Final Report to the *DOE Office of Science* on research into

Atomic and Molecular Physics Effects on Ion Flow into Hot Surfaces

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Covering the Period February 15, 2010 to February 14, 2013

1 Executive Summary

Objective

Develop a predictive, integral transport model of atomic and molecular physics effects on deuterium and helium ion flow through a neutral background gas.

Overview

This *Final Report* summarizes activities and anticipated activities from February 15, 2010 to February 14, 2013 for the OFES-funded investigation of one-dimensional ion flow between nearly transparent, electrodes when atomic and molecular physics effects play a major role.

Significant progress was made during the project in the following areas:

1. Upgrading an integral equation C code to give output of key quantities on a regular grid in radius and energy for use in comparing to experiments,
2. Updating the Mathematica! notebooks that support the modeling in the C code and the post-processing of parametric runs to generate contour and 3D plots of selected parameters versus radius and energy,
3. Using the modified integral-transport computer code and Mathematica! post-processing tools to compare the code's predictions with experimental results,
4. Presenting the research at national and international conferences and workshops, and
5. Giving seminars and presenting the results to visitors.

Research during this project at the University of Wisconsin Fusion Technology Institute (UW FTI) on ion and neutral flow through an arbitrary, monotonic potential difference created by nearly transparent electrodes accomplished the following: (1) developed and implemented an integral equation approach for atomic physics effects in helium plasmas; (2) extended the analysis to coupled integral equations that treat atomic and molecular deuterium ions and neutrals; (3) implemented the key deuterium and helium atomic and molecular cross sections; (4) added negative ion production and related cross sections; and (5) benchmarked the code against experimental results. The analysis and codes treat the species D^0, D_2^0, D^+, D_2^+, D_3^+, D^- and, separately at present, He^0 and He^+. Extensions enhanced the analysis and related computer codes to include He^{++} ions plus planar and cylindrical geometries.

The project's results have been distributed through the UW FTI's research web site at http://fti.neep.wisc.edu/research. As described below, the researchers have also published archival journal papers and given presentations at professional conferences on the results generated by the research. Potentially important applications of this research are to fusion reactor divertors and limiters, and also to alternate applications such as plasma processing, plasma thrusters, and neutron sources.

2 Background

Investigations of charged-particle flow between planar electrodes date back to Child [1] and Langmuir [2]. For spherically symmetric geometry, Langmuir and Blodgett first investigated the problem [3]. Charged-particle flow between electrodes possesses a long history [4,5,6,7,8,9,10,11,12,13,14,15] that continues to the present day [for example, 16,17,18,19,20, 21]. Important applications include plasma processing, plasma thrusters, and ion diodes. The Child-Langmuir problem has been solved for totally ionized plasma, but the presence of neutral gas and multiple species greatly complicates the problem, which remains unsolved and under-investigated. The problem appears to be intractable analytically.

For a nearly transparent inner electrode in spherical geometry, ions accelerated inward by a voltage difference continue through the electrode and potentially form a converged core, as shown in Figure 1. The operation of devices of this type, called gridded *inertial-electrostatic confinement* (IEC) devices has led to a rudimentary understanding of the concept, primarily in high-pressure, glow-discharge regimes [22,23,24,25,26,27,28,29,30,31,32,33,34,35]. Several IEC experiments have existed, including devices at the University of Wisconsin, the University of Illinois, the University of Maryland, Los Alamos National Laboratory, NASA Marshall Space Flight Center, several universities in Japan—including Kyoto University, Kansai University, and the Tokyo Institute of Technology, plus the University of Sydney, Australia. Results from the UW and other experiments have been used to benchmark the theoretical results derived during the research.

The motivation for recent IEC research was primarily to produce neutrons and protons by fusion reactions for use in detecting landmines, creating radioisotopes, and other applications [36]. The FESAC subcommittee on non-electric applications of fusion identified these near-term applications as important directions for fusion research. Optimizing IEC devices, unfortunately, remains largely an empirical process, as is also the case for many plasma processing systems and plasma thrusters. This situation stems partly from the operation of these devices in high-pressure background gas regimes (>0.133 Pa = 1 mTorr), where charge exchange and ionization complicate the flow and theoretical analysis becomes challenging. Even for the case of a totally ionized plasma there remain open issues and considerable controversy regarding the extent and lifetime of a converged core in an IEC device [37,38,39]. Important applications include plasma processing, plasma thrusters, ion diodes, and neutron sources.

