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SOME CONSIDERATIONS OF ASH ENRICHMENT AND ASH EXHAUST BY A SIMPLE DIVERTOR

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Some Considerations of Ash Enrichment and Ash Exhaust by a Simple Divertor

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Some possible methods of simplifying the poloidal divertor are discussed based on results from the DIVA Experiment. A few realistic divertors, especially a simple divertor for the ash enrichment and the ash exhaust, are proposed for a fusion device of the Intor size.

Keywords: DIVA Tokamak, Poloidal Divertor, Ash Exhaust, Ash Enrichment, Intor Device

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単純ダイバータにおける灰濃縮と灰排気に関する考察

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ポロイダル・ダイバータの簡単化の可能な方法について，DIVA実験結果に基づいて議論する。いくつかの現実的なダイバータ，とくに灰濃縮と灰排気のダイバータ，をIntor大の核融合装置に対して提案する。

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CONTENTS

目　　次

1. Introduction

Ash exhaust is one of the most important problem to develop a fusion reactor. The essential difficulty of the ash exhaust is due to the following reason: In a normal condition, the neutral particle density is low and the necessary pumping speed is unrealistic, e.g. $S = 1.6\times10^7$ ℓ/sec with $n_o = 10^{11}$ cm^{-3}, $n_\alpha/n_o = 0.1$ and $P_{th} = 450$ MW where S, n_o, n_α and P_{th} are the effective pumping speed, neutral atom density, ash density and thermal output of the reactor. This situation is due to the high pumping speed of the plasma column and the neutral particle flux to the plasma column must be equal to the particle loss flux from the plasma. Therefore the neutral density must be low in a normal conditions as shown in the example. Some methods to avoid this situation have been proposed. One method is to increase the particle outflux from the plasma by steeping the density gradient only near the boundary$^{1)}$ or enhancing the plasma transport only near the boundary plasma$^{2)}$. These schemes are simple if these equilibriums are obtained and stable. The other method is the classical divertor in which neutralized particles in the burial chamber cannot easily flow back to the main plasma. The classical divertor, however, requires a rather high pumping speed and is too complex to be applied to a reactor. The complexity of the divertor is due to the long throat, the divertor coils inside the vacuum vessel (and inside the toroidal coil) and the high heat flux density. If these problems can be mitigated, the divertor becomes simple and realistic.

The heat flux density can be reduced by employing some edge cooling methods, e.g. light impurity cooling or cold gas blanket$^{1)3)}$. If the edge cooling induce adverse effects on the plasma confinements, the other method is necessary. In the DIVA experiment, the non-axisymmetric magnetic field was shown to give an ergotic region near the old separatrix, e.g. $\delta B/B_t \sim 0.2\%$ gave about 5 mm thickness of the ergotic region in the DIVA with the minor radius of 10 cm$^{4)}$. Therefore, a small non-axisymmetric field can easily spread the scrape-off layer in the Intor-size device, e.g. 10 cm or 20 cm. The mirror effect may increase the width. The peak value of the heat flux, however, was observed to be rather higher than the mean value. Therefore it is necessary to swing the scrape-off plasma as in JT-60. Adding these methods, the neutralizer plate can be put so that the scrape-off layer is almost parallel to the neutralizer plate. These methods reduce the heat flux density down to about 100 W/cm^2

The long throat is due to the small conductance from the divertor chamber to the main chamber which suppress the back flow of particles including impurities, ash and fuel. For example, the length of the throat is 6 m with a conductance of 10^6 ℓ/s for 0.1 eV He and a throat width of 15 cm in an Intor size device. If we can decrease the conductance with a short throat, the divertor becomes simple because the short throat permit us to put the coils outside the vacuum vessel and even outside the toroidal coils. Results from the DIVA Experiment suggest this possibility. The scrape-off plasma was shown to flow well along the magnetic field lines5) and the magnetic field has a large toroidal component. Therefore, thin plates can be put along the magnetic field lines and can reduce the conductance. For example, about 10 plates for each throat reduce the conductance by a factor of 30.

The experimental results show that the conductance of impurities and also ash particles is much smaller than that of fuel particles because of the following reasons:6)7) Impurities and He are easily ionized up to multi ionized states in the divertor, and ionized ions are accelerated back to the neutralizer plate because of the flow of the scrape-off layer and the space potential and flow hardly into the main chamber. The fuel particles, however, can easily flow into the main chamber from a simple divertor because the charge exchange process is dominant. Therefore even a simple divertor can enrich the ash and pump out the enriched ash by a reasonable pumping system, e.g. the required effective pumping speed is about 3×10^5 ℓ/sec.

These simple considerations based on the experimental results give a simple and realistic divertor in a fusion reactor. Some simple divertors, especially a divertor for the ash enrichment and the ash exhaust are briefly discussed and proposed in this paper.

2. Reference reactor

An Intor size device is employed for an example. Main parameters are summarized in Table I. The average particle confinement time was assumed to be equal to the energy confinement time following the experimental results8). A schematic drawing of the cross-sectional view of the device is shown in Fig. 1. A simple divertor system was employed as shown in Fig. 1. The D-shape was usually employed. Therefore the additional divertor current is very small as shown in Fig. 2.

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3. Characteristics of scrape-off plasma and some simple divertors

The parameters of the scrape-off layer in the divertor are given by the empirical scaling laws which were obtained in DIVA[8].

$$\bar{T}_b = \frac{3}{\gamma}\bar{T}\,\frac{P_\alpha - P_{cx} - P_R}{P_\alpha} \times \frac{\bar{\tau}_p}{\tau_E}$$

$$D = \frac{1}{10}D_B$$

$$v_f = 0.3C_s$$

$$\bar{n}_b d = \frac{\pi ab}{4\bar{\tau}_p v_f}\cdot\frac{\bar{B}_t}{\bar{B}_p}\bar{n}_e$$

where, $\bar{T}_b$, γ, P_{cx}, P_R, D , D_B, v_f, C_s, $\bar{n}_b$, $\bar{B}_p$ and d are mean temperature of the scrape-off plasma in the divertor chamber, heat conduction rate to the neutralizer plate, charge exchange loss, radiation loss, diffusion constant across the magnetic surface, the Bohm diffusion coefficient, particle flow velocity in the divertor chamber, sound velocity, mean density in the divertor chamber, poloidal magnetic field in the divertor and thickness of the scrape-off layer plasma. d is assumed 20 cm including the ergotic layer, diffusion effect and mirror effect. The ergotic layer has a thickness of about 15 cm with $\delta B/B_t \simeq 0.2\%$. The divertor efficiencies for particle and heat were assumed 80% and $\bar{B}_t/B_p = 15$. In order to avoid a high heat flux on a narrow region of the neutralizer plate, the magnetic surface has to be vibrated as in JT-60. In this reference, 10 cm swing was assumed. In Fig. 3, an example is shown, the vibration width is about 10 cm and 1.0 MAT is vibrated in this case. The heat conduction rate was assumed 20 including the secondary electron effects[9].

