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Recycling Process of Impurities in Tokamak Discharges

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In the recycling process of impurities in a plasma, only the sputtering of first wall materials is usually considered. In the present study, not only sputtering of metal but desorption of sorbed layers by particles and reflection of incident impurity ions at the limiter are also introduced. The behaviour of impurities in the discharges of recent Tokamaks is interpreted quantitatively and the result is applied to a future large Tokamak. The nonmetallic impurity concentrations may attain plateaus in the early stage of a discharge which are lower than the permissible levels, because the desorption yield by particles may probably be decreased by discharge cleaning. On the contrary the metallic impurity concentrations tend to increase beyond the permissible levels, since the self-sputtering yield of impurity ions will become larger than unity with the increase of plasma temperatures. In this respect the method to reduce the metallic impurities is important.

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トカマクプラズマでの不純物リサイクリング過程

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次代の大型トカマクでは，プラズマ中の水素以外のイオン（不純物）の量の低減が要請される。近年の実験では，不純物は放電の初期に急増し，以後はほぼ一定値を示す傾向が得られている。本報告では，プラズマと壁表面との相互作用が，衝撃粒子による壁金属のスパッター，収着層の脱離，表面における粒子の反射という現象で記述できるとするモデルにより，実験で得られいる不純物発生挙動が定量的に説明できることを示す。その解釈の延長として，ガス不純物は放電洗浄による脱離比の低下に，金属不純物は磁気リミター部におけるダイバータ効果によって，不純物量を許容値以下に押えうる可能性があることを述べる。

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1. INTRODUCTION

Impurities play an important role in Tokamak discharges. The contamination of a plasma by impurities will be one of the most serious problems in the stage of demonstrating the scientific feasibility of Tokamak plasma confinement. In Tokamak plasmas, there exist metallic impurities produced at the limiter and the wall as well as nonmetallic ones desorbed from sorbed layers on the limiter and wall surfaces.

The permissible levels of impurity concentration in a future large Tokamak are of the order of a few percents for the nonmetallic impurities and of the order of one tenth of the nonmetallic for the metallic which have been estimated from the radiation losses due to impurities [2]. In recent experiments (ST[3], ATC[4], TFR[5]), impurities contaminate the plasma in the early stage of the discharges and the ratio of their concentrations to that of hydrogen ions is rather constant during the discharges.

To explain these experimental results not only qualitatively but also quantitatively, we shall discuss the recycling processes of impurities taking account of sputtering of the limiter and wall materials, desorption of sorbed layers and reflection of impurity ions. An estimation is then made on the impurity concentration in a future large Tokamak to find whether it can be kept lower than a tolerable level.

2. IMPURITY CONCENTRATIONS IN TOKAMAK PLASMAS

Continuous efforts have been made in the past to measure impurity concentrations in Tokamak plasmas, especially in Princeton Plasma Physics Laboratory. Quantitative vacuum ultraviolet (UV) measurements of various ST Tokamak discharges show that the concentration of metallic impurities (Fe, Mo) is about 0.1 % to 1.5 % of the electron density and that of nonmetallic (oxygen) is about 1 % to 10 % [3]. Impurity concentrations obtained in a typical ATC discharge are less than 3 % of electron density for the nonmetallic impurity (oxygen) and 0.15 % for metallic impurities (Fe, Mo)[4]. In both cases impurities are present from the beginning of the discharge without a substantial change thereafter. Such a stationary behaviour of the impurity concentration indicates steady recycling of the impurities. The preliminary data in TFR show a similar trend but in some discharges carbon was observed in almost the same amount as oxygen [3]. The radial distribution of high-Z material is obtained from X-ray

measurements in ST and there exists no extreme accumulation in the center, but may exist variations within a factor of 2 [3]. A similar observation is made in TFR by rather indirect methods [5].

On the contrary a different impurity behaviour was observed in Tokamaks of USSR. By analysing soft X-ray in T-4, impurities are found to be localized in a relatively narrow region near the plasma column axis and the total amount of the impurities in the central region of the plasma column increased steadily during the discharge [6].

In this paper, it is shown that such impurity behaviours may be almost understood by considering recycling process. The reason why the difference in the radial distribution of impurities exists between measurements of PPPL and USSR is an important problem but is not discussed in this paper.