3 Accomplishments of the Research Project

Introduction: This section summarizes the accomplishments of the present phase of the research project, DE-FG02-04ER54745, which extended from February 15, 2010 February 14, 2013.

The PI and Co-PI initially attacked this problem in order to understand the behavior of University of Wisconsin (UW) inertial-electrostatic confinement (IEC) neutron and proton sources. In the UW experiments, ions are formed in a source region outside of a nearly transparent anode, drift through it, are accelerated inward by a voltage difference through a background gas (P~1 mTorr), continue through a nearly transparent cathode, then reverse the process through another cathode-anode pair. Space charge and ion flows dominate these devices, driving complex and interrelated phenomena, particularly when atomic and molecular physics effects become important. The essential physics of gridded IEC devices appears schematically in Fig. 1 for a spherical IEC configuration. When ions pass through the device, charge exchange events are modeled as attenuating that pass's current, and a next-generation, ion is born. Ionization and dissociation events also create a next-generation ion and electron. This project's integral equation analysis follows this infinite recursion of generations of ion current, self-consistently accounting for the birth energies. The dominant plasma regimes and physics effects vary, but can be characterized for the spherical problem approximately as (1) atomic physics in the low-density sheaths at large radii, (2) streaming plasma at intermediate radii, and (3) high-density plasma physics at small radii. All three regions are strongly interconnected by the flowing ions.

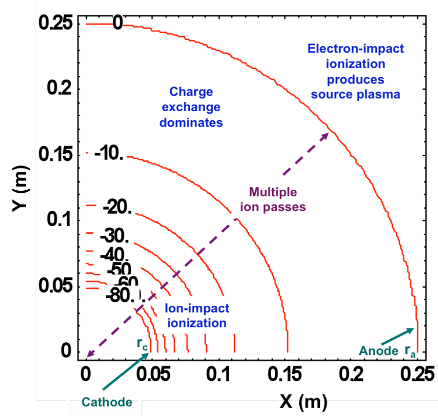

Fig. 1: Essential features of inertial-electrostatic confinement physics. Multiple generations of ions are tracked. Electrostatic potential contours are shown in red.

Accomplishments: This research project on the theory of spherically convergent ion flow between nearly transparent electrodes accomplished the following:

1. Implemented in a C code and a Mathematica® notebook the cross sections for the key relevant atomic and molecular physics processes using the IAEA Atomic and Molecular Data Information System (AMDIS) database plus other sources as necessary.[40] These cross sections include charge exchange, ionization, dissociation, etc.

2. Published in *Physics of Plasmas* the integral equation approach to modeling neutral and singly ionized atomic species in spherical geometry plus generating reacting ion and neutral energy spectra.[41]

3. Developed, implemented, and benchmarked against experimental results a version of the integral equation approach that includes charge exchange, ionization, and dissociation in

singly ionized plasma-neutral gas mixtures composed of atoms and molecular deuterium. Published a companion paper on this molecular case in *Physics of Plasmas*.[42]

4. Formulated and implemented the inclusion of the non-zero ion birth velocity of daughter ions resulting from dissociation of molecular ions by introducing an equivalent source radius approach; this research is included in the paper submitted under item 2.[42]
5. Added negative ion production and flow to the theory and molecular code via a subroutine that post-processes reactions with the predicted positive ion and neutral currents.
6. Developed a set of tools for running large sets of parametric cases and for performing numerical analysis and graphical examination of the results of the integral equation computer code. These have been used for both papers mentioned above.
7. Refined and published in *Physics of Plasmas* a source-region, rate-equation model that includes molecular and multiple species created by streaming electrons.[43]

The research project addressed the problem of analyzing atomic and molecular ion interactions (charge exchange, dissociation, and ionization of background gas) during the radial bounce motion of ions in an electrostatic potential well. Charge exchange reactions generate a "hot" neutral and a "cold" ion, ionization of background gas also creates a cold ion, and dissociation can create hot and cold ions and neutrals. Both hot and cold ions are accelerated by the electrostatic potential and produce new hot neutrals and cold ions. After summing over the infinite number of radial passes and generations of ions, a Volterra integral equation for the source of cold ions is derived; from this source function, the energy spectrum of the ions and energetic neutrals is obtained, along with other macroscopic quantities of interest. The details of the integral equation approach to this problem for both the atomic and the molecular case are given in the associated *Physics of Plasmas* papers, Refs. 41 and 42; a summary of the molecular equations is presented below.

