Impurity Electron Core Effect in ORMAK

D. L. Shaeffer

MASTER

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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 \$3.50, Microfiche \$3.00

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration/United States Nuclear Regulatory Commission, 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.

Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

IMPURITY ELECTRON CORE EFFECT IN ORMAK

D. L. Shaeffer

Date Published - March 1977

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, 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.

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

SUMMARY	v
REVIEW OF IMPURITY ELECTRON CORE EFFECT	1
ANALYSIS OF ORMAK DATA.	5
CONCLUSIONS AND DISCUSSION.	6
ACKNOWLEDGMENTS	9
REFERENCES.	10

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SUMMARY

The impurity electron core effect on plasma resistance treated by Kirillov et al.¹ is included in the analysis of ORMAK discharge data to ascertain whether a significant reduction will occur in the value of $\langle Z \rangle$ determined from the resistance anomaly calculation. Results indicate that only elements of high atomic number (such as gold) will reduce $\langle Z \rangle$ significantly (about 15%). Iron $\langle Z \rangle$ is reduced about 5%. This is contrary to the analysis by Kirillov et al.¹ of TM-3 data which was taken early in the discharge when the impurity stripping was still in progress. Because the core effect varies roughly as Z_j^{-2} (Z_j being the average charge state of the impurity), a more pronounced reduction in $\langle Z \rangle$ will occur early in the discharge when the impurity stripping is incomplete.

REVIEW OF IMPURITY ELECTRON CORE EFFECT

Kirillov et al.¹ attempt to explain the observed tokamak resistance anomalies, which lie in the range of 2 to 50 for TM-3, by the presence of ionized heavy impurities, such as iron, molybdenum, tungsten, etc. However, the larger anomalies required impurity ion densities larger than what might reasonably occur experimentally. In an attempt to reduce the required impurity ion densities, the effect of the residual electronic core on the momentum transfer cross section for electron-impurity collisions is considered. The residual electrons are assumed to reside in a smeared electron cloud surrounding the nucleus rather than having the net charge located at a point in the nucleus. The Thomas-Fermi model is used to calculate the electron core effect.

Kirillov et al. define the anomaly factor, A , as the ratio of the actual plasma resistance to the theoretical resistance of a fully ionized hydrogen plasma. Thus,

$$A = \sum_j \frac{F_{ej}^{fr}}{F_{ei}^{fr}} = \sum_j \frac{n_j \langle v v \sigma_{ej} \rangle}{n_j \langle v v \sigma_{ei} \rangle} \quad (1)$$

where $F_{ej}^{fr} = -m_e n_j \langle v v \sigma_{ej} \rangle$ is the frictional force between an electron and ions of species j , v is the relative velocity between electrons and ions of species j , and σ_{ej} is the momentum transfer cross section. The angle brackets above indicate averaging over a Maxwellian velocity distribution of electrons. The subscript i refers to protons.

Using their notation, the momentum transfer cross section is written

$$\sigma_{ej} = \int (1 - \cos \theta) d\sigma = 4\pi \rho_1^2 \int_{\min}^{\max} [Z - F(q)]^2 \frac{dq}{q} \quad (2)$$

where

$$\rho_1 = \frac{e^2}{mv^2} \quad (3)$$

$$q = |p - p'| / \hbar = (2mv/\hbar) \sin (\theta/2) \quad (4)$$

$$F(q) = \int_0^{r_0} n(r) \frac{\sin qr}{qr} 4\pi r^2 dr \quad (5)$$

$$N_e = \int_0^{r_0} n(r) 4\pi r^2 dr = Z - Z_j \quad (6)$$

Here m is the electron mass, $n(r)$ is the radially dependent density of electrons in the cloud surrounding the ion, Z is the atomic number of the impurity species, and Z_j is the average charge state. The total number of electrons in the impurity electron cloud is N_e . The electron core form factor is $F(q)$ and is determined by Kirillov et al. from the Thomas-Fermi model. If $N_e = 0$ (i.e., fully stripped) there is no form factor and the usual coulomb cross section is obtained from Eq. (2).

