$^2$ is slightly larger than that of fuel particles. For the change of $P_w^n$ the average helium density increases more than twice because of the increase of the helium confinement time. Figure 5 illustrates the effect of the diffusion constant $C_D$ on the helium concentration and flux. The $\Gamma_\alpha/\Gamma_f$ decreases nearly in proporation to the decrease of $C_D$, while the decrease of the helium density concentration is about half that of $\Gamma_\alpha/\Gamma_f$. The change of $\Gamma_\alpha/\Gamma$ is due to the change of $\Gamma_f$ because the $\Gamma_\alpha$ does not change for given $R_\alpha$ and $P_w^n$ in a steady state. For the change of $C_D$ the average helium density decreases by the factor corresponding to the decrease of the helium confinement time, i.e., by a factor of about 2.5, while the average fuel density varies slightly because of the fixed $P_w^n$. The $\tau_\alpha$ is approximately equal to the $\tau_p$ near $R_\alpha \sim 1$ for $C_D = 12$ as seen in Figs.3 and 4. In case of $C_D = 4$ $\tau_\alpha \sim \tau_p$ is obtained for $R_\alpha \sim 0.8$.

Figure 6 shows the effect of the maximum penetration depth $\ell$ as a function of pellet fueling. The case of $\ell = 1.0$ and $h_\ell = h_p$ which gives a flat source profile to reach the plasma center does not make large differences in the density concentration and confinement time of helium from the reference case of $C_p = 0.5$, $\ell = 0.5$ and $h_\ell = 0$. The similar results are found for the cases with helium recycling. The deep penetration increases somewhat the helium ash accumulation. Pellet injection to reach the plasma center would not be necessary to improve particle confinement.

We have shown the results of parametric surveys in order to find the effect of particle source profiles and recycling on the helium density concentration and the particle confinement, fixing the neutron wall loading. The following is a summary of the results.

The helium flux escaping from the main plasma increases rapidly with increasing $R_\alpha$, while the increase in the helium density concentration is relatively small for $R_\alpha < 0.8$. As a result the required pumping speed for helium can be considerably reduced by raising the recycling fraction to $R_\alpha \sim 0.8$ without appreciably large enhancement in β-value.

The helium density concentration increases nearly in proportion to an increase of the neutron wall loading i.e. average fusion power density. Reducing the diffusion constant $C_D$ decreases largely the helium density concentration. The value of $C_D = 12$ recommended at the INTOR workshop will require a considerable margin in β-value for a commercial reactor having the neutron wall loading of a few $MW/m^2$ and a large plasma radius.

References

(1) Sako, K., Tone, T. Seki, Y., Iida, H., Yamato, H., et al.: Engineering Aspects of the JAERI Proposal for INTOR (I) and (II), JAERI-M 8503 and 8518 (1979).

(2) DIVA Group: Nucl. Fusion 18, 1619 (1978).

(3) IAEA, International Tokamak Reactor, Zero Phase, IAEA, Vienna (1980).

(4) Shimomura, Y., Sako, K., Shinya, K.: Some Condiderations of Ash Enrichment and Ash Exhaust by a Simple Divertor, JAERI-M 8294, (1979).

(5) Freeman, R.L. and Jones, E.M.: Atomic Collision Processes in Plasma Physics Experiments CLM-R 137 (1974).

(6) Riviere, A.C.: Nucl. Fusion 11, 363 (1971).

(7) Lotz, W.: Z. phys. 216, 241 (1968).

(8) Ware, A.A.: Phys. Rev. Lett., 25, 15 (1970). Hinton, F.L. and Wiley, J.C.: Phys. Rev. Lett., 29, 298 (1972).

(9) Seki, Y., Shimomura, Y., Maki, K., Azumi, M., Takizuka, T.: Nucl. Fusion 20, 1213 (1980).

