181
6-5-78

Ch. 127

ORNL/TM-6339

Comments on the Effects of Gas Injection Upon Radial Particle Fluxes in the ISX-A Flow Reversal Experiment

W. M. Stacey, Jr.
D. J. Sigmar

MASTER

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION · FOR THE DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$4.50 ; Microfiche \$3.00

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, contractors, subcontractors, or their employees, makes any warranty, express or implied, nor assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product or process disclosed in this report, nor represents that its use by such third party would not infringe privately owned rights.

Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

COMMENTS ON THE EFFECTS OF GAS INJECTION UPON RADIAL PARTICLE
FLUXES IN THE ISX-A FLOW REVERSAL EXPERIMENT

W. M. Stacey, Jr.
School of Nuclear Engineering, Georgia Institute of Technology
Atlanta, Georgia

and

D. J. Sigmar
On leave of absence from Massachusetts Institute of Technology

Date Published - May, 1978

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 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or 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.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

CONTENTS

ABSTRACT	v
INTRODUCTION	1
GENERAL CONSIDERATIONS	1
ISX-A FLOW REVERSAL EXPERIMENT	6
SUMMARY	14
REFERENCES	15

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

A recently formulated theory about the effects of sources upon particle transport in the collisional regime is applied to estimate the magnitude of effects which would be expected in the ISX-A flow reversal experiment.

INTRODUCTION

In the collisional, or Pfirsch-Schlüter, regime of neoclassical transport theory, the ∇B and curvature drifts tend to cause a charge separation, and flows are set up in the flux surface to prevent this charge separation. These poloidal flows result in a parallel collisional momentum exchange which drives radial particle fluxes. The theory for a two-species plasma has been worked out by Rutherford.¹ Ohkawa has suggested that the poloidal flows can be modified by particle (and heat) sources, thus altering the radial particle fluxes and providing a means of impurity control. Burrell² has worked out the theory for this poloidal asymmetry effect, and it has recently been investigated in the ISX-A (Impurity Studies Experiment) flow reversal experiments. Introduction of a particle source also results in the introduction of a parallel momentum source (or sink), and the parallel momentum exchange between the source and the plasma drives a radial particle flux in the same manner as does the parallel collisional momentum exchange between different plasma species. The theory for this parallel momentum exchange effect has been worked out by Stacey.³

The magnitudes of each of these two source effects have been estimated for the ISX-A flow reversal experiments. In addition, the conditions under which the two effects reinforce or oppose each other have been established.

GENERAL CONSIDERATIONS

The expressions for flux-surface averaged radial particle fluxes given in Ref. 3 are:

$$\begin{aligned}
\Gamma_{ir} = & - \frac{2\epsilon^2 n_i m_i v_{iz}}{(eB_\theta^0)^2} \left\{ \left[\left(c_1 + \frac{c_2^2}{c_3} \right) \left(\frac{1}{n_i} \frac{\partial p_i}{\partial r} - \frac{1}{zn_z} \frac{\partial p_z}{\partial r} \right) - \frac{5}{2} \frac{c_2}{c_3} \frac{\partial T_i}{\partial r} \right] \right. \\
& + \frac{1}{2} R_0 eB^0 \left[\left(c_1 + \frac{c_2^2}{c_3} \right) \left(\frac{a_{in}}{n_i} - \frac{a_{zn}}{n_z} \right) - \frac{c_2}{c_3} \frac{a_{iT}}{n_i T_i} \right] \left. \right\} \\
& - \frac{2\epsilon}{cB_\theta^0} \langle \xi_{i\parallel} n_i v_{i\parallel} \rangle \cos \theta, \quad (1)
\end{aligned}$$

$$\begin{aligned}
\Gamma_{zr} = & \frac{2\epsilon^2 n_i m_i v_{iz}}{z(eB_\theta^0)^2} \left\{ \left[\left(c_1 + \frac{c_2^2}{c_3} \right) \left(\frac{1}{n_i} \frac{\partial p_i}{\partial r} - \frac{1}{zn_z} \frac{\partial p_z}{\partial r} \right) - \frac{5}{2} \frac{c_2}{c_3} \frac{\partial T_i}{\partial r} \right] \right. \\
& + \frac{1}{2} R_0 eB^0 \left[\left(c_1 + \frac{c_2^2}{c_3} \right) \left(\frac{a_{in}}{n_i} - \frac{a_{zn}}{n_z} \right) - \frac{c_2}{c_3} \frac{a_{iT}}{n_i T_i} \right] \left. \right\} \\
& - \frac{2\epsilon}{zeB_\theta^0} \langle \xi_{z\parallel} n_z v_{z\parallel} \rangle \cos \theta. \quad (2)
\end{aligned}$$

The nomenclature is defined in Ref. 3, and the coordinate system is given in Fig. 1.