The parameters are summarized in Table II. The temperature is 750 eV and seems too high. If the equilibrium temperature is low, $(P_{cx} + P_R)^{-1}$ or $\tau_E/\bar{\tau}_p$ has to be reduced as discussed in ref.(10). However, $P_{cx} + P_R$ is usually assumed to be rather small and $\tau_E/\bar{\tau}_p$ is usually assumed to be unity or a larger value. Therefore the high scrape-off plasma is automatically assumed in a usual case. In this paper, discussions follow the usual case but edge cooling is highly recommended to avoid a high heat flux and a serious wall erosion as shown in Fig. 4. The heat flux density is designed to be rather law and wall erosion of the neutralizer plates is serious in this case[11]. Therefore a strong wall material for the wall erosion has to be employed.

The plasma line density in the divertor chamber is very important not only for the impurity control but for fuel and ash exhaust. Two different line densities shown in Fig. 5 are important. One is $\bar{n}_b d \simeq 5\times10^{12}$ cm^{-2} and the other is $\bar{n}_b \ell \simeq 2\times10^{13}$ cm^{-2}. The first line density $\bar{n}_b d$ is not enough for shielding sputtered impurities, reflected fuel particles and reflected ash particles from the neutralizer plate. The line density $\bar{n}_b d$, however, is thick for thermal ash particles whose energy is assumed 0.1 eV in this paper. The second line density $\bar{n}_b \ell$ is sufficiently thick for sputtered impurity particles from the neutralizer palte and thick for reflected ash from the neutralizer plate. Neither $\bar{n}_b d$ nor $\bar{n}_b \ell$ is not thick for fuel particles because charge exchange process is dominant for fuel particles. The ionized ions are easily ionized upto multi ionized states and accelerated by field particles and space potential to the neutralizer plate, as observed both in the experiment and in a numerical simulation$^{7)\,12)}$. Therefore ionized ions flow hardly into the main chamber from the divertor chamber. These characteristics are summarized as follows.

1) Sputtered impurities from the neutralizer plate flow hardly into the main chamber and some of sputtered impurities flow freely into the pumping region.
2) Almost all the reflected helium atoms are ionized and flow back to the neutralizer plate, or flow freely into the pumping region.
   The thermal helium is easily ionized and flow hardly into the main chamber.
3) Fuel particles flow easily back to the main chamber with a high effective conductance.

These considerations show that the simple divertor is effective for controlling impurities from the neutralizer plates and also effective for the ash exhaust but not effective for the fuel exhaust. Therefore the simple divertor is different a little from the classical divertor because of its non fuel-exhaust.

The above discussion shows that the conductance of the divertor throat has a different value for each element, i.e. the conductance is high for the fuel and low for the ash and the impurities.

If it is necessary to reduce the neutral particle density in the main chamber, the conductance from the divertor to the main chamber has to be recuced for the fuel as in the classical divertor. The conductance can be easily to be decreased by dividing the scrape-off layer plasma along the magnetic field lines as shown in Fig. 6. The thin plates set along the field lines do not strongly affect the plasma flow from the main chamber into the divertor chamber because the plasma flows along the magnetic field lines as observed in the experiment. The thin plates, however, reduce conductance for neutral gases mainly by increasing the effective throat length as shown in Fig. 7. This example shows that a few plates reduce the throat conductance down to the expected value in the classical divertor with a long throat. Therefore the required pumping system in the simple divertor is lower than in the classical divertor.

If the serious impurity content due to charge-exchange particles is avoided by employing a suitable material and suitable structure for the main first surface, the divertor is required only for controlling impurity produced by charged particle and exhausting the ash. In this case, the divertor does not need the plates to increase the effective length of the throat, because the ash and impurities flow hardly into the main chamber. An artificial pumping system is not necessary for impurities in a gas impurity free reactor because metal impurities stick easily onto the vacuum surface. Therefore the pumping system is necessary only for the ash-exhaust. Only a small fraction of the ash lost from the main plasma is necessary to be pumped out because the burning time is much longer than the average particle confinement time$^{11)}$. In the reference reactor, only 10% of the lost ash from the main plasma has to be pumped out. Therefore it is rather easy to pump out the ash from the reactor. Adding the above consideration, the ash is enriched by the simple divertor because the ash flows hardly into the main chamber but the fuel flows easily into the main chamber. The relation between the required pumping speed, the total neutral atom density in the divertor chamber and the ash enrichment factor is shown in Fig. 8. If the enrichment factor is 5, the required pumping speed is only 25,000 l/s with the neutral atom density of 10^{12} cm^{-3} in the divertor chamber and 50,000 l/sec with the density of 5×10^{11} cm^{-3}. These reasonable values of the pumping speed are obtained even by the mechanical pumps. The enrichment factor of $4\sim5$ may be rather easily obtained as shown in Fig. 9 because the conductance for the ash is much smaller than that for the fuel. In this case, a very simple divertor as shown in Fig. 10 can be employed and the pumping system

is required only in some parts of the divertor chamber.

4. Conclusions

The results from the DIVA Experiment suggest simple and realistic divertors not only for the impurity control but for the ash exhaust in a fusion reactor. The simple and realistic divertors have neither large spaces nor coils inside the vacuum bessel. The results also suggest the ash enrichment action by a simple divertor, and the action can reduce the pumping speed for the ash exhaust down to a reasonable value. Even if a neutral free plasma is required in the main chamber, the simple divertor with the throat plates is more effective than the classical divertor. The detailed design of a simple divertor requires more detailed studies, especially on the conductance for each element, which will be done in the near future.

