ORNL/FEDC--83/14

DE84 010639

ORNL/FEDC-83/14
Dist. Category UC-20 c,d

Fusion Energy Division

TWO-POINT MODEL FOR DIVERTOR TRANSPORT

J. D. Galambos

and

Y-K. M. Peng

Date Published - April 1984

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
UNION CARBIDE CORPORATION
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. W-7405-eng-26

MASTER

20
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CONTENTS

LIST OF FIGURES	v
LIST OF TABLES	vii
ABSTRACT	ix
1. INTRODUCTION	1
2. MODEL	2
3. MODEL VERIFICATION	11
4. RESULTS	14
5. SUMMARY	22
REFERENCES	25

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Approximation of divertor geometry used in the two-point model	3
2	Conceptual diagram of neutral transport model	7
3a	Plasma density at the plate vs plasma density at the throat	15
3b	Mach number at the throat vs plasma density at the throat	15
3c	Percentage of heat transferred via conduction (μ) vs throat density	16
3d	Plasma temperature at the throat vs plasma density at the throat	16
3e	Plasma temperature at the plate vs plasma density at the throat	17
4	(a) Sensitivity of results to assumption of the shape factor α for low recycling. (b) High recycling case, $R = 0.9$	19
5	Particle flux at the throat vs R for several throat densities	21
6	Plate temperature vs R for several throat densities	21

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Input used in comparisons with refs. [5] and [6]	12
2a	Results of comparison with ref. [5]	13
2b	Results of comparison with ref. [6]	13

ABSTRACT

Plasma transport along divertor field lines was investigated using a two-point model. This treatment requires considerably less effort to find solutions to the transport equations than previously used one-dimensional (1-D) models and is useful for studying general trends. It also can be a valuable tool for benchmarking more sophisticated models.

The model was used to investigate the possibility of operating in the so-called high density, low temperature regime. It was found that there is a density threshold below which increases in neutral recycling do not result in high densities and low temperatures near the plate. Below the threshold, the solutions are characterized by plate densities less than the throat density and nearly constant temperature along the field line. Above the threshold density, temperature gradients and high plate densities are achievable with high neutral recycling. For present-day-type experiments with injection powers of about 2 MW, the density threshold is $\sim 10^{13} \text{ cm}^{-3}$. Implications for the feasibility of achieving low temperatures at the divertor plate in future devices such as the Tokamak Fusion Core Experiment (TFCX), with 50 MW of heating power, are that high edge densities ($> 7 \times 10^{13} \text{ cm}^{-3}$) are required. If these high edge densities are not possible, other approaches (such as radiative cooling via impurity injection) may be necessary for long divertor plate lifetimes.

In addition, a limit on the throat density for high neutral recycling was observed, above which steady-state solutions were not found. For the TFCX example used here, the limit was $> 10^{14} \text{ cm}^{-3}$, but for present-day experiments with lower power levels, the limit is $\sim 3 \times 10^{13} \text{ cm}^{-3}$.

1. INTRODUCTION

Poloidal divertors and limiters are presently the leading candidates for particle and heat removal in the next generation of tokamaks. While the use of limiters results in simpler poloidal field (PF) coil designs, divertors suffer no leading edge problem and experimental results indicate better high-Z impurity shielding with divertor operation [1-3]. A potentially greater advantage of divertors is the decoupling of the plasma in contact with the collector plate from the main plasma, resulting in lower temperatures at the plate (compared to those adjacent to the main plasma). This advantage has important ramifications with regard to the collector plate lifetime, since sputtering yields drop rapidly below certain temperature thresholds. If the plasma temperature at the plate can be kept below approximately 50 eV, medium- and high-Z materials are expected to result in acceptable lifetimes [4]. Recently, the issue of maintaining a temperature gradient along divertor field lines has received increased attention.

Several one-dimensional (1-D) (along the field line) codes have been developed [5-7] and used to model both present-day experiments and International Tokamak Reactor (INTOR)-like conditions. The most sophisticated model is a two-dimensional (2-D) (along and perpendicular to the field) code that has been used to investigate divertor transport for conditions typical of present-day experiments [Poloidal Divertor Experiment (PDX) and ASDEX] [8,9]. A common ingredient of these studies is a treatment of the neutral transport, which plays an important role in the buildup of density and temperature gradients along the field. Due to the complexity of these codes, their use has generally been restricted to the examination of specific cases, and these models are not well suited to the examination of overall trends in divertor plasma behavior.

In order to perform more general surveys of divertor plasma characteristics, we have developed a "two-point" model that is more analytical in nature than the earlier studies. The model involves integration of the transport equations along the field lines, with results in terms of the end-point plate and edge plasma quantities. Although information about the intermediate plasma properties is not explicitly retained in

this analytical process, it is a valuable tool for providing insight into the coupling of the quantities of interest (i.e., the conditions at the plate and those at the main plasma edge).

The method used in the two-point model is shown in Sect. 2, and a comparison of the results with the more sophisticated models is presented in Sect. 3. Results are presented in Sect. 4, showing examples of the two-point model applications. These results are summarized in Sect. 5.

2. MODEL

For the purposes of this model, the actual divertor geometry is approximated as a region of straight field lines, as depicted in Fig. 1. The divertor region extends from the sheath adjacent to the collector plate [henceforth called plate (p)] to the throat (t) where the scrape-off plasma is removed from the main plasma. Beyond the throat, the plasma conditions in the scrapeoff adjacent to the main plasma (edge plasma) vary slowly along the field lines. In this sense the throat quantities can be thought of as indicative of the edge plasma. The steady-state transport equations along the field lines are:

$$\frac{\partial}{\partial x} nV = -S_n , \quad (1)$$

$$\frac{\partial}{\partial x} [nmV^2 + nT(1 + r)] = S_p , \quad (2)$$

and

$$\frac{\partial}{\partial x} \left\{ q_e + nV \left[\frac{1}{2} mV^2 + \frac{5}{2} nT(1 + r) \right] \right\} = S_E , \quad (3)$$

where S_n , S_p , and S_E are the particle, momentum, and energy sources associated with neutral recycling; n is particle density; T is the electron temperature; V is the fluid flow speed toward the plate; r is the ion-to-electron temperature ratio; m is the ion mass; and q_e is the