These expressions are for a two-component (ion-impurity) plasma transport model as suggested by Rutherford,¹ and the first bracketed term in each equation corresponds to his result. Burrell² extended Rutherford's work to include the effect of spatially asymmetric — in the poloidal variable — sources. The second bracketed term in each equation is Burrell's result — a_{in} , a_{zn} , and a_{iT} are the $\sin \theta$ components of the respective particle (in, zn) and heat (iT) sources. The last term in each equation is the parallel source momentum transfer term introduced by Stacey,³

$$\langle \xi_{i\parallel} n_i v_{i\parallel} \rangle \cos \theta \equiv m_i \int_0^{2\pi} S_i(\theta) \cos \theta \left\{ \int \vec{v} [g_i(\vec{v}) - f_i(\vec{v})] d^3v \right\}_\parallel d\theta, \quad (3)$$

ORNL/DWG/FED-78-286

Fig. 1. Coordinate system.

and a similar definition is introduced for the impurity term. Here $g_i(\vec{v})$ is the velocity distribution of the source of plasma ions and $f_i(\vec{v})$ is the velocity distribution of the bulk plasma ions. The parallel component of the first moment of these distributions enters Eq. (3). [Terms similar to Eq. (3) but involving the radial component of the first moment have been dropped in writing Eqs. (1) and (2) because their magnitude is estimated to be small.] The quantity S_i is the source strength.

We can estimate the magnitude of the last term in Eq. (1) for the case in which the source has no net parallel momentum,

$$\left[\int \vec{v} g_i(\vec{v}) d^3v \right]_{\parallel} = 0, \quad (4)$$

so that

$$\langle \xi_{i\parallel} n_i v_{i\parallel} \rangle_{\cos} \equiv - \frac{m_i}{2\pi} \int_0^{2\pi} \cos \theta S_i(\theta) v_{i\parallel} d\theta.$$

Using the relation

$$v_{i\parallel} \approx v_{i\phi} \approx - \frac{2\epsilon \cos \theta}{eB_{\theta}^0} \left(\frac{1}{n_i} \frac{\partial p_i}{\partial r} - eE_r \right), \quad (5)$$

and neglecting the radial electric field,

$$\left| \frac{2\epsilon}{eB_{\theta}^0} \langle \xi_{i\parallel} n_i v_{i\parallel} \rangle_{\cos} \right| \approx \left| \frac{2\epsilon^2 m_i S_i}{(eB_{\theta}^0)^2} \frac{1}{n_i} \frac{\partial p_i}{\partial r} \right|,$$

from which we conclude that the relative magnitude of the last-to-first terms in Eq. (1) is

$$R_{\parallel}/PS \approx \frac{S_i}{n_i v_{iz}}. \quad (6)$$

If the source of ions arises from charge exchange and ionization of injected gas, then Eq. (6) becomes

$$R_{\parallel}/PS = \frac{n_b (\langle \sigma_{cx} v \rangle + \langle \sigma_{ion} v \rangle)}{\alpha v_{ii}}, \quad (7)$$

where $\alpha \equiv (n_z z^2/n_i)$, v_{ii} is the ion-ion collision frequency, n_b is the injected gas ionization source density, n_z is the impurity ion density, and $\langle \sigma_{cx} v \rangle$ and $\langle \sigma_{ion} v \rangle$ are the charge exchange and ionization reaction rates between gas atoms and plasma ions, respectively.

