DOE/ET/52025--11

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MOVING GAS BLANKET PERFORMANCE STUDY*

by

Z. El Derini and W. M. Stacey, Jr.
School of Nuclear Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

August 1979

*Work supported by U.S. Department of Energy, Contract No. ET-78-S05-5683 with Georgia Institute of Technology

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Abstract

A semi-analytical model has been developed to describe the boundary region between the plasma and the wall in the presence of a moving neutral gas blanket. This study shows that the velocity of the gas blanket is determined by the particle and heat fluxes out of the plasma, the thickness of the neutral gas blanket and the cross field diffusion. In order for the gas blanket to be small, as required by reactor considerations, the gas blanket velocity has to be relatively large. The variation of the neutral gas blanket performance as a function of the plasma, wall and gas blanket parameters is examined and numerical examples are given.

I. Introduction

Various methods have been proposed to control the impurity influx inside the plasma. One of these is the neutral gas blanket.[1,5] A simple model for the transport of particle across the boundary region in the presence of a static neutral gas blanket was discussed in Refs. 6, 7 and 8. From the study on the static gas blanket one can draw the conclusion that the static gas blanket is a good means for impurity control only for low heat and high particle fluxes out of the plasma. For a fixed particle flux out of the plasma, as the heat flux increases, the thickness of the gas blanket should increase to a point where it becomes impossible to include it in a fusion reactor. The purpose of this paper is to study the performance of a moving gas blanket and to determine the required velocity of the gas blanket in order to have a practical boundary region thickness. The model of Ref. 6 was extended to include a moving gas blanket with velocity v_g. In section II, the difference between the static and moving gas blanket is discussed. A study of the required velocity of the gas blanket velocity as a function of the particle and heat fluxes out of the plasma, the neutral gas blanket strength and thickness, and the neutral reflection coefficient from the wall is presented in section III. This study determines the characteristic of the neutral gas blanket (neutral source, thickness and velocity) that are required to efficiently shield the plasma.

II. Model Description

The model of Ref. 6 is extended to include a moving gas blanket with velocity v_g. In order to model the parallel loss in the boundary region we postulate that the residence time, $\tau_{||}$, for an ion is given by $\tau_{||} = \frac{L}{v_g}$ where L is the mean distance travelled along with the gas blanket, i.e. the distance where it is introduced to the point of its collection, and v_g is the gas blanket flow velocity. This situation holds for the case where ν_{cn} and ν_{in} are greater than $\frac{L}{v_{th}}$ which in turn should be higher than $\frac{\delta_s}{v_{D_\perp}}$, where ν_{en} and ν_{in} are the electron and ion neutral collision frequency, δ_s is the boundary region thickness and $v_{D_\perp}$ is the particle drift velocity. This condition implies that both electrons and ions will have enough collisions with the neutral particle and move along with the same velocity v_g of the gas blanket.

The ion density satisfies

$$\frac{d}{dx}\left(- D_\perp \frac{dn_i}{dx}\right) + \frac{n_i}{\tau_{||i}} - n_e\, n_{\binom{c}{h}} \langle\sigma v\rangle_{i\binom{c}{h}} + n_e\, n_i\, \langle\sigma v\rangle_R = 0 \qquad (1)$$

where $D_\perp$ is the cross field diffusion which is taken to be Bohm diffusion with a variable coefficient, $\tau_{||}$ is the ion residence time, n_e, n_i, n_c and n_h are the electron, ion, cold and hot neutral densities respectively, $\langle\sigma v\rangle_i$ and $\langle\sigma v\rangle_R$ are the electron impact ionization and recombination rate. The ion continuity equation can be written as

$$\frac{d^2 n_i}{dx} = \frac{n_i}{\lambda^2} + \frac{n_i^2}{\gamma^2} , \qquad (2)$$

where $\lambda^2 = \dfrac{\tau_{||i}\, D_{\perp i}}{\left(1 - \tau_{||i}\, R_1\, n_c\, \langle\sigma v\rangle_{ic} - \tau_{||i}\, R_1\, n_h\, \langle\sigma v\rangle_{ih}\right)}$,

$\gamma^2 = \dfrac{D_{\perp i}}{R_1\, \langle\sigma v\rangle_R}$, and $R_1 = \dfrac{n_e}{n_i}$.

The solution is expressed as

$$\int_{n_o}^{n_o} \frac{dn_i}{\sqrt{n_i^2\,(n_i - \xi) + C_o}} = - \sqrt{\frac{2}{3}} \int_o^x \frac{dx}{\gamma} \qquad (3)$$

where $\xi = \frac{3}{2}\,\frac{\gamma^2}{\lambda^2}$.

The solution is an elliptic function where the constant c_o and n_o are determined from the following boundary conditions: a) total plasma flux across the plasma boundary has to equal the total loss of confined plasma and b) zero ion density or flux at the first wall.

Similar to Ref. 6, the problem of penetration and interaction of cold and hot neutrals with plasma is solved using a one group neutron transport equations.

The neutral impurity, n_{nz}, and the impurity ion, n_z, satisfy the following equations.

$$n_{nz} \, v_{nz} = \gamma^{w} \, \Gamma_{cx} \, E_2 \left[\int_x^{\delta_s} (zn_z + n_i) \frac{\langle\sigma v\rangle_{ze}}{v_{nz}} \, dx' \right] , \tag{4}$$

and

$$n_z(x) = \int_o^x \frac{\cosh (K_z x_o) \sinh K_z (\delta_s - x) \, S(x_o) \, dx_o}{D_{\perp z} \, K_z \cosh K_z \delta_s} + \int_x^{\delta_s} \frac{\sinh K_z (\delta_s - x_o) \cosh K_z x \, S(x_o) \, dx_o}{D_{\perp z} \, K_z \cosh K_z \delta_z} , \tag{5}$$

where $K_z = \left(D_{\perp z} \, \tau_{||z}\right)^{-1/2}$.