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References


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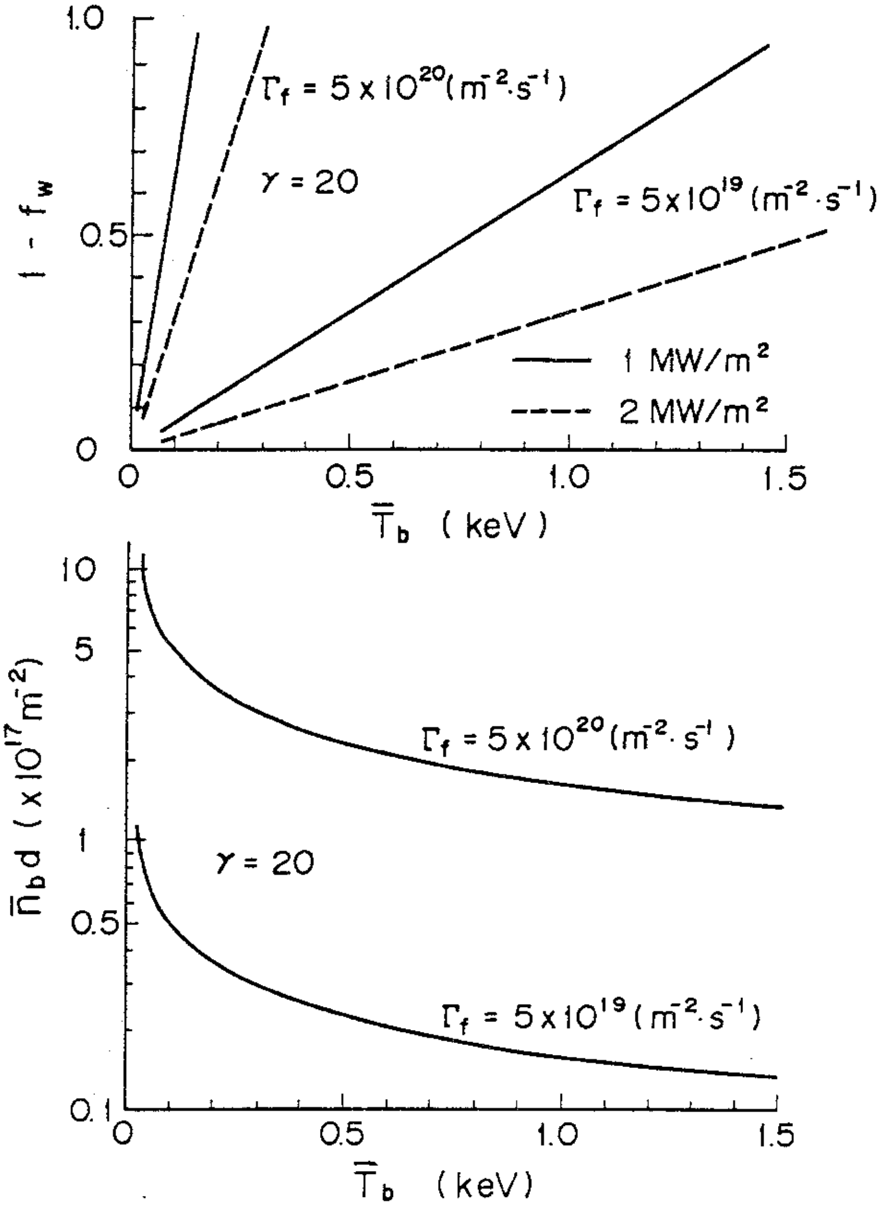


Fig.1 Relations among the scrape-off plasma parameters given by the empirical scaling laws in Eqs. (1) - (3)