The relative magnitudes of the parallel and poloidal effects can be evaluated by estimating the ratio of the third-to-second terms in Eq. (1), limiting our attention to ion particle sources for this purpose,

$$R_{\parallel}/\theta \approx \frac{\left| S_i \frac{1}{n_i} \frac{\partial p_i}{\partial r} \right|}{\left| \frac{1}{2} v_{iz} R_0 e B_0 a_{in} \right|}. \quad (8)$$

We have made use of the approximations that led to Eq. (6) and assumed a source velocity distribution that satisfied Eq. (4) in order to arrive at Eq. (8).

Finally, the relative magnitudes of the poloidal asymmetry and the collisional momentum exchange terms in the equation for the radial impurity flux and the ion flux can be estimated from the ratio of the second-to-first terms in Eq. (1) or (2).

$$R_{\theta/PS} \approx \left| \frac{\frac{1}{2} R_0 e B^0 a_{in}}{\frac{\partial p_i}{\partial r}} \right|. \quad (9)$$

ISX-A FLOW REVERSAL EXPERIMENT

As a specific example, the flow reversal experiment in ISX is considered. A nominal set of parameters chosen to represent this experiment is shown in Table 1. In this experiment, a source of hydrogen gas is introduced at the bottom of the torus ($\theta = 3\pi/2$) through a large number of openings spaced around the torus. This gas source varied up to 200 torr $\times$ l/s, which reduces to a maximum source rate of 6.6×10^{21} molecules, or 1.22×10^{22} atoms, per second entering into the chamber. Assuming that only $\sim 1/4$ of these get into the plasma, we can represent the neutral gas source as⁴

$$s = c \times 10^{21}/\text{sec} \quad , \quad c < 3-4 \quad .$$

Table 1. ISX-A Nominal Parameters (Flow Reversal Experiment)

Major radius, R	0.92 m
Plasma radius, a	0.26 m
Average density, $\bar{n}$	$1 \times 10^{19} \text{ m}^{-3}$
Temperature	See Fig. 2
Plasma current, I	123 kA
Toroidal field, B^0	15 kG

In order to estimate the magnitude of the source effects upon particle transport, Eqs. (6)-(8) are evaluated at the plasma boundary ($r = 26$ cm) and at one mean free path (mfp) (for the injected gas) into the plasma. The injected gas source is translated into a uniform flux over the lower half of the plasma surface ($\pi < \theta < 2\pi$)

$$\Gamma_b^0 = \frac{c \times 10^{21}}{2\pi^2 a R},$$

and the neutral density at one mfp into the plasma is

$$n_b = \frac{e^{-1} \Gamma_b^0}{V_b} = e^{-1} n_b.$$

Combining these results and evaluating V_b at 3 eV,

$$n_b = 3.28 \text{ c} \times 10^{15} \text{ m}^{-3}. \quad (10)$$

We estimate the plasma density and temperature and the pressure gradient directly from the experimental data shown in Fig. 2. We use the electron temperature because the ion temperature is not accurately known. The pressure gradient is estimated from the intervals 15 cm to 20 cm and 20 cm to 26 cm for regions 1 mfp from the boundary and at the boundary, respectively. We estimate that one mean free path into the plasma is 10 cm to 15 cm. Our values for the parameters which enter our calculations are given in Table 2.

Using the values in Table 2, Eq. (7) yields

$$R_{||}/PS = \begin{cases} 2.05 \times 10^{-2} \left(\frac{c}{\alpha}\right), & \text{boundary} \\ 4.69 \times 10^{-2} \left(\frac{c}{\alpha}\right), & 1 \text{ mfp} \end{cases} \quad (11)$$

Now we examine the poloidal asymmetry term. The poloidal dependence of the ion source due to neutral gas interactions with the plasma is assumed to have a $\sin \theta$ distribution in the lower half of the torus,

ORNL/DWG/FED-78-173

COUNTERCLOCKWISE

DATE: 2-14-78

SEQUENCE: 02148 T. CIX

 $t = 40 \text{ msec}$ $I = 123.11 \pm 0.32 \text{ kA}$ $B_T = 15.05 \pm 0.26 \text{ kG}$ $\bar{n}_e = (1.05 \pm 0.23) \times 10^{13} \text{ cm}^{-3}$ $V = 1.45 \pm 0.13 \text{ V}$

Fig. 2. ISX-A temperature and density profiles.