The heat flow equations for ions and electrons are

$$- \frac{d\,Q_e}{dx} + \frac{n_e T_e}{\tau_{||}} + W_{rad} + EL - c_1 \, n_i \, n_e \left(\frac{T_i - T_e}{T_e^{3/2}}\right) + E_{Re} = 0 \tag{6}$$

$$- \frac{d\,Q_i}{dx} + \frac{n_i T_i}{\tau_{||}} + 2 \, n_i \, n_o \langle\sigma v\rangle_{cx} \, \alpha_{cx} (1 - \alpha_e) \, T_i + c_1 \, n_i \, n_e \left(\frac{T_i - T_e}{T_e^{3/2}}\right) + \left(T_i - T_n\right) \nu_{in} \, n_i \, f_{in} + E_{Ri} = 0 \tag{7}$$

where Q is the heat flux, W_{rad} is the radiated power by bremstrahlung, line and recombination processes, α_e is the energy reflection coefficient of the wall, EL and ER are the total energy loss due to ionization and recombination. In the ion heat equation, an additional term, which represents the heat loss by elastic collision with neutrals is incorporated.

This term is equal to $(T_i - T_n)\, n_i\, \nu_{in}\, f_{in}$, where ν_{in} is the collision frequency of ions with neutrals, f_{in} represents the fraction of heat being lost by elastic collision, T_i and T_n are the ion and neutral temperature, respectively. The heat equations are integrated over the boundary region, assuming average temperature T_e and T_i for the entire zone and that $Q\,(\delta_s)$ vanishes at the wall, and then solved for the average temperature in the boundary region.

III. Analysis

For the purpose of this analysis, the main gas blanket parameters are taken to be: toroidal magnetic field, 30 kg, reflected neutral and neutral gas blanket temperature, 1 eV; impurity temperature, 4 eV; particle flux out of the plasma, 2.5×10^{20} #/m²sec; heat flux out of the plasma ranges from 1×10^5 to 1×10^6 w/m²; and carbon or stainless steel first wall. The ion and electron heat fluxes are chosen to behave neoclassically since the presence of a neutral gas blanket is found to easily stabilize the trapped ion modes and to render ineffective the destabilizing ∇B drift resonances for the trapped electron modes. In order to display examples of the performance of the neutral gas blanket, we choose the following parameters: (1) $\frac{Q_w}{Q_p}$ is the fraction of the heat energy flowing from the plasma into the "scrape-off" region that subsequently reaches the first wall either as radiative energy or by charge exchange neutrals. (2) $\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$ is the ratio of the sum of the particle fluxes which hits the wall as charge exchange neutral, Γ_{cxw}, and ions, Γ_{iw}, to the ion flux Γ_p, excaping from the plasma. (3) $n_z(o)$ is the impurity concentration at the plasma boundary, $x = 0$. Thus, $n_z(o)$ provides a relative measure of the impurity concentration in the plasma, normalized to the magnitude of the particle flux out of the plasma.

The ionization probability, P_z^i , defined as the probability that a neutral impurity coming from the wall will be ionized before reaching the separatrix is almost 100%.

1. Heat Flux out of the Plasma

The heat flux out of the plasma, Q_p, is the most important parameter which determines the thickness and the velocity of the gas blanket. The main conclusions drawn from the study conducted in Refs. 6, 7 and 8 are: 1) for a fixed external cold neutral source, S_{ex}, particle flux escaping from the plasma, Γ_p, and neutral gas blanket thickness, δ_s, there exists a minimum heat flux, Q_p, below which no steady state solution exists; and 2) that the higher the heat flux out of the plasma, the wider should be the static gas blanket thickness. These conclusions have been obtained under the assumption of constant average boundary region temperature. Figure 1 shows Q_p as a function of δ_s for an external neutral source of 4×10^{20} #/m²sec and a graphite liner. Steady state solution exists only in the shaded area. Curve (b) is determined from the condition that the heat flux out of the plasma should be greater than the losses due to radiation, heating the cold neutral, etc... Line (a) comes from the fact that the particle density is low so that the ion electron equilibration term is insufficient to exchange the available large energy between electrons and ions; steady state solution probably exists with sufficiently high electron temperature, but this would not be a realistic cool gas blanket. Line (a) is given roughly by $Q_{p_{max}} \approx \alpha \Gamma_p^{5/3} S_n^{1/3} \delta_s$ (8), where α is a constant, Γ_p, S_n and δ_s are the particle flux out of the plasma, the external neutral source of the gas blanket and the thickness of the gas blanket respectively. For a typical fusion reactor with heat flux 1×10^6 w/m² and particle flux $\sim 1 \times 10^{20}$ #/m²sec, steady state solution exists if the thickness of the gas blanket is greater than 1 m. It is clear from equation 8 that the upper limit of Q_p depends on the neutral source strength of the gas blanket to the power one third, however, by increasing the external neutral source the slope of line (a) increases but at the same time curve (b) is raised and it is hard to find a steady state solution only by changing the neutral density of the gas blanket. For point (3) no solution exists unless the particle flux out of the plasma increases or the gas blanket flows with a given minimum velocity v_g.

In Fig. 2 we plotted the minimum gas blanket velocity, v_g, as a function of the heat flux out of the plasma for two different wall reflection coefficient, R_w. From this figure one can draw the following conclusions: (a) The higher the heat flux out of the plasma, the higher v_g should be; (b) The minimum neutral gas velocity increases with the increase of R_w.

Figure 3 shows the heat loss in the boundary region due to charge exchange with cold neutral, Q_{cx}, due to radiation, Q_{rad}, and by transport along the gas blanket, Q_B, as a function of the neutral gas blanket velocity, v_g. For low v_g, the major heat loss is by charge exchange with cold neutrals. The ratio $\frac{Q_{cx}}{Q_p}$ increases as v_g decreases. This figure indicates also that radiation losses are negligible for graphite. Tables 1 and 2 show the neutral gas blanket parameters as a function of Q_p for carbon and stainless steel first wall. From column 2 of these tables we notice that the fraction of heat which will reach the first wall through radiative energy or by charge exchange neutrals is smaller than the case of static gas blanket, but still higher than the divertor. The heat given to the wall decreases as Q_p increases. This is due to the decrease in the radiated power.