Acknowledgement

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Table I Parameters of a reference reactor

Major radius	R	5	m
Minor radius	a/b	1.2/1.8	m
Plasma volume	V	200	m^3
Plasma surface area	S	300	m^2
Toroidal field	B_t	5	T
Plasma current	I_p	4.75	MA
Thermal out put	P_{th}	450	MW
α-particle out put	P_α	90	MW
Mean temperature	$\bar{T}$	10	keV
Mean fuel density	$\bar{n}_f$	1.2×10^{20}	m^{-3}
Mean ash density	$\bar{n}_\alpha$	1.2×10^{19}	m^{-3}
Energy confinement time	τ_E	1.5	s
Average particle confinement time	$\bar{\tau}_p$	1.5	s
Total particle loss flux	F_p	1.8×10^{22}	s^{-1}
Ash loss flux	F_α	1.6×10^{21}	s^{-1}
Ash flux to pump	$F_{\alpha o}$	1.6×10^{20}	s^{-1}
Burning duration	τ_B	200	s

Table II Parameters of scrape-off plasma in the divertor*

Scrape-off width	d	20 cm
Through width	d_t	30 cm
Throught length	ℓ_t	50 cm
Divertor efficiency	η_h, η_p	80 %
Plasma line density	$n_b d$	5×10^{12} cm^{-2}
Temperature	$\bar{T}_b$	750 eV
Area of neutralizer plates	S_n	90 m^2
Mean heat flux density to neutralizer plate	f_{qn}	40 W/cm^2
Maximum f_{qN}	f_{qnmax}	<120 W/cm^2
Vibration width of matnetic surface in divertor	d_v	10 cm

* Assuming $P_R+P_{cx} = 0,5\ P_\alpha$

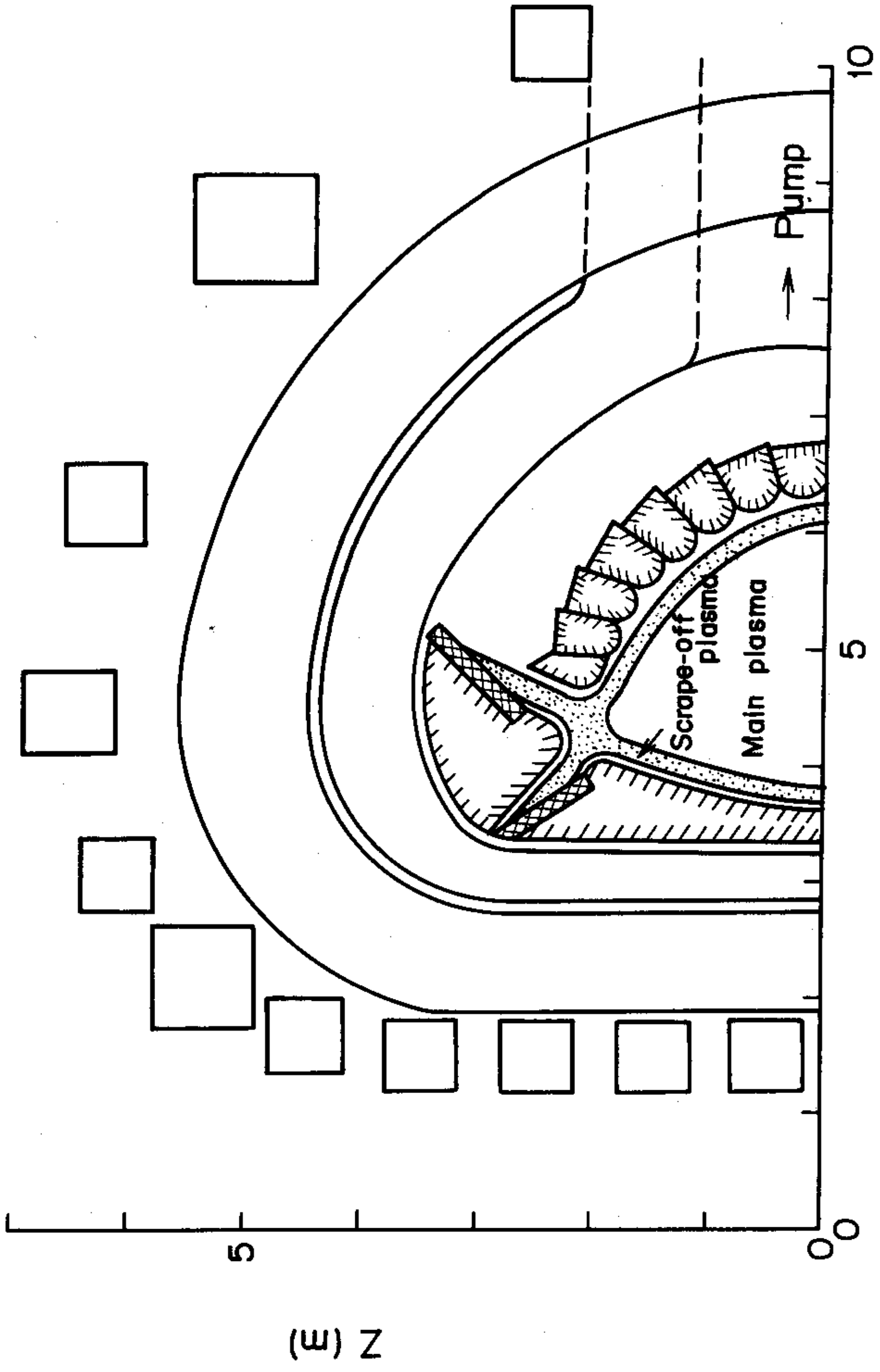
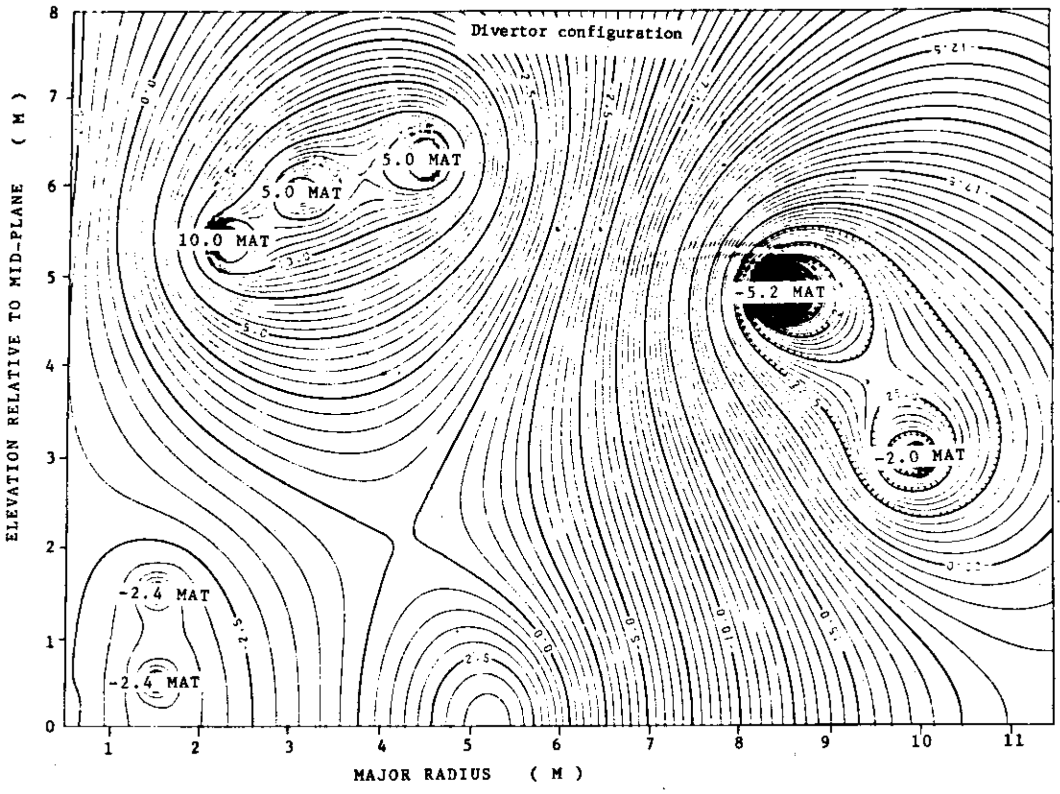
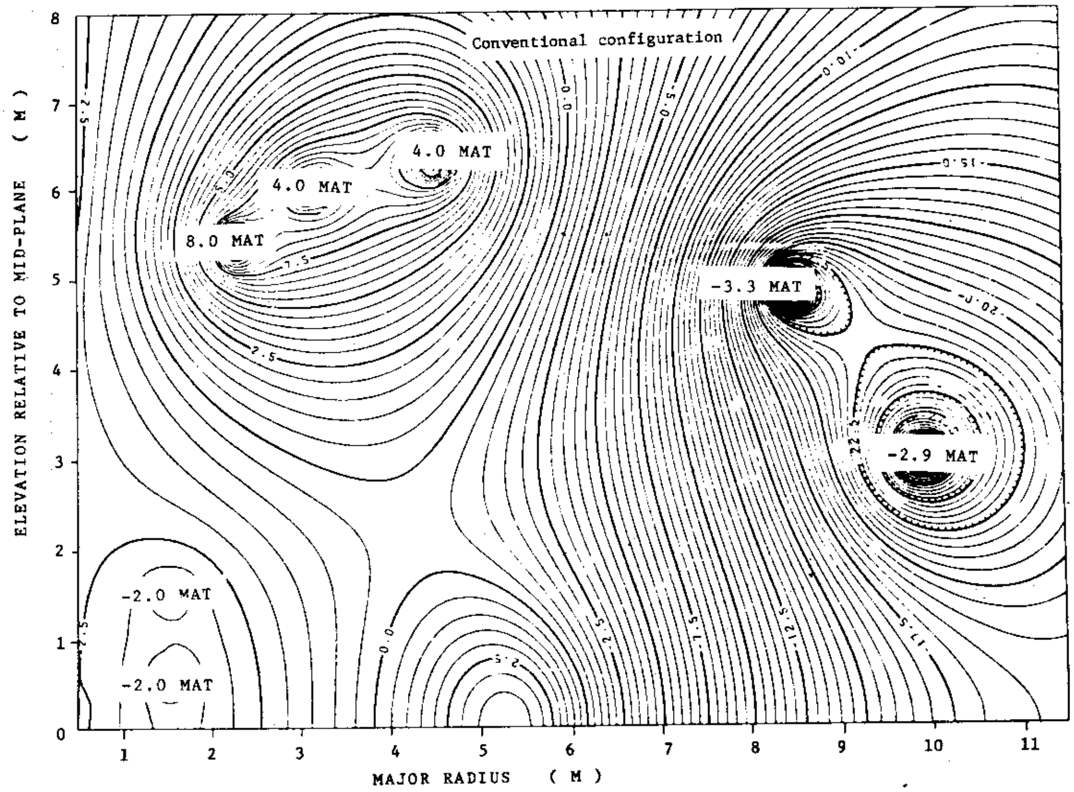