Molecular Case: For the molecular case, three species of positive ions, D^+, D_2^+, and D_3^+, can exist in the source region, and these will interact with the background D_2^0 gas to produce D^0, D^+, D_2^0, and D_2^+, but not D_3^+. Therefore, integral equations must be written and solved simultaneously only for D^+ and D_2^+. The analysis is couched in terms of an initial source function, $A_i(r)$, due to ions coming from the source region, and a source function, $S_i(r)$, due to all succeeding generations. For the deuterium case, this leads to two integral equations:

$$S_1(r) = A_1(r) + \int_r^b K_{11}(r,r')S_1(r')dr' + \int_r^b K_{12}(r,r')S_2(r')dr' \qquad (1)$$

$$S_2(r) = A_2(r) + \int_r^b K_{21}(r,r')S_1(r')dr' + \int_r^b K_{22}(r,r')S_2(r')dr' \qquad (2)$$

where $S_i(r)$ is the source at radius r of ion species i (D^+ or D_2^+ for i=1 or 2), A_i gives the contribution of source ions born at the anode radius (r=b), and $K_{ij}(r,r')$ is the kernel that incorporates the details of the atomic and molecular physics processes and relates $S_i(r)$ to $S_j(r')$ at larger radii:

$$K_{ij}(r,r') = n_g \sigma_{ij}\left[E(r,r')\right]\left(\frac{r'^2}{r^2}\right)\frac{g_j(r,r') + T_c^2 \dfrac{g_{cpj}(r')}{g_j(r,r')}}{1 - T_c^2 g_{cpj}(r')} \tag{3}$$

where n_g is the gas density, σ_{ij} is the total cross section for all reactions that produce species *i* from species *j*, φ is the electrostatic potential, T_c is the cathode transparency, $E(r,r')=q[\varphi(r')-\varphi(r)]$ is the energy at *r* of a particle born at r', g_{cpj} is the complete-pass trajectory attenuation probability for species *j*, and the partial-pass attenuation function g_j is:

$$g_j(r,r') = \exp\{-\int_r^{r'} n_g \sigma_{cx}\left[\varphi(r') - \varphi(r)\right]\} \tag{4}$$

The inward ion flux (s≡j) is given by

$$F_s^{in}(r,E) = 4\pi e r'^2 \frac{S_s(r')}{\left|\dfrac{\partial e\varphi}{\partial r'}\right|}\left(\frac{g_s(r,r')}{1 - T_c^2 g_{cps}(r')}\right) + 4\pi e b^2 h_s \Gamma f_s(r)\delta\left(E - e\varphi(r)\right) \tag{5}$$

where Γ is the flux at the source boundary, *s* represents the species, h_s is the species fraction, and $f_s(r)$ gives the attenuation of species *s*. The outward ion flux is given by an analogous expression. Two papers document our basic integral-equation approach to modeling atomic and molecular effects on spherically convergent positive ion flow through a neutral background gas that has been implemented in the codes.[41,42]

The 3D plot in Fig. 2 illustrates the use of a Mathematica® post-processor to help understand the effects occurring in the plasma. The plots shown in Fig. 3 illustrate the increased attenuation as pressure increases of ion currents flowing through the background gas and the creation of new currents from the original ions.

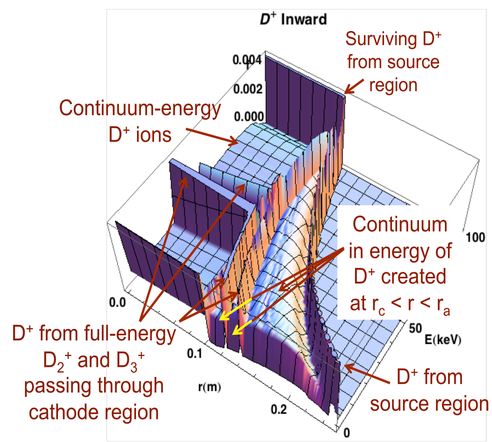

Fig. 2. Illustration of ion currents passing through the plasma for the D^+ component of the source plasma. Figure's z-axis only extends to 0.005, which truncates nearly delta-function behavior of source currents. Parameters for this case are V=100 kV, I=100 mA, P=2 mTorr, cathode radius=0.1 m, anode radius=0.25 m, and source distribution of D^+:D_2^+:D_3^+=0.06:0.23:0.71.