After making some approximations, Kirillov et al. arrive at an expression for the momentum transfer cross section which is applicable to all electron energies. They perform the averaging procedure indicated by Eq. (1) and find that the core effect leads to a multiplicative correction factor, f_C , in the usual coulomb logarithm, i.e.,

$$f_C = 1 + \lambda_j \quad (7)$$

$$\lambda_j = \frac{(Z/Z_j)^2 - 1}{4 \Lambda_j} \ln \left[1 + \frac{3}{2} \gamma^4 \left(\frac{T_e}{R_y} \right)^2 \right] \quad (8)$$

$$\gamma = \frac{3}{2} \frac{N_e^{2/3}}{Z} \quad (9)$$

and Λ_j is the coulomb logarithm for species j .

$$\Lambda_j = \ln \left(\frac{D}{Z_j} \rho_1 \right) \quad (10)$$

D is the Debye length and ρ_1 is the ninety degree deflection impact parameter. T_e is the electron temperature (eV), and R_y is the Rydberg constant equal to 13.6 eV. The anomaly factor given by Eq. (1) is then written as

$$A = 1 + \sum_j \frac{n_j}{n_e} Z_j^2 \left(1 - \frac{1}{Z_j} - \frac{\ln Z_j}{\Lambda_i} + \frac{\Lambda_j}{\Lambda_i} \lambda_j \right) \quad (11)$$

where the subscript j refers to the j th impurity species, and Λ_i is the electron-ion (proton) coulomb logarithm.

The neutral term which appears in the corresponding equation derived by Kirillov et al. has been neglected here because of its smallness. The last term within the parentheses of Eq. (11) represents the electron core effect. From Eq. (8) one can see that in the absence of a core, i.e., $Z = Z_j$, the core correction factor f_C is unity and the λ_j term in Eq. (11) is zero.

The anomaly factor A may be arrived at in a different manner by defining A to be the ratio of electron-impurity collision frequency $\nu_e^{Z=Z}$ to the electron-ion (proton) collision frequency $\nu_e^{Z=1}$. Thus,

$$\nu_e^{Z=Z} = B(T_e) n_i \Lambda_i \left\{ 1 + \sum_j \frac{n_j Z_j^2}{n_i} \frac{\Lambda_j}{\Lambda_i} \right\}. \quad (12)$$

Here $B(T_e)$ is the electron temperature dependent part which varies as $T_e^{3/2}$ and contains the appropriate constants. We now account for the impurity electron core effect by multiplying Λ_j by f_C . Also,

$$\Lambda_j = \Lambda_i - \ln Z_j. \quad (13)$$

Then the anomaly factor becomes

$$A = \frac{\nu_e^{Z=Z}}{\nu_e^{Z=1}} = \frac{n_i}{n_e} \left\{ 1 + \sum_j \frac{n_j Z_j^2}{n_i} \left[\left(1 - \frac{\ln Z_j}{\Lambda_i} \right) (1 + \lambda_j) \right] \right\} \quad (14)$$

$$= \frac{n_i}{n_e} \left\{ 1 + \sum_j \frac{n_j Z_j^2}{n_i} \left[1 - \frac{\ln Z_j}{\Lambda_i} + \frac{\Lambda_j}{\Lambda_i} \lambda_j \right] \right\}. \quad (15)$$

From charge neutrality, we have

$$\frac{n_i}{n_e} = 1 - \sum_j \frac{n_j Z_j}{n_e} . \quad (16)$$

Substituting into Eq. (15) we obtain

$$A = 1 + \sum_j \frac{n_j Z_j^2}{n_e} \left[1 - \frac{1}{Z_j} - \frac{\ln Z_j}{\Lambda_i} + \frac{\Lambda_j}{\Lambda_i} \lambda_j \right] , \quad (17)$$

which is the expression derived by Kirillov et al.

The correction term λ_j is largest for elements of high atomic number Z where

$$\lambda_j \sim \left(\frac{Z}{Z_j} \right)^2 . \quad (18)$$

Kirillov et al. gave an example of tungsten ($Z = 74$) ionized to $Z_j = 20$ at $T_e = 1$ keV. They find $\lambda_j = 0.8$. Thus a substantial part of the resistance anomaly may be explained by the electron core effect. In this example, the effective- Z (or $\langle Z \rangle$) necessary to explain the resistance anomaly is approximately 80% lower than that without the core consideration.

