90c 116
7-22-83 PPPL-2015

UC20-F

I-10359

PPPL-2015

Dr. 16098

PPPL--2015

DES3 014912

VERTICAL POLOIDAL ASYMMETRIES OF LOW-Z
ELEMENT RADIATION IN THE PDX TOKAMAK

By

K. Brau, S. Suckewer, S.K. Wong

JUNE 1983

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

REPRODUCED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT NO. DE-AC02-75-OR0-2073.

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED.

VERTICAL POLOIDAL ASYMMETRIES OF LOW-Z ELEMENT RADIATION IN THE PDX TOKAMAK

K. Brau,* S. Suckewer

Plasma Physics Laboratory, Princeton University,
Princeton, New Jersey 08544

and

S. K. Wong

GA Technologies, San Diego, California

ABSTRACT

Vertical poloidal asymmetries of hydrogen isotopes and low-Z impurity radiation in the PDX tokamak may be caused by poloidally asymmetric sources of these elements at gas inlet valves, limiters or vacuum vessel walls, asymmetric magnetic field geometry in the region beyond the plasma boundary, or by ion curvature drifts. Low ionization states of carbon (C II- C IV) are more easily influenced by edge conditions than is C V. Vertical poloidal asymmetries of C V are correlated with the direction of the toroidal field. The magnitude of the asymmetry agrees with the predictions of a quasifluid neoclassical model. Experimental data and numerical simulations are presented to investigate different models of impurity poloidal asymmetries.

* Current address: Association Euratom-CEA sur la fusion,
Département de recherches sur la fusion contrôlée,
Centre d'études nucléaires,
Fontenay aux Roses, France

INTRODUCTION

Observations of pronounced vertical asymmetries in hydrogen isotope and impurity line emission from tokamak plasmas in recent years have prompted a reconsideration of impurity transport processes near the plasma boundary. To the extent that low-Z element behavior in axisymmetric, large aspect ratio toroidal confinement devices can be described by a set of fluid or kinetic equations, it is generally assumed at low order in an expansion parameter that the impurity density is distributed symmetrically on flux surfaces. This result, common to both fluid and kinetic theories of plasma transport, is primarily due to the anticipated rapid parallel transport along field lines. The theory breaks down if strongly poloidally asymmetric sources of impurities are present or if the symmetry of magnetic flux surfaces has been destroyed. Either of these two situations can occur in the region of plasma beyond the limiter radius where hydrogen and the lowest ionization states of an impurity ion reside.

These arguments are less valid within the main plasma volume. Although some fraction of the poloidal variation of the lower ionization states propagates inward by the combination of collisional ionization and radial transport, the rapid parallel motion along field lines tends quickly to establish poloidal symmetry on a flux surface. Therefore any mechanism which is invoked to explain vertical asymmetries of a relatively highly ionized impurity must account for this rapid parallel transport. Such is the case with the standard neoclassical theory of impurity transport. When the appropriate set of moment equations are solved to first order in the expansion parameter (the inverse aspect ratio

$\epsilon = r/R$), impurity concentrations are no longer poloidally symmetric on a flux surface. These poloidal variations result from a combination of parallel friction between the main and impurity ions that is created by radial density and temperature gradients and the vertical ion drift due to the curvature of the toroidal magnetic field. The coupling between the poloidal variations in the impurity density and the vertical drift produces the normally inward transport of impurities predicted by neoclassical theory.

According to the theory, the sign and magnitude of vertical asymmetries depends on the ion collisionality and on the vertical ion drift. A correlation between impurity poloidal asymmetries and these quantities was first reported for the case of VUV emission from O V and O VI in the Alcator A tokamak.¹ The magnitude of the asymmetries was found to scale approximately with a quantity equal to the distance which an impurity ion drifts radially during a poloidal excursion of one radian. It was claimed that vertical asymmetries were the result of outwardly drifting impurity ions striking the limiter on the side of the plasma in the direction of the vertical drift. In the case of higher ionization states closer to the center of the plasma which did not drift beyond the limiter radius, asymmetries were attributed to the coupling through collisional ionization to the asymmetries of the lower ionization states. Subsequently, the Alcator scaling of impurity asymmetries was reproduced by different authors using the standard neoclassical theory of trace impurity transport in a collisional plasma. These results were independent of interactions between the edge plasma and the limiter.