Table 2. Parameters Used in Evaluating ISX-A Flow Reversal Experiment

Quantity	Units	Boundary	1 mfp into Plasma
n	m^{-3}	$2 \times 10^{18} = 1/5 \bar{n}$	$5 \times 10^{18} = 1/2 \bar{n}$
T	eV	25	100
n_b	m^{-3}	$8.9 \times 10^{15} \quad c = n_b^0$	$3.28 \times 10^{15} \quad c = e^{-1} n_b^0$
$\langle \sigma_{cx} v \rangle + \langle \sigma_{ion} v \rangle$	m^3/s	3×10^{-14}	6×10^{-14}
v_{ii}	s	1.3×10^4	4.2×10^3
$\frac{2}{R_0 e B^0} \frac{\partial P}{\partial r}$	m^{-3}/s	1.9×10^{21}	1.2×10^{22}

$$S_i(r, \theta) = \begin{cases} -S_i^0(r) \sin \theta, & \pi < \theta < 2\pi \\ 0 & , \quad 0 < \theta < \pi \end{cases} \quad (12)$$

The term a_{in} is the $\sin \theta$ component of the source,

$$a_{in} = \frac{1}{\pi} \int_0^{2\pi} S_i(\theta) \sin \theta \, d\theta = -\frac{S_i^0}{\pi} \int_{\pi}^{2\pi} \sin^2 \theta \, d\theta = -\frac{S_i^0}{2} \quad (13)$$

Thus Eq. (8) yields

$$R_{||/\theta} = \frac{\left| \frac{2}{R_0 e B^0} \frac{\partial p_i}{\partial r} \right|}{2n_i \alpha v_{ii}} \quad (14)$$

Using the values from Table 2, this becomes

$$R_{||/\theta} \approx \begin{cases} 0.29/\alpha, & 1 \text{ mfp} \\ 0.036/\alpha, & \text{boundary} \end{cases} \quad (15)$$

The magnitude of the poloidal asymmetry effect relative to the collisional momentum exchange can be evaluated by using Eq. (13) in Eq. (9)

$$R_{\theta/PS} = \frac{\frac{1}{2} n_i n_b (\langle \sigma_{cx} v \rangle + \langle \sigma_{ion} v \rangle)}{\frac{2}{R_0 e B^0} \frac{\partial p_i}{\partial r}} \quad (16)$$

and using the values in Table 2

$$R_{\theta/PS} = \begin{cases} 1.4 \times 10^{-1} c, & \text{boundary} \\ 4.1 \times 10^{-2} c, & 1 \text{ mfp} \end{cases} \quad (17)$$

Thus, Eqs. (11), (15), and (17) provide estimates of the relative effects in ISX-A as a function of the gas injection source ($S = c \times 10^{21}$ atoms/sec) and the impurity parameter, $\alpha = n_z z^2 / n_i$.

For the neon experiment in ISX-A, 20 torr · l/s of neon was injected for 0.2 ms.⁴ Taking into account the uncertainty of how much neon gets into the plasma and how it is distributed, the value of α can be estimated as

$$0.1 < \alpha < 0.5 \quad (18)$$

Taking $c = 3$ as a plausible upper limit on the gas getting into the plasma, we evaluate Eqs. (11) and (17) for $\alpha = 0.2$ and $\alpha = 0.5$. The results are shown in Table 3.

From these estimates, we conclude that: 1. the parallel momentum exchange between the source and the plasma is comparable to the collisional momentum exchange in affecting ion radial fluxes over a significant outer region, and 2. the poloidal asymmetry effect on ion and impurity fluxes is only significant in a small region at the boundary. The parallel momentum transfer from the incident neutrals to the plasma ions directly affects the radial plasma ion flux, which in turn affects the

plasma pressure profile, thus indirectly affecting the impurity flux. Although it is not possible to make a quantitative estimate of this indirect effect, we infer from Table 3 that the parallel momentum transfer effect may be comparable to the poloidal asymmetry effect of the source upon the impurity flux.

Table 3. Ratio of Parallel and Poloidal "Source-Driven" Radial Fluxes to Pfirsch-Schlüter Radial Flux at Two Locations in the ISX-A Flow Reversal Equipment^a

	Boundary	1 mfp into plasma
<u>$\alpha = 0.2$</u>		
$R_{\parallel}/PS$	0.31	0.70
R_{θ}/PS	0.42	0.12
<u>$\alpha = 0.5$</u>		
$R_{\parallel}/PS$	0.12	0.28
R_{θ}/PS	0.42	0.12

^a $R_{\parallel}/PS$ refers to the ion flux, while R_{θ}/PS refers to the ion and impurity fluxes.