ORNL-DWG 83-4068 FED

(a)

(b)

Fig. 1. Approximation of divertor geometry used in the two-point model.

electron heat conduction ($k_0 T^{5/2}$). Ion heat conduction (which is much smaller than electron heat conduction), cross-field transport effects, and impurity radiation losses are neglected. Integration of Eq. (3) results in

$$\left(\frac{T_t}{T_p}\right)^{7/2} - 1 = \frac{7Q_t L \mu}{2k_0 T_p^{7/2}}, \quad (4)$$

where

$Q_t \equiv$ heat flux at the throat,

$\mu \equiv$ percentage of heat transported in the divertor via conduction,

$$= 1 - \frac{1}{Q_t L} \int_p^t \int_x^t S_E dx' + nV \left[\frac{1}{2} mV^2 + \frac{5}{2} nT(1 + r) \right] dx. \quad (5)$$

Using the boundary conditions for the heat flux through the sheath at the plate,

$$Q_t - \int_p^t S_E dx = n_p V_p T_p (\gamma_e + r_p \gamma_i), \quad (6)$$

where $\gamma_{e(i)}$ is the heat transfer coefficient for electrons (ions) across the sheath. Equation (4) can be written as

$$\left(\frac{T_t}{T_p}\right)^{7/2} - 1 = \left(\frac{n_p}{n_{VT}}\right)^{7/3}, \quad (7)$$

where

$n_{VT} \equiv$ temperature gradient density threshold,

$$= \left(\frac{2k_o}{7L\mu} \right)^{3/7} \frac{Q_t^{4/7} \left(1 - \frac{\int_p^t S_E dx}{Q_t} \right)}{(\gamma_e + r_p \gamma_i) [(1 + r_p)/m]^{1/2}} \quad (8)$$

Here, the flow speed at the plate is taken to be the sound speed $V_p = [T_p(1 + r_p)/m]^{1/2}$ (ref. [10]). Using the momentum balance to solve for T_t/T_p and substituting into Eq. (7) yields:

$$\left[\frac{n_p}{n_T} \left(1 + \frac{\bar{V}_R R}{2} \right) \frac{2(1 + r_p)}{(1 + r_p)} \frac{1}{1 + M_t^2} \right]^{7/2} - 1 = \left(\frac{n_p}{n_{VT}} \right)^{7/3}, \quad (9)$$

where

$R \equiv$ recycle coefficient defined as the fraction of the particle flux at the plate resulting from neutral ionization in the diverter,

$$= \int_p^t S dx / n_p V_p, \quad (10)$$

$\bar{V}_R \equiv$ the average speed of the ionized neutrals normalized by the flow speed at the plate,

$$= \int_p^t S_p/m dx \Bigg/ \int_p^t S dx [T_p(1 + r_p)/m]^{1/2}, \quad (11)$$

$M_t =$ the Mach number at the throat.

Using Eqs. (1) and (2), M_t can be expressed, in terms of the other parameters in Eq. (9), as

$$M_t = [a/(1 - a)]^{1/2},$$

where

$$a = n_p/n_t \cdot (1 - R)^2 / [2(1 + \bar{V}_R R/2)] \quad (12)$$

To find solutions to Eq. (9), which contains information from all three transport equations, it is necessary to provide a framework for calculating the neutral source quantities R , $\bar{V}_R$, $\int S_E dx$, and the heat conduction term μ .

The recycle coefficient R is a function of the actual divertor geometry, pumping speed, and neutral transport in the divertor plasma. Its precise evaluation requires a large numerical effort, and to keep the present analysis on an analytic basis, R is varied as a free parameter. Although considerable simplification is gained by taking this approach, some consistency is sacrificed. In this regard, the results from the model should be viewed with the caveat that, in general, larger recycling values apply for higher densities.

The other source terms can be expressed in terms of R as explained below. A fraction r_n (fast reflection) of the incident flux on the plate is reflected with the fraction r_e of the incident energy (see ref. [11] for the expressions used for r_n and r_e). The rest of the incident particle flux is assumed to be emitted from the plate in the form of cold molecules at the wall temperature (slow-reflection component). (Figure 2 is a conceptual illustration of the ionization branches for these components.) The fraction of the fast-reflection component that is initially ionized (f_{ion-f}), as opposed to charge exchanged [$= \langle \sigma v \rangle_{ion} / (\langle \sigma v \rangle_{ion} + \langle \sigma v \rangle_{cx,f})$], contributes $mV_0 \sin \theta$ to the momentum source. $V_0 = r_e (T_p r_p \gamma_i / m)^{1/2}$ is the "fast" neutral speed, and $\langle \sigma v \rangle_{ion(cx-f)}$ is the ionization (fast component charge exchange) cross section (see refs. [11] and [12] for the charge-exchange and ionization cross sections, respectively) and is evaluated at the average (T_{av}) of the plate and throat temperatures. The $\sin \theta$ term is approximately B_p/B_T (0.1 throughout this work) and accounts for the fact that the field lines are nearly parallel to the plate and that only a small fraction of the neutral velocity is directed along the field line, on

ORNL-DWG 83C-4089R FED

Fig. 2. Conceptual diagram of neutral transport model. (i = ionization, cx-f = fast neutral charge exchange, and cx-s = slow neutral charge exchange.)

the average. The component of the fast-reflection neutrals that initially charge exchange ($f_{cx-f} = 1 - f_{ion-f}$) contributes $m(V_0 \sin \theta + V_{av})$ to the momentum source, where V_{av} is the average of the plate and throat flow speeds. The fraction of the slow-reflection component that initially charge exchanges [$f_{cx-s} = \langle \sigma v \rangle_{cx-s} / (\langle \sigma v \rangle_{ion} + \langle \sigma v \rangle_{cx-s})$] contributes mV_{av} to the momentum source. The small momentum contribution from the direct ionization of the slow-reflection neutrals is neglected. By approximating the ratios for the various branches of ionization and charge-exchange reactions as being constant throughout the divertor, the momentum source can be expressed:

$$\int_p^t S_p dx = m n_p V_p R \left\{ r_n [f_{ion-f} V_0 \sin \theta + f_{cx-f} (V_0 \sin \theta + V_{av})] + (1 - r_n) f_{cx-s} V_{av} \right\}. \quad (13)$$