While it accounted successfully for the Alcator A data, the theory

could not explain both the large magnitude and the time varying behavior of poloidal asymmetries of low-Z impurity radiation observed in the PLT tokamak.² This may have been partially a consequence of the higher impurity content of PLT ($Z_{eff} \sim 3 - 4$) in which collisions among impurity ions dominate the ion dynamics. No correlation between the vertical drift parameter and the magnitude of low-Z impurity asymmetries was detected. Instead poloidal asymmetries were attributed to details of the gas input programming, positioning of the aperture limiter, edge ion temperature, and plasma MHD stability. (Along similar lines, observations of enhanced impurity line emission near the limiter in Alcator A were attributed to the effect of local recycling.³)

In this paper we hope to resolve some of the theoretical issues surrounding poloidal asymmetries of low-Z impurity emission in tokamaks by focusing on our experimental investigations of the poloidal distribution of carbon impurities in the PDX tokamak. A distinction will be made between the behavior of the lower ionization states of carbon (C II, C III) normally located at or beyond the limiter radius in PDX circular discharges, and that of C V, which is generally peaked several centimeters inside the limiter radius. We shall attempt to account for the observed asymmetries of C V on the basis of four different theoretical models. In addition to the mechanisms mentioned above, i.e., inward propagation of asymmetries by collisional ionization and neoclassical transport, two others will be discussed. The first involves charge exchange recombination between a poloidally asymmetric neutral hydrogen profile and impurity ions, and the second, a poloidally varying radial diffusion coefficient. Experimental evidence for each of the theories will be presented, along with the results of an

appropriate two-dimensional numerical modeling of carbon transport.

The remainder of this paper is organized as follows. In Sec. I we describe the experimental apparatus for the measurement of radial impurity scans, and some aspects of the PDX tokamak that are relevant to the interpretation of the data. In Sec. II we survey the measurements of poloidal asymmetries of carbon emission with respect to the different theoretical models. In Sec. III we discuss our results from the numerical modeling.

I. EXPERIMENTAL DETECTION SYSTEM

The PDX Fast Rotating Mirror (FARM) diagnostic, (Fig. 1) based on a prototype model used on PLT,² performs continuous vertical (radial) or horizontal (toroidal) scans of the spectral line emission in the range 2000 Å – 6500 Å. The spatial scanning element is a rectangular aluminized quartz prism which can be rotated 90° in a direction orthogonal to its axis of rotation to select between vertically and horizontally scanning lines of sight. A set of two UV grade quartz lenses focuses plasma radiation onto the entrance slit of a 0.5 m air monochromator. For vertically scanning lines of sight, the angular region in which radiation is detected by the system corresponds to a rectangular spot 2-cm wide by 0.4-cm high at the nominal location of the magnetic axis of a PDX discharge. A shaft encoder mounted to the drive shaft of the rotating mirror allows the angular coordinate of the rotating mirror to be determined absolutely as a function of time. Due to slight variations in the mirror rotation speed (approximately 720 RPM) from scan to scan, and also to the magnetic axis during

a discharge, the uncertainty in the radial location of maximum signal intensity is roughly 1–2 cm. The signal was digitized using a 10 bit A/D converter at a sampling rate of 25 kHz, and subsequently analyzed with a PDP-10 computer.