A number of assumptions have been made in the preceding analysis. We have used an ion-impurity plasma model. This is probably valid as long as the ion-impurity collisional momentum exchange exceeds the ion-electron collisional momentum exchange (i.e., $|R_{iz}| > |R_{ie}|$) which is the case when $\alpha > c_1 \sqrt{m_e/m_i}$, where $c_1 > 1$ is an anomaly factor associated with the fact that particle transport in tokamaks is greater than is predicted on the basis of neoclassical collisional theory. Our plasma model is probably appropriate, on this count, for $c_1 \leq 10$.

A second assumption concerns the relation, Eq. (5), used for the parallel ion velocity. This expression is derivable from the radial

momentum balance to lowest order in ϵ . (See Ref. 5 for a general discussion.) We ignored the radial electric field in Eq. (5). This field is not accurately known in ISX-A. In comparable tokamaks this neglect would amount at most to an order unity enhancement of the parallel velocity. Thus, by ignoring E_r we are underestimating the magnitude of the parallel momentum transfer effect of the source injection.

We have based our estimates on parameters evaluated at one mean free path for neutral gas into the plasma and at the boundary. Actually, the gas source affects the transport within an interval extending from the edge of the plasma to a few mfp inside, and the relevant parameters vary appreciably over this interval. However, local evaluation of the various effects on representative flux surfaces, using inasmuch as possible experimentally obtained values, should serve to identify the relative magnitudes of these effects.

Since it is apparent that the parallel momentum transfer and poloidal asymmetry effects are both present in the ISX experiment, it is important to establish whether the two effects are additive or compensatory. For gas injection from the bottom of the torus with no preferred parallel direction, Eq. (4) is satisfied, and the expressions following Eq. (4) can be used to estimate the parallel momentum transfer term. For this purpose, we assume that the poloidal dependence of the ion source due to neutral gas interactions with the plasma has a $\sin \theta$ distribution in the lower half of the torus, as given by Eq. (12), and that the plasma ion pressure gradient is negative (i.e., the pressure decreases from the center out). Then we may estimate

$$\begin{aligned} \frac{2\epsilon}{eB_\theta^0} \langle \xi_{i||} n_i v_{i||} \rangle \cos \approx & \frac{m_i S_i^0}{2\pi} \left(\frac{2\epsilon}{eB_\theta^0} \right)^2 \left| \frac{1}{n_i} \frac{\partial p_i}{\partial r} \right| \int_{\pi}^{2\pi} \sin \theta \cos^2 \theta d\theta \\ & = - \frac{2}{3} \frac{S_i^0 2\epsilon^2}{\pi (eB_\theta^0)^2} \left| \frac{1}{n_i} \frac{\partial p_i}{\partial r} \right| < 0 . \quad (19) \end{aligned}$$

This term enters Eq. (1) with a minus sign so that the effect of the parallel momentum transfer is a positive contribution to Γ_{ir} . This enhancement of the outward ion flux will act to flatten the ion pressure profile, which has the effect of making a negative term in Eq. (2) smaller, thus tending to enhance the outward impurity flux. This result depends only upon the location of the gas source [Eq. (12)] and not upon the direction of the toroidal field, so it is insensitive to field reversal.

Now we examine the poloidal asymmetry terms. Since there is no heat source and no impurity source, $a_{zn} = a_{iT} = 0$ in Eqs. (1) and (2). The term a_{in} is given by Eq. (15). It enters Eq. (1) with a minus sign when the toroidal field is in the clockwise direction shown in Fig. 1 ($B^0 > 0$), and a_{in} enters Eq. (1) with a plus sign when the toroidal field is in the counterclockwise direction ($B^0 < 0$). The term a_{in} enters Eq. (2) with the opposite sign. Thus, for a clockwise toroidal field, the poloidal asymmetry effect enhances the radial outward ion flux and enhances the radial inward impurity flux. Just the opposite effect is obtained when the toroidal field is in the counterclockwise direction. These qualitative effects are summarized in Table 4.