To account for radiative energy losses associated with neutral recycling, an average energy loss per ionization (Δ_E) [11] is used. This is evaluated at T_{av} , and the average of the plate and throat density n_{av} . Because the fast-reflection component has an energy comparable to the plasma temperature, no energy sink is taken for the charge exchange of these neutrals. However, the slow-reflection component is considerably colder than the divertor plasma, and an energy loss of $3/2 T_{av} + 1/2 mV_{av}^2$ is taken for the initial charge exchange of a slow-reflection neutral. With these definitions, the energy source term can be expressed:

$$\int_p^t S_E dx = R n_p V_p \left[\Delta_E + (1 - r_n) f_{cx-s} \left(\frac{3}{2} T_{av} + \frac{1}{2} mV_{av}^2 \right) \right]. \quad (14)$$

The final term requiring additional treatment is μ [see Eq. (5)]. Rigorous evaluation of μ requires a knowledge of the density, temperature, Mach number, and energy source profile throughout the divertor region. We chose a method to calculate μ that introduces assumptions

but allows the analytic nature of this treatment to be retained. First, the energy loss term in Eq. (5) is neglected since most of the energy losses occur in the vicinity of the plate. Also, the profile for the ion-to-electron temperature ratio r and density n between the plate ($x = 0$) and throat ($x = L$) is assumed to be of the form

$$f(x) = f(0) + [f(L) - f(0)] \left[1 - \left(1 - \frac{x}{L} \right)^\alpha \right], \quad (15)$$

where α is the polynomial coefficient (the sensitivity of the results to the shape factor α is discussed later). Using the continuity equation, the Mach number profile is

$$M(x) = 1 - R' \frac{n_p [T_p (1 + r_p)]^{1/2}}{n [T (1 + r)]^{1/2}}, \quad (16)$$

and when coupled with the momentum balance, the temperature profile is

$$T(x) = \left[(\bar{V}_R R') + 2 - (1 - R)^2 \frac{n_p}{n} \right] \frac{n_p T_p (1 + r_p)}{n (1 + r)}, \quad (17)$$

where

$R' \equiv$ the fraction of ionization at x

$$= \frac{\int_0^x S_n dx}{\int_0^L S_n dx}, \quad (17a)$$

$(\bar{V}_R R)' \equiv$ fraction of momentum source at x

$$= \bar{V}_R R \frac{\int_0^x S_p dx}{\int_0^L S_p dx}. \quad (17b)$$

To evaluate R' and $(\bar{V}_R R)'$, the neutral sources are approximated as the following exponentially decreasing functions:

$$S_n \propto \left[r_n e^{x/\lambda_1} + (1 - r_n) e^{-x/\lambda_2} \right] \quad (18a)$$

and

$$S_p \propto r_n \left[f_{\text{ion-f}} V_0 \sin \theta e^{-x/\lambda_1} + f_{\text{cx-f}} (V_0 \sin \theta + V_{\text{av}}) e^{-x/\lambda_3} \right] \\ + (1 - r_n) V_{\text{av}} f_{\text{cx-s}} e^{-x/\lambda_4}, \quad (18b)$$

where

$\lambda_j \equiv$ mean free path for fast-reflection ionization ($j = 1$), slow-reflection ionization ($j = 2$), fast-reflection charge exchange ($j = 3$), slow-reflection charge exchange ($j = 4$),

$$= V_j / (n_{\text{av}} \langle \sigma v \rangle_j \sin \theta),$$

$$V_j = V_0 \quad (j = 1, 3),$$

$$= 1.5 \times 10^5 \text{ cm/s} \quad (j = 2, 3) \text{ ("wall temperature" speed)}.$$

For a chosen shape coefficient α for the density and temperature ratio profiles, the heat conduction parameter μ can be numerically integrated straight forwardly using Eqs. (15)–(18). We note that the shape coefficients α assumed in Eq. (15) are used only in the evaluation of μ and are not required elsewhere in the analysis.

Using the framework outlined above, it is possible to find a set of plate and throat conditions satisfying Eqs. (1)–(3) and (6). For a given n_t and R , initial guesses for T_p , $\bar{V}_R$, and n_p are picked and the software package HYBRID [13] is used to iterate these values to a set that satisfies Eqs. (6), (9), and (11). This procedure is fast, typically

requiring ≤ 0.2 s of CPU time to converge to a consistent set on the CRAY-1 computer and is quite useful in performing parameter surveys. Although the concept of the two-point model was originally developed in refs. [14] and [15], this work retains significantly more information. In particular, we include the continuity equation, the flow term in the momentum equation, heat convection, and the source terms in all three equations. By including the source terms, the role of neutral recycling in achieving low plate temperatures can be investigated. Also, inclusion of the heat convection has important ramifications for the form of the solutions found for low recycling. In addition, this is the first work of its type to evaluate solutions over a wide range of parameters.

3. MODEL VERIFICATION

Several comparisons of the model used here with full 1-D calculations have been done and indicate good agreement. The results from the comparisons with (a) Harbour and Morgan [5] and (b) Shimada et al. [6] are presented below. For consistency of comparison to the models, the following modifications were introduced for these calculations: (1) the momentum source was set to 0; (2) for comparison in case (b), Δ_E was artificially increased to mimic the effect of impurity radiation included in ref. [6] so that the total radiative losses were the same. Table 1 shows the input values used (taken from refs. [5] and [6]) and Tables 2a and 2b show the results of the comparison for various shape factors assumed for the density profile (α_n). The results from the two-point model are within $\sim 10\%$ of those of the more sophisticated 1-D solutions. It is also seen that the results of the comparison are not sensitive to the choice of α_n . Although not indicated in Table 1, the results from the two-point model were very insensitive ($< 1\%$ sensitivity) to variation of α_r for the temperature ratio profile over $1 \leq \alpha_r \leq 8$ in case (a), and in case (b), which assumes $T_i = T_e$, the results are independent of α_r .