During most of the period in which the data presented below were obtained, the inner wall of the vacuum vessel was shielded by a set of highly reflective, titanium-carbide-coated, graphite tiles that were designed to absorb incident neutral beam power. To minimize reflections from the tiles in vertical scans of the plasma, a viewing dump (80 cm $\times$ 10 cm) was mounted on the inner wall. It was found on the basis of toroidal scans of line emission that the dump reduced the signal intensity by as much as 40% as a result of eliminating reflections. In the vertical and horizontal directions the sensitivity of the FARM system, excluding effects due to reflections from the vacuum vessel, was independent of the angular position of the scanning mirror.

In PDX discharges can be run in either a circular or diverted configuration. In this paper only data obtained during circular discharges are presented because of the difficulty in interpreting impurity emission in the region beyond the magnetic separatrix in diverted discharges. Circular discharges are normally confined using two movable carbon rail limiters located above and below the plasma. For a several month period only the upper limiter was employed. The FARM is located approximately 180° toroidally around the vacuum vessel from the rail limiters. A second method of creating circular plasma configurations is to use the inner wall armor as a toroidally continuous "bumper" limiter. For the data presented in this paper $R_{maj} = 125 - 154$ cm and $a = 30 - 44$ cm.

Data analysis

The technique of Abel inversion is frequently used to convert line integrated intensities to local plasma emissivities. Usually the inversion assumes cylindrical symmetry or else some expansion in poloidal harmonics. We have developed a fast, relatively accurate method of inverting asymmetric chordal profiles without recourse to Abel inversion which is well-suited to analyzing large numbers of radial scans. The emissivity profile is assumed to have the following form:

$$I(r, \theta) = I_0 \exp[-((r - r_s)/\delta)^2] (1 + \eta \sin \theta) \quad (1)$$

where r_s is the radius of maximum emissivity, δ the width at half maximum, and η is defined as the asymmetry parameter. The corresponding chordal intensity profile is determined by integrating this function along fifty vertically scanning lines of sight. By analogy with the quantities r_s , η , and δ , there are three parameters which characterize the chordal profile: the radial position of maximum intensity, the ratio of the maximum intensity above and below the midplane, and the width of the distribution. By numerically integrating $I(r, \theta)$ for a wide range of values of r_s , δ , and η , a simple empirical relationship can be found which relates the two sets of parameters defining the emissivity and chordal profiles.

II. EXPERIMENTAL OBSERVATIONS

In the PDX tokamak low-Z impurity line emission arises from two regions in the discharge: the main plasma, defined here as the volume inside

the limiter radius, and the limiter shadow, which refers to the region between the limiter radius and the vacuum vessel walls. In the latter region flux surfaces are not well-defined, and the poloidal distribution can be affected by recycling or local sources of impurities. Figure 2 is a schematic of the magnetic flux geometry of a standard PDX circular discharge. In the limiter shadow, defined as the region of plasma beyond the flux surface bounded by the upper and lower limiters, the distance between the limiter radius and the walls of the vacuum vessel varies with poloidal angle. Furthermore, the length of the emitting region of an impurity located in the limiter shadow depends to a large extent on the electron temperature, typically 10–20 eV, and on other factors which are poorly known and may vary with poloidal angle. Hence, small scale modulations in the chordal intensity profiles of the lowest ionization states of carbon and oxygen in PDX may reflect variations in the length of the emitting region, differences in the impurity source rates, recycling of impurities, and so on, rather than a variation in the impurity concentration on a flux surface. Figure 3 is an example of a chordal profile of C III which exhibits this behavior. The irregular structure of the profile is repeated throughout the discharge and sometimes over many days of operation.

While the majority of chordal profiles of C III did not exhibit these small scale spatial variations, they were often characterized by large vertical asymmetries. In general, the position of maximum intensity was located 1–2 cm beyond the limiter radius. These asymmetries may be related to conditions at the edge of the plasma. In Fig. 4 chordal profiles of C III and C V have been plotted for a set of circular discharges with similar operat-

ing parameters but for two different major radial positions of the magnetic axis. Note that the radial profile of C III for the $R=152$ cm discharge is extremely asymmetric in comparison to the standard $R=143$ cm discharge. This may have been due to an error in the magnetic feedback positioning system which caused the large major radius discharge to impinge on the bottom half of the vacuum vessel. Because only C III is strongly asymmetric, this is a clear indication of a poloidally asymmetric source of carbon at the edge. Line integrated radiated power profiles measured by a vertically scanning bolometer array also showed a strong peaking of the radiation at the edge of the plasma below the midplane for the $R=152$ cm discharge.