Table 4. Particle Source Effects upon Radial Particle Fluxes in ISX-A

	<u>Case 1</u>	<u>Case 2</u>
	Clockwise toroidal field ^a	Counterclockwise toroidal field
Parallel momentum transfer	Drives plasma ions outward Drives impurity ions outward	Drives plasma ions outward Drives impurity ions outward
Poloidal asymmetry	Drives plasma ions outward Drives impurity ions inward	Drives plasma ions inward Drives impurity ions outward

^aAs shown in Fig. 1.

SUMMARY

Injection of hydrogen into ISX-A has (at least) two effects upon radial particle fluxes. The parallel momentum transfer between the injected gas and the plasma ions drives a radial ion flux. The poloidal asymmetry of the injected gas alters the radial ion and impurity fluxes by altering the poloidal flows in the flux surfaces. We have used experimental data to evaluate the theoretical estimates for the magnitude of these effects in the outer region of the ISX-A plasma. Our estimates are summarized in Table 3.

The parallel momentum transfer effect should enhance the outward flow of plasma ions above the Pfirsch-Schlüter flow. This enhancement should be on the order of 50% over the outer 10-15 cm of the plasma (and is actually larger at one mean free path into the plasma than at the boundary) and is independent of the direction of the toroidal magnetic field. This enhancement of the radial ion flux should indirectly affect the radial impurity flux by altering the radial pressure profile. (It also affects the ambipolar electric field, but we did not consider this.)

The poloidal asymmetry effect should affect the plasma ion and impurity flows with opposite sign, but in equal magnitude. This effect should be on the order of 50% only in the outermost 1-2 cm of the plasma and should decrease rapidly with distance into the plasma, being on the order of 10% at one mean free path into the plasma. This effect is dependent upon the direction of the toroidal magnetic field.

REFERENCES

1. P. H. Rutherford, Phys. Fluids 17(19), 1782 (1974).
2. K. H. Burrell, Phys. Fluids 19(3), 401 (1976).
3. W. M. Stacey, Jr., "The Effect of Sources Upon Collisional Transport in Tokamaks," Georgia Tech Report, GTFR-1 (1977), submitted to Phys. Fluids.
4. M. Murakami and K. H. Burrell, private communication (1978).
5. S. P. Hirshman, Phys. Fluids 19, 155 (1976).

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

ORNL/TM-6339
Dist. Category UC-20g

INTERNAL DISTRIBUTION

1. L. A. Berry	12. J. Sheffield
2. J. D. Callen	13. D. Steiner
3. R. A. Dandl	14-47. D. J. Sigmar
4. R. A. Dory	48-49. Laboratory Records Department
5. G. G. Kelley	50. Laboratory Records, ORNL-RC
6. H. H. Haselton	51. Document Reference Section
7. P. N. Haubenreich	52-53. Central Research Library
8. M. S. Lubell	54. Fusion Energy Division Library
9. O. B. Morgan	55. Fusion Energy Division
10. H. Postma	Communications Center
11. M. W. Rosenthal	56. ORNL Patent Office

EXTERNAL DISTRIBUTION

57. Bibliothek, Max-Planck Institute für Plasmaphysik, 8046 Garching bei München, Federal Republic of Germany
58. Bibliothèque, Service du Confinement des Plasmas, C.E.A., B.P. No. 6, 92, Fontenay-aux Roses (Seine), France
59. Lung Cheung, Department of Electronics, University Science Center, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong
60. J. F. Clarke, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
61. R. W. Conn, Fusion Technology Program, Nuclear Engineering Department, University of Wisconsin, Madison, WI 53706
62. CTR Library, c/o Alan F. Haught, United Technologies Research Laboratory, East Hartford, CT 06108
63. CTR Reading Room, c/o Allan N. Kaufman, Physics Department, University of California, Berkeley, CA 94720
64. J. Narl Davidson, School of Nuclear Engineering, Georgia Institute of Technology, Atlanta, GA 30332
65. Documentation S.I.G.N., Département de la Physique du Plasma et de la Fusion Contrôlée, Association EURATOM-CEA sur la Fusion, Centre d'Études Nucléaires, B.P. 85, Centre du TRI, 38041 Grenoble, Cedex, France
66. W. R. Ellis, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
67. Harold K. Forsen, Exxon Nuclear Co., Inc., 777 106th Avenue, N.E., C-000777, Bellevue, WA 98009
68. Harold P. Furth, Princeton Plasma Physics Laboratory, Princeton University, Forrestal Campus, P.O. Box 451, Princeton, NJ 08540
69. Roy W. Gould, California Institute of Technology, Mail Stop 116-81, Pasadena, CA 91125
70. Robert L. Hirsch, Exxon Research and Engineering, P.O. Box 101, Florham Park, NJ 07932

