MODELING OF HYDROCARBON FUELING

J. T. Hogan
A. Pospieszczyk
Fusion Energy Division

MODELING OF HYDROCARBON FUELING

J. T. Hogan

A. Pospieszczyk
Institut für Plasmaphysik, Kernforschungsanlage Jülich

Date Published: July 1990

Prepared for the
Office of Fusion Energy
Budget Activity No. AT 05

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400
CONTENTS

ABSTRACT ............................................. v

I. INTRODUCTION ..................................... 1

II. MODEL ............................................... 2

III. COMPARISON WITH EXPERIMENTS ..................... 6
    A. Setup of PISCES experiments ........................ 6
    B. Comparison ......................................... 7
    C. Discussion ......................................... 9

IV. APPLICATION TO PLASMA FUELING .................... 10

V. DISCUSSION ......................................... 12

REFERENCES .......................................... 13
ABSTRACT

We have compared a database of rate coefficients for CH$_4$ with experiments on PISCES-A to understand the role of carbon-based impurities in determining the fueling profile of carbon-dominated machines. A three-dimensional Monte Carlo model that embodies the Ehrhardt-Langer CH$_4$ breakup scheme (*Collisional Processes of Hydrocarbons on Hydrogen Plasmas*, PPPL-2477, Princeton Plasma Physics Laboratory, September 1987) has been developed. The model has been compared with spectroscopic observations of the spatial variation of the hydrocarbon product decay rates, and reasonable agreement has been found. The comparison is sensitive to the non-Maxwellian electron distribution and to observed spatial inhomogeneities in the electron density and temperature profiles. Applications of the model to parameters characteristic of the tokamak scrape-off layer are presented.
I. INTRODUCTION

Gas fueling in large tokamaks is mostly confined to a region within 10 cm of the last closed flux surface (compared with a plasma minor radius of 50 to 125 cm). However, tokamak confinement properties are strongly influenced by conditions in the edge plasma. In particular, a sharp change in the electron density gradient within a few centimeters of the edge, accompanied by a cessation of edge turbulence, appears to be a feature of the puzzling L-H transition that signals the beginning of significantly improved confinement during tokamak discharges. Theoretically, the edge value of the electron density gradient has been found to be an important variable in a number of turbulence models. Thus, knowledge of the details of the fueling process at the edge is important for understanding core transport.

Following the lead of the TEXTOR group, many fusion experimental groups have adopted "carbonization"\(^1\) of the plasma-facing components to enlarge the operating space and improve confinement properties. As a result, experiments are conducted with a plasma that is strongly dominated by carbon impurities. In such machines, studies have indicated the presence of hydrocarbon molecular species, and these are thought to play a significant role.\(^2\)

Thus, quantitative modeling of plasma fueling in carbon-dominated machines requires the construction of models for which molecular constituents such as CH\(_4\), C\(_2\)H\(_2\), and C\(_2\)H\(_4\) may be an important source of neutral hydrogen. However, the molecular data required for the construction of such models are very sketchy at present.

This situation has been surveyed by Ehrhardt and Langer,\(^3\) who have compiled a provisional database of reaction rates for CH\(_4\). The rates in this database are the core of our hydrocarbon fueling model. Many of the rates in the database are estimated by extrapolation from those of similar molecules, and the authors of ref. 3 stress the provisional nature of their compendium.

A series of experiments on hydrocarbon breakup under typical fusion edge plasma conditions has been conducted on the PISCES-A facility at the University of California, Los Angeles. Neutral molecules were injected along the magnetic field from a nozzle into the PISCES axial mirror plasma, and spectroscopic observations of the spatial variation of the densities of the breakup products of the influx jet of molecules were made.\(^4\) These experiments are the first to permit a detailed comparison of the Ehrhardt-Langer database with measurement.