Secondly, we note that the smaller poloidal asymmetry of C V is independent of the C III distribution. Poloidal asymmetries in the lower ionization states of carbon can in principle be transmitted to the higher ionization states by a combination of inward radial transport and collisional ionization. This in fact was among the explanations of the observation of poloidal asymmetries in the more highly ionized impurity species in Alcator A¹ and of subsequent measurements of toroidal asymmetries in the same tokamak.³ Asymmetries in the charge states near the plasma boundary that were directly affected by the vertical ion drift to the limiter constituted an asymmetric source function for the more highly stripped ions. The difficulty with this theory in explaining the PDX observations is that the parallel diffusion time of C V is much shorter than the time required for a carbon ion to drift radially from the position of C III to C V. In PDX the parallel transport is sufficiently fast so that the asymmetry of C III has practically no influence on the poloidal distribution of C V. This topic

is explored further in the numerical modeling section.

Figure 5 illustrates the effect of gas recycling on the poloidal distribution of impurities. The line integrated densities of two discharges with similar parameters are plotted as a function of time in the upper two figures; the lower graphs are radial scans (chordal profiles) of C III during the same period of time. In the right hand set of graphs the asymmetry of C III reversed direction at 620–650 msec into the discharge. Simultaneously, the electron density leveled off for approximately 30 msec. We have determined that this flattening of the electron density was not caused by a change in gas fueling, but was probably a result of increased recycling of hydrogen and/or impurities at the plasma boundary. The reversal of the impurity asymmetry was observed in approximately twenty discharges for which the density flattening occurred, but never in discharges where the density decreased monotonically at the end of the discharge. In all of the discharges only the upper limiter was in use. It is therefore possible that the reversal of the C III asymmetry was due to impurity recycling at the upper limiter, since the intensity of the C III emission increased in the upper half of the discharge during the flattening of the electron density. (For the value of q at the plasma periphery the carbon plume emitted near the limiter would have traversed a poloidal angle of 40° , assuming purely parallel motion, as it reached the toroidal location of the FARM.)

Impurity poloidal asymmetries have also been attributed to charge exchange recombination of impurity ions with a poloidally asymmetric neutral hydrogen profile.⁴ According to this theory, the sign of the asymmetries of the neutral species is opposite that of the ions. In PDX we have obtained chordal

profiles of $H\beta$, C III, and C V emission under similar discharge conditions. Generally, the vertical asymmetry of the neutral component is the same as that of carbon ions, although there are examples in which the poloidal asymmetry of H^0 changes sign during a discharge, but the distribution of the ionized species remains constant. Both of these results directly contradict the predictions of the theoretical model.

We have already noted the importance of plasma-surface interactions and vacuum vessel geometry in explaining the poloidal variations in the chordal profiles of the lowest impurity ionization states. As was seen in Fig. 4, however, the vertical asymmetry of a more highly ionized impurity such as C V is unrelated to edge conditions. These exceptions notwithstanding, in a majority of cases the sign of the vertical asymmetries of carbon and oxygen is the same and depends only on the direction of the toroidal magnetic field. Figure 6 represents a set of radial scans of C III, C V, O III, and O V in a series of similar ohmically heated hydrogen discharges with the following parameters: $a = 30$ cm, $n_e \sim 2.7 \times 10^{13} \text{ cm}^{-3}$, $B_T = 21.7$ kG, and $I_p \sim 200$ kA. The direction of the asymmetries of carbon and oxygen is opposite the vertical ion drift in each case. The magnitude of the asymmetry is largest for the lower charge states of C III and O III and is a decreasing function of radius from O V to C V. It is unlikely that the impurity source functions are the reason for the asymmetry, since the sources of carbon and oxygen may in general be different and the distributions of C III and O III are similar. These data also demonstrate that the vertical ion drift, if indeed it is the mechanism producing the asymmetry, has the same influence on carbon and oxygen impurities.