3. RECYCLING PROCESS OF IMPURITIES

Considering the interaction between the plasma and the wall, two kinds of particle should be remarked as shown in Fig. 1. One is charged particles which mostly bombard the limiter, the other is hot neutral particles which uniformly bombard the wall of vacuum vessel. When the interactions between these particles and the wall are described by sputtering of metals, desorption of sorbed layers by particles and reflection of incident impurity ions, the time dependence of impurity concentrations during a discharge in hydrogen is given by [2,8,18]:

$$\frac{dNz}{dt} = \eta_1 \frac{N_p}{\tau_p} + \eta_2 \frac{\gamma}{1-\gamma}\left(\frac{N_p}{\tau_p} + \frac{dN_p}{dt}\right) + (R+\eta_3-1)\frac{Nz}{\tau_z} \qquad (1)$$

where N_p and Nz are the total number of hydrogen and each impurity ions, τ_p and τ_z are their respective pargicle confinement times, η_1 and η_3 are their respective sputtering or desorption yields, η_2 is the sputtering or desorption yield by hot neutral particles, R is the reflection coefficient of impurity ions and γ is the rate of hot hydrogen neutral particles escaping from the plasma for each incident cold neutral particles.

The first two terms in Eq. (1) represent the impurity which is released from the limiter surface by hydrogen ion bombardment and that from the vacuum wall surface by hydrogen neutral particle bombardment respectively. The last is the sum of the impurity ions diffusing out from a plasma, the impurity particles reflecting at the limiter surface and

those which are released from the limiter surface by impurity ion bombardment.

If the coefficient of the last term $(R+\eta_3-1)$ is negative, Nz/Np reach a plateau which is described by:

$$\frac{Nz}{Np} = \frac{\tau_z}{\tau_p} \frac{\eta_1+\eta_2\gamma(1-\gamma)}{1-R-\eta_3} \qquad (2)$$

This situation may be the case in recent Tokamaks because of $R \sim 0$, $\eta_3 < 1$ for metalic impurities and $R \sim 0.5$, $\eta_3 < 0.1$ for nonmetallic impurities.

4. EVALUATION OF COEFFICIENTS

In this section we estimate sputtering yields, desorption yields by particles and reflection coefficients to consider recycling processes by Eq. (1). These coefficients depend on incident particle energies which are considered to be plasma boundary temperatures, $10 \sim 100$ eV, for charged particles and of the order of average ion temperatures, $30 \sim 300$ eV, for hot neutral particles in recent Tokamaks [7][17].

(A) SPUTTERING YIELDS

Behrisch estimated the dependence of the sputtering yield on the incident energy when hydrogen ions bombard stainless steel, using the experimental data of sputtering yield by hydrogen ions at high incident energies, those by rare gas ions at low incident energies and a computed threshold energy of sputtering for each incident ion [8]. The authors also estimated the sputtering yield by low energy hydrogen ions, using the experimental sputtering yield of Mo by rare gas ions at low incident energies [9] and the dependence of sputtering yield on the incident ion mass when various kinds of ions bombard the Ag target at 5 keV energy [10]. From these estimates the sputtering yield of stainless steel and Mo by 100 eV hydrogen ions is considered to be $10^{-3} \sim 10^{-4}$ which may be applied in the case of hydrogen neutral particle bombardment.

The self-sputtering yield of metal impurity is calculated under the assumption of random slowing down in an infinite medium [11]. The calculated results has an agreement with experimental values within a factor of 2. The self-sputtering yield at perpendicular incidence up to several hundreds eV of ion energy is given by [11]:

$$\eta_3 = \frac{3}{4\pi^2} \frac{0.26E}{U_0} \tag{3}$$

where E is the incident ion energy and U_0 the sublimation energy of target metal. The constant 0.26 is the coefficient which is calculated for the self-sputtering [11]. Using the sublimation energy of Mo and Fe (6.9 eV and 4.15 eV) the self-sputtering yields by 100 eV Mo and Fe ions is computed to be 0.29 and 0.48 respectively. From Eq. (3) and the consideration of sputtering yield at incident energies above several hundred eV the self-sputtering yield increases with incident energies.

(B) DESORPTION YIELDS BY PARTICLES

Desorption of sorbed layers by particles is a complicated problem but it is convenient for understanding a discharge cleaning effect to use the following simplified equation [12].

$$\frac{dn}{dt} = -nj\sigma \tag{4}$$

where n is the surface density of sorbed layer, j the particle flux density and σ the cross-section for desorption. Equation (4) is used for the electron-impact desorption. In the case of the desorption by ions or particles, source term from deeper layers should be considered in right hand side of Eq. (4). Solving Eq. (4), the desorption yield and the cross-section for desorption are;

$$\eta = n\sigma = n_0\sigma e^{-j\sigma t} \tag{5}$$

$$\sigma = -\frac{1}{j}\frac{d(\ell n\eta)}{dt} \tag{6}$$

where n_0 is the initial surface density. The cross-section for desorption is determined by Eq. (6) when the time variation of desorption yield is known in the experiment.