We compare the predictions of the Ehrhardt-Langer database with the results of the PISCES-A experiments for CH\(_4\). The goal is to obtain a preliminary assessment of the validity of the rates for application to plasma modeling. The model is then applied to typical parameters of tokamak scrape-off layer plasmas.
II. MODEL

The major physical processes governing H\textsuperscript{0} penetration into tokamak plasmas have been established for some time.\textsuperscript{5–7} Reaction rates for electron impact dissociation and ionization and for charge exchange with plasma ions are embodied in multidimensional Monte Carlo codes to calculate the expected spatial distribution of H\textsuperscript{0} in the plasma. The models used to treat the H\textsuperscript{0} penetration process require a detailed description of the breakup of H\textsubscript{2}. The treatment needed for the CH\textsubscript{4} problem is generally similar, and this discussion focuses on those aspects which are novel for the treatment of the influx and breakup of the more complex hydrocarbon molecules in the plasma.

The most important new requirement is the need to follow the dynamics of intermediate ionized stages of the molecules, since some reaction channels have ionic products. Hence, the straight-line paths that form the basis of Monte Carlo models for H\textsuperscript{0} transport must be modified to allow for motion along a magnetic field line.

The Ehrhardt-Langer rates have been included in a three-dimensional (general geometry) neutrals Monte Carlo code (GEORGE), which follows the dynamics of influx neutrals in a static plasma background. The code was started by G. G. Kelley and is described in refs. 8 and 9. The code includes the reactions described in these papers and the additional reaction processes shown in Table I.

Only electron collision reactions have been considered, because of their dominance in the PISCES-A experiments. The p\textsuperscript{+} + CH\textsubscript{n} reactions described in ref. 5 were not included.

As discussed in ref. 3, most of the rates in the database are inferred from others. Table I presents a comparative description of these relations. As can be seen, only about a quarter of the rates (7 out of 25, as indicated by asterisks) are backed by direct measurement in the relevant energy range. The estimates for the others (particularly those for CH and CH\textsuperscript{+}) are indirect. Thus, accuracy within a factor of two is all that can be expected.

To treat complex reaction events in the Monte Carlo code, the rates are first grouped by molecular type and the chance of any kind of a collision event is evaluated. If a collision event occurs, then the type of event is evaluated within the subgroup of reactions for that type. For example, with an incident CH\textsubscript{4} molecule the weighted sum of the probabilities of the first three rates in Table I is evaluated and compared with a random number. If an event is probable, then these three rates are compared to each other separately to determine which output channel is followed.

As shown by Table I, an incoming CH\textsubscript{4} molecule can become CH\textsuperscript{+}, CH\textsubscript{3}, or CH\textsubscript{3}. The CH\textsubscript{3} will continue straight-line motion according to

\[ x_{\text{new}} = x_{\text{old}} + v_x \Delta t, \]
Table 1. Rate data (based on ref. 3)