Table 1. Input used in comparisons with refs. [5] and [6]

Quantity	Case a	Case b
R	0.471	0.810
n_t (cm ⁻³)	3.66×10^{13}	1.8×10^{13}
$r_p(t)$	1.02 (0.703)	1.0 (1.0)
Q_t (W/cm ²)	3100	1700 ^a
L	1500	1333
$\gamma_{e(i)}$	3.8 (4.3)	3.9 (3.9) ^b

^aCalculated using $Q_t = 1 \text{ MW}/(4\pi R \delta B_p/B_t)$, $\delta \equiv$ scrapeoff width = 10 cm.

^bCalculated with Eq. (6), assuming $\gamma_e = \gamma_i$.

Table 2a. Results of comparison with ref. [5]

Case a	$\alpha_n = 4$	$\alpha_n = 6$	$\alpha_n = 8$	Ref. [5]
T_t (eV)	27.1	27.6	27.8	26.7
T_p (eV)	10.1	10.8	11.1	10.8
M_t	0.712	0.663	0.643	0.725
n_p (10^{13} cm^{-3})	8.80	7.98	7.65	8.60
$\int_p^t S_E dx/Q_t$	0.14	0.13	0.13	0.15^a

^aNumber is from figures contained in ref. [5].

Table 2b. Results of comparison with ref. [6]

Case b	$\alpha_n = 6$	$\alpha_n = 8$	$\alpha_n = 12$	Ref. [6]
T_t (eV)	35.2	35.0	34.7	$\approx 37^a$
T_p (eV)	4.4	4.43	4.49	$\approx 4^a$
M_t	0.292	0.289	0.286	0.26
n_p (10^{13} cm^{-3})	7.85	7.70	7.53	$\approx 9.1^a$
$\int_p^t S_E dx/Q_t$	0.50	0.50	0.51	0.50

^aNumber is from figures contained in ref. [6].

4. RESULTS

To illustrate the use of the two-point model, parameters expected in the proposed TFCX device [16] are used as input. Following the prescriptions in ref. [11] for calculating flow area in the divertor channel, the throat heat flux Q_t is found to be 1.2×10^4 W/cm², and the divertor field line length L is 600 cm. Also, unless otherwise stated, the heat transfer coefficients used in ref. [5] are used here [i.e., $r_{e(i)} = 3.8(4.3)$], and $r_{p(t)} = 1.0$. The corresponding solutions for the plate density, throat Mach number, heat conduction indicator μ , throat temperature, and plate temperature are displayed in Figs. 3a-3e, respectively. The dotted lines in these figures are boundaries beyond which (higher n_t) $T_p < 5$ eV and the model begins to break down. The lower density for which solutions are found is governed by the condition $L > \lambda$ (collisional mean free path), which is necessary for the fluid treatment to be valid. A striking feature of the results is the different form of the solutions for high recycling ($R \geq 0.75$) and low recycling ($R \leq 0.75$). In the low recycling cases, no "limiting" n_t exists; whereas, for the high recycling cases, there is a limiting n_t above which solutions cannot be found. Another feature of the high recycling cases is the existence of an "upper branch" of solutions, as indicated for the $R = 0.96875$ case in Fig. 3a. These upper branch solutions approach very high densities ($n_p \geq 10^{17}$ cm⁻³ in this example) as n_t decreases from the limiting n_t , with corresponding very low temperatures ($T_p < 1$ eV), and therefore are not considered in this work.

It is interesting to note that below $n \cong 5 \times 10^{13}$ cm⁻³, the solutions for plate density are similar for low and high recycling and are characterized by $n_t > n_p$. This ordering occurs because even with low recycling, the throat Mach number is small and the flow term in the momentum balance is negligible at the throat. Also, at these low densities (high temperatures), the strong heat conduction prevents a temperature gradient so that $T_p = T_t$. With these constraints the momentum balance implies $n_p \sim 1/2 n_t$ (neglecting the momentum source), which is close to the values shown in Fig. 3a.

Fig. 3a. Plasma density at the plate vs plasma density at the throat.

Fig. 3b. Mach number at the throat vs plasma density at the throat.

Fig. 3c. Percentage of heat transferred via conduction (μ) vs throat density.

Fig. 3d. Plasma temperature at the throat vs plasma density at the throat.

Fig. 3e. Plasma temperature at the plate vs plasma density at the throat.

As expected, the throat Mach number (Fig. 3b) decreases with increased recycling from about 0.25 at low recycling to only a few percent at high recycling. Also, following a contour of constant R , it is observed that M_t tends to increase as n_t increases, which corresponds to an increase in the amount of heat convection. The increase in heat convection is reflected by decreases in μ (as indicated in Fig. 3c). This effect is much more pronounced for the low recycling regime in which μ varies by orders of magnitude.

The different forms of the solutions between high and low R are a reflection of the more dramatic change in μ for the low R compared to the high R . As μ decreases, the temperature gradient threshold density (n_{VT}) [Eq. (8)] increases. Thus, as n_t increases, the increasing dominance of heat convection (decreasing μ) makes it more difficult to maintain a temperature gradient (increasing n_{VT}). This strong variation in μ for low R tends to wash out the nonlinear variation of n_p with n_t , and no limiting n_t is found. On the other hand, for the high recycling cases, the variation of μ with n_t is rather slight, and changes in n_{VT} are dominated by the neutral recycling energy loss term that increases with n_t (since the throat flux increases). The increasing energy loss tends to decrease n_{VT} as n_t increases, which manifests itself in the extremely nonlinear rise of n_p with n_t seen in the high R cases.

To test the sensitivity of the model on the assumption of the density shape profile α_n , high ($R = 0.9$) and low ($R = 0.5$) recycling cases with TFCX parameters were run while varying α_n from 2 to 8. The resulting n_p vs n_t curves are shown in Fig. 4(a) and (b). It is evident that the form of the solutions is not sensitive to the exact value of α_n , and for both cases, the results are insensitive to the choice of α_n in the region of interest ($n_t \leq 10^{14} \text{ cm}^{-3}$). The primary sensitivity in the high recycling case is the "limiting" n_t value that varies from $1.5 \leq n_t (10^{14} \text{ cm}^{-3}) \leq 2.0$ as α_n is increased from 2 to 8. Also shown in these examples is the result assuming $\mu = 1$ (heat conduction only). This assumption leads to only slight differences for the high recycling case but introduces an entirely different form of the solution for the low recycling case. For low recycling, it is apparent that accounting for heat convection is important.