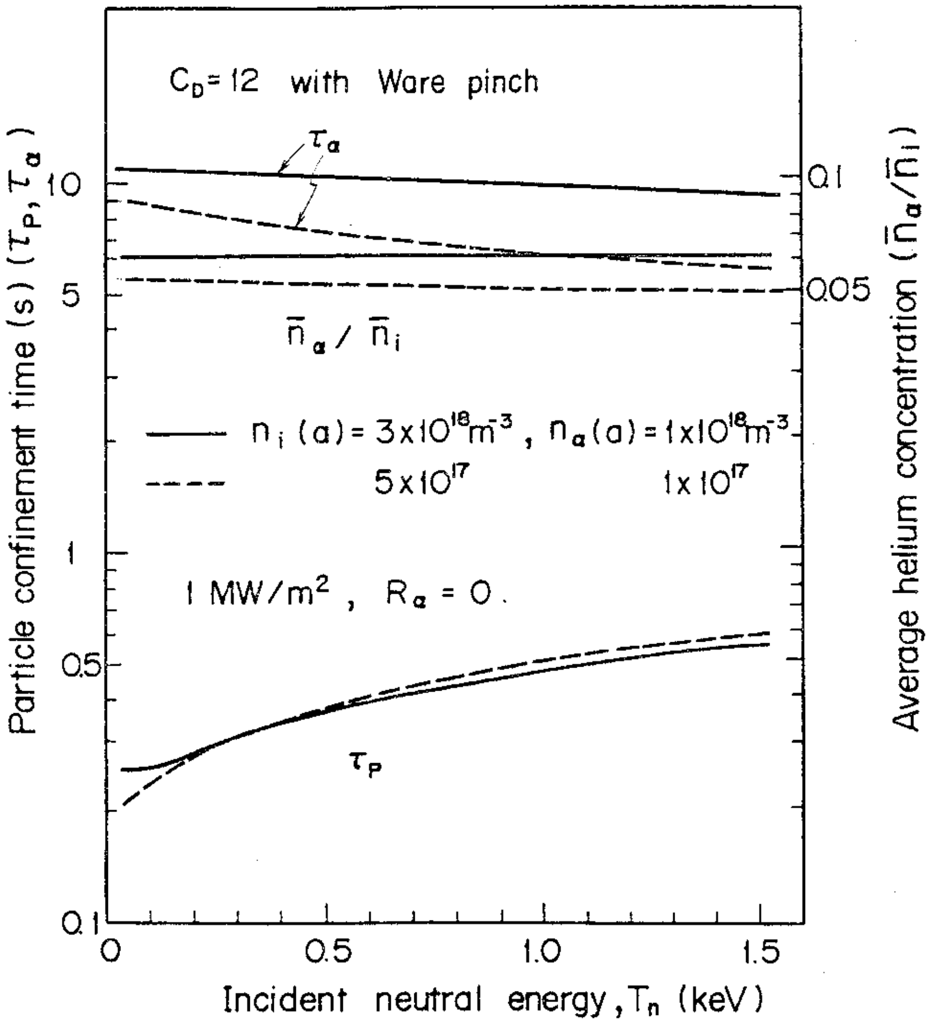


Fig.2a Particle confinement times and average helium density concentration as a function of the incident energy of neutral fuel particles