We have only a few appropriate experimental data of the cross-section for desorption. One is $10^{-14} \sim 10^{-15}$ cm^2 in the experiment in which the 230 eV rare gas ions bombard the sorbed layers of rare gases on glass surface and this value was obtained under the condition of $n_0 \sim 10^{15}$ cm^{-2} [13]. The other is 2×10^{-17} cm^2 for hydrogen that released from the surface

when 5.6 keV D^+ ions bombard the sorbed layer on stainless surface and in this case n_0 is 10^{17} cm^{-2} [14].

Now we estimate the desorption yield η (ie $n\sigma$ in Eq. (5)) of sorbed oxygen layers on limiter or vacuum wall surface from these experimental data. The authors think the difference between desorption cross-sections of rare gases and hydrogen originate in the difference of sorption energy. The energy of physisorption of rare gases is less than that of chemisorption in hydrogen by a factor of 10. Concerning oxygen the energy of chemisorption is larger than that of hydrogen by a factor of 3 ~ 4. Therefore the desorption cross-section of oxygen will be less than that of hydrogen. The other parameter in desorption yield is the surface density. This depends on the ion range which is approximately proportional to the incident ion energy. As described before, the incident ion energy is of the order of 100 eV in recent Tokamaks. Then the surface density of oxygen on limiter or vacuum wall is less than that of hydrogen in the experiment of 5.6 KeV D^+ ion bombardment.

From these estimates the initial desorption yield of chemisorbed oxygen by 100 eV H^+ ions may be considered to be about 0.1. The desorption yield of chemisorbed oxygen will decrease with continued discharges, since the surface density of chemisorbed oxygen decreases as described in Eq.(5). The rate of decrease is determined by the number of oxygen particles which is evacuated to the vacuum system. In the very final stage the surface density will diminish to less than 10^{13} cm^{-2} which corresponds to the solute oxygen in bulk metal if the solubility of oxygen to the metal is 10 p.p.m. or so. In this situation the desorption yield of oxygen is considered to be less than 10^{-4} which is negligible for production of impurity on the wall.

(C) REFLECTION COEFFICIENTS

The reflection coefficient depends strongly on the mass ratio of incident ions to target atoms and weekly on incident ion energies. When a metal ion bombards the metal whose mass number is equal to that of the incident ion, the reflection coefficient is considered very small according to the calculation based on random slowing down by elastic collisions in an infinite medium [15]. On the contrary some fractions of incident ions are reflected in the light element bombardment. Behrisch compiled some experimental data and computed results of the reflection coefficient

in hydrogen ion bombardment (Fig. 2) [8]. When the incident energy of hydrogen ions is 100 eV the reflection coefficient is about 0.5. In the oxygen ion bombardment the reflection coefficient may become half as large from the estimation concerning to the mass ratio of incident ion to target atom [15][16].

5. RESULTS

The time dependence of impurity concentrations in hydrogen plasma can be computed by Eq. (1), using plasma parameters of ST Tokamak and the evaluated values of coefficients which represent the interaction between plasma and wall. For this purpose we need the time variations of plasma particle confinement time and hydrogen ion density which is approximated by the electron density. These are approximated by the following equations in a typical discharge of ST Tokamak [3][17].

$$\begin{aligned}
\bar{n}_e &= 10^{11} + 10^{13} t \quad (cc^{-1}) \quad 0 \leqq t \leqq 1.5 \text{ msec} \\
\bar{n}_e &= 1.5 \times 10^{13} \quad (cc^{-1}) \quad t > 1.5 \text{ msec} \\
\tau_p &= 1 + 0.43\, t \quad (\text{msec}) \quad t \leqq 40 \text{ msec} \\
\tau_p &= 17 \quad (\text{msec}) \quad t > 40 \text{ msec}
\end{aligned} \tag{7}$$

The evaluation of γ in Eq. (1) is an important problem in itself but we set $\gamma = 0.1$ in this discussion, since the second term in Eq. (1) affects the total number of each impurity ions in the order of γ comparing with the first term of Eq. (1).

The time dependence of nonmetallic impurity concentration during a discharge when τ_z is equal to τ_p is shown in Fig. 3. First three cases show the effect of the reflection coefficient which is considered to be less than 0.5 for oxygen ions as described in section 4. The large reflection coefficient renders the plateau value of impurity concentration higher as also understood by Eq. (2). In the case 4 we set $\eta_1 = 0.01$ and $\eta_2 = 0.1$ considering that a discharge cleaning effect is more effective on the limiter than on the vacuum wall since the incident particle flux density on the limiter is larger in a factor of $10^2 \sim 10^4$ than that on the vacuum wall. The rate of increase in the initial stage of a discharge is greater than that in the case 1 in which we set $\eta_1 = 0.01$ and $\eta_2 = 0.01$. When a discharge cleaning is not sufficient, the desorption yield might

become 0.05 that is the value of η_1, η_2 and η_3 in the case 5. The plateau value of impurity concentration attains to 10 % of the electron density in this case. In every cases of Fig. 3 the impurity concentration increases in the initial stage of a discharge to the plateau value which is determined by Eq. (2) as observed in the discharges of ST, ATC and TFR in which τ_z is nearly equal to τ_p.