Fig. 1 Cross-sectional view of the reference reactor

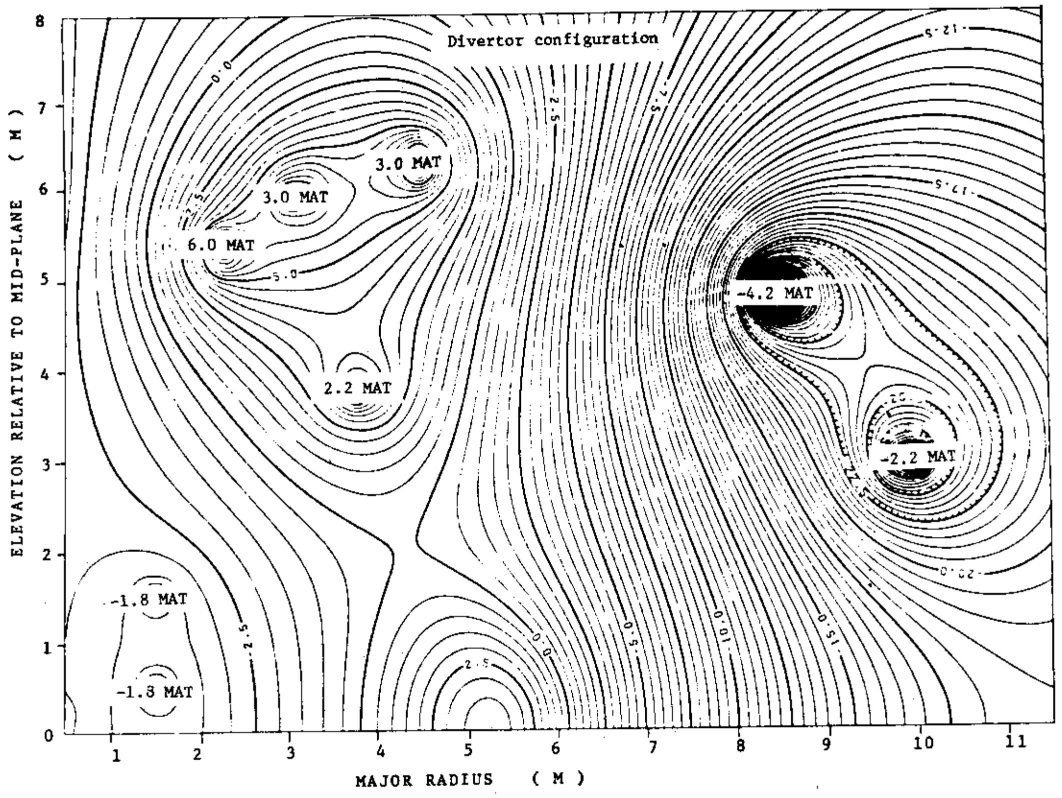


Free boundary equilibrium of INTOR plasma with divertor.