A correlation between vertical poloidal impurity asymmetries and the direction of the toroidal field was first observed in the Alcator A tokamak.¹ The magnitude of the asymmetry was found to scale with a quantity equal to the radial excursion of an impurity ion (due to the ∇B drift) during a poloidal transit of one radian. To explain the magnitude and direction of the impurity poloidal asymmetries observed on Alcator A, and also to account for the change in asymmetries during a single discharge sometimes observed in PLT,² Burrell and Wong⁵ developed a neoclassical fluid model for small poloidal impurity asymmetries. Impurity asymmetries arise as a result of the return flows of ions along flux surfaces induced by poloidal variations of density and temperature created by the ion vertical drift. The theory correctly predicted the scaling of the impurity asymmetry on Alcator A. It was also in principle capable of accounting for reversals in the sign of the asymmetry, as this depends on the relative magnitudes of the ion density and temperature gradients, which can change during a discharge.

Before embarking on a more quantitative discussion of these concepts, we illustrate the relationship between the vertical ion drift and impurity asymmetries in PDX. In Fig. 7 are shown two chordal profiles of C III obtained during "inner wall" operation, i.e., in which the graphite tiles on the inboard side of the vacuum vessel were used as a toroidally continuous bumper limiter. The central emissivity maximum is caused by the desorption of carbon from the inner wall armor. Hence, the source of carbon is symmetric about the horizontal midplane. Nevertheless, the sign of the vertical poloidal asymmetry of C III is in the same direction with respect to the vertical ion drift as observed in Alcator A.

Figure 8 illustrates the effect of reversing the toroidal field on the poloidal asymmetry of C III and C V for a set of otherwise nearly identical discharges. For each radial scan the sign of the asymmetry is opposite the direction of the vertical ion drift.

To establish a quantitative relationship between the magnitude of the impurity asymmetries in PDX and the predictions of the neoclassical transport model we have focused on C V because it is relatively unaffected by conditions at the edge of the plasma. Thus it is possible to isolate the effects of the vertical ion drift from those of impurity recycling, and so on. There are, however, a few points which must be addressed. First, although PDX plasmas are relatively clean ($Z_{eff} < 2$), collisions between impurity ions, ignored in the theory, probably constitute an important part of the impurity dynamics. Second, the model of Burrell and Wong does not consider either atomic physics or anomalous radial transport, both of which determine the radial distribution of impurity species. Third, the model treats ions in the Pfirsch-Schlüter regime, while the bulk ions and to some extent C V are in the plateau regime. One of the authors of this paper (S. K. Wong) has reformulated the neoclassical fluid equations of impurity transport in which atomic physics and radial anomalous diffusion terms are included, and ions may be in either the plateau or fluid regimes. The major simplification of this theory is in the form of the collision operator. A derivation of these equations is given in the appendix. One can make an approximate comparison between the magnitude and scaling of the observed asymmetries of C V with the predictions of the quasifluid model by retaining three terms in the impurity transport equation (Eq. 11 of Appendix) to obtain

$$\eta_{qf} = \frac{2\sqrt{2}eRm_i q^2 Z_I^2}{eB_T \tau_i} \left[\frac{1}{L_n} + \left(1 - \xi - \frac{1}{Z_I} \right) \frac{1}{L_T} \right] - \frac{Z_I \sqrt{\pi} \epsilon \rho_{i0}}{2L_T} \frac{T_e}{T_e + T_i} \quad (2)$$