The dependence of nonmetallic impurity concentration upon τ_z is shown in Fig. 4 which is the results in cases: $\tau_z = \tau_p$, $\tau_z = 5\tau_p$ and $\tau_z = \tau_p/3$. If τ_z is larger than τ_p as measured in Tokamaks of USSR, the total impurity concentration increases gradually during a discharge as shown in Fig. 4 and in the case 5 of Fig. 5. But even if τ_z is larger than τ_p, nonmetallic impurity concentration may have the plateau value which is described by Eq. (2). In future large Tokamaks this plateau value will be able to be kept lower than the permissible level which is of the order of a few percents of hydrogen ions when desorption yields (η_1, η_2, η_3) by particles are decreased by discharge cleaning.

On the contrary the metallic impurity concentration increases strongly during a discharge if the self-sputtering yield of impurity ions is larger than unity. The self-sputtering yield is varied from 0.5 to 1.5 in initial four cases of Fig. 5 in which we set $\eta_1 = \eta_2 = 0.001$, R = 0 as described in section 4 and $\tau_z = \tau_p$. In recent Tokamaks the self-sputtering yield may be about 0.5 as shown in section 4 and then the metallic impurity concentration also increases in the initial stage of a discharge to the plateau value which is decided by Eq. (2). These phenomena were observed in the discharges of ST, ATC and TFR in which τ_z is nearly equal to τ_p. The condition of $\tau_z = 5\tau_p$ is set in the case 5 which is used before for the interpretation of the data in USSR. The self-sputtering yield is proportional to the incident particle energy up to several hundreds eV as described in Eq. (3). Therefore methods of decreasing effective self-sputtering yield of metallic impurities are very important in future large Tokamaks.

6. CONCLUSIONS

(1) Steady state concentrations can be achieved if η_3+R<1. This is very probable for the sorbed layers just due to depletion at the surface. No diverter may be needed for preventing nonmetallic impurities.

(2) For the metallic impurities the source terms are the sputtering yields; η_1, η_2, η_3. They all increases with higher ion temperatures. If R+η_3 becomes larger than 1, the only way to obtain steady state concentrations is to introduce a further sink for the impurities. One of them is the diverter effect of metallic impurities in a magnetic limiter chamber and the other is the honey-comb structure of the limiter or wall surfaces [9][20].

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REFEREMCES

[1] 5th Int. Conf. on Plasma Phys. and Controlled Nuclear Fusion Research, Tokyo (1974).

[2] TAZIMA, T., et al., Ref. (1), Second part of paper CN-33/A1-2.

[3] BRETZ, N., DIMOCK, D., et al., Ref. (1), CN-33/A3-1.

[4] BOL, K., CECCHI, C.C., DEMARCO, F., et al., Ref. (1), CN-33/A4-2.

[5] BRETON, C., et al., Ref. (1), CN-33/A6-1.

[6] VERSHKOV, V. A., MIRNOV, S. V., Nucl. Fusion 14 383 (1974).

[7] PARSONS, C. R., et al., Plasma Phys. 16 267 (1974).

[8] BEHRISCH, R., KADOMTSEV, B. B., Ref. (1), CN-33/S-2.

[9] WEIJSENFELD, C. H., HOOGENDOORN, A., Conf. on Ion. Phen. in Gases 124 (1961).

[10] GRØNLUND, F., MOORE, W. J., J. Chemical Phys. 32 1540 (1960).

[11] SIGMUND, P., Phys. Review 184 383 (1969).

[12] REDHEAD, P. A., HOBSON, J. P., KORNELSEN, E. V., The Physical Bases of Ultra-high Vacuum, Chapman and Hall LTD. London, 1968.

[13] JAMES, L. H., LECK, J. H., CARTER, G., Brit. J. Appl. Phys. 15 681 (1964).

[14] McCRACKEN, G. M., Vacuum 24 463 (1974).

[15] BØTTIGER, J., DAVIES, J. A., SIGMUND, P., WINTERBON, K. B., Rad, effects 11 69 (1971).

[16] BØTTIGER, J., WINTERBON, K. B., Rad. Effects 20 65 (1973).

[17] DIMOCK, D. L., EUBANK, H. P., HINNOV, E., JOHNSON, L. C., MESERVEY, E. B., Princeton Plasma Physics Laboratory MATT-906 (1972).