71. Raymond A. Huse, Manager, Research and Development, Public Service Gas and Electric Company, 80 Park Place, Newark, NJ 07101
72. T. Hsu, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
73. V. E. Ivanov, Physical-Technical Institute of the Ukrainian Academy of Sciences, Sukhumi, U.S.S.R.
74. A. Kadish, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
75. L. M. Kovrizhnikh, Lebedev Institute of Physics, Academy of Sciences of the U.S.S.R., Leninsky Prospect 53, Moscow, U.S.S.R.
76. Guy Laval, Groupe de Physique Théorique, Ecole Polytechnique, 91 Palaiseau, Paris, France
77. Library, Centre de Recherches en Physique des Plasma, 21 Avenue des Bains, 1007, Lausanne, Switzerland
78. Library, Culham Laboratory, United Kingdom Atomic Energy Authority, Abingdon, Oxon, OX14 3DB, United Kingdom
79. Library, FOM-Institut voor Plasma - Fysica, Rijnhuizen, Jutphaas, Netherlands
80. Library, Institute for Plasma Physics, Nagoya University, Nagoya, Japan 464
81. Library, International Centre for Theoretical Physics, Trieste, Italy
82. Library, Laboratorio Gas Ionizzati, Frascati, Italy
83. Dsumber G. Lominadze, Academy of Sciences of the Georgian S.S.R., 8 Dzerzhinski St., 38004, Tbilisi, U.S.S.R.
84. Oscar P. Manley, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
85. D. G. McAlees, Exxon Nuclear Co., Inc., Research and Technology Laser Enrichment Department, 2955 George Washington Way, Richland, WA 99352
86. J. E. McCune, School of Engineering, Department of Aeronautics and Astronautics, Bldg. 37-391, Massachusetts Institute of Technology, Cambridge, MA 02139
87. Claude Mercier, Service du Theorie des Plasmas, Centre d'Études Nucléaires, Fontenay-aux-Roses (Seine), France
88. K. G. Moses, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
89. D. Pfirsch, Institute for Plasma Physics, 8046 Garching bei München, Federal Republic of Germany
90. Plasma Physics Group, Department of Engineering Physics, Australian National University, P.O. Box 4, Canberra A.C.T. 2600, Australia
91. Robert E. Price, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
92. A. Rogister, Institute for Plasma Physics, KFA, Postfach 1913, D-5170, Jülich 1, Federal Republic of Germany
93. W. Sadowski, Office of Fusion Energy, G-234, Department of Energy, Washington, DC 20545
94. V. D. Shafranov, I. V. Kurchatov Institute of Atomic Energy, 46 Ulitsa Kurchatova, P.O. Box 3402, Moscow, U.S.S.R.

95. Yu. S. Sigov, Institute of Applied Mathematics of the U.S.S.R. Academy of Sciences, Miuskaya, Sq. 4, Moscow A-47, U.S.S.R.
96. W. M. Stacey, Jr., School of Nuclear Engineering, Georgia Institute of Technology, Atlanta, GA 30332
97. J. B. Taylor, Culham Laboratory, United Kingdom Atomic Energy Authority, Abingdon, Oxon, OX14 3DB, United Kingdom
98. Thermonuclear Library, Japan Atomic Energy Research Institute, Tokai, Naka, Ibaraki, Japan
99. Francisco Verdaguer, Director, Division of Fusion, Junta de Energia Nuclear, Madrid 3, Spain
100. Director, Research and Technical Support Division, Department of Energy, Oak Ridge Operations, P.O. Box E, Oak Ridge, TN 37830
- 101-276. Given distribution as shown in TID-4500, Magnetic Fusion Energy (Distribution Category UC-20g, Theoretical Plasma Physics)