<table>
<thead>
<tr>
<th>Rate</th>
<th>Reaction</th>
<th>Product</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>*R₁</td>
<td>e⁻ + CH₄</td>
<td>CH₄⁺ + 2e⁻</td>
<td>Measurement</td>
</tr>
<tr>
<td>*R₂</td>
<td>CH₃⁺ + H₀⁺ + 2e⁻</td>
<td></td>
<td>Measurement</td>
</tr>
<tr>
<td>*R₃</td>
<td>CH₃ + H₀⁺ + e⁻</td>
<td>Subtracts measured dissociative ionization from measured total cross section</td>
<td></td>
</tr>
<tr>
<td>R₄</td>
<td>e⁻ + CH₄⁺</td>
<td>CH₃ + H⁺ + e⁻</td>
<td>No measurement, R₄ = 1/4 R₁</td>
</tr>
<tr>
<td>R₅</td>
<td>CH₃⁺ + H₀⁺ + e⁻</td>
<td>No measurement, R₅ = 3/4 R₁</td>
<td></td>
</tr>
<tr>
<td>R₆</td>
<td>CH₃ + H₀³</td>
<td>Total R₆ + R₇ measured for E &lt; 1 eV, extrapolated for E &gt; 1 eV; R₆ = 1/4 Rₑxp</td>
<td></td>
</tr>
<tr>
<td>R₇</td>
<td>CH₂ + 2H₀⁺</td>
<td>As for R₆, R₇ = 3/4 Rₑxp</td>
<td></td>
</tr>
<tr>
<td>*R₈</td>
<td>e⁻ + CH₃⁺</td>
<td>CH₃⁺ + 2e⁻</td>
<td>CD₃ measurements extrapolated below &lt;15 eV</td>
</tr>
<tr>
<td>*R₉</td>
<td>CH₂⁺ + H₀⁺ + 2e⁻</td>
<td>From CD₃ measurements</td>
<td></td>
</tr>
<tr>
<td>R₁₀</td>
<td>CH₂ + H₀⁺ + e</td>
<td>No measurement, R₁₀ = 3/4 R₃</td>
<td></td>
</tr>
<tr>
<td>R₁₁</td>
<td>e⁻ + CH₃⁺</td>
<td>CH₂ + H⁺ + e⁻</td>
<td>No measurement, R₁₁ = 1/3 R₁₀</td>
</tr>
<tr>
<td>R₁₂</td>
<td>CH₂⁺ + H₀⁺ + e⁻</td>
<td>No measurement, R₁₂ = 2/3 R₁₀</td>
<td></td>
</tr>
<tr>
<td>R₁₃</td>
<td>CH₂ + H₀⁺</td>
<td>Total measured for E &lt; 1 eV, extrapolated for higher E, other channels neglected</td>
<td></td>
</tr>
<tr>
<td>*R₁₄</td>
<td>e⁻ + CH₂⁺</td>
<td>CH₂⁺ + 2e⁻</td>
<td>From CD₂ measurement (E &lt; 200 eV) and CH₄ (E &gt; 200 eV)</td>
</tr>
<tr>
<td>*R₁₅</td>
<td>CH⁺ + H₀⁺ + 2e⁻</td>
<td>Measurement (CD₂)</td>
<td></td>
</tr>
<tr>
<td>R₁₆</td>
<td>CH + H₀⁺ + e⁻</td>
<td>No measurement, R₁₆ = 1/2 R₃</td>
<td></td>
</tr>
<tr>
<td>R₁₇</td>
<td>e⁻ + CH₂⁺</td>
<td>CH + H⁺ + e</td>
<td>No measurement, R₁₇ = 1/2 R₁₆</td>
</tr>
<tr>
<td>R₁₈</td>
<td>CH⁺ + H₀⁺ + e⁻</td>
<td>No measurement, R₁₈ = 1/2 R₁₆</td>
<td></td>
</tr>
<tr>
<td>R₁₉</td>
<td>CH + H₀⁺</td>
<td>Total measured for E &lt; 1 eV, extrapolated for higher E, other channels neglected</td>
<td></td>
</tr>
</tbody>
</table>
Table 1. (continued)

<table>
<thead>
<tr>
<th>Rate</th>
<th>Reaction</th>
<th>Product</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>R20</td>
<td>e⁻ + CH</td>
<td>CH⁺ + 2e⁻</td>
<td>No measurement, adopted CH₄ data</td>
</tr>
<tr>
<td>R21</td>
<td>C⁺ + H⁰ + 2e⁻</td>
<td>No measurement, total R₂₁ + R₂₂ assumed = 1/2 R₉; R₂₁ = 1/2 total</td>
<td></td>
</tr>
<tr>
<td>R22</td>
<td>C + H⁺ + 2e⁻</td>
<td>No measurement, total R₂₁ + R₂₂ assumed = 1/2 R₉; R₂₂ = 1/2 total</td>
<td></td>
</tr>
<tr>
<td>R23</td>
<td>C + H⁰ + e⁻</td>
<td>No measurement, R₂₃ = 1/4 R₃</td>
<td></td>
</tr>
<tr>
<td>R24</td>
<td>e⁻ + CH⁺</td>
<td>C + H⁺ + e⁻</td>
<td>No measurement, R₂₄ = 1/2 R₂₃</td>
</tr>
<tr>
<td>R25</td>
<td></td>
<td>C⁺ + H⁰ + e⁻</td>
<td>No measurement, R₂₅ = 1/2 R₂₃</td>
</tr>
</tbody>
</table>

\[
y_{new} = y_{old} + v_y \delta t,
\]
\[
z_{new} = z_{old} + v_z \delta t,
\]

where the coordinates are \(x, y, z\); the time step is \(\delta t\); and the particle velocities are \(v_x, v_y, v_z\).