[18] DUCHS, D., HAAS, G., PFIRSCH, D., VERNICKEL, H., IAEA Work shop on Fusion Reactor Design Problems (Culham, 1974) Paper NO. 30.

[19] YOSHIKAWA, M., JAERI-M 5849 (1974) in Japanese.

[20] CRAMER, S. N., OBLOW, E. M., Nucl. Fusion 15 339 (1975).

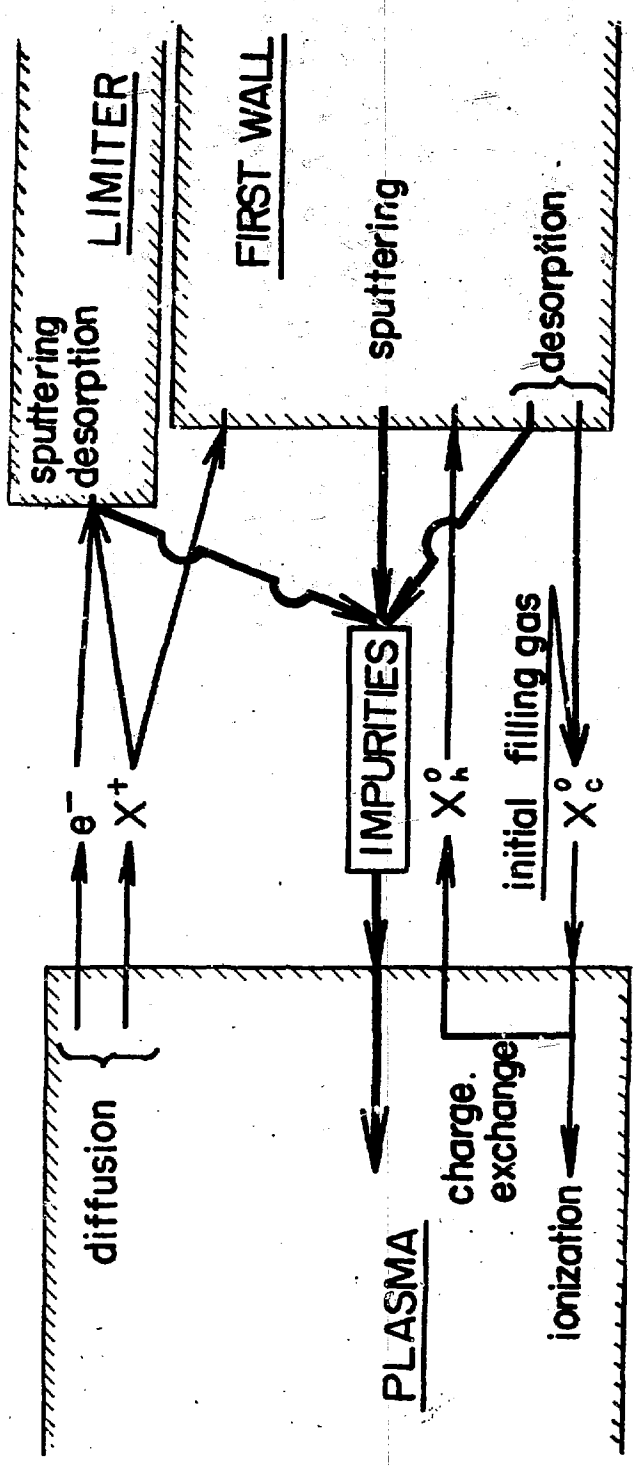


Fig. 1 Interaction of a Tokamak plasma with the wall.