From column 3 $\frac{\Gamma_{iw} + \Gamma_{cxw}}{\Gamma_p}$ is greater than 1, this is due to charge exchange recycling in the gas blanket.

The sputtering coefficient increases as Q_p increases in this case, this explains the behavior of the impurity concentration in the plasma.

2. Particle Flux out of the Plasma

Table 3 shows the effect of decreasing the particle flux out of the plasma, Γ_p, on the boundary region parameters. As Γ_p increases, the heat and particle fluxes as well as the impurity concentration increases. The higher the particle flux out of the plasma the lower will be the minimum neutral gas velocity.

3. Neutral Gas Blanket Velocity

In Fig. 4 we plotted the average ion temperature as a function of S_n for three different neutral gas blanket velocity for graphite. Figure 4 shows that the average temperature is almost constant for low neutral source and then drops as S_n increases. The flat portion of the curve is due to the fact that S_n is still negligible compared to the reflected neutral from the wall due to ion bombardment. It is clear from this figure that 1) the higher the neutral gas blanket velocity the higher will be the average ion temperature of the boundary region, 2) and for a given temperature, the neutral sources decreases as v_g decreases. From this figure one can also explain why the results of Fig. 2. Suppose that we start with point (1) in this figure, we notice that no solution exists with $v_g = 8 \times 10^3$ cm/sec and in order to get a steady state solution S_n or Q_p have to decrease. Another alternative is to increase the neutral gas blanket velocity v_g.

Figure 5 shows the average electron and ion temperature in the boundary region as a function of v_g. The calculations reveal that T_e is comparable to T_i for a static gas blanket and graphite liner and that the difference $(T_i - T_e)$ is small for low v_g.

In Fig. 6 the minimum neutral gas blanket velocity has been drawn for two different values of gas blanket thickness as a function of the heat flux out of the plasma, for stainless steel first wall. Wider gas blanket thickness requires a lower blanket velocity.

Tables 4 and 5 show the variation in the boundary region performance parameters with v_g. The results in Table 4 are for graphite liner, while in Table 5 are for stainless steel first wall. The explanation of the results in Tables 4 and 5 follows:

a. The fraction of heat energy and particle flux that reach the first wall decreases as v_g increases. This behavior is due to the decrease of the ion density in the boundary region.

b. The impurity concentration, $n_z(o)$, decreases as v_g increases. This is mainly due to the fact that the ion density decreases, which in turn will decrease the ionization probability and consequently the impurity source.

c. Steady state solution exists only for $v_g > 5 \times 10^3$ cm/sec for reactor type fluxes.

4. Blanket Thickness

Figure 6 shows the effect of the neutral gas blanket thickness, δ_s, on the minimum velocity v_g. For a given heat flux out of the plasma it is clear that δ_s decreases as the neutral gas velocity increases.

5. Neutral Return from the Wall

As shown in Fig. 2 the minimum blanket velocity decreases as the reflection coefficient decreases. Table 6 shows the variation of the boundary region characteristics as a function of the wall reflection coefficient, R_w. As R_w decreases, the particle density in the boundary region decreases, this in turn will decrease both the heat and particle fluxes to the wall as well as the impurity concentration in the plasma.

6. Neutral Gas Blanket Source

As the gas blanket source, S_n, increases the ion density in the boundary region increases. This explains the behavior of the particle and heat fluxes to the wall and the impurity concentration as shown in Table 7, 8. The impurity level decreases for iron as S_n changes from 5×10^{20} to 1×10^{21} because of the decrease in the average electron temperature of the boundary region.

7. Cross Field Diffusion Coefficient

As the cross field diffusion coefficient, $D_\perp$, decreases, the ion density in the neutral gas blanket increases. This increase is due mainly to the low temperature of the boundary region and high ionization rate, and due to the fact that the particle flux out of the plasma is constant. As $D_\perp$ decreases, the impurity concentration increases as a result of high particle density, i.e. high ionization probability. The heat flux to the wall is almost constant, and the particle flux to the wall increases due to the increase of the ionization rate. These conclusions are deduced from Table 9.

IV. Conclusion

The model of Ref. 6 was extended to represent a moving neutral gas blanket. We have used this model to study the requirements on the neutral gas blanket parameters such as the velocity, the neutral source strength and the thickness of the gas blanket in order to efficiently shield the plasma. Under the assumption of a constant average boundary region temperature, this study shows that for a near term fusion reactor the neutral gas blanket velocity ranges between 50 and 100 m/sec in order to obtain a reasonable boundary region thickness. Speeds on the order of 50 to 100 m/sec are feasible for gas puffing but are questionable for steady state neutral gas flow and more research is required in this respect. We expect that by refining the model and taking a space dependent temperature the minimum required neutral gas velocity will be lower. From this study one can draw the following conclusions.

1. The velocity of the neutral gas blanket, v_g, increases as the heat flux out of the plasma increases.

2. The higher the particle flux out of the plasma, the lower will be v_g.

3. As v_g increases, both the heat loss by charge exchange with the cold neutral and the heat loss to the wall decrease.

4. The thickness of the boundary region is determined by both the cross field diffusion coefficient and the neutral gas blanket velocity.

5. The difference between the average ion and electron temperature increases as the gas blanket velocity or the radiation losses increases.