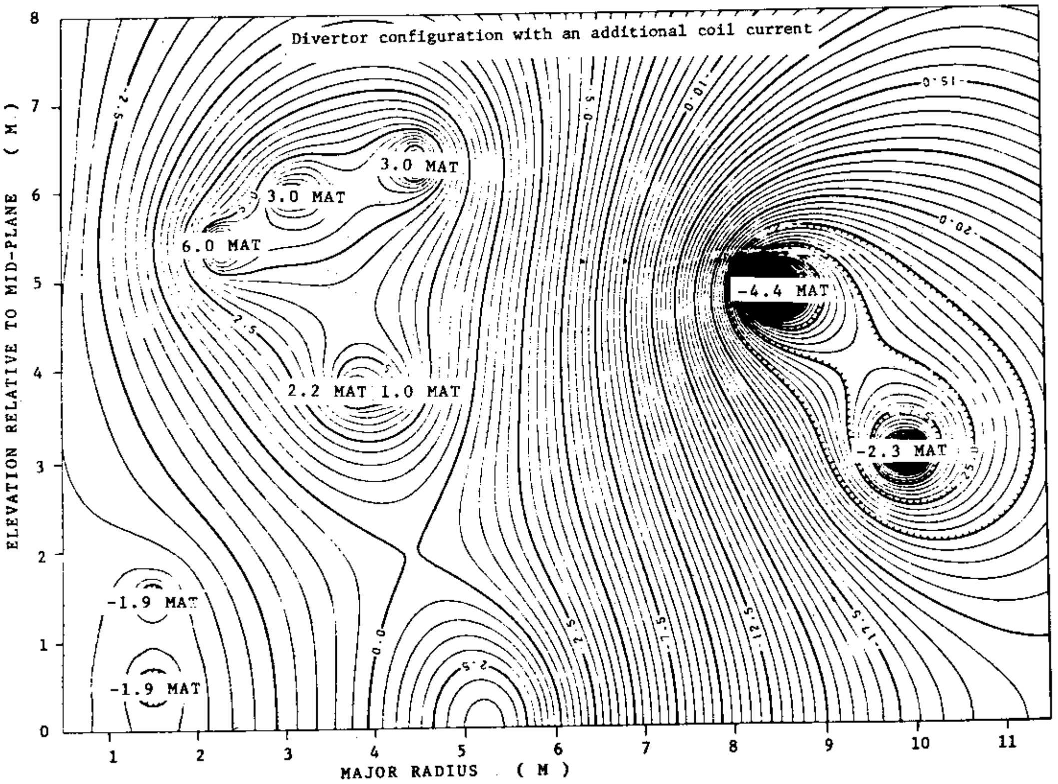


Free boundary equilibrium of INTOR plasma without divertor.

Fig. 2 Examples of magnetic surfaces and coil currents with and without the divertor

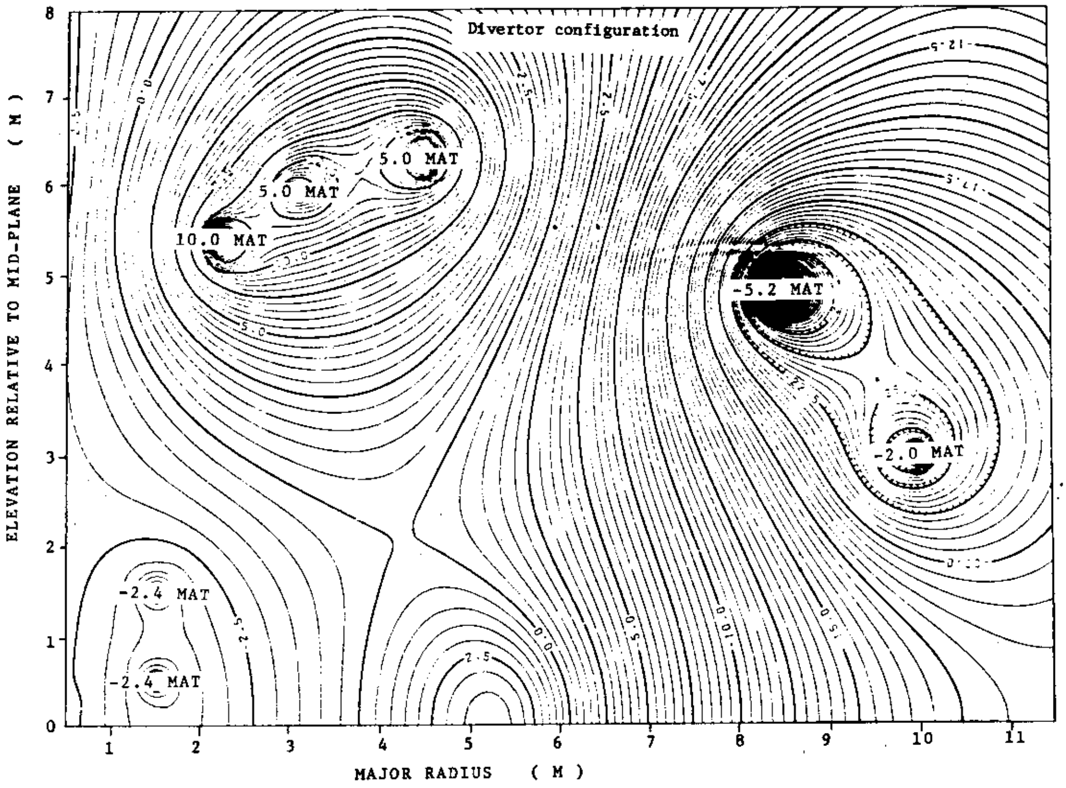


Free boundary equilibrium of INTOR plasma with divertor placed both inside and outside of the toroidal field coils.