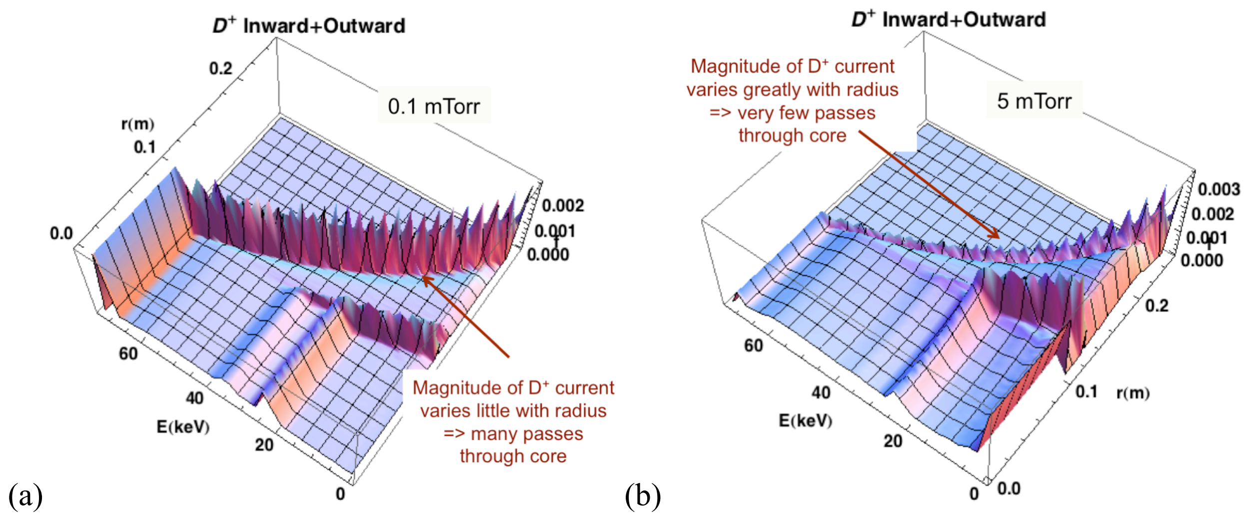

Fig. 3. Illustration of increased attenuation of current and creation of new currents in going from low pressure (a) to high pressure (b). Parameters for this case are V=70 kV, I=100 mA, P=2 mTorr, cathode radius=0.1 m, anode radius=0.20 m, and source distribution of D^+:D_2^+:D_3^+=0.06:0.23:0.71.

Negative Ions: Experimental results for ion flow through gases at ~0.133 Pa (1 mTorr) clearly showed the presence of negative ions that lead to ~10% effects on current and fusion-product generation.[44] Therefore, during the most recent research period, negative ion physics has been added to the molecular code as a post-processing subroutine that takes the positive-ion and neutral currents, then calculates the negative-ion, resulting neutral, and fusion reactions produced. To add negative ions to the analysis, the source functions were extended from depending exclusively on *r* to also depending on energy *E*. The negative ion source function is then

$$S_N^{in,out}(r,E)dE = \sum_{species} n_g \sigma F_{species}^{in,out}(r,T')dT'$$

where *T* is the particle's kinetic energy. The negative ion energy spectra are given by

$$F_N^{in,out}(r,E) = \int S_N(r',E)\,p(r,r',E)\,dr'$$

where the probability of a negative ion born at *r*' with energy *E* reaching *r* is

$$p(r,r',E) = \exp\left[-\int n_g \sigma_{strip}(r'')dr''\right]$$

and σ_{strip} is the electron-stripping cross section. A contour plot of the current of negative ions vs. kinetic energy and radius generated by the revised code appears in Fig. 4. Note how this plot shows the increased kinetic energy of negative ions due to their acceleration between the cathode and anode by the electric field that exists there.