6. The impurity level in the plasma decreases as v_g increases.

References

1. B. Lehnert, Nucl. Fusion, 8, 173 (1968).
2. T. A. Oliphant, Nucl. Fusion, 13, 521 (1973); Nucl. Fusion, 16, 263 (1973).
3. G. K. Verboom, J. Rem, Nucl. Fusion, 13, 69 (1973),
4. B. Lehnert, Nucl. Fusion, 13, 958 (1973).
5. T. A. Oliphant, J. Nucl. Materials, 53, 62 (1974).
6. W. M. Stacey and Z. El-Derini, "Divertor and Gas Blanket Model and Studies," Transactions of ANS 1978 Winter Meeting, November 12-16, 1978, Washington, D. C.
7. Z. El-Derini and W. M. Stacey, "Performance of Neutral Gas Blankets for Plasma Impurity Control," Transactions of ANS 1979 Annual Meeting, June 3-8, 1979, Atlanta, Georgia.
8. Z. El-Derini and W. M. Stacey, "Interim Report on Divertor and Gas Blanket Impurity Control Study," GTFR-8 (April 1979).

Table 1

Blanket parameters as a function of heat flux out of the plasma
(Γ_p = 2.5 x 10^{16} #/cm^2, δ = 30 cm, S_n = 5 x 10^{16}, v_g = 1 x 10^4 cm/sec, graphite liner)

Q_p w/m^2	Q_w/Q_p	$\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$	$\frac{n_z(0)}{\Gamma_p}$
1 x 10^5	.60	3.7	.1 x 10^{-2}
2 x 10^5	.59	3.3	.12 x 10^{-2}

Table 2

Blanket parameters as a function of heat flux out of the plasma
(Γ_p = 2.5 x 10^{16} #/cm^2, δ = 30 cm, S_n = 1 x 10^{16}, v_g = 1 x 10^4 cm/sec, stainless steel)

Q_p w/m^2	Q_w/Q_p	$\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$	$\frac{n_z(0)}{\Gamma_p}$
1 x 10^5	.55	2.1	.23 x 10^{-3}
2 x 10^5	.54	2.04	.35 x 10^{-3}
3 x 10^5	.52	1.97	.45 x 10^{-3}
4 x 10^5	.48	1.77	.49 x 10^{-3}

Table 3

Blanket parameters as a function of confinement time

(Q_p = 1 x 10^5 w/m^2, δ = 30 cm, v_g = 1 x 10^4 cm/sec, S_n = 1 x 10^{21}, graphite)

τ_{conf}	Q_w/Q_p	$\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$	$\frac{n_z(o)}{\Gamma_p}$
1.3	.60	3.7	.1 x 10^{-2}
1	.69	12.6	.19 x 10^{-2}
.75	.69	39.1	.24 x 10^{-2}

Table 4

Blanket parameters as a function of blanket velocity

(Q_p = 1 x 10^5 w/m^2, Γ_p = 2.5 x 10^{16} #/cm^2, δ = 30 cm, S_n = 5 x 10^{16}, graphite)

V_g cm/sec	Q_w/Q_p	$\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$	$\frac{n_z(o)}{\Gamma_p}$
5 x 10^3	.79	6.1	.75 x 10^{-2}
8 x 10^3	.62	4.0	.11 x 10^{-2}
1 x 10^4	.60	3.7	.1 x 10^{-2}
3 x 10^4	.5	2.8	.39 x 10^{-3}

Table 5

Blanket parameters as a function of neutral blanket velocity
(Q_p = 1 x 10^5 w/m^2, Γ_p = 2.5 x 10^{16} #/cm^2, δ = 30 cm, $\mathcal{S}_n$ = 1 x 10^{16}, stainless steel)

Vg(cm/sec)	Q_w/Q_p	$\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$	$\frac{n_z(o)}{\Gamma_p}$
5 x 10^3	.69	5.3	.19 x 10^{-3}
1 x 10^4	.55	2.1	.23 x 10^{-3}
1 x 10^5	.23	.93	.40 x 10^{-5}

Table 6

Blanket parameters as a function of the neutral source strength
(Q_p= 1 x 10^5 w/m^2, Γ_p = 2.5 x 10^{16} #/cm^2 sec, δ = 30 cm, Vg = 10^4 cm/sec, graphite)

$\mathcal{S}_n$ #/cm^2 sec	Q_w/Q_p	$\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$	$\frac{n_z(o)}{\Gamma_p}$
1 x 10^{20}	.53	2.1	.55 x 10^{-3}
5 x 10^{20}	.60	3.7	.1 x 10^{-2}
1 x 10^{21}	.63	6.3	.16 x 10^{-2}

Table 7

Blanket parameters as a function of external neutral source
(Q_p = 1 x 10^5 w/m^2, Γ_p = 2.5 x 10^{16} #/cm^2 sec, δ = 30 cm, Vg = 10^4 cm/sec, graphite)

S_n	Q_w/Q_p	$\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$	$\frac{n_z(o)}{\Gamma_p}$
1 x 10^{20}	.55	2.1	.23 x 10^{-3}
5 x 10^{20}	.64	4.2	.25 x 10^{-3}
1 x 10^{21}	.70	7.2	.24 x 10^{-3}

Table 8

Blanket parameters as a function of wall reflection coefficient
(Q_p = 10^5 w/m^2, Γ_p = 2.5 x 10^{16} #/cm^2 sec, S_n = 5 x 10^{16} #/cm^2 sec, V_g = 10^4 cm/sec, graphite)

R_w	Q_w/Q_p	$\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$	$\frac{n_z(o)}{\Gamma_p}$
1	.6	3.7	.1 x 10^{-2}
.5	.55	2.4	.66 x 10^{-3}
0	.48	1.7	.4 x 10^{-3}

Table 9

Blanket parameters as a function of cross field diffusion coefficient
($Q = 1 \times 10^5$ w/m^2, $\Gamma_p = 2.5 \times 10^{16}$ #/cm^2 sec, $S_n = 5 \times 10^{16}$ #/cm^2 sec, $R_w = 1$, graphite)

$D_\perp$	Q_w/Q_p	$\frac{\Gamma_{cxw} + \Gamma_{iw}}{\Gamma_p}$	$\frac{n_z(o)}{\Gamma_p}$
D_B	.6	3.7	$.1 \times 10^{-2}$
$D_B/1.5$	.599	4.1	$.11 \times 10^{-2}$
$D_B/2$	.592	4.2	$.12 \times 10^{-2}$