ANALYSIS OF ORMAK DATA

The high $\langle Z \rangle$ obtained in ORMAK discharges has been a persistent problem in that the calculated $\langle Z \rangle$ necessary to explain the resistance anomaly has historically been larger than that inferred from experimentation.² The question we now ask is, "Can the impurity electron core effect explain any significant part of the ORMAK resistance anomaly?"

The core effect has been incorporated into the static discharge data analysis program ZØRDIC.³ The results from the analysis of two different data sets are shown in Tables 1 through 4. The Z_c model³ (i.e., $\langle Z \rangle$ considered to be constant across the plasma) is used here. We compare the results for a gold and an iron impurity model with and without the core effect. We immediately see that the iron model decreases $\langle Z \rangle$ by only 4 to 5% (Tables 2 and 4). On the other hand, gold ($Z = 79$) decreases $\langle Z \rangle$ by 14 to 16% (Tables 2 and 4). Thus only impurities of high atomic number will contribute significantly to the reduction of $\langle Z \rangle$. In the case of the dataset 09025N.A, the core effect reduces $\langle Z \rangle$ from 8.0 to 6.9 for gold and from 8.0 to 7.7 for iron. The x-ray analyses⁴ of the same ORMAK data indicate a $\langle Z \rangle$ of about 6 for an iron model, although there is a large experimental uncertainty. Such analyses have not been performed for a gold model.

CONCLUSIONS AND DISCUSSION

The electron core effect due to impurities of intermediate atomic number Z (such as iron) will not appreciably reduce the $\langle Z \rangle$ necessary to explain the ORMAK resistance anomalies. The heavier impurities (such as gold) more appreciably reduce $\langle Z \rangle$, although not as significantly as for TM-3 reported by Kirillov et al. This discrepancy is due to the fact that the analyses performed on TM-3 data are only 4 msec into the discharge. The stripping process is still operative at this time, and the average charge state Z_j is lower than the average charge state which is estimated with a temperature rise time of ~ 15 msec and thus is closer to the equilibrium state of ionization. Because $\lambda_j \sim Z_j^2$ and because tungsten strips to about $Z_j \sim 40$ for $T_e = 1$ keV, the electron core effect will be about four times smaller than the non-steady-state example given by Kirillov et al.

We should also point out that the treatment of Kirillov et al. neglects the core effects on terms associated with electron-electron collisions and the non-Maxwellian distribution of electrons. Perhaps the Spitzer-Härm⁵ problem should be reworked to include the impurity electron core effect. In addition, the treatment of Kirillov et al. does not include neoclassical effects.

Table 1. The effect on the amount of iron and gold required to satisfy the resistance anomaly of dataset 09025N.A

	M_{Fe} (moles)	M_{Au} (moles)	$\frac{n_{\text{Fe}}(0)}{n_e(0)}$ (%)	$\frac{n_{\text{Au}}(0)}{n_e(0)}$ (%)
No core	7.0×10^{-7}	2.2×10^{-7}	1.0	0.30
Core	6.7×10^{-7}	1.9×10^{-7}	0.95	0.26
% Δ	4.3	14.0	5.0	13.0

Table 2. The effect on the $\langle Z \rangle$ of dataset 09025N.A

	$\langle Z \rangle_{\text{Fe}}$	$\langle Z \rangle_{\text{Au}}$
No core	8.0	8.0
Core	7.7	6.9
% Δ	3.8	14.0

Table 3. The effect on the amount of iron and gold required to satisfy the resistance anomaly of dataset 08185N.B

	M_{Fe} (moles)	M_{Au} (moles)	$\frac{n_{\text{Fe}}(0)}{n_e(0)}$ (%)	$\frac{n_{\text{Au}}(0)}{n_e(0)}$ (%)
No core	4.3×10^{-7}	1.4×10^{-7}	1.35	0.44
Core	4.0×10^{-7}	1.2×10^{-7}	1.32	0.39
% Δ	7.5	14.0	2.2	11.0

Table 4. The effect on the $\langle Z \rangle$ of the dataset 08185N.B

	$\langle Z \rangle_{\text{Fe}}$	$\langle Z \rangle_{\text{Au}}$
No core	9.6	9.6
Core	9.1	8.1
% Δ	5.2	16.0

ACKNOWLEDGMENTS

The author would like to thank A. Mense and M. Murakami for their very helpful discussions during this investigation. Thanks are also extended to M. Murakami for providing the data for analysis.