Fig. 4. (a) Sensitivity of results to assumption of the shape factor α for low recycling. Also shown is the case with $\mu = 1$. (b) High recycling case, $R = 9$.

The flux at the divertor throat, $\Gamma_t = (n_t V_t)$ vs R , is shown in Fig. 5 for several throat densities. These values are found by using the same input used in the previous example (Fig. 3). Following a contour of constant throat density, the throat flux decreases as recycling increases. This is due to the reduced throat Mach number at high recycling. To maintain a constant throat flux with increasing recycling, it is necessary for n_t to increase. Another conclusion from these results is that the throat fluxes for $n_t \geq 10^{13} \text{ cm}^{-3}$ should be sufficient to exhaust helium ash. Namely, for the Tokamak Fusion Core Experiment (TFCX) fusion power of 250 MW (10^{20} alphas per second) (with a maximum helium concentration of 5%), an exhaust rate of $10^{18} \text{ cm}^{-2} \cdot \text{s}^{-1}$ is required. This criterion is easily satisfied for $R \leq 0.99$ and $n_t \geq 3 \times 10^{13} \text{ cm}^{-3}$ (assuming equal transport of helium and hydrogen).

A primary objective of this investigation is to examine the feasibility of achieving low plate temperatures to alleviate the erosion from sputtering. To illustrate the effect of recycling on plate temperature, we have plotted T_p vs R for several throat densities in Fig. 6 (using the same input as in Figs. 3-5). To attain $T_p \leq 50 \text{ eV}$ (considered acceptable for medium- to high- Z materials), it is necessary that $n_t \geq 3 \times 10^{13} \text{ cm}^{-3}$. Increases of recycling do not significantly reduce T_p unless $n_t \geq 7 \times 10^{13} \text{ cm}^{-3}$ (i.e., unless $n_t \geq n_{VT}$). That is, below the threshold density, heat conduction overwhelms the tendency of recycling to produce temperature gradients. Implications of this threshold toward achieving low plate temperatures in other devices can be predicted by noting that n_{VT} increases with larger power levels, making it more difficult to lower T_p via recycling. For example, present-day experiments (PDX, ASDEX, Doublet III) with injection powers of only 1 to 2 MW have temperature gradient thresholds (n_{VT}) three to four times lower than the TFCX case, and INTOR [11] will have an even higher n_{VT} than TFCX.

The energy losses from neutral recycling do reduce n_{VT} , but for power levels expected to occur in an ignited device such as TFCX, they produce only a moderate effect on lowering n_{VT} . For example, even in the high recycling case ($R = 0.96875$) in Fig. 3, the maximum reduction

Fig. 5. Particle flux at the throat vs R for several throat densities.

Fig. 6. Plate temperature vs R for several throat densities.

in n_{VT} from the energy source term is about 1/2. To further alleviate the requirements for achieving temperature gradients, it has been proposed to enhance the radiative losses by adding impurities and expanding the divertor volume [14]. Unless it is possible to maintain edge densities at $\geq 3 \times 10^{13} \text{ cm}^{-3}$ in a TFCX-type device, it may be necessary to add impurities to operate with $T_p \leq 50 \text{ eV}$.

5. SUMMARY

Plasma transport along divertor field lines was investigated using a two-point model. This treatment requires considerably less effort to find solutions to the transport equations than previously used 1-D models and is useful for studying general trends. It also can be a valuable tool for benchmarking more sophisticated models.

The model was used to investigate the possibility of operating in the so-called high density, low temperature regime. It was found that there is a density threshold below which increases in neutral recycling do not result in high densities and low temperatures near the plate. Below the threshold, the solutions are characterized by plate densities less than the throat density and nearly constant temperature along the field line. Above the threshold density, temperature gradients and high plate densities are achievable with high neutral recycling. For present-day-type experiments with injection powers of $\sim 2 \text{ MW}$, the density threshold is near 10^{13} cm^{-3} . Implications for the feasibility of achieving low temperatures at the divertor plate in future devices such as TFCX (with $\sim 50 \text{ MW}$ of heating power) are that high edge densities ($> 7 \times 10^{13} \text{ cm}^{-3}$) are required. If these high edge densities are not possible, other approaches (such as radiative cooling via impurity injection) may be necessary for long divertor plate lifetimes.

In addition, a limit on the throat density for high neutral recycling was observed, above which steady-state solutions were not found. For the TFCX example used here, the limit was $> 10^{14} \text{ cm}^{-3}$, but for lower power level, present-day experiments, the limit is $\sim 3 \times 10^{13} \text{ cm}^{-3}$.

Note that the actual throat density, which is indicative of the main plasma edge density, is governed by both cross-field transport

effects from the main plasma and transport effects along the divertor field lines. This work dealt only with the transport effects along divertor field lines, with the throat density treated as a free variable. Even though the solutions presented here do satisfy the divertor transport equations, only some of these solutions will exist when the constraints associated with the coupling to the main plasma transport are considered. This extension is a logical next step in the study of divertor transport. Nevertheless, the results here do provide an indication of the general trends that can be expected.

REFERENCES

- [1] M. A. Mahdavi et al., *Phys. Rev. Lett.* 47, 1062 (1981).
- [2] M. Shimada et al., *Nucl. Fusion* 22, 653 (1982).
- [3] M. Keilhacker et al., p. 351 in *Proceedings of the 8th International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, vol. 2, Brussels, 1980 (IAEA, Vienna, 1981).
- [4] W. M. Stacey et al., *Nucl. Technol./Fusion* 4, 203 (1983).
- [5] P. J. Harbour and J. G. Morgan, *Models and Codes for the Plasma Edge Region*, CLM-R-234, Culham Laboratory, Abingdon, Oxfordshire, England, 1982.
- [6] M. Shimada and JAERI Team, "Modeling of Dense and Cold Divertor Plasma in D-III," presented at the Symposium on Energy Removal and Particle Control in Toroidal Fusion Devices, Princeton, New Jersey, 1983.
- [7] W. Schneider, D. Heifetz, K. Lackner, J. Neuhauser, D. Post, and K. G. Rauh, "Modeling of the ASDEX Scrape-off and Divertor," presented at the Symposium on Energy Removal and Particle Control in Toroidal Fusion Devices, Princeton, New Jersey, 1983.
- [8] M. Petravic, D. Post, D. Heifetz, and J. Schmidt, *Phys. Rev. Lett.* 48, 326 (1982).
- [9] M. Petravic, D. Heifetz, and D. Post, *J. Nucl. Mater.* 111 & 112, 294 (1982).
- [10] F. Chen, *Introduction to Plasma Physics*, Plenum Press, New York, 1977.
- [11] M. F. A. Harrison, P. J. Harbour, and E. S. Hotson, *Nucl. Technol./Fusion* 3, 432 (1983).
- [12] R. L. Freeman and E. M. Jones, *Atomic Collision Processes in Plasma Physics Experiments*, CLM-R-137, Culham Laboratory, Abingdon, Oxfordshire, England, 1974.
- [13] J. J. More, B. S. Garbow, and K. E. Hillstrom, *User Guide for Minipack-1*, ANL-80-74, Argonne National Laboratory, Chicago, 1980.
- [14] N. Ohya-yu, J. C. DeBoo, and M. A. Mahdavi, *Radiative Cooling in the Expanded Boundary*, GA-A16434, GA Technologies, San Diego, 1982.