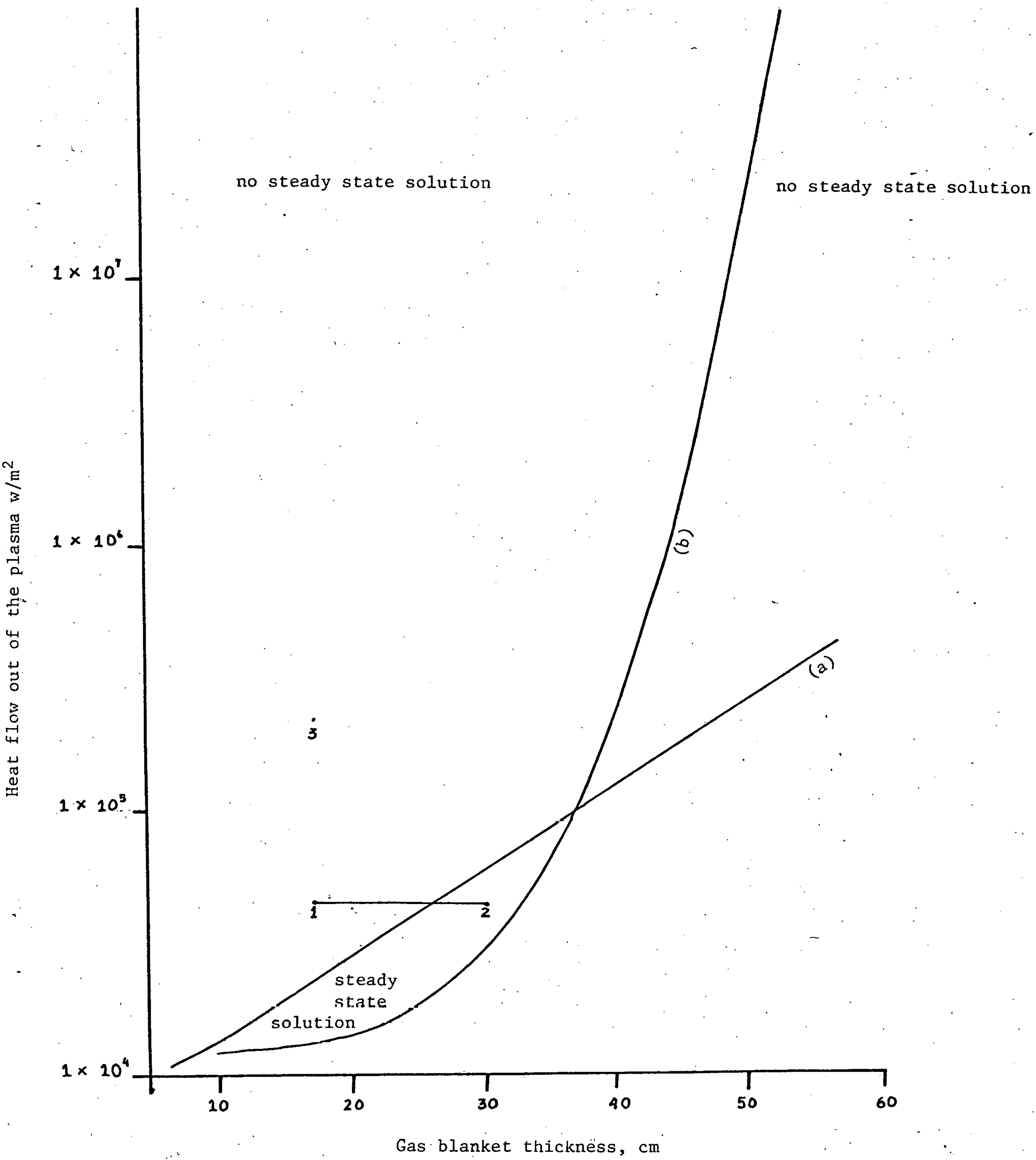

Fig. 1. Heat flux out of the plasma as a function of the neutral gas blanket thickness