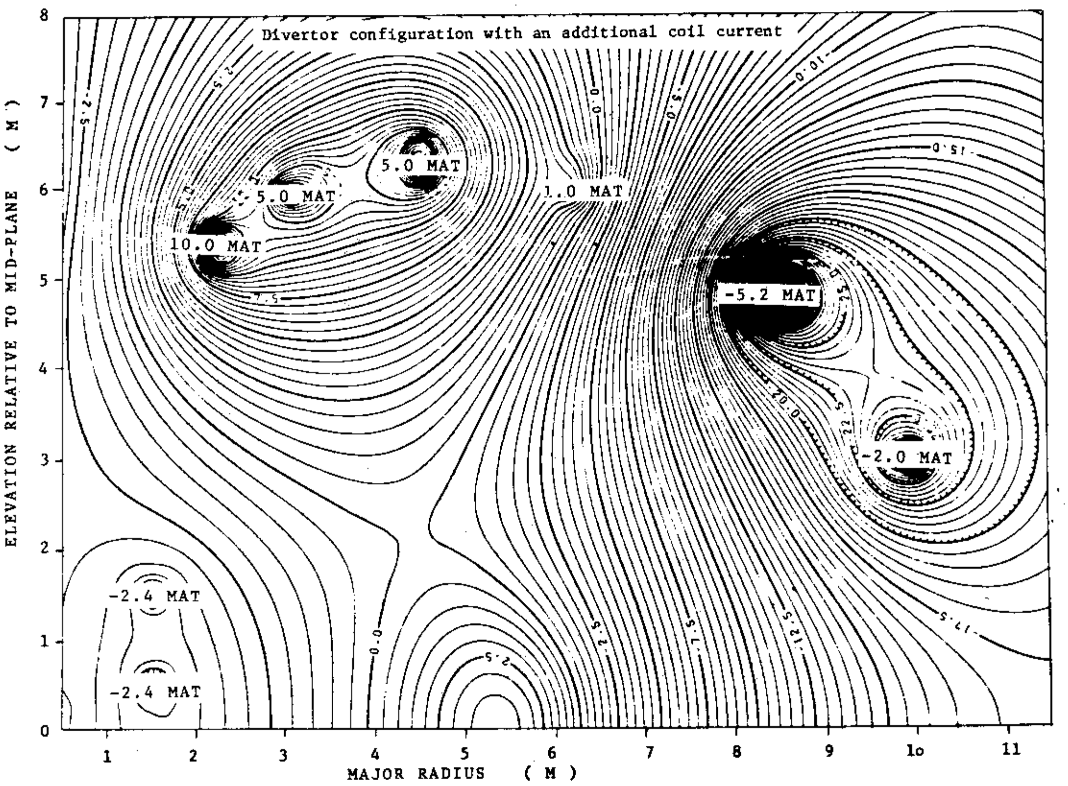


Free boundary equilibrium of INTOR plasma with separatrix swung radially outside by about 10 cm. Divertor coils are placed both inside and outside the toroidal field coils.

Fig. 3-a Examples of divertor configurations with different coil currents.



Free boundary equilibrium of INTOR plasma with divertor.



Free boundary equilibrium of INTOR plasma with separatrix swung radially outward by about 10 cm.

Fig. 3-b Examples of divertor configurations with different coil currents

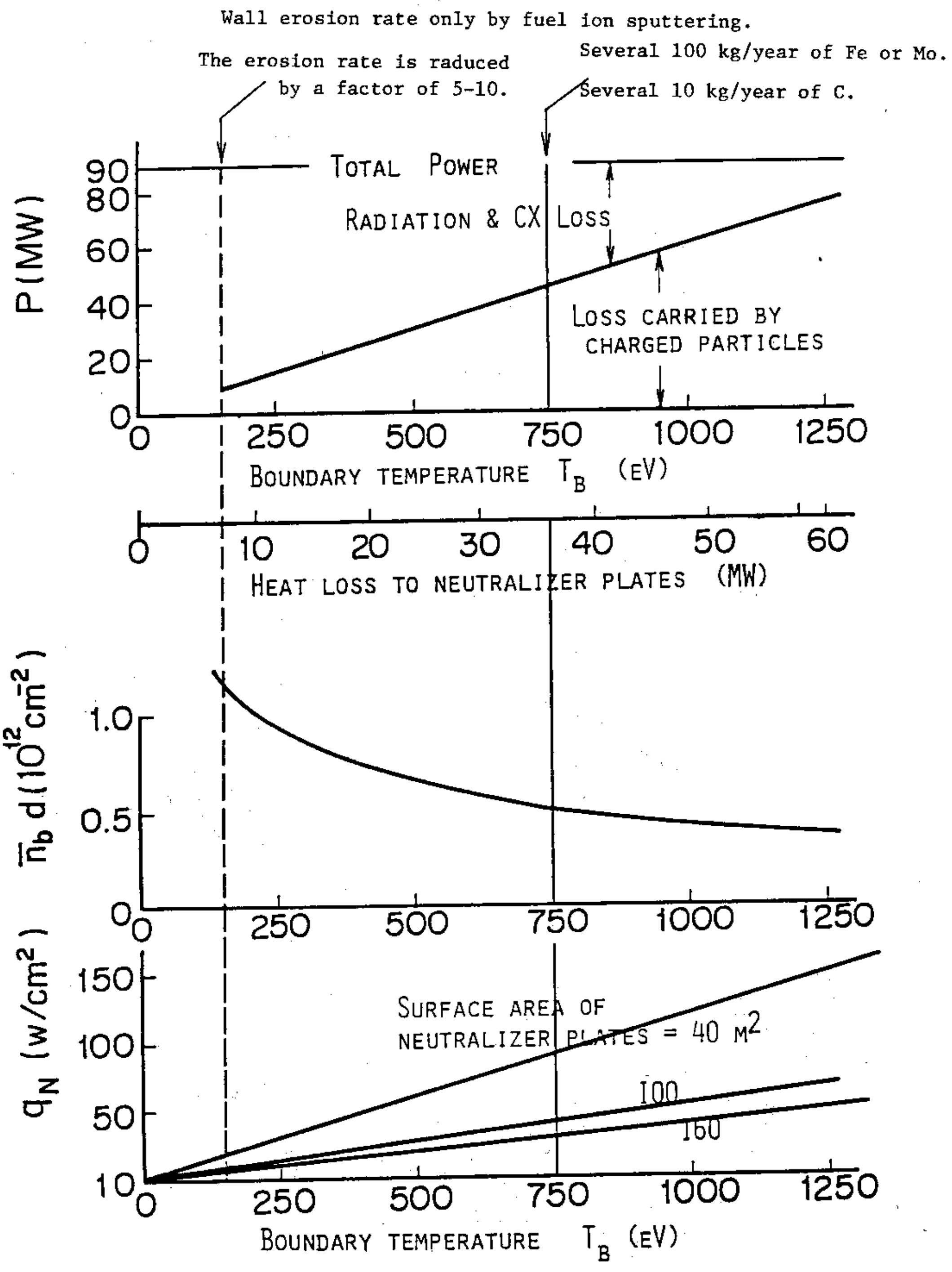


Fig. 4 Relation between boundary temperature (T_b), power loss (P), heat flux density (q_N) wall erosion rate, and plasma line density ($\bar{n}_b d$)