- [15] M. A. Mahdavi et al., *J. Nucl. Mater.* 111 & 112, 355 (1982).
- [16] C. A. Flanagan et al., *Toroidal Fusion Core Experiment: Design Studies Based on Superconducting and Hybrid Toroidal Field Coils*, to be published at Oak Ridge National Laboratory.

ORNL/FEDC-83/14
Dist. Category UC-20 c,d

INTERNAL DISTRIBUTION

1. S. K. Borowski	18. V. C. Srivastava
2. E. C. Crume	19. D. J. Strickler
3. J. L. Dunlap	20. N. A. Uckan
4. G. M. Fuller	21. T. Uckan
5-9. J. D. Galambos	22-23. Laboratory Records Department
10. G. E. Gorker	24. Laboratory Records, ORNL-RC
11. L. M. Hively	25. Document Reference Section
12. Y-K. M. Perg	26. Central Research Library
13. W. T. Reiersen	27. Fusion Energy Division
14. J. A. Rome	Library
15. M. J. Saltmarsh	28. Fusion Energy Division
16. T. E. Shannon	Publications Office
17. J. Sheffield	29. ORNL Patent Office

EXTERNAL DISTRIBUTION

50. M. A. Abdou, Associate Director, FPP/207, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
51. N. A. Amherd, Fusion Power Program, Advanced Systems Department, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94304
52. J. L. Anderson, CMB-3, Mail Stop 348, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
53. M. Anderson, Tennessee Valley Authority, 1300 Commerce Bank Building, Chattanooga, TN 37401
54. O. A. Anderson, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720
55. D. J. Anthony, Advanced Power Program, Advanced Energy Programs Department, Building 2, Room 551, General Electric Company, Schenectady, NY 12345
56. C. C. Baker, FPP/208, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
57. T. H. Batzer, L-536, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
58. J. E. Baublitz, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
59. J. Bauer, Physical Research Division, Sandia National Laboratories-Livermore, Livermore, CA 94550
60. J. F. Baur, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92158
61. D. S. Beard, Office of Fusion Energy, Office of Energy Research, Mail Stop G-256, U.S. Department of Energy, Washington, DC 20545
62. R. J. Beeley, ETEC, Rockwell International, P.O. Box 1449, Canoga Park, CA 91304

43. D. C. Berkey, Vice President & General Manager, Energy System and Technology Division, General Electric Company, P.O. Box 7600, Stamford, CT 06904
44. K. L. Black, Department E452, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
45. R. Botwin, C47-05, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
46. W. B. Briggs, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
47. G. Bronner, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
48. J. N. Brooks, FPP/207, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
49. S. C. Burnett, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
50. J. D. Callen, Department of Nuclear Engineering, University of Wisconsin, Madison, WI 53706
51. V. S. Chan, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
52. R. G. Clemmer, Fusion Power Program, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
53. D. R. Cohn, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
54. W. S. Cooper, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720
55. J. W. Coursen, C36-05, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
56. R. W. Conn, School of Chemical, Nuclear, and Thermal Engineering, Boelter Hall, University of California, Los Angeles, CA 90024
57. J. G. Crocker, EG&G Idaho, P.O. Box 1625, Idaho Falls, ID 83401
58. A. E. Dabiri, Energy Systems and Conservation Division, Science Applications, Inc., P.O. Box 2351, La Jolla, CA 92038
59. C. C. Damm, L-441, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
60. R. C. Davidson, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139
61. N. A. Davies, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
62. J. W. Davis, E457, Building 81/1/B7, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
63. M. J. Davis, Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185
64. S. O. Dean, Director, Fusion Energy Development, Science Applications, Inc., 2 Professional Drive, Suite 249, Gaithersburg, MD 20760
65. J. F. Decker, Office of Fusion Energy, Department of Energy, Mail Stop G-256, Washington, DC 20545
66. D. DeFreece, E451, Building 81/1/B7, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
67. A. Deitz, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544

68. D. A. Dingee, Program Manager, Fusion Technology, Pacific Northwest Laboratories, Battelle Boulevard, Richland, WA 99352
69. J. N. Doggett, L-441, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
70. H. Dreicer, Division Leader, CRT, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
71. D. Ehst, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
72. G. A. Eliseev, I. V. Kurchatov Institute of Atomic Energy, P.O. Box 3402, 123182 Moscow, U.S.S.R.
73. W. R. Ellis, Office of Fusion Energy, Department of Energy, Mail Stop G-256, Washington, DC 20545
74. B. A. Engholm, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
75. H. P. Eubank, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
76. F. Farfaletti-Casali, Engineering Division, Joint Research Center, Ispra Establishment, 21020 Ispra (Varese), Italy
77. J. J. Ferrante, Manager, Building 36-241, Large Superconducting Program, General Electric Company, 1 River Road, Schenectady, NY 12345
78. J. File, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
79. P. A. Finn, Fusion Power Program, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
80. H. K. Forsen, Bechtel Group, Inc., Research & Engineering, P.O. Box 3965, San Francisco, CA 94119
81. J. S. Foster, Jr., Building R4-2004, TRW Defense and Space Systems, 1 Space Park, Redondo Beach, CA 90278
82. T. K. Fowler, Associate Director for MFE, L-436, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
83. J. W. French, EBASCO Services, Inc., Forrestal Campus, CN-59, Princeton University, Princeton, NJ 08544
84. H. P. Furth, Director, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
85. J. G. Gavin, Jr., President, A01-11, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
86. G. Gibson, Westinghouse Electric Corporation, Fusion Power Systems Department, P.O. Box 10864, Pittsburgh, PA 15236
87. J. R. Gilleland, Manager, Fusion Project, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
88. V. A. Glukhikh, Scientific-Research Institute of Electro-Physical Apparatus, 188631 Leningrad, U.S.S.R.
89. M. Y. Gohar, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
90. W. D. Goins, Tennessee Valley Authority, 1300 Commerce Union Bank Building, Chattanooga, TN 37401
91. D. A. Goldberg, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720
92. R. Goldston, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544