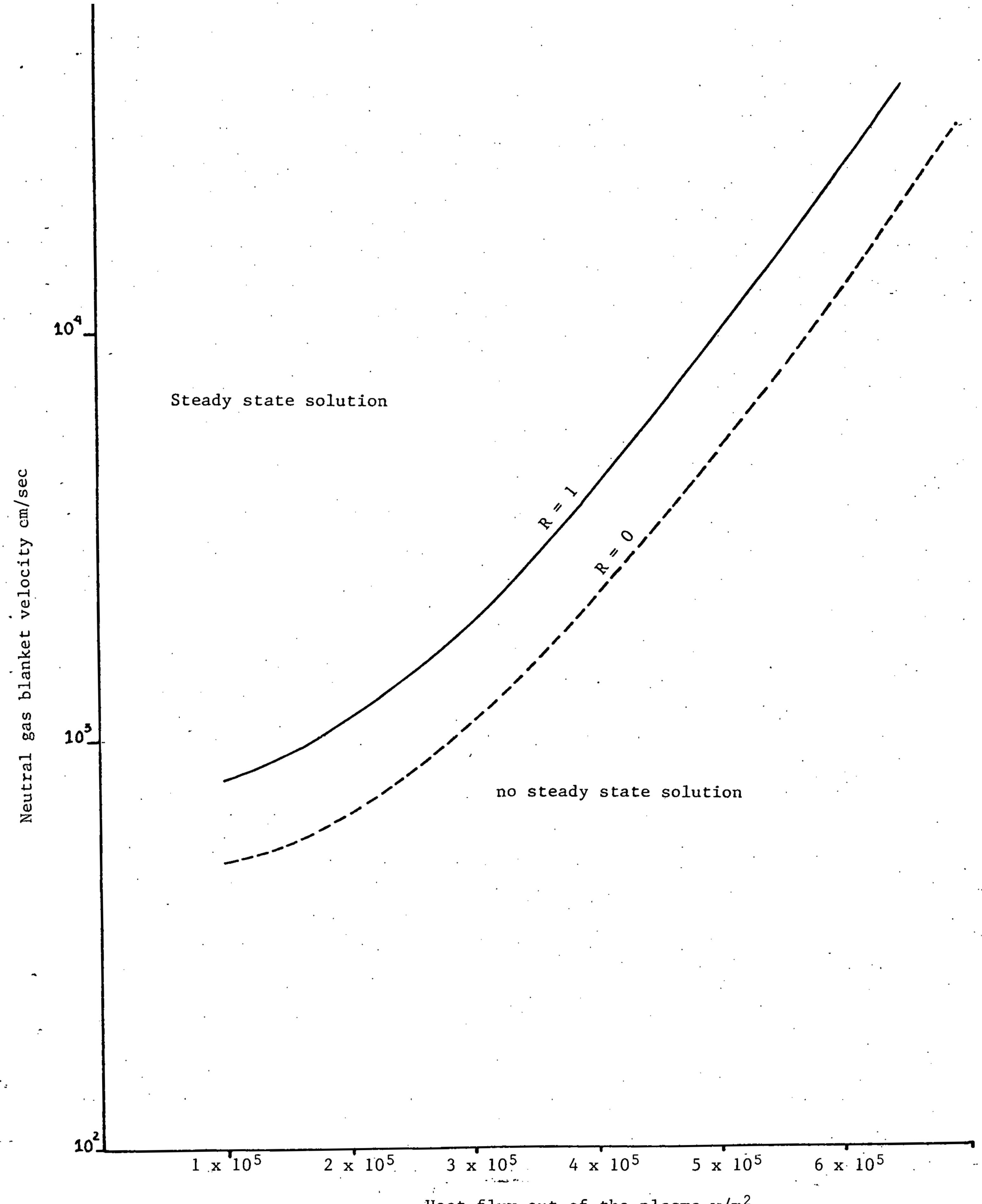

Fig. 2. Minimum flow velocity as a function of the heat flux out of the plasma

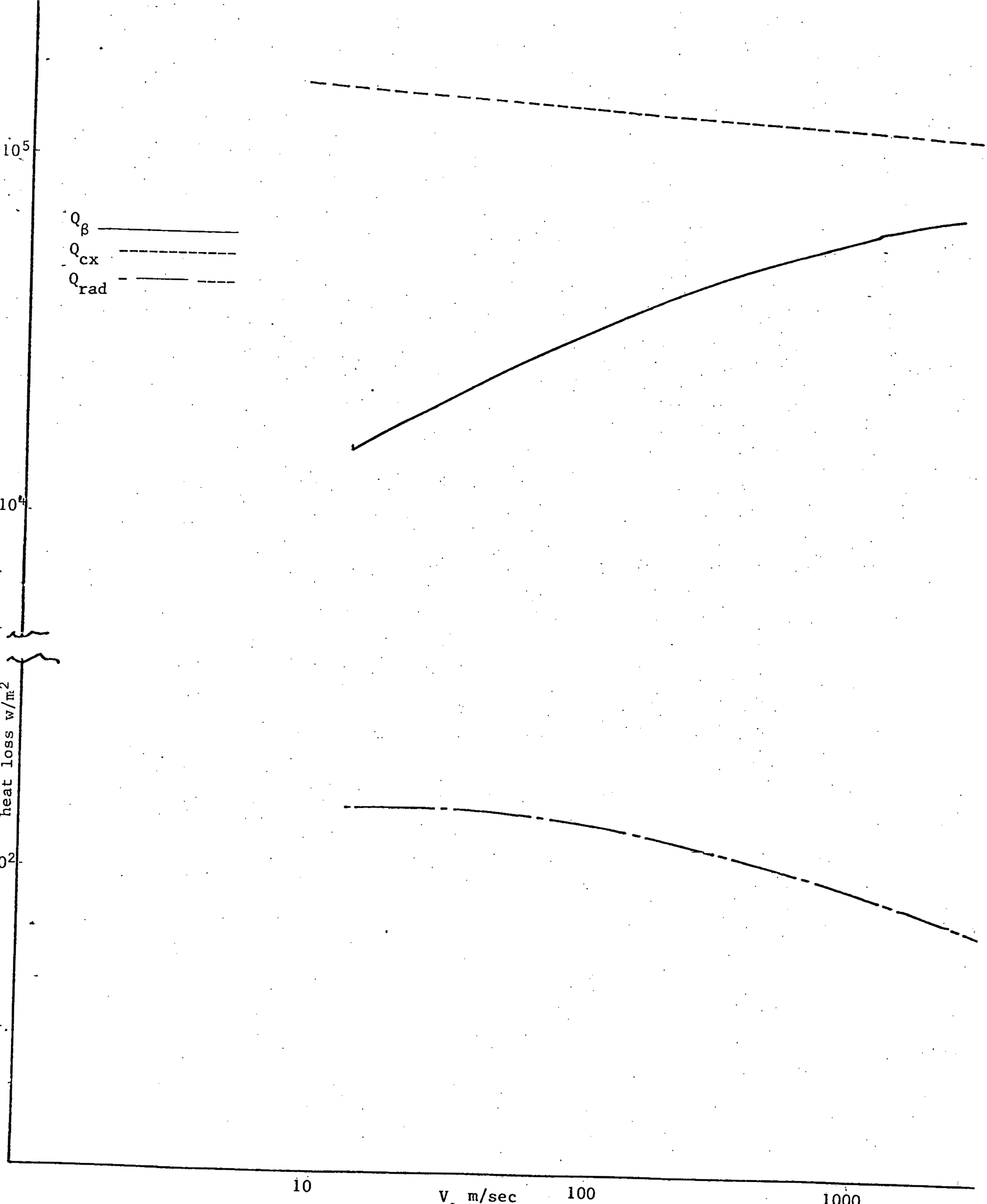