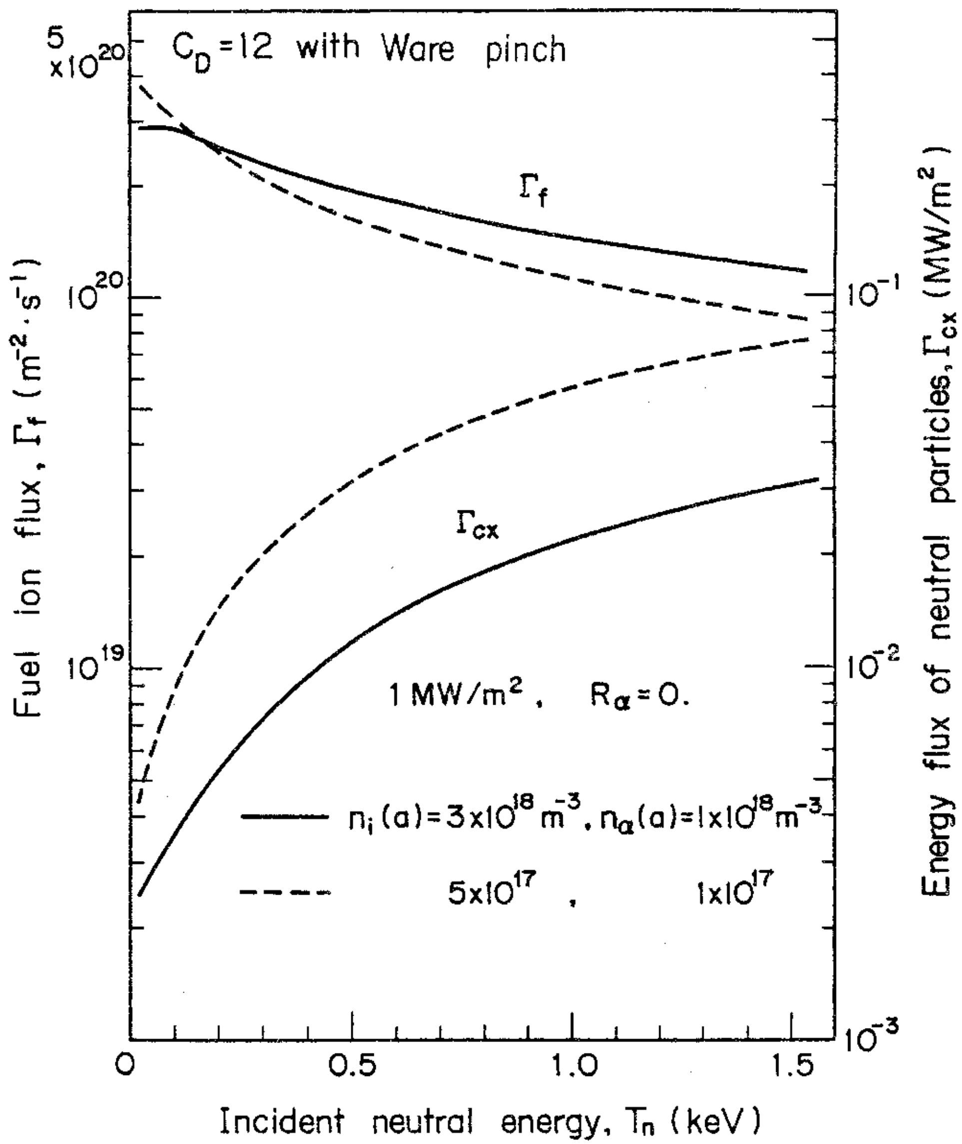


Fig.2b Fuel ion flux and the energy flux due to charge exchange as a function of the incident energy of neutral fuel particles