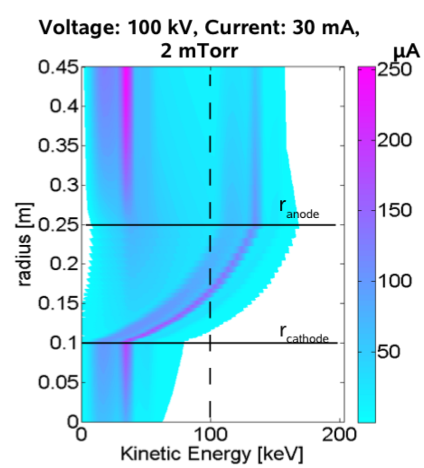

Fig. 4. Dependence of the current of negative ions on radius and kinetic energy.

Sequential Mean Free Path: In the process of seeking to determine which reactions should be included in the integral transport theory and codes, the question arose of how to compare the importance of various chains of reactions. That is, if several paths lead from a current of one species through multiple channels to the creation of another species, and competing reactions attenuate the currents of the many species involved, does a simple technique for selecting among the branches of such a reaction tree exist? The PI and a graduate student, Eric Alderson, who is supported on funds independent of this grant, discovered that such a technique exists and the resulting expressions are relatively simple.[45]

For example, take the case of a constant-density background and constant cross section, so that mean free paths do not depend on location. Define $\lambda_{ij} \equiv (n_g \sigma_{ij})^{-1}$ to be the mean free path for species *i* to become species *j*, and λ_{id} to be the mean free path for destruction of species *i* by *j* or other species. Under these assumptions, a two-step process leads to $\lambda_{13} = \frac{\lambda_{1d}\lambda_{2d}}{\lambda_{12}\lambda_{23}}(\lambda_{1d} + \lambda_{2d})$ and a three-step process leads to $\lambda_{14} = \frac{\lambda_{1d}\lambda_{2d}\lambda_{3d}}{\lambda_{12}\lambda_{23}\lambda_{34}}(\lambda_{1d} + \lambda_{2d} + \lambda_{3d})$.

When no other processes compete, $\lambda_{1d}=\lambda_{12}$, $\lambda_{2d}=\lambda_{23}$, … and these formulas reduce to the intuitively satisfying results that $\lambda_{13}=\lambda_{12}+\lambda_{23}$ and $\lambda_{14}=\lambda_{12}+\lambda_{23}+\lambda_{34}$. The obvious pattern that emerges from the two-step and three-step solutions led us to the general form of the solution, and we were able to prove rigorously that:[45]

$$\lambda_{1m} = \left(\prod_{i=1}^{m-1} \frac{\lambda_{id}}{\lambda_{i(i+1)}}\right)\left(\sum_{j=1}^{m-1} \lambda_{jd}\right) \qquad (6)$$

Dissemination of the research

Presentations to visitors

Presentations that at least partially included this research were given to several visitors either at UW-Madison or, in the case of Dr. Phelps, at an APS-DPP lunch meeting:

- Dr. Steve Koonin, then Under Secretary of Energy (discussion of fusion research program and fusion reactor design in general, Madison, 13 April 2011).
- Dr. Bob Conn, President, Kavli Foundation (20 April 2010).
- Prof. Kazuyuki Noborio, Kyoto University, and six graduate students (30 June 2011).
- Dr. Harrison Schmitt, (23 September 2011)
  Former Apollo 17 astronaut and geologist, and former Senator, New Mexico.
- Dr. Steve Zinkle, Nuclear Science and Engineering Directorate Chief Scientist, ORNL (11 October 2011).
- Dr. Rick Nebel, Tibbar Technologies (12 October 2011).
- Dr. Ady Hershcovitch, Brookhaven National Laboratory (25 October 2011).
- Dr. Art Phelps, University of Colorado & JILA (16 November 2011).

Archival journal papers

The following archival journal papers related to this research have been published during the most recent phase of this research project. Those most closely associated with this research project are starred (*) and two key papers are doubly starred.

1. G.L. Kulcinski and J.F. Santarius, "Non-Electric Applications of the Inertial Electrostatic Confinement Fusion Concept," *Fusion Science and Technology* **64**, 365 (2013).

2. G.L. Kulcinski, J.F. Santarius, G.A. Emmert, R.L. Bonomo, E.C. Alderson, G.E. Becerra, L.M. Garrison, K.B. Hall, A.M. McEvoy, M.K. Michalak, and C.M. Schuff, "Recent Advances in IEC Physics and Technology at the University of Wisconsin," *Fusion Science and Technology* **64**, 373 (2013).