For charged reaction products, however, straight-line flight is replaced by motion along magnetic field lines. Two different geometries are required for the results presented in this paper.

For the PISCES-A experiment it is assumed that the field lines are straight and one-dimensional. Thus, the charged particle motion is described by

\[
x_{new} = x_{old},
\]
\[
y_{new} = y_{old},
\]
\[
z_{new} = z_{old} + v_z \delta t,
\]

where \(z\) is the axial direction of the applied magnetic field and \(v_z\) is the axial velocity component of the original cosine distribution from the nozzle. On subsequent electron collisions in which an ion reverts to a neutral, the \(x\) and \(y\) velocity components are sampled from a random gyroangle distribution.

To model the tokamak scrape-off layer, the charged particles are assumed to follow flux surfaces (which are the basis for the GEORGE code):
\[ \psi_{\text{new}} = \psi_{\text{old}} + \delta \psi_{\text{anomalous}}, \]

\[ \phi_{\text{new}} = \phi_{\text{old}} + v_\phi \delta t, \]

\[ \theta_{\text{new}} = \theta_{\text{old}} + v_\theta \delta t, \]

where \( \psi \) is the flux surface label, \( \phi \) is the toroidal angle, and \( \theta \) is the poloidal angle. The \( v_\phi \) and \( v_\theta \) components are computed from those of the neutral particle at the time of the collision event. The cross-surface diffusion (\( \delta \psi_{\text{anomalous}} \)) is determined by an assumed cross-field transport diffusivity, which is assumed to be \( D_A = 10^4 \) cm\(^2\)/s for the tokamak scrape-off layer calculations.
III. COMPARISON WITH EXPERIMENTS

A. Experimental setup of PISCES experiments

A general schematic of the PISCES-A experiments is shown in Fig. 1 (details have been presented in refs. 10–12). The gas flow of CH₄ molecules from the nozzle is ionized and dissociated by the electrons in the helium plasma. Electron temperatures and densities are inferred from Langmuir probe measurements, and the conditions for the modeling calculations are shown in Table II. Optical multichannel analysis of the emitted molecular
Table 2. Plasma parameters for experiments

<table>
<thead>
<tr>
<th>Shot</th>
<th>$T_e^{\text{hot}}$ (eV)</th>
<th>$T_e^{\text{cold}}$ (eV)</th>
<th>$n_e$ ($10^{12}$ cm$^{-3}$)</th>
<th>Hot fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13417</td>
<td>45.0</td>
<td>8.0</td>
<td>2.5</td>
<td>39.0</td>
</tr>
<tr>
<td>13427</td>
<td>36.1</td>
<td>13.0</td>
<td>3.0</td>
<td>86.0</td>
</tr>
<tr>
<td>12027</td>
<td>44.1</td>
<td>—</td>
<td>1.6</td>
<td>100</td>
</tr>
<tr>
<td>13401</td>
<td>27.2</td>
<td>—</td>
<td>1.7</td>
<td>100</td>
</tr>
</tbody>
</table>

spectra was made to establish the axial variation of the density of the breakup products, and the results of the modeling are compared with these measurements.

The Langmuir probe measurements in the higher density cases (with parameters closer to typical tokamak scrape-off layer conditions) show the existence of a two-temperature electron energy distribution. In these cases we have identified “hot” and “cold” electron components and have used rate coefficients from Table I weighted by the relative electron density. That is, the rate coefficients used in the modeling for the reactions in Table I are:

$$S_{\text{total}} = n_e^{\text{total}} R_{\text{total}} = n_e^{\text{hot}} R(T_e^{\text{hot}}) + n_e^{\text{cold}} R(T_e^{\text{cold}}).$$

B. Comparison

The calculated distributions of CH$_4$ breakup products for PISCES run 13417 are shown in Fig. 2. Figure 2(a) shows the distribution of neutral products (CH$_4$, CH$_3$, CH$_2$, CH) as a function of axial distance from the nozzle, and Fig. 2(b) shows the ion product distributions (CH$_4^+$, CH$_3^+$, CH$_2^+$, CH$^+$). One of the implicit predictions of the model described in ref. 3 is that the CH$_4$ breakup proceeds through this sequence. (The direct production of C from CH$_4$ has been observed in molecular beam experiments, and this represents an alternative reaction path not considered here.)