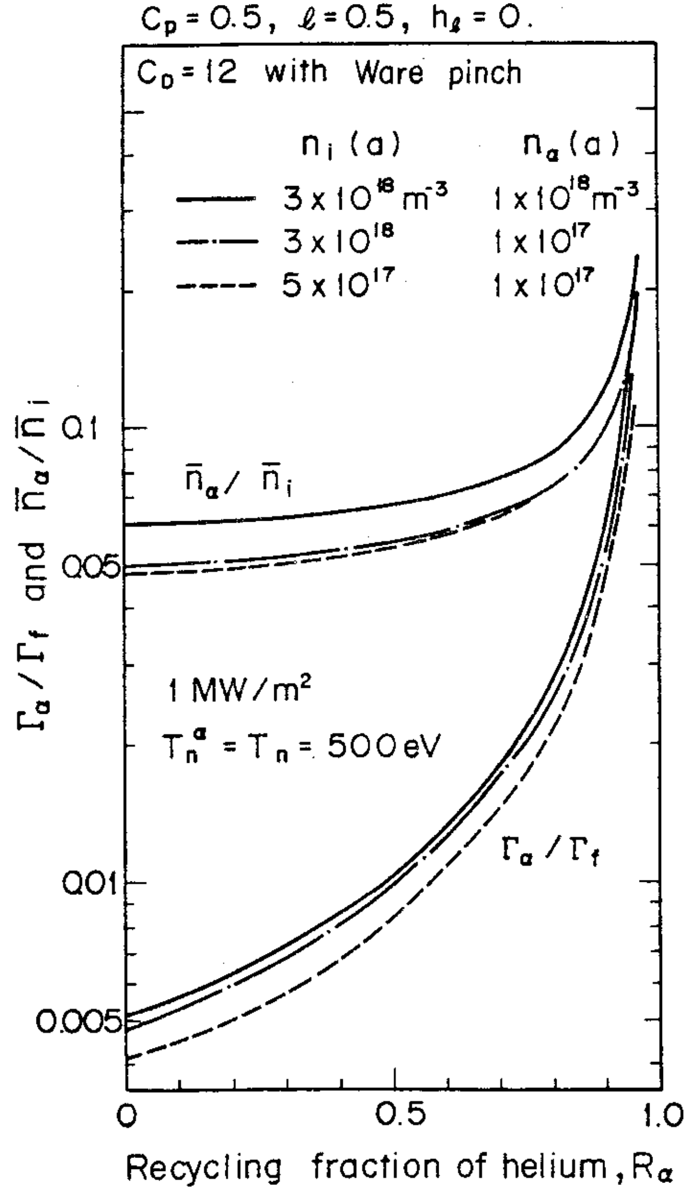


Fig.3a Helium concentration in density and flux as a function of the helium recycling fraction for various boundary densities

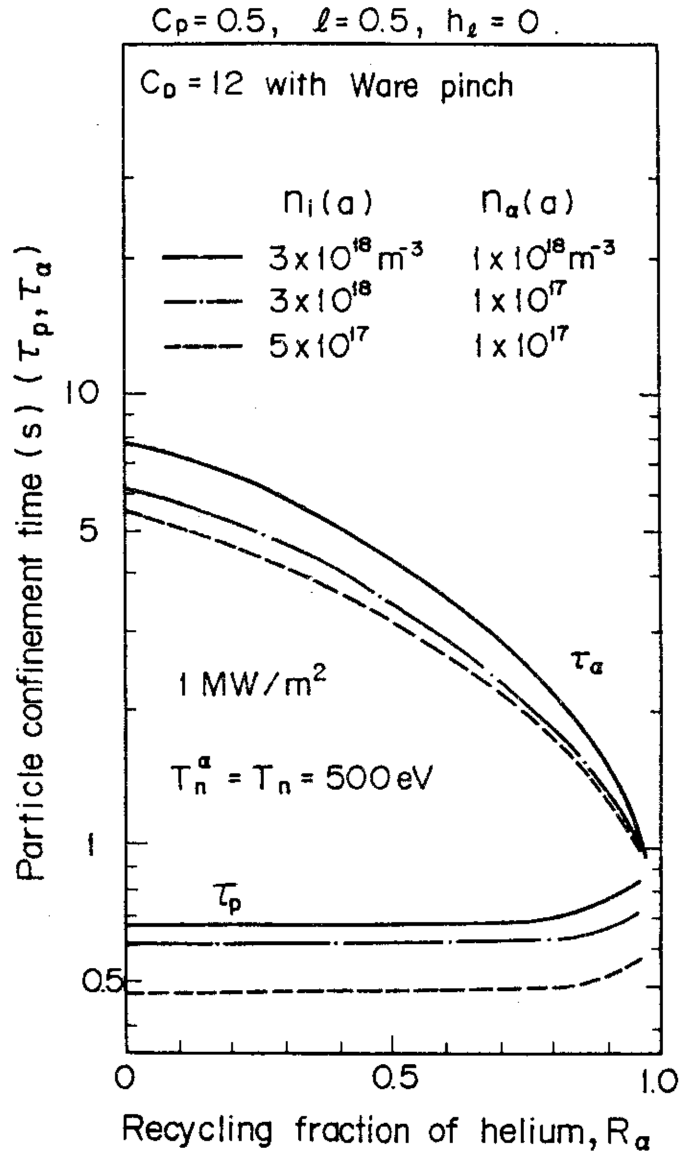


Fig.3b Particle confinement times as a function of the helium recycling fraction for various boundary densities