3. * E.C. Alderson and J.F. Santarius, "Analytic Determination of the Mean Free Path of Sequential Reactions," *American Journal of Physics* **80**, 316 (2012).

4. G.L. Kulcinski, J.F. Santarius, G.A. Emmert, R.L. Bonomo, E.C. Alderson, G.E. Becerra, L. Campbell, D.C. Donovan, B.J. Egle, L.M. Garrison, A.M. McEvoy, M.K. Michalak, C.M. Schuff, and S.J. Zenobia, "New Insight into Gridded Inertial Electrostatic Confinement (IEC) Fusion Devices," *Fusion Science and Technology* **60**, 607 (2011).

5. * S. Krupakar Murali, G.A. Emmert, J.F. Santarius, and G.L. Kulcinski, "Effects of Chamber Pressure Variation on the Grid Temperature in an Inertial Electrostatic Confinement Device," *Physics of Plasmas* **17**, 102701 (2010).

6. ** G.A. Emmert and J.F. Santarius, "Atomic and Molecular Effects on Spherically Convergent Ion Flow I: Single Atomic Species," *Physics of Plasmas* **17**, 013502 (2010).

7. ** G.A. Emmert and J.F. Santarius, "Atomic and Molecular Effects on Spherically Convergent Ion Flow II: Multiple Molecular Species," *Physics of Plasmas* **17**, 013503 (2010).

8. * D.R. Boris, G.L. Kulcinski, J.F. Santarius, D.C. Donovan, and G.R. Piefer, "Measuring D(d,p)T Fusion Reactant Energy Spectra with Doppler Shifted Fusion Products," *Journal of Applied Physics* **107**, 123305 (2010).

9. * S. Krupakar Murali, J.F. Santarius, and G.L. Kulcinski, "Consolidated Electron Emission Effects in an IEC Device," *Plasma Sources Science and Technology* **19**, 045029 (2010).

10. S. Krupakar Murali, J.F. Santarius, and G.L. Kulcinski, "Study of Thermionic Electrons in an Inertial Electrostatic Confinement (IEC) Device using a Novel 'Chordwire' Diagnostic," *Fusion Science and Technology* **57**, 281 (2010).

11. * D.R. Boris, E. Alderson, G. Becerra, D.C. Donovan, B. Egle, G.A. Emmert, L. Garrison, G.L. Kulcinski, J.F. Santarius, C. Schuff, and S.J. Zenobia, "Deuterium Anions in Inertial Electrostatic Confinement Devices," *Physical Review E* **80**, 036408 (2009).

12. G.L. Kulcinski, J.F. Santarius, G.A. Emmert, R.L. Bonomo, E.C. Alderson, G.E. Becerra, D.R. Boris, D.C. Donovan, B.J. Egle, J.H. Sorebo, and S.J. Zenobia, "Near Term Applications of Inertial Electrostatic Confinement Fusion Research," *Fusion Science and Technology* **56**, 493 (2009).

Technical presentations

The following technical presentations related to the present phase of the research project have been given:

Poster presentations:

1. J. Santarius, G. Emmert, G. Kulcinski, R. Bonomo, E. Alderson, G. Becerra, L. Garrison, K. hall, A. McEvoy, M. Michalak, and C. Schuff, "Overview of Inertial Electrostatic Confinement Plasma Physics Research at the University of Wisconsin," APS Division of Plasma Physics Annual Meeting (Providence, RI, 29 Oct-2 Nov 2012).
2. G. Emmert and J. Santarius, "Modeling Two-Charge State Helium Plasmas," APS Division of Plasma Physics Annual Meeting (Providence, RI, 29 Oct-2 Nov 2012).
3. G. Emmert, J. Santarius, and E. Alderson, "Integral Transport Analysis of Ions Flowing through Neutral Gas," APS Division of Plasma Physics Annual Meeting (Salt Lake City, Utah, 14-18 November 2011).
4. E.C. Alderson, J.F. Santarius, G.A. Emmert, and G.L. Kulcinski, "Negative Ion Studies in an IEC Fusion Device," APS Division of Plasma Physics Annual Meeting (Salt Lake City, Utah, 14-18 November 2011).
5. G. Becerra, G. Kulcinski, and J.F. Santarius, "Optimization and Characterization of a Helicon Ion Source on an Inertial Electrostatic Confinement Device for Helium-3 Fusion," Gaseous Electronics Conference (Salt Lake City, Utah, 14-18 November 2011).
6. G.A. Emmert, J.F. Santarius, E.C. Alderson, and D.C. Donovan, "Inertial Electrostatic Confinement Modeling and Comparison to Experiments," APS Division of Plasma Physics Annual Meeting (8-12 November 2010, Chicago, Illinois).