where Z_I is the charge of the impurity ion, τ_i the ion collision frequency, ξ a constant equal to 1.5 and -0.75 in the plateau and banana regimes, respectively, R the major radius, and the ion temperature T_i is assumed to be equal for all the ion species. The asymmetry parameter η_{qf} is defined by the relation

$$n_I(\theta, r) = n_I(r)(1 + \eta_{qf} \sin \theta). \quad (3)$$

Figure 9 is a plot of the experimental value of η measured for roughly 600 radial scans of C V in PDX versus the quasifluid model predictions. Information about both the ion temperature and density profiles was not available in the majority of the data; hence T_i and T_e were taken to be constant over the entire data set. The temperature of C V, in general, does not fluctuate by more than $\pm 10\%$ in the circular ohmically heated discharges for which we have data ($T_i \sim 180 - 220$ eV). The density profile was measured by the TV Thomson Scattering diagnostic, or, if such data were not available, a parabolic profile was fit to the measurements of the line integrated density. The safety factor q at the radius corresponding to the C V shell was determined by interpolation from the value at the edge. If the discharge parameters were nearly constant over the course of several radial scans, the data were averaged. In the figure the volume of a box is linearly proportional to the number of scans.

In PDX at the radius of the C V shell the main plasma ions lie in the transition region between the plateau and collisionless regimes ($\nu_e \sim 1$). We have therefore plotted the experimental data assuming each collisionality as a

separate case. According to Fig. 9 (a) if the plateau regime formula is used, the agreement with the theoretical prediction (dashed line) is very poor. However, in the banana regime (Fig. 9b) the agreement is excellent. To obtain a more accurate representation of the theoretical value of η requires a correct solution for the quantity ξ , which lies somewhere between 1.5 and -0.75 in the banana-plateau transition regime.

The quasifluid model of poloidal asymmetries treats ion collisions using a simple Lorentz collision operator. In the plateau regime one must resort to a completely kinetic approach in order to treat ion-ion encounters properly, which involves a reformulation of the problem in terms of the drift kinetic equation. An expression for the vertical impurity asymmetry in this kinetic theory has been obtained by neglecting atomic physics and assuming trace impurities. Because the radial distribution of C V is well separated in space from adjacent ionization states, as a first approximation the atomic coupling due to ionization and recombination can be ignored. In the limit where the mass of the impurity ion is much greater than the plasma ion we have

$$\eta_k = -\frac{1}{2} \sqrt{\frac{m_I}{m_i}} \rho_i q \left[\frac{n_i'}{n_i} + \left(\frac{3}{2} - \frac{Z_I}{2\pi^{1/2}} \sqrt{\frac{m_i}{m_I}} \right) \frac{T_i'}{T_i} \right] \quad (4)$$

where the subscripts I and i refer to impurities and protons, respectively, and ρ_i is the proton Larmor radius in the toroidal field. Figure 10 (b) is a plot of the asymmetry parameters of C V versus η_k . Although the magnitude of the asymmetry predicted by the kinetic model is within the range of observations, the functional dependence is completely incorrect. Since the asymmetry of C V scales with electron density (Fig. 10(a)), however, the lack of agreement between

the kinetic model and experiment may be related to the fact that η_k depends on the density gradient rather than the density itself.

III. NUMERICAL MODELING

We have developed a computer code to solve an arbitrary set of coupled 2-D transport equations for the case of carbon impurities in PDX. The code is based on a finite element routine supplied by IMSL, and an atomic physics package used in one-dimensional simulations of impurity transport.⁷ The general set of coupled equations to be solved are of the form

$$\begin{aligned} \frac{\partial n^i}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial \theta} D_\theta \frac{\partial n^i}{\partial \theta} + \frac{1}{r} \frac{\partial}{\partial r} r D_r \frac{\partial n^i}{\partial r} + \\ f^i(r, \theta) \frac{\partial n^i}{\partial \theta} + g^i(r, \theta) \frac{\partial n^i}{\partial r} = \\ n_e [\alpha_{i+1} n^{i+1} + S_{i-1} n^{i-1} - \alpha_i n^i - S_i n^i] \end{aligned} \quad (5)$$

where D_θ and D_r are poloidal and radial diffusion coefficients, f^i and g^i are arbitrary functions with units of velocity, and the α_j and S_j are recombination and ionization rate coefficients, respectively. Because we are interested only in equilibrium solutions, the time derivative term is set to zero. The density of one of the lowest ionization states (C^0 or C^{+1} , depending on the problem) is specified at the boundary. Figure 11 is a plot of the density, temperature, and q profiles for the PDX discharges modeled below.