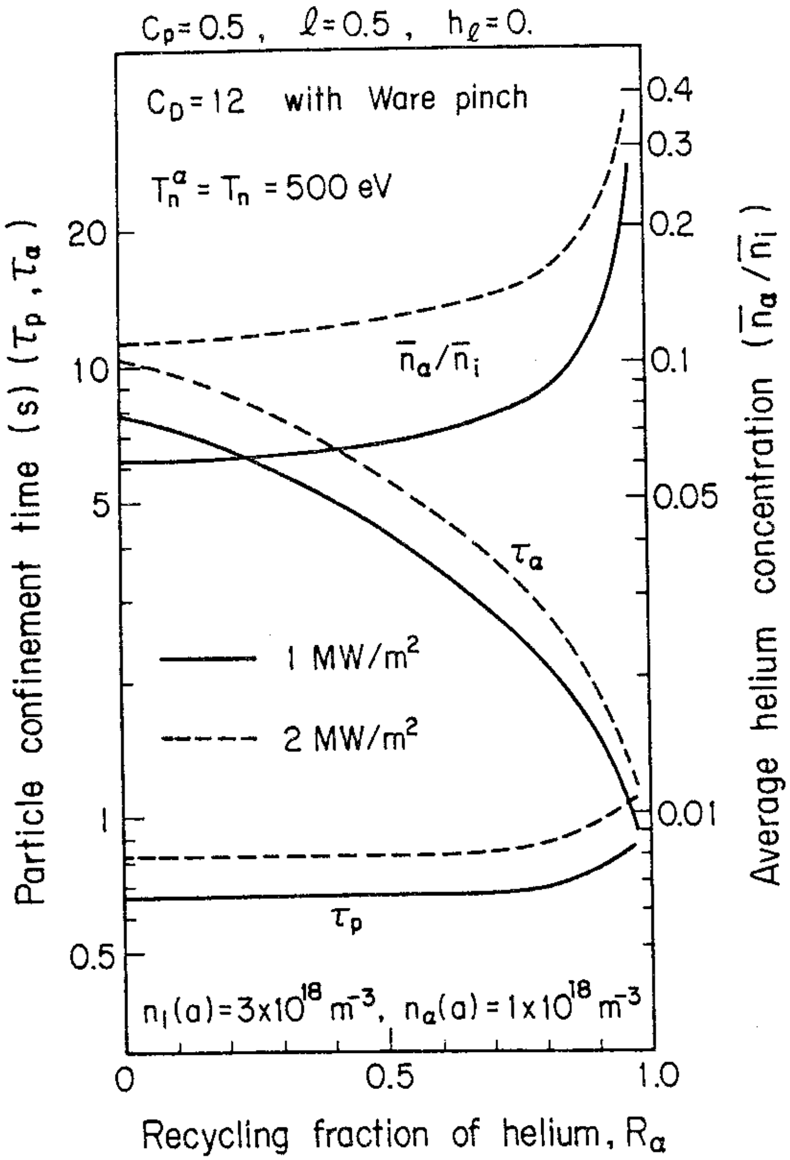


Fig.4 Particle confinement times as a function of the helium recycling fraction for different values of neutron wall loading