Fig. 3. Heat loss mechanisms as a function of the neutral gas blanket velocity

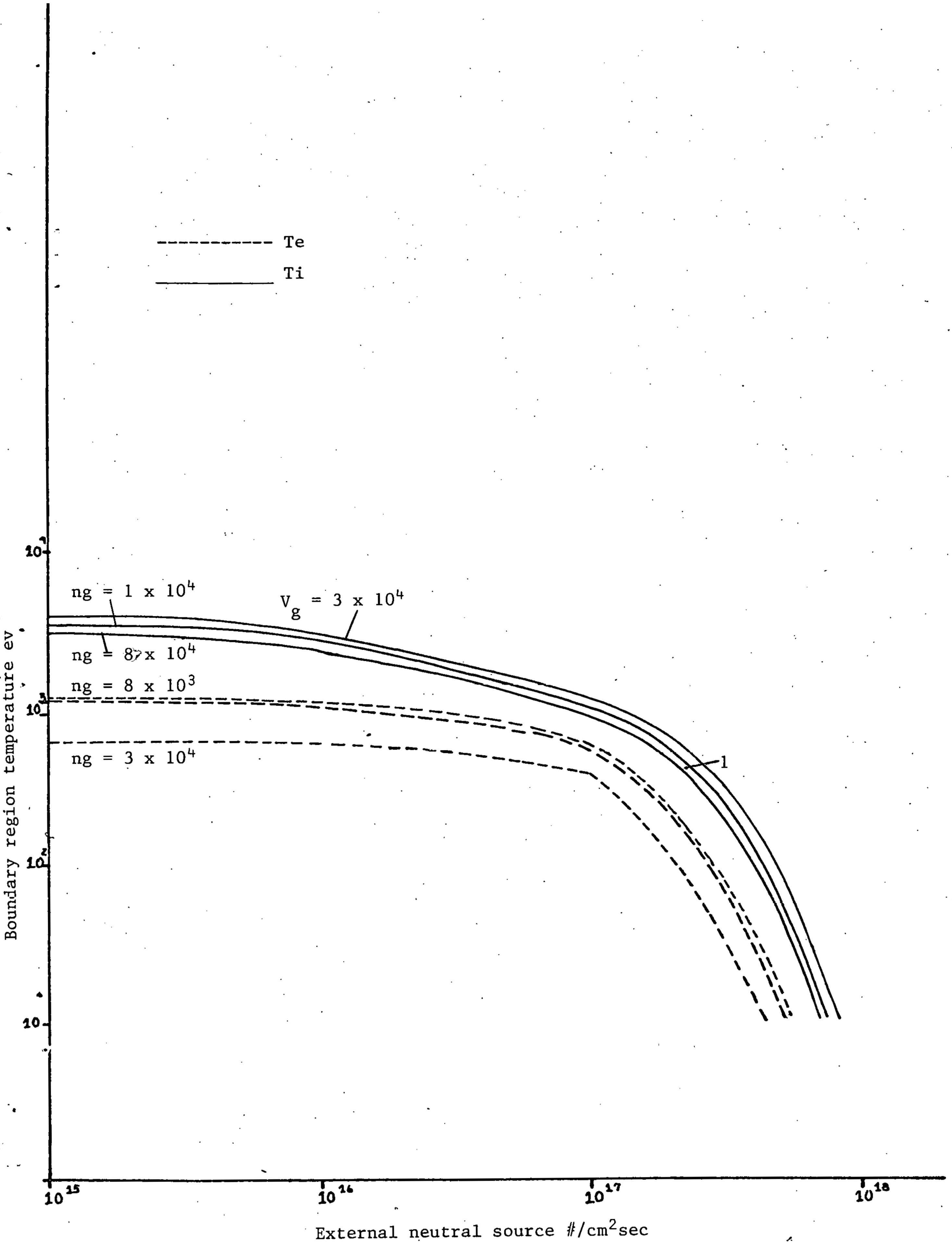

Fig. 4. Average boundary region temperature as a function of the neutral gas blanket strength