REFERENCES

1. V. D. Kirillov, B. A. Trubnikov, and S. A. Trushin, "Role of Impurities in Anomalous Plasma Resistance," *Sov. J. Plasma Phys.* . 1: 2 (March-April 1975).
2. L. A. Berry et al., *Proc. 5th Intl. Conf. on Plasma Physics and Controlled Nuclear Fusion Research*, 1: 101 (1975).
3. D. L. Shaeffer and M. Murakami, "ZØRDIC, a New ORMAK Data Analysis Code with Impurity Modeling," ORMAK Technical Memo 230 (September 1976).
4. G. Jahns and M. Murakami (ORNL), private communication.
5. L. Spitzer and R. Härm, *Phys. Rev.* 89: 977 (1953).

INTERNAL DISTRIBUTION

1. C. F. Barnett	22. D. G. McAlees
2. L. A. Berry	23. A. T. Mense
3. C. E. Bush	24. J. T. Mihalcz
4. J. D. Callen	25. M. Murakami
5. J. F. Clarke	26. R. V. Neidigh
6. R. E. Clausing	27. G. H. Neilson
7. R. J. Colchin	28. V. K. Pare
8. E. C. Crume	29-36. D. L. Shaeffer
9. J. L. Dunlap	37. D. Steiner
10. P. H. Edmonds	38. L. D. Stewart
11. A. C. England	39. D. W. Swain
12. C. A. Foster	40. J. B. Wilgen
13. J. T. Hogan	41. W. R. Wing
14. H. C. Howe	42. S. J. Zweben
15. R. C. Isler	43-44. Central Research Library
16. P. W. King	45. Document Reference Section
17. G. L. Jahns	46-47. Laboratory Records Department
18. T. C. Jernigan	48. Laboratory Records, ORNL-RC
19. G. G. Kelley	49. ORNL Patent Office
20. H. E. Ketterer	50-51. Fusion Energy Division Library
21. J. F. Lyon	52. Fusion Energy Reports Office

EXTERNAL DISTRIBUTION

53. C. M. Braams, FOM-Instituut voor Plasma-Fysica, Rijnhuizen, Jutphaas, the Netherlands
54. A. M. Budker, Nuclear Physics Institute, Siberian Academy of Sciences, Novosibirsk 90, U.S.S.R.
55. Prof. Piero Caldirola, Laboratorio di Fisica del Plasma ed Elettronica Quantistica del C.N.R., Via Celoria 16, 20133 Milano, Italy
56. Department of Nuclear Engineering Sciences, 202 Nuclear Science Center, University of Florida, Gainesville, FL 32611
57. Library, Centre de Recherches en Physique des Plasmas, 21 Avenue des Bains, 1007 Lausanne, Switzerland
58. T. Consoli, Centre d'Etudes Nucleaires de Grenoble, Avenue des Martyrs-38-Grenoble, France
59. Anne Davies, Tokamak Systems Branch, Division of Magnetic Fusion Energy, Mail Station G-234, Energy Research and Development Administration, Washington, DC 20545