Talks:

1. J.F. Santarius and G.A. Emmert, "IEC Device Core Physics Explorations," US-Japan IEC Workshop (College Park, MD, 14-16 Oct 2012).
2. G.A. Emmert and J.F. Santarius, "Modeling Two-Charge State Helium Plasmas," (College Park, MD, 14-16 Oct 2012).
3. G.A. Emmert, J.F. Santarius, and E.C. Alderson, "Update on the VICTER Code for Modeling Gridded, Spherically Symmetric IEC Devices," US-Japan-Australia IEC Workshop (Sydney, Australia, 7-8 December 2011).

4. J.F. Santarius, G.A. Emmert, and E.C. Alderson, “Theoretical Exploration of UW IEC Device Operation at Moderate Pressures,” US-Japan-Australia IEC Workshop (Sydney, Australia, 7-8 December 2011).
5. E.C. Alderson, J.F. Santarius, G.A. Emmert, and G.L. Kulcinski, “Negative Ion Studies in an IEC Fusion Device,” US-Japan-Australia IEC Workshop (Sydney, Australia, 7-8 December 2011).
6. G.E. Becerra, G.L. Kulcinski, and J.F. Santarius, “Enhancement of an IEC Device with a Helicon Ion Source for Helium-3 Fusion,” US-Japan-Australia IEC Workshop (Sydney, Australia, 7-8 December 2011).
7. J.F. Santarius, “Inertial-Electrostatic Confinement Fusion Experiments and Theory at UW-Madison,” Nuclear Engineering Colloquium, Purdue University (West Lafayette, Indiana, 15 September 2010).
8. G.A. Emmert, “Integral Transport Modeling of Spherically Symmetric, Gridded IEC Devices,” 11th US-Japan Workshop on IEC Fusion (Osaka, Japan, 20-21 October 2010).
9. J.F. Santarius, “Exploration of IEC Device Operating Regimes,”11th US-Japan Workshop on IEC Fusion (Osaka, Japan, 20-21 October 2010).

Appendix 1: Biographical Sketches

John F. Santarius, PI

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Education	B.S.	California Institute of Technology	Physics	1973
	Ph.D.	University of Texas-Austin	Physics	1979

Professional Experience

2005 – present	Assoc. Dir. for Alternate Applications and Concepts, Fusion Technology Institute
2004 – present	Research Professor, UW-Madison, Engineering Physics Department
1987 – 2003	Senior Scientist (PI Status, 2001), UW-Madison, Dept. of Engineering Physics
1982 – present	Plasma Engineering Group Leader, Fusion Technology Institute
1982 – 1986	Associate Scientist, UW-Madison, Engineering Physics Department
1979 – 1981	Assistant Scientist, UW-Madison, Engineering Physics Department

Professional Societies	APS, AIAA, IEEE
Courses Taught	Plasma Space Propulsion (developed and taught from notes)
	Astrodynamics (taught using existing textbook)
	Resources from Space (several lectures and significant contributions)
Awards	Excellence in Fusion Engineering, Fusion Power Associates, 1991
	Certificate of Appreciation (Technical Planning Activity), US DOE, 1988

Technical Accomplishment and Present Research Highlights

- Investigate plasma physics and engineering issues for magnetic-confinement, inertial-confinement, and pulsed-power fusion, including power-plant design and energy conversion.
- Have published papers on tokamaks, stellarators, field-reversed configurations, tandem mirrors, dipoles, inertial-confinement fusion, magneto-inertial fusion, and inertial-electrostatic confinement. Co-author of 13 major, multi-institutional (industry, national lab, university) fusion reactor studies.
- Model UW inertial-electrostatic confinement experiments on producing neutrons for clandestine materials detection and radioisotopes for nuclear medicine
- Participate in industrial efforts to produce commercial electric fusion power.
- Suggested the possibility of a major lunar resource of ^{3}He fusion fuel; contributed to subsequent Fusion Technology Institute work verifying the existence and feasibility of this resource. Explore applications of advanced fusion fuels and concepts to terrestrial power, space power, and space propulsion.