The modeling results are compared with the measured CH$_2$ distribution for this case in Fig. 3. The decay rate predicted by the model for CH$_2$ is approximately a factor of two larger than the measured rate. The position of the peak in the CH$_2$ density is also discrepant, with the model maximum shifted downstream by about 5 mm. As discussed in Sec. III.C, the position of the peak is sensitive to the assumed ambient plasma profiles, especially the sheath conditions at the nozzle.
Fig. 2. Density variation along the axis of the breakup products from CH₄ incident from a nozzle to the left. (a) The neutral products. (b) The ion products.

Fig. 3. Model results for CH₂ distribution for PISCES run 13417 compared with the spectroscopically measured distribution.
The results for CH and CH\textsuperscript{+} are shown in Figs. 4(a) and 4(b). Here the decay rates are more nearly in agreement, but the CH\textsuperscript{+} rise rate is lower than measured. The position of the peak density is shifted downstream, but this is a consequence of the discrepancy for CH\textsubscript{2}.

Fig. 4. Model and measured results for (a) the CH distribution and (b) the CH\textsuperscript{+} distribution.

C. Discussion

An estimate of the effect of the assumed plasma sheath profile is shown in Fig. 5. The model results are shown for both the nominal case with uniform density and temperature profile and for a case with density and temperature rising by 20% toward the nozzle position. This effect can account for a shift in the predicted position of the peak by up to 1.5 cm. Note, though, that the decay rate is unaffected.

The possible effect of uncertainties in the hot electron component of the plasma has been tested. Shifts in the predicted peak position of up to 1 cm have been found when comparing model calculations with $T_\text{e}^{\text{hot}}$ within ±20 eV of the nominal value (45 eV).
IV. APPLICATION TO PLASMA FUELING

To estimate the effect of hydrocarbon molecular fueling on typical tokamak scrape-off layer plasmas, we assume plasma profiles:

\[ T_e(x) = T_e^{\text{LCFS}} \exp[-(x - x_{\text{LCFS}})/\lambda], \]

\[ n_e(x) = n_e^{\text{LCFS}} \exp[-(x - x_{\text{LCFS}})/\lambda], \]

where \( \lambda = 2 \text{ cm}, T_e^{\text{LCFS}} = 50 \text{ eV}, \) and \( n_e^{\text{LCFS}} = 10^{13} \text{ cm}^{-3}; \) LCFS refers to the last closed flux surface. In this case the magnetic field direction is almost perpendicular to the influx direction of CH\(_4\), so that the breakup dynamics are compressed in the radial direction, in comparison with those of the PISCES-A experiments. The ion breakup products are transported along the field lines with slower radial motion.
We compare the hydrogen density produced in the edge plasma region by hydrogen molecular fueling (5-eV Franck-Condon atoms emitted from the wall) and by hydrocarbon fueling (H atoms emitted in the successive breakup of CH$_4$). Figure 6(a) shows the radial distribution of ion products and exhibits the longer lifetime of the ions with respect to radial transport compared with Fig. 2(b). Figure 6(b) shows that the penetration of hydrogen is actually improved with hydrocarbon fueling, and the penetration depth is increased by a factor of five (measured by the relative positions of one e-folding length from the maximum hydrogen density).