60. S. O. Dean, Office of Confinement Systems, Division of Magnetic Fusion Energy, Mail Station G-234, Energy Research and Development Administration, Washington, DC 20545
61. Director, Technical Library, Defense Atomic Support Agency, Sandia Base, Albuquerque, NM 87115
62. A. M. Dupas, Documentation S.I.G.N., Department de la Physique du Plasma et de la Fusion Contrôlée, Association EURATOM-CEA sur la Fusion, Centre d'Etudes Nucleaires, BP 85 Centre du Tri, 38041 Grenoble CEDEX, France
63. O. C. Eldridge, Physics Department, Hunter College/CUNY, 695 Park Avenue, New York, NY 10021
64. H. P. Eubank, Plasma Physics Laboratory, Princeton University, Princeton, NJ 08540
65. H. K. Forsen, Exxon Nuclear Co., Inc., 777 106th Avenue, NE, Bellevue, WA 98004
66. T. K. Fowler, University of California, Lawrence Radiation Laboratory, P.O. Box 808, Livermore, CA 94551
67. H. P. Furth, Plasma Physics Laboratory, Princeton University, Princeton, NJ 08540
68. R. W. Gould, Professor of Electrical Engineering and Physics, Bldg. 116-81, California Institute of Technology, Pasadena, CA 91109
69. Harold Grad, Courant Institute, New York University, 251 Mercer Street, New York, NY 10012
70. H. R. Griem, Department of Physics, University of Maryland, College Park, MD 20742
71. G. Guest, General Atomic Co., P.O. Box 81608, San Diego, CA 92138
72. I. Gverdsiteli, Physico-Technical Institute, Georgian Academy of Sciences, Sukhumi, U.S.S.R.
73. A. M. Hamende, International Centre for Theoretical Physics, Trieste, Italy
74. Research Laboratory of Electronics, Document Room 36-412, Attention J. Hewitt, Massachusetts Institute of Technology, Cambridge, MA 02139.
75. T. Hiraoka, Japan Atomic Energy Research Institute, Tokai, Ibaraki, Japan

76. P. Hubert, Service de Recherches sur la Fusion Contrôlée, Centre d'Etudes Nucleaires, Fontenay-aux-Roses (Seine), France
77. K. Husimi, Institute for Plasma Physics, Nagoya University, Nagoya, Japan
78. D. W. Ignat, Division of Magnetic Fusion Energy, Mail Station G-234, Energy Research and Development Administration, Washington, DC 20545
79. E. E. Kintner, Division of Magnetic Fusion Energy, Mail Station G-234, Energy Research and Development Administration, Washington, DC 20545
80. E. Komar, D. V. Efremov Scientific Research Institute of Electro-Physical Apparatus, Leningrad, U.S.S.R.
81. H. E. Knoepfel, Laboratorio Gas Ionizzati, C.P. 65, 00044 Frascati (Roma) Italy
82. Librarian, Physical Sciences Laboratory, P.O. Box 6, Stoughton, WI 53589
83. Librarian, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52240
84. Librarian, Institute for Plasma Physics, 8046 Garching bei München, Federal Republic of Germany
85. Librarian, Culham Laboratory, Abingdon, Oxfordshire, OX14 3DB, England
86. Plasma Physics Library, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08540
87. M. J. Lubin, Department of Mechanical and Aerospace Sciences, University of Rochester, Rochester, NY 14627
88. G. H. Miley, Professor, Department of Nuclear and Electrical Engineering, 214 Nuclear Engineering Laboratory, University of Illinois, Urbana, IL 61801
89. T. Ohkawa, General Atomic Company, P.O. Box 81608, San Diego, CA 92138.
90. D. Palumbo, Directorate General for Research and Training, EURATOM, 51 Rue Belliard, Brussels 5, Belgium
91. Plasma Laboratory Reading Room, Room 20A-222, Massachusetts Institute of Technology, Cambridge, MA 02139
92. F. Prevot, Chef du Service de Confinement des Plasmas, C.E.A., B.P. No. 6, 92 Fontenay-aux-Roses (Seine) France

93. M. S. Rabinovich, Lebedev Institute of Physics, Academy of Sciences of the U.S.S.R., Leninsky Prospect 53, Moscow, U.S.S.R.
94. Center for Plasma Physics and Thermonuclear Research, Physics Building 330, University of Texas, Austin, TX 78712
95. Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, Japan
96. F. L. Ribe, Los Alamos Scientific Laboratory, P.O. Box 1663, Los Alamos, NM 87544
97. D. J. Rose, Massachusetts Institute of Technology, Room 24-210, Cambridge, MA 02139
98. Eugene Velikov, Thermonuclear Laboratory, Kurchatov Institute of Atomic Energy, 46 Ulitsa Kurchatova, Post Box 3402, Moscow, U.S.S.R.
99. H. H. Woodson, Department of Electrical Engineering, University of Texas, Austin, TX 78712
100. Director, Research and Technical Support Division, ERDA-ORO, P.O. Box E, Oak Ridge, TN 37830
- 101-127. Technical Information Center, P.O. Box 62, Oak Ridge, TN 37830