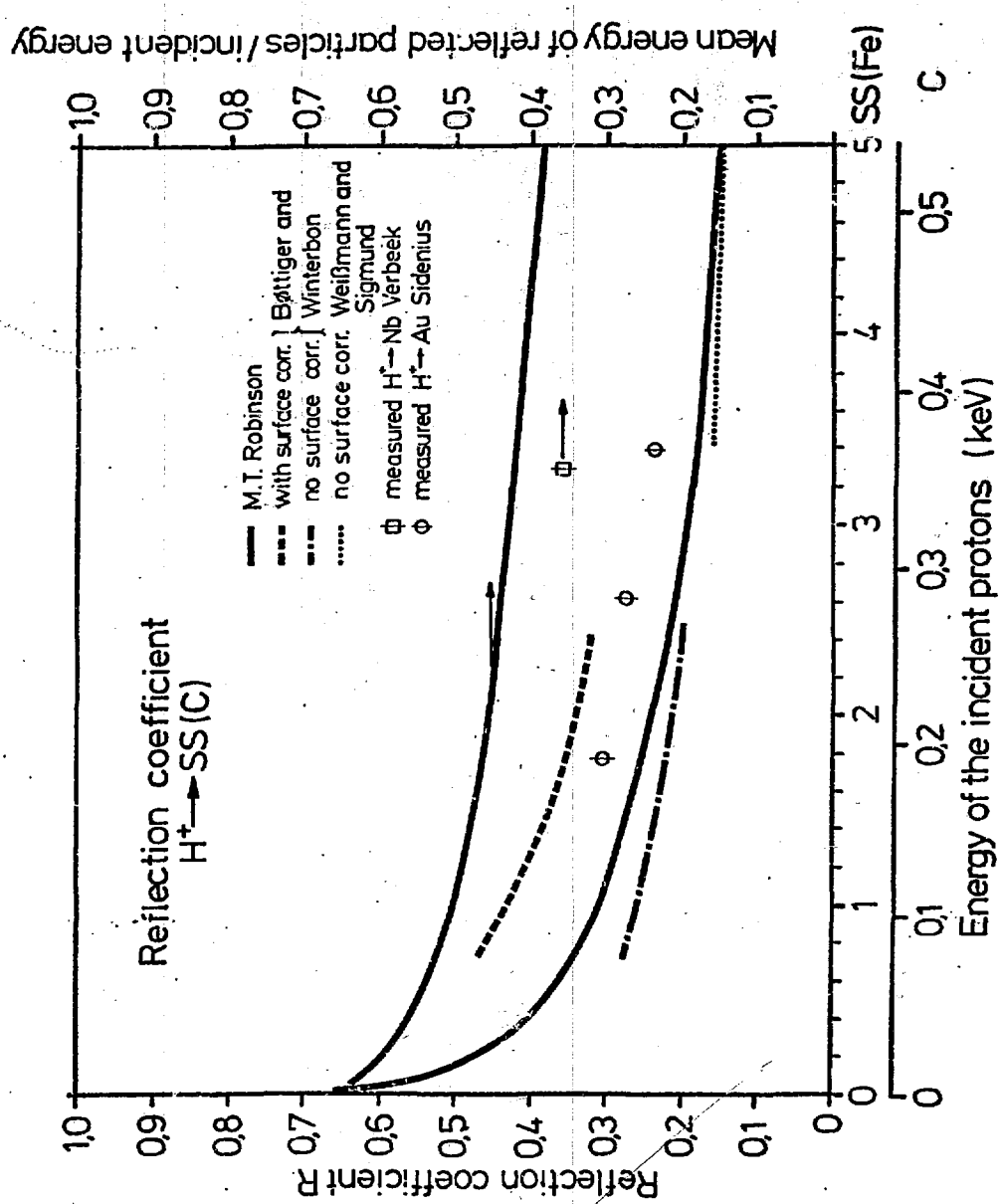
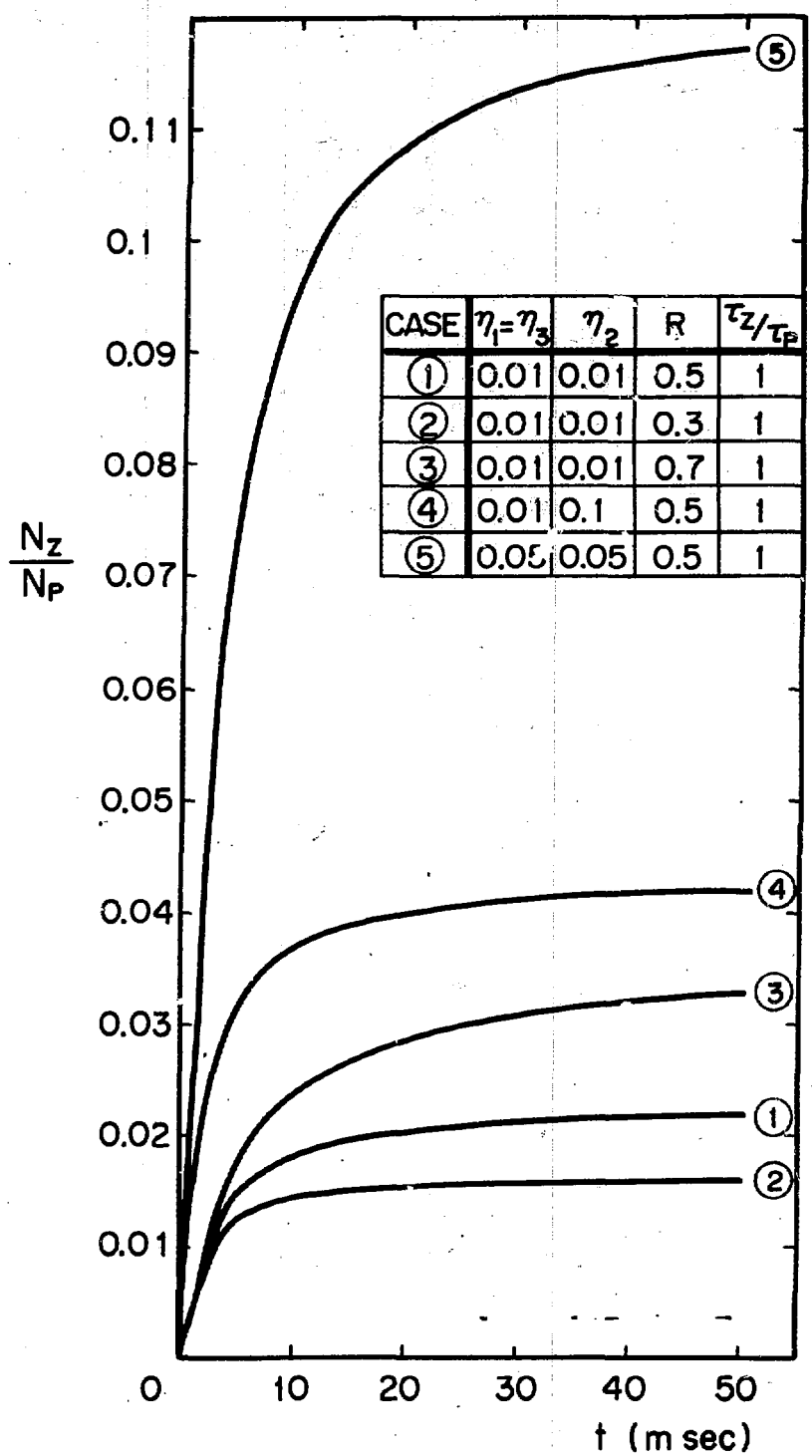