We first investigated the effect of a nonsymmetric source of neutral carbon on the poloidal distribution of the successive ionization states. In the simulation the radial transport of impurity ions is described by anomalous diffusion and inward convection, and the parallel transport by collisional diffusion. The latter assumption breaks down when the mean free path of an impurity ion is less than the parallel connection length qR . In PDX the transition from the collisional to the collisionless regime occurs a few centimeters within the radius of C V. Hence the numerical model is appropriate for C II- C IV and marginally valid for C V. We have neglected the radial and parallel ion motions due to magnetic field curvature and parallel friction. The 2-D diffusion equation for an impurity ion is given by

$$-\frac{D_{\parallel}}{R^2 q^2} \frac{\partial^2 n_j}{\partial \theta^2} - \frac{1}{r} \frac{\partial}{\partial r} r D_A \frac{\partial n_j}{\partial r} - \frac{1}{r} \frac{\partial n_j v_A}{\partial r} = \Sigma_j \quad (8)$$

where D_A is an anomalous radial diffusion coefficient, $D_{\parallel}$ the parallel diffusion coefficient, equal to v_{th}^2/ν_i , v_A an anomalous convective velocity, and Σ_j represents ionization and recombination terms. D_A and v_A are determined empirically by comparison of the numerically calculated radial emissivity profiles of C III and C V with the experimental data. Because this procedure does not determine D_A and v_A uniquely, we experimented with different combinations of the diffusion and convection coefficients. We found that the poloidal asymmetry is nearly independent of the specific combination of diffusion and convection provided that they reproduce the correct radial dependence. In all of the numerical simulations, $D_A = 10^4 \text{ cm}^2 \text{ sec}^{-1}$ and $v_A = -2000(r/a) \text{ cm/sec}$, where a is the minor radius. The poloidal distribution of neutral carbon is assumed to vary as $1 + 0.25 \sin \theta$.

In Fig. 12 we have plotted the asymmetry parameters of C II-C VI as

a function of radius. The four graphs were obtained assuming different values of ion collision frequency. It is clear that the asymmetry disappears for C V unless ν_i was increased by a factor of ten from its experimental value. This lack of influence of the source function on the C V distribution is in agreement with experiment (see Fig. 4). These results further indicate that the poloidal asymmetry of C V cannot be due to vertical ion drifts of the lower ionization states to the limiter.

We now wish to determine whether the lack of correlation between the poloidal asymmetry of neutral hydrogen and low-Z impurity emission is consistent with theory. It is thus necessary to establish at what value of n_0/n_e the charge exchange recombination rate of neutral hydrogen with carbon impurities becomes comparable to the parallel transport rate. Our numerical model is the same as used in the previous example, with the neutral hydrogen distribution given by

$$n_0(r, \theta) = n_0(r)(1 + .4 \sin \theta). \quad (7)$$

The radial profile of the neutral density was determined by a one-dimensional simulation of neutral radial transport.⁶ As a result of recent theoretical calculations⁸⁻¹² and experimental measurements¹³ of charge exchange recombination rates for neutral hydrogen with the different ionization states of carbon, the uncertainties now range from 25% to a factor of two, which is less than the uncertainty in $n_0(r)$. For the purposes of simulation we allowed $n_0(r)$ to be increased by factors of 2, 5, and 10. At the boundary neutral carbon was assumed to be poloidally symmetric.