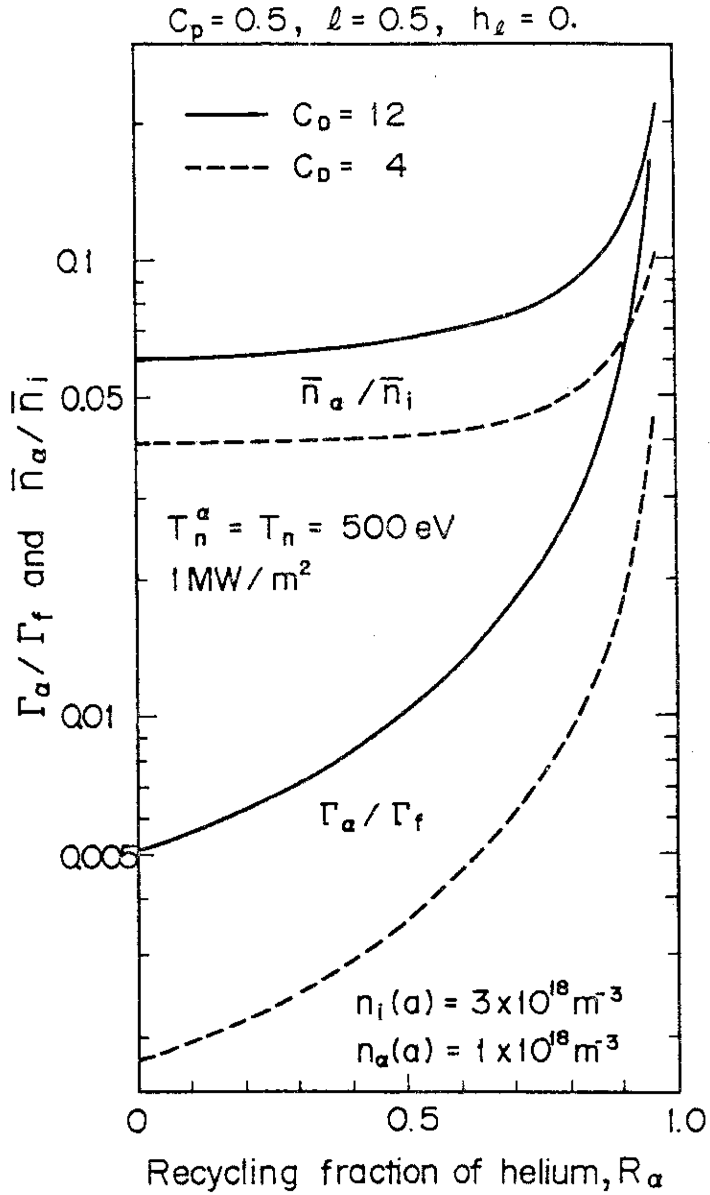


Fig.5 Helium concentration in density and flux as a function of the helium recycling fraction for different diffusion constants in Eq.(10)

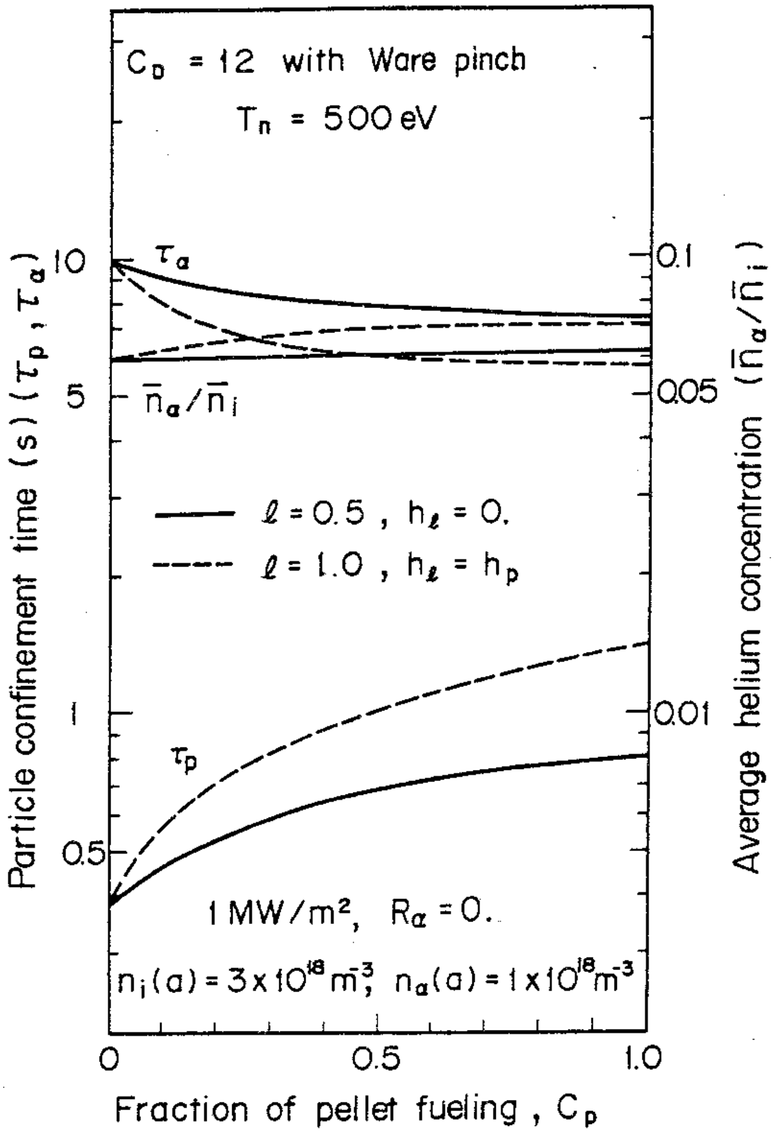


Fig.6 Particle confinement times and average helium concentration as a function of the pellet fueling fraction for different pellet source profiles