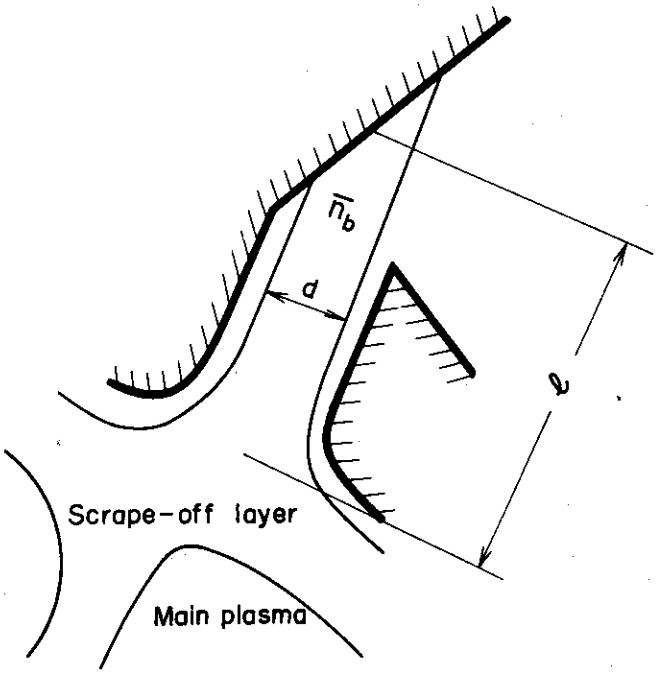


Fig. 5 Two different line densities, i.e. $\bar{n}_b d$ and $\bar{n}_b \ell$

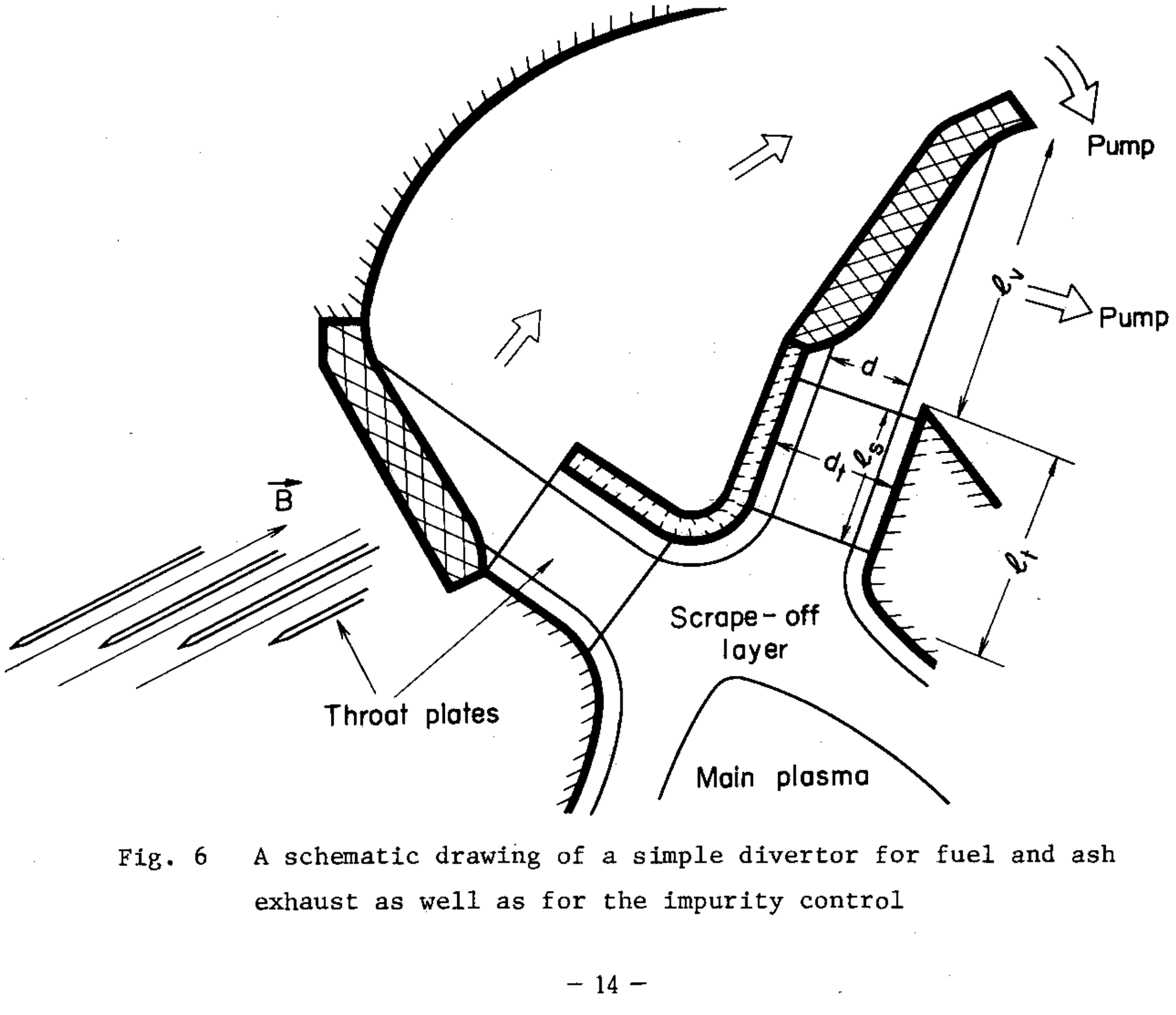


Fig. 6 A schematic drawing of a simple divertor for fuel and ash exhaust as well as for the impurity control

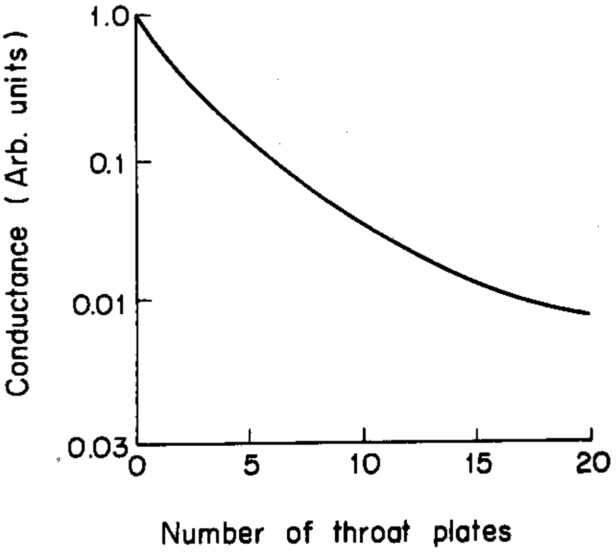


Fig. 7 Reduction of the conductance by setting throat plates along magnetic field lines as shown in Fig. 6. Assuming $d_t = 30$ cm, $\ell_s = 30$ cm, and $B_p/B_t = 1/15$.