Our results are shown in Fig. 13. There appears to be a threshold neutral density above which the asymmetric neutral hydrogen profile has an effect on the carbon distribution, roughly $n_0/n_e \sim 5 \times 10^{-3}$. The charge state most affected by charge exchange recombination is C IV. Notice that C V and C VI are cylindrically symmetric. Thus charge exchange recombination can be an important contribution to the vertical asymmetry of C III and C IV if the neutral hydrogen fraction at the edge exceeds 5×10^{-3} . To account for the observed poloidal asymmetry of C V, the neutral fraction of hydrogen at the edge must be larger than 5×10^{-2} .

We did not model the full neoclassical quasifluid theory of poloidal asymmetries for the following reasons. Because the ion species of greatest interest, C V, lies in a region where the theory is least accurate ($\nu_e \sim 1$), invoking the full numerical machinery is somewhat inappropriate since the equations themselves may not be correct for this transition collisionality. The estimates of η obtained by retaining only three terms in the impurity transport equation are probably as accurate as the current theory permits. To determine whether the neglect of other quantities in the equation, such as atomic physics terms and anomalous radial diffusion, is justified, we modeled a simpler form of the impurity transport equation in which the poloidal variation of the electrostatic potential was ignored, and ions were assumed to be only in the collisional or plateau regimes. The values of η for C V derived from this numerical simulation agreed to within 10% of the value obtained by neglecting anomalous diffusion and atomic physics. (In order to have the model produce large asymmetries to enable better comparison with the simplified approach, the temperature gradient

scale length was assumed to be infinite, thereby neglecting the thermal force term.)

Finally, to investigate the effect of a poloidally varying anomalous radial diffusion coefficient on the carbon distribution in PDX, the following equation was modeled:

$$-\frac{D_{\parallel}}{R^2 q^2} \frac{\partial^2 n_k}{\partial \theta^2} - \frac{1}{r} \frac{\partial}{\partial r} r D_A(\theta) \frac{\partial n_k}{\partial r} = S_k \quad (8)$$

where $D_A(\theta)$ is taken to be of the form

$$D_A(\theta) = (1 + 0.25 \cos \theta) D_A. \quad (9)$$

with $D_A = 10^4 \text{ cm}^2 \text{ sec}^{-1}$, and the neutral carbon profile assumed to be cylindrically symmetric. We found that the asymmetry parameter of every species was less than 0.02 unless D_A and ν_i were each increased by a factor of five. Thus the parallel transport is simply too rapid to sustain poloidal asymmetries caused by an asymmetric diffusion coefficient.

SUMMARY AND CONCLUSIONS

In PDX there is a qualitative difference in the impurity behavior of ionization states in the Pfirsch-Schlüter regime (C II- C IV) and those in the plateau regime (C V) which relates to the proximity to the limiter. Impurity species located within the shadow of the limiter are more subject to edge processes such as recycling, and therefore vary substantially with plasma conditions, while the asymmetry of C V, which is located several centimeters inside the plasma

boundary, varies less with edge conditions. Both the experimental observations and the numerical simulations indicate that the C V asymmetry is not affected by that of the outer charge states. In general, the sign of the asymmetries of low ionization states of both carbon and oxygen is opposite the direction of the vertical ion drift. The magnitude of the asymmetry generally decreases towards the center of the discharge. A quasifluid neoclassical model of impurity transport reproduces the observed asymmetries of C V if the main ions are assumed to lie in the banana regime. A simplified kinetic formulation of the problem leads to asymmetries of approximately the correct magnitude, but does not reproduce the observed scaling.

ACKNOWLEDGMENTS

We would like to thank Dr. R. Hulse for making his one-dimensional transport code available, and Dr. R. Goldston for a critical reading of the manuscript. Some of the data discussed in this paper were provided by Dr. D. Johnson, Dr. B. Grek, Dr. G. Schmidt, and Dr. D. Mansfield. We wish to thank the