Fig. 2 Reflection coefficient of hydrogen ions.



CASE	$\eta_1=\eta_3$	η_2	R	τ_z/τ_p
①	0.01	0.01	0.5	1
②	0.01	0.01	0.3	1
③	0.01	0.01	0.7	1
④	0.01	0.1	0.5	1
⑤	0.05	0.05	0.5	1

Fig. 3 Nonmetallic impurity concentrations during a typical Tokamak discharge on the condition of $_z$ = $_p$.

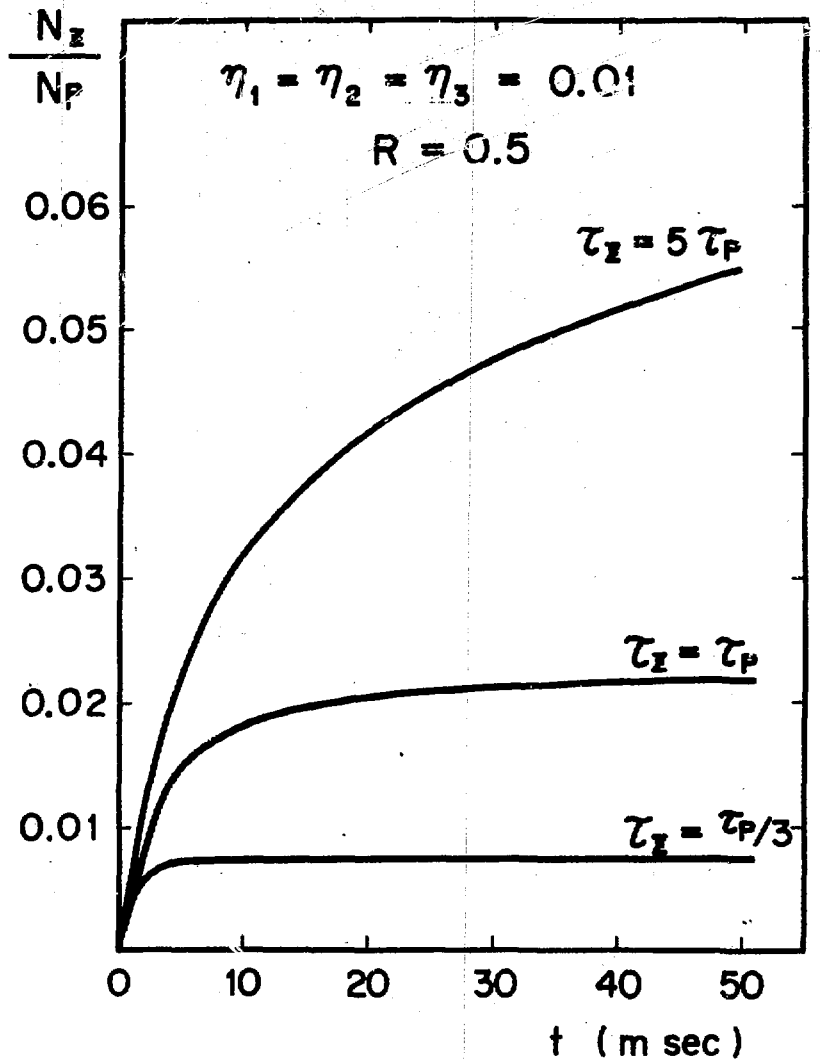


Fig. 4 The effect of particle confinement time of nonmetallic impurities to their concentrations during a discharge.