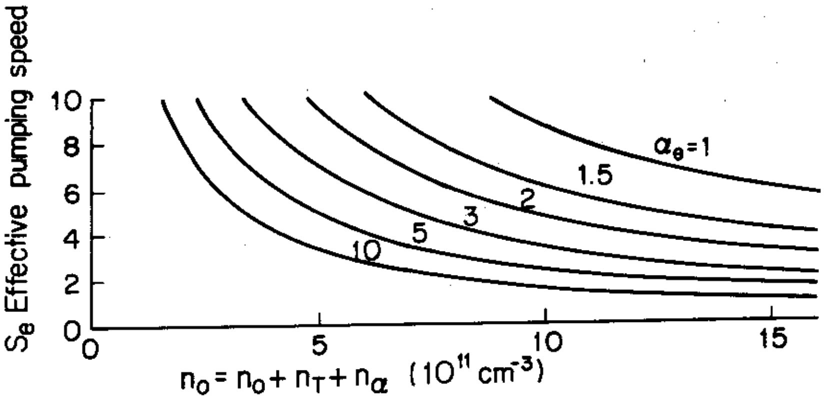


Fig. 8 Pumping speed for ash exhaust with enrichment system of ash. α_e: enrichment rate. $\alpha_e = 1$ corresponds to $n_\alpha/n_o = 0.1$ without enrichment and $\alpha_e = 10\ n_\alpha/n_o$ in the burial chamber.

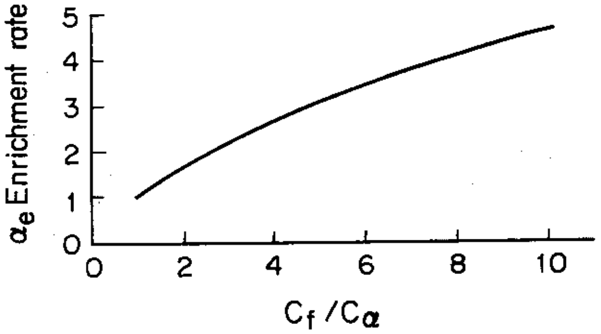


Fig. 9 Enrichment rate (α_e), back flow conductance for fuel (c_f) and for ash (c_α). It seems easy to obtain $\alpha_e \gtrsim 4$ with the simple divertor with $\ell_t = 50$ cm, $\ell_v = 70$ cm, $d = 20$ cm and $d_t = 30$ cm as shown in Fig. 10.

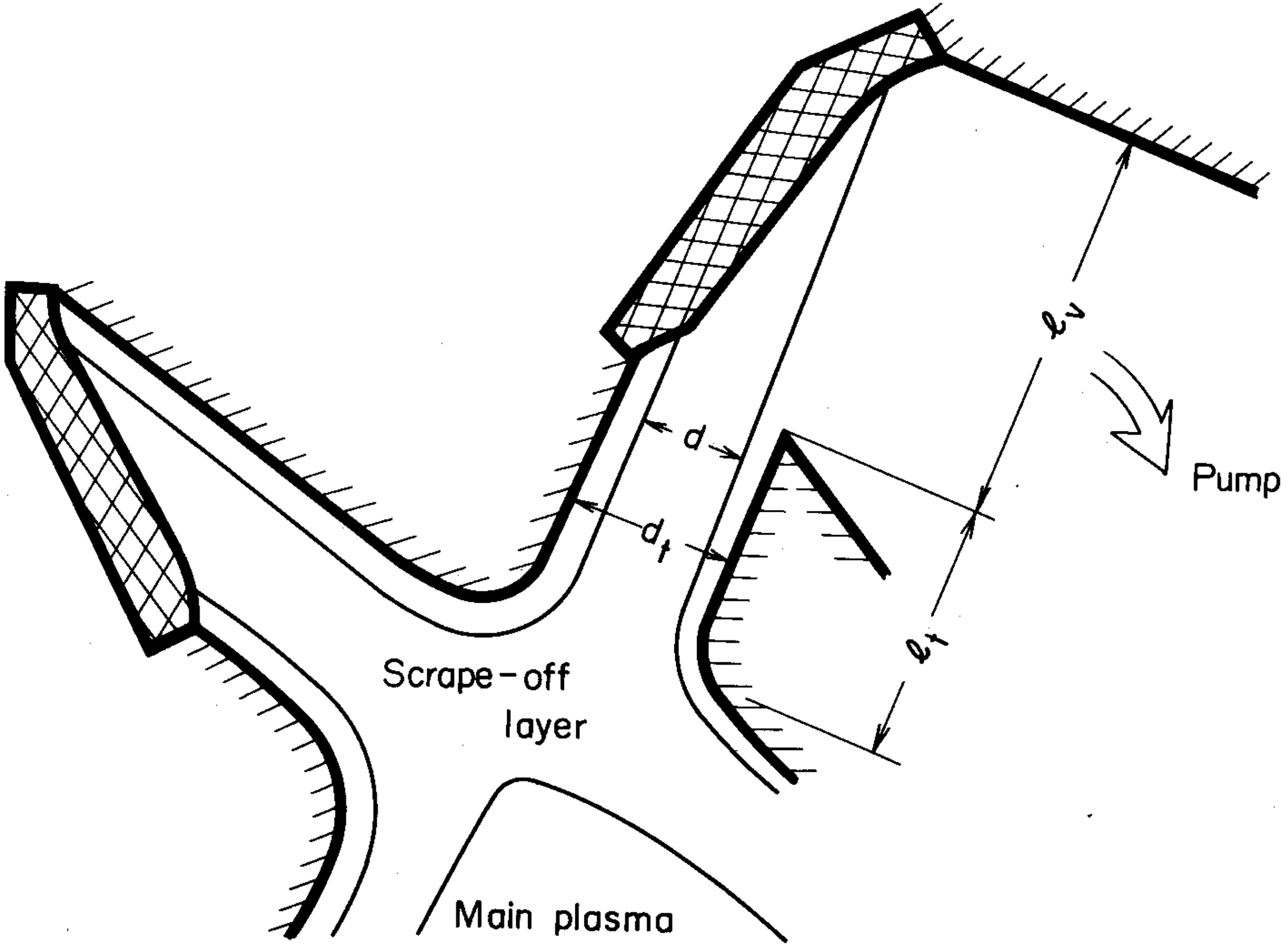


Fig. 10 A schematic drawing of a simple divertor for ash enrichment and ash exhaust as well as for the impurity control