Publication and Presentation Summary

Authored or co-authored 86 refereed publications, 13 major fusion engineering design studies, and 36 non-refereed conference papers or reports. Presented over 100 talks at national and international scientific meetings, industries, universities, or national laboratories. Served as guest editor for two special D-^{3}He issues of the American Nuclear Society's journal *Fusion Technology* (1992). Have given numerous public service talks to civic and education audiences, including grade schools, middle schools, college audiences, Rotary clubs, and senior citizen groups. Created worldwide web tutorials on spacecraft trajectories, plasma thrusters, and fusion space propulsion.

Selected Relevant Publications

1. E.C. Alderson and J.F. Santarius, "Analytic Determination of the Mean Free Path of Sequential Reactions," *American Journal of Physics* **80**, 316 (2012).
2. G.L. Kulcinski, J.F. Santarius, G.A. Emmert, R.L. Bonomo, E.C. Alderson, G.E. Becerra, L. Campbell, D.C. Donovan, B.J. Egle, L.M. Garrison, A.M. McEvoy, M.K. Michalak, C.M. Schuff, and S.J. Zenobia, "New Insight into Gridded Inertial Electrostatic Confinement (IEC) Fusion Devices," *Fusion Science and Technology* **60**, 607 (2011).
3. L.C. Steinhauer and J.F. Santarius, "Challenge End-Plugged FRC Concept," Journal of Fusion Energy **29**, 577 (2010).
4. G.A. Emmert and J.F. Santarius, "Atomic and Molecular Effects on Spherically Convergent Ion Flow I: Single Atomic Species" & "II: Multiple Molecular Species," *Physics of Plasmas* **17**, 013502 & 013503 (2010).
5. D.R. Boris, E. Alderson, G. Becerra, D.C. Donovan, B. Egle, G.A. Emmert, L. Garrison, G.L. Kulcinski, J.F. Santarius, C. Schuff, and S.J. Zenobia, "Deuterium Anions in Inertial Electrostatic Confinement Devices," *Physical Review E* **80**, 036408 (2009).
6. J.F. Santarius, G.L. Kulcinski, R.P. Ashley, D.R. Boris, B.B. Cipiti,, S. Krupakar Murali, G.R. Piefer, R.F. Radel, T.E. Radel, and A.L. Wehmeyer, "Overview of University of Wisconsin Inertial-Electrostatic Confinement Fusion Research," *Fusion Science and Technology* **47**, 1238 (2005).
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Education

Ph.D.	1968	Physics, Stevens Institute of Technology
M.S.	1964	Physics, Rensselaer Polytechnic Institute
B.S.	1961	Engineering Science, University of California-Berkeley (Elected to Pi Tau Sigma and Tau Beta Pi honorary Societies)

Professional Experience-Industry

Summer 1978	Guest Scientist, Institut für Plasmaphysik
1976-1977	Guest Scientist, Institut für Plasmaphysik
1961-1964	Analytical Engineer, United Aircraft Corp.
1958-1960	Engineering Aide, Rocketdyne
1957	Engineering Aide, NASA

Professional Experience-Education

2001-present	Emeritus Professor, University of Wisconsin
1992-2001	Department Chair, Engineering Physics
1979-2001	Professor, University of Wisconsin-Madison
1972-1979	Associate Professor, University of Wisconsin-Madison
1968-1972	Assistant Professor, University of Wisconsin-Madison

Research Interests

Research activity is in the area of plasma engineering with emphasis on plasma sheaths and plasma-surface interactions, plasma flow to surfaces, and modeling of plasma performance for fusion reactor systems studies.

Career Highlights

Supervised 21 Ph.D. theses in Nuclear Engineering & Engineering Physics, and Electrical Engineering. Graduates are employed in industry, at national laboratories and at universities.
Published 66 papers in refereed technical journals, all in the areas of basic plasma physics, industrial plasma physics and controlled fusion.
Consultant for Oak Ridge National Laboratory (1978-1980), Fusion Power Associates (1982-88 and 1992), and Prentice Hall (1998 and 2002).
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Listed in Who's Who.

Selected Publications (sheath and plasma surface interactions related – from a total of 66 publications)

1. G.L. Kulcinski and G.A. Emmert, "First Wall Surface Problems for a D-T Tokamak Reactor Design," *J. Nucl. Materials,* **53**, 31 (1974).
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