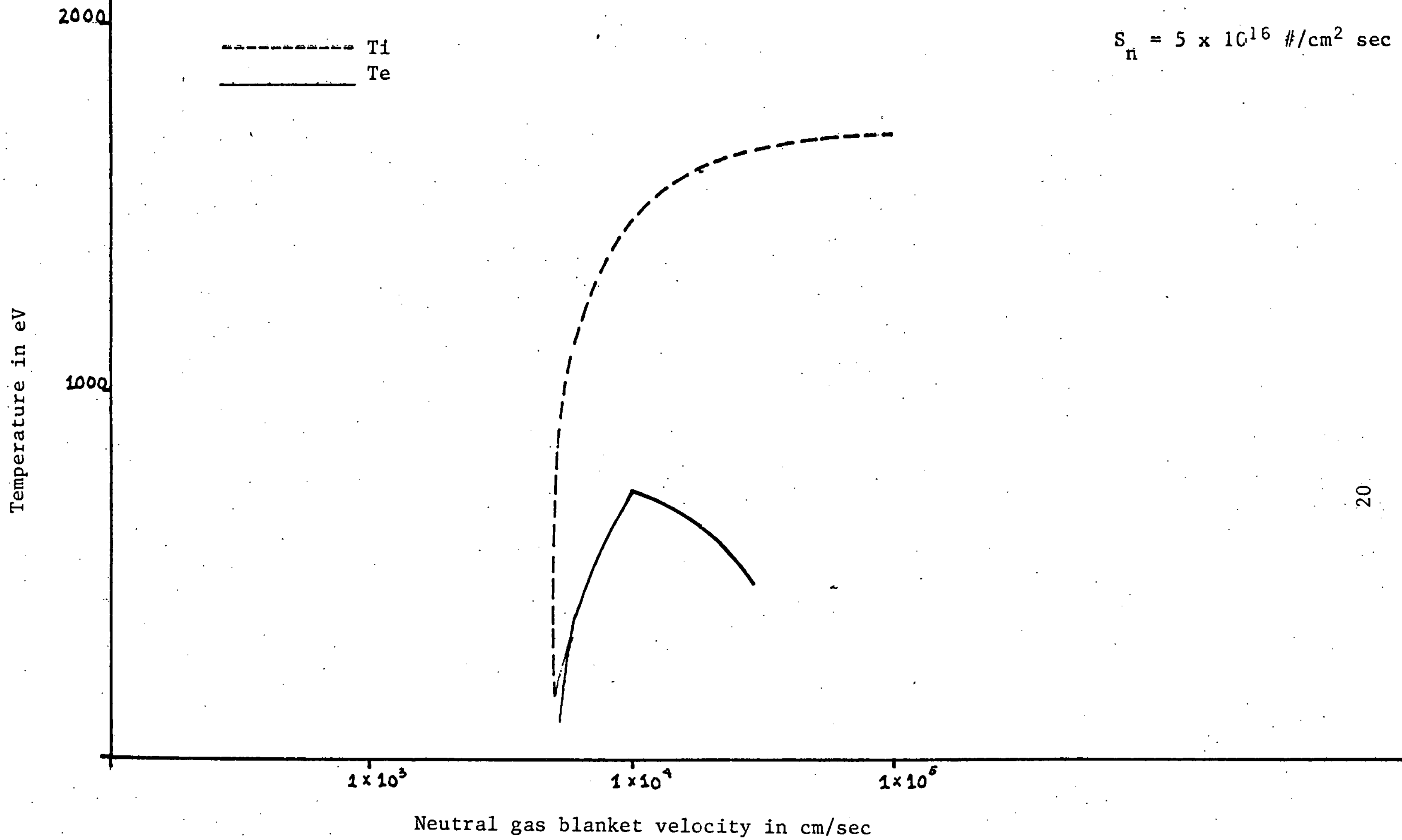

Fig. 5. Average boundary region temperature as a function of the neutral gas blanket velocity

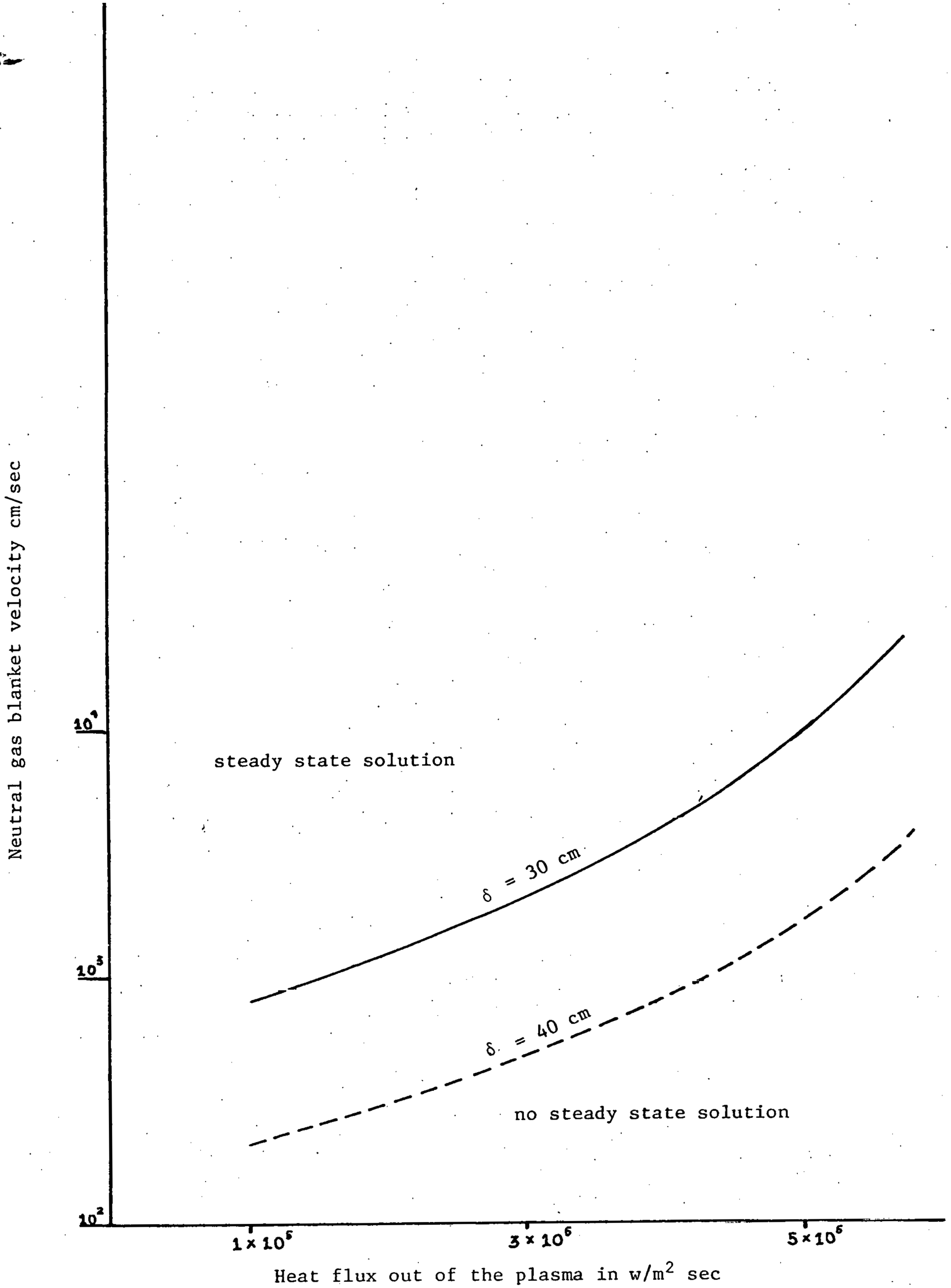

Fig. 6. Minimum neutral gas blanket velocity as a function of the heat flux out of the plasma for two different neutral gas blanket thickness