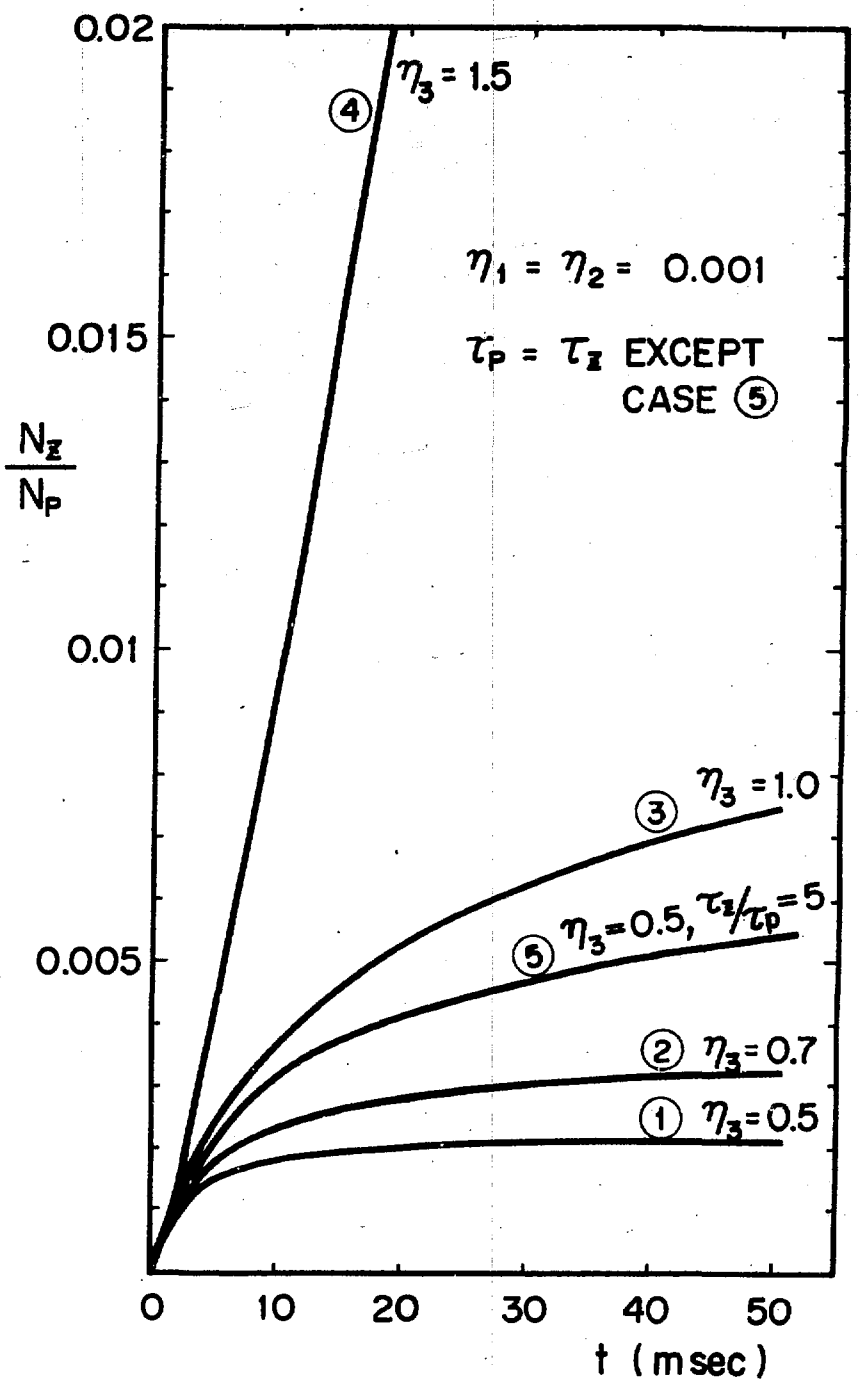


Fig. 5 Metallic impurity concentrations during a typical Tokamak discharge and the effect of its particle confinement time.