![Graph showing comparison of hydrogen density in the scrape-off layer for Franck-Condon and CH$_4$ fueling processes, assuming typical tokamak scrape-off layer parameters.](image)

Fig. 6. Comparison of hydrogen density in the scrape-off layer for Franck-Condon and CH$_4$ fueling processes, assuming typical tokamak scrape-off layer parameters.
The data presented in ref. 3 have been incorporated in a 3-D Monte Carlo transport model and tested against measured CH₄ breakup rates in the PISCES-A device. Agreement is within the factor of two accuracy stated in ref. 3. Uncertainties in the background plasma distributions (both spatial and energy) may contribute to this discrepancy. In light of the provisional nature of the rate data used (see Table I), the overall agreement can be considered quite good. Application of this model to typical tokamak edge parameters shows that there can be a significant difference in the edge fueling source when hydrocarbon and molecular hydrogen fueling processes are compared.
REFERENCES

INTERNAL DISTRIBUTION

1. C. C. Baker
2. L. A. Berry
3. B. A. Carreras
4. R. A. Dory
5. J. L. Dunlap
6. H. H. Haselton
7-16. J. T. Hogan
17. M. S. Lubell
18. R. A. Phaneuf
19. M. J. Saltmarsh
20. J. Sheffield
21–22. Laboratory Records Department
23. Laboratory Records, ORNL-RC
24–25. Central Research Library
26. Document Reference Section
27. Fusion Energy Division Library
28–29. Engineering Technology/Fusion Energy Division Publications Office
30. ORNL Patent Office