93. M. B. Gottlieb, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
94. R. W. Gould, Department of Applied Physics, California Institute of Technology, Pasadena, CA 91109
95. M. W. Griffin, Department E236, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
96. C. R. Head, Office of Fusion Energy, Department of Energy, Mail Stop G-256, Washington, DC 20545
97. W. Heinz, Institut für Technische Physik, Kernforschungszentrum Karlsruhe GmbH, Postfach 3640, 7500 Karlsruhe 1, Federal Republic of Germany
98. C. D. Henning, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
99. G. K. Hess, Office of Fusion Energy, Department of Energy, Mail Stop ER-701, Washington, DC 20545
100. T. Hiraoka, JT-60 Project Office I, Japan Atomic Energy Research Institute, Tokai Research Establishment, Tokai, Ibaraki, Japan
101. R. L. Hirsch, Manager, Synthetic Fuels Research, Exxon Research and Engineering Company, P.O. Box 4255, Baytown, TX 77520
102. J. J. Holmes, Westinghouse-Hanford Engineering Development Laboratory, P.O. Box 1970, Richland, WA 99352
103. W. G. Homeyer, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
104. J. C. Hosea, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
105. D. Hwang, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
106. G. J. Inukai, Department E231, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
107. D. L. Jassby, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
108. J. B. Joyce, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
109. R. A. Krakowski, CTR-12, Mail Stop 641, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
110. G. L. Kulcinski, University of Wisconsin, Department of Nuclear Engineering, Engineering Research Building, Room 439, 1500 Johnson Drive, Madison, WI 53706
111. D. L. Kummer, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
112. T. S. Latham, Mail Stop 44, United Technologies Research Center, Silver Lane, East Hartford, CT 06108
113. L. R. Ledman, Office of Fusion Energy, Department of Energy, Mail Stop G-256, Washington, DC 20545
114. L. M. Lidsky, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
115. C. S. Liu, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
116. E. F. Lowell, General Manager, Energy Systems Programs Department, Building 2-455, General Electric Company, 1 River Road, Schenectady, NY 12345
117. D. J. McFarlin, Mail Stop 44, United Technologies Research Center, Silver Lane, East Hartford, CT 06108

118. R. McGrath, Fusion Power Program, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
119. V. A. Maroni, CEN/205, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
120. W. Marton, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
121. L. G. Masson, EG&G Idaho, Idaho National Engineering Laboratory, P.O. Box 1625, Idaho Falls, ID 83401
122. D. G. McAlees, Exxon Nuclear Company, Inc., 777 106th Avenue, NE, Bellevue, WA 98009
123. D. M. Meade, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
124. A. T. Mense, Building 107, Post B2, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
125. L. Michaels, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
126. D. Mikkelsen, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
127. R. L. Miller, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
128. R. G. Mills, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
129. J. T. D. Mitchell, Culham Laboratory, Abingdon, Oxfordshire OX 3DB, United Kingdom
130. R. W. Moir, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
131. D. B. Montgomery, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
132. K. Moses, R-1/1078, TRW Defense and Space Systems, 1 Space Park, Redondo Beach, CA 90278
133. R. E. Muller, Aerojet Manufacturing Company, P.O. Box 4210, Fullerton, CA 92934
134. A. E. Munier, Grumman Aerospace Company, P.O. Box 31, Bethpage, NY 11714
135. M. R. Murphy, Office of Fusion Energy, Department of Energy, Mail Station G-256, Washington, DC 20545
136. R. E. Nygren, FPP/207, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
137. T. Ohkawa, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
138. M. Okabayashi, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
139. D. Overskei, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
140. R. R. Parker, Francis Bitter National Magnet Laboratory, 170 Albany Street, Cambridge, MA 02139
141. B. Pease, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, United Kingdom
142. M. Pelovitz, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
143. F. W. Perkins, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544

144. M. Petravic, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
145. M. Porkolab, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139
146. D. E. Post, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
147. L. K. Price, Department of Energy, Oak Ridge Operations, P.O. Box E, Oak Ridge, TN 37830
148. R. E. Price, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
149. D. H. Priestler, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, Department of Energy, Washington, DC 20545
150. F. A. Puhn, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
151. J. Purcell, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
152. R. V. Pyle, University of California, Lawrence Berkeley Laboratory, Berkeley, CA 94720
153. J. M. Rawls, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
154. P. J. Reardon, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
155. M. Roberts, Office of Fusion Energy, Department of Energy, Mail Stop G-256, Washington, DC 20545
156. J. D. Rogers, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
157. F. L. Robinson, Tennessee Valley Authority, 1300 Commerce Bank Building, Chattanooga, TN 37401
158. M. L. Rogers, Monsanto Research Corporation, Mound Laboratory Facility, P.O. Box 32, Miamisburg, OH 45342
159. M. N. Rosenbluth, RLM 11.218, Institute for Fusion Studies, University of Texas, Austin, TX 78712
160. L. Ruby, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720
161. P. H. Rutherford, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
162. D. D. Ryutov, Institute of Nuclear Physics, Siberian Branch of the Academy of Sciences of the U.S.S.R., Sovetskaya St. 5, 630090 Novosibirsk, U.S.S.R.
163. M. M. Sabado, EBASCO Services, Inc., A Site, Building 1-A, Forrestal Campus, Princeton, NJ 08544
164. J. A. Schmidt, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
165. J. Schultz, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
166. F. R. Scott, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94304
167. G. Sheffield, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
168. C. E. Singer, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544