EXTERNAL DISTRIBUTION

32. Office of the Assistant Manager for Energy Research and Development, U.S. Department of Energy, Oak Ridge Operations Office, P.O. Box E, Oak Ridge, TN 37831
33. J. D. Callen, Department of Nuclear Engineering, University of Wisconsin, Madison, WI 53706-1687
34. R. W. Conn, Department of Chemical, Nuclear, and Thermal Engineering, University of California, Los Angeles, CA 90024
36. S. O. Dean, Fusion Power Associates, Inc., 2 Professional Drive, Suite 248, Gaithersburg, MD 20879
37. H. K. Forsen, Bechtel Group, Inc., Research Engineering, P.O. Box 3965, San Francisco, CA 94119
38. J. R. Gilleland, L-644, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
39. R. W. Gould, Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125
40. R. A. Gross, Plasma Research Laboratory, Columbia University, New York, NY 10027
41. D. M. Meade, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543
43. W. M. Stacey, School of Nuclear Engineering and Health Physics, Georgia Institute of Technology, Atlanta, GA 30332
44. D. Steiner, Nuclear Engineering Department, NES Building, Tibbetts Avenue, Rensselaer Polytechnic Institute, Troy, NY 12181
45. R. Varma, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India
46. Bibliothek, Max-Planck Institut für Plasmaphysik, Boltzmannstrasse 2, D-8046 Garching, Federal Republic of Germany
47. Bibliothek, Institut für Plasmaphysik, KFA Jülich GmbH, Postfach 1913, D-5170 Jülich, Federal Republic of Germany
48. Bibliothek, KfK Karlsruhe GmbH, Postfach 3640, D-7500 Karlsruhe 1, Federal Republic of Germany
49. Bibliothèque, Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne, 21 Avenue des Bains, CH-1007 Lausanne, Switzerland
50. R. Aymar, CEN/Cadarache, Département de Recherches sur la Fusion Contrôlée, F-13108 Saint-Paul-lez-Durance Cedex, France
51. Bibliothèque, CEN/Cadarache, F-13108 Saint-Paul-lez-Durance Cedex, France
52. Library, Culham Laboratory, UKAEA, Abingdon, Oxfordshire, OX14 3DB, England
53. Library, JET Joint Undertaking, Abingdon, Oxfordshire OX14 3EA, England
54. Library, FOM-Instituut voor Plasmaphysica, Rijnhuizen, Edisonbaan 14, 3439 MN Nieuwegein, The Netherlands
55. Library, National Institute for Fusion Science, Chikusa-ku, Nagoya 464-01, Japan
56. Library, International Centre for Theoretical Physics, P.O. Box 586, I-34100 Trieste, Italy
57. Library, Centro Ricerche Energia Frascati, C.P. 65, I-00044 Frascati (Roma), Italy
58. Library, Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Kyoto 611, Japan
59. Plasma Research Laboratory, Australian National University, P.O. Box 4, Canberra, A.C.T. 2601, Australia
60. Library, Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, 801-1 Mukoyama, Naka-machi, Naka-gun, Ibaraki-ken, Japan
61. G. A. Eliseev, I. V. Kurchatov Institute of Atomic Energy, P.O. Box 3402, 123182 Moscow, U.S.S.R.
62. V. A. Glukhikh, Scientific-Research Institute of Electro-Physical Apparatus, 188631 Leningrad, U.S.S.R.
63. I. Shpigel, Institute of General Physics, U.S.S.R. Academy of Sciences, Ulitsa Vavilova 38, Moscow, U.S.S.R.
64. 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.
65. O. Pavlichenko, Kharkov Physical-Technical Institute, Academical St. 1, 310108 Kharkov, U.S.S.R.
66. Deputy Director, Southwestern Institute of Physics, P.O. Box 15, Leshan, Sichuan, China (PRC)
67. Director, The Institute of Plasma Physics, P.O. Box 26, Hefei, Anhui, China (PRC)
73. R. E. Mickens, Atlanta University, Department of Physics, Atlanta, GA 30314
74. M. N. Rosenbluth, University of San Diego, La Jolla, CA 92037
75. D. Schnack, SAIC, 10260 Campus Point Drive, San Diego, CA 92121
76. Duk-In Choi, Department of Physics, Korea Advanced Institute of Science and Technology, P.O. Box 150, Chong Ryang-Ri, Seoul, Korea
77. Library of Physics Department, University of Ioannina, Ioannina, Greece
78. C. De Palo, Library, Associazione EURATOM-ENEA sulla Fusione, CP 65, I-00044 Frascati (Roma), Italy
79. Theory Department Read File, c/o D. W. Ross, Institute for Fusion Studies, University of Texas, Austin, TX 78712
80. Theory Department Read File, c/o R. Parker, Director, Plasma Fusion Center, NW 16-202, Massachusetts Institute of Technology, Cambridge, MA 02139
81. Theory Department Read File, c/o R. White, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543
82. Theory Department Read File, c/o L. Kovrizhnykh, Lebedev Institute of Physics, Academy of Sciences, 53 Leninsky Prospect, 117924 Moscow, U.S.S.R.
83. Theory Department Read File, c/o B. B. Kadomtsev, I. V. Kurchatov Institute of Atomic Energy, P.O. Box 3402, 123182 Moscow, U.S.S.R.
84. Theory Department Read File, c/o T. Kamimura, National Institute for Fusion Studies, Nagoya 464, Japan
85. Theory Department Read File, c/o C. Mercier, Departemente de Recherches sur la Fusion Controlee, B.P. No. 6, F-92260 Fontenay-aux-Roses (Seine), France
86. Theory Department Read File, c/o T. E. Stringer, JET Joint Undertaking, Abingdon, Oxfordshire OX14 3EA, United Kingdom
87. Theory Department Read File, c/o R. Briscoe, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, United Kingdom
88. Theory Department Read File, c/o D. Biskamp, Max-Planck-Institut fur Plasmaphysik, Boltzmannstrasse 2, D-8046 Garching, Federal Republic of Germany
89. Theory Department Read File, c/o T. Takeda, Japan Atomic Energy Research Institute, Tokai Fusion Research Establishment, Tokai-mura, Naka-gun, Ibaraki-ken, Japan
90. Theory Department Read File, c/o J. Greene, General Atomics, P.O. Box
85608, San Diego, CA 92138-5608
91. Theory Department Read File, c/o R. Cohen, Lawrence Livermore National
Laboratory, P.O. Box 5511, Livermore, CA 94550
92. Theory Department Read File, c/o R. Gerwin, CTR Division, Los Alamos
National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
93. D. Reiter, Institut für Plasmaphysik, KFA Jülich GmbH, Postfach 1913,
D-5170 Jülich, Federal Republic of Germany
94. A. Nicolai, Institut für Plasmaphysik, KFA Jülich GmbH, Postfach 1913,
D-5170 Jülich, Federal Republic of Germany
95. D. Post, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ
08543
96. W. Langer, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ
08543
97. S. Cohen, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ
08543
98–145. Given distribution as shown in OSTI-4500, Magnetic Fusion Energy (Category
Distribution UC-427, Theoretical Plasma Physics)