169. T. J. M. Sluyters, Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973
170. D. Smith, Materials Science Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
171. G. E. Smith, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
172. R. I. Smith, Board Chairman, Public Service Electric and Gas Company, 80 Park Place, Newark, NJ 07101
173. L. Soroka, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720
174. L. Southworth, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
175. I. Spighel, Lebedev Physical Institute, Leninsky Prospect 53, 117924 Moscow, U.S.S.R.
176. W. M. Stacey, Jr., Georgia Institute of Technology, School of Nuclear Engineering, Atlanta, GA 30332
177. D. Steiner, Rensselaer Polytechnic Institute, Nuclear Engineering Department, NES Building, Tibbits Avenue, Troy, NY 12181
178. E. Stern, Grumman Aerospace Corporation, CN-59, Forrestal Campus, Princeton, NJ 08544
179. L. D. Stewart, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
180. W. Stodiek, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
181. P. M. Stone, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, U.S. Department of Energy, Washington, DC 20545
182. I. N. Sviatoslavsky, Room 33, Engineering Research Building, 1500 Johnson Drive, University of Wisconsin, Madison, WI 53706
183. T. Tamano, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
184. R. E. Tatro, Manager, Energy Systems, M.Z. 16-1070, General Dynamics-Convair Division, P.O. Box 80847, San Diego, CA 92138
185. F. Tenney, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
186. F. Thomas, B-20-5, Grumman Aerospace Corporation, Bethpage, NY 11714
187. K. I. Thomassen, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
188. R. J. Thome, Francis Bitter National Magnet Laboratory, 170 Albany Street, Cambridge, MA 02139
189. S. L. Thomson, Bechtel Group, Inc., P.O. Box 3965, San Francisco, CA 94119
190. V. T. Tolok, Kharkov Physical-Technical Institute, Academical St. 1, 310108 Kharkov, U.S.S.R.
191. C. Trachsel, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
192. J. R. Treglio, General Dynamics-Convair Division, P.O. Box 80847, San Diego, CA 92138
193. A. W. Trivelpiece, Office of Fusion Energy, Office of Energy Research, Mail Station G-256, Department of Energy, Washington, DC 20545
194. L. R. Turner, Fusion Power Program, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439

195. M. A. Ulrickson, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
196. E. H. Valeo, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
197. T. C. Varljen, Westinghouse Electric Corporation, P.O. Box 10864, Pittsburgh, PA 15236
198. R. Varma, Physical Research Laboratory, Navrangpura, Ahmedabad, India
199. H. F. Vogel, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
200. A. Wait, Building 36-421, General Electric Company, 1 River Road, Schenectady, NY 12345
201. K. E. Wakefield, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
202. D. Weldon, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
203. J. C. Wesley, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
204. S. Whitley, Tennessee Valley Authority, 1300 Commerce Bank Building, Chattanooga, TN 37401
205. W. R. Wilkes, Monsanto Research Corporation, Mound Laboratory Facility, P.O. Box 32, Miamisburg, OH 45342
206. J. E. Wilkins, EG&G Idaho, Idaho National Engineering Laboratory, P.O. Box 1625, Idaho Falls, ID 83401
207. H. Willenberg, Mathematical Sciences Northwest, Inc., P.O. Box 1887, Bellevue, WA 98009
208. J. E. C. Williams, Francis Bitter National Magnet Laboratory, 170 Albany Street, Cambridge, MA 02139
209. P. Willis, Building 23, Room 298, General Electric Company, 1 River Road, Schenectady, NY 12345
210. T. F. Yang, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
211. H. H. Yoshikawa, W/A-62, Hanford Engineering Development Laboratory, P.O. Box 1970, Richland, WA 99352
212. K. M. Young, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
213. N. E. Young, EBASCO Services, Inc., Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
214. K. M. Zwilsky, National Materials Advisory Board, National Academy of Sciences, 2101 Constitution Avenue NW, Washington, DC 20418
215. Bibliothek, Max-Planck Institut fur Plasmaphysik, D-8046 Garching bei Munchen, Federal Republic of Germany
216. Bibliothek, Institut fur Plasmaphysik, KFA, Postfach 1913, D-5170 Julich, Federal Republic of Germany
217. Bibliotheque, Centre de Recherches en Physique des Plasmas, 21 Avenue des Bains, 1007 Lausanne, Switzerland
218. Bibliotheque, Service du Confinement des Plasmas, CEA, B.P. No. 6, 92 Fontenay-aux-Roses (Seine), France
219. Documentation S.I.G.N., Departement de la Physique due Plasma et de la Fusion Controlee, Association EURATOM-CEA, Centre d'Etudes Nucleaires, B.P. 85, Centre du Tri, 38041 Grenoble, Cedex, France

- 220. Library, Culham Laboratory, UKAEA, Abingdon, Oxfordshire OX14 3DB, England
- 221. Library, FOM Instituut voor Plasma-Fysica, Rijnhuizen, Jutphaas, Netherlands
- 222. Library, Institute of Physics, Academia Sinica, Beijing, Peoples Republic of China
- 223. Library, Institute for Plasma Physics, Nagoya University, Nagoya 464, Japan
- 224. Library, International Centre for Theoretical Physics, Trieste, Italy
- 225. Library, JET Joint Undertaking, Abingdon, Oxfordshire, OX14, DB, England
- 226. Library, Laboratoria Gas Ionizzati, Frascati, Italy
- 227. Plasma Research Laboratory, Australian National University, P.O. Box 4, Canberra, ACT 2000, Australia
- 228. Thermonuclear Library, Japan Atomic Energy Research Institute, Tokai, Naka, Ibaraki, Japan
- 229. Library, Plasma Physics Laboratory, Kyoto University, Gokasho Uji, Kyoto, Japan
- 230. Office of the Assistant Manager for Energy Research and Development, Department of Energy, Oak Ridge Operations, Oak Ridge, TN 37830
- 231-426. Given distribution as shown in TID-4500, Magnetic Fusion Energy, (Distribution Category UC-20 c,d: Reactor Materials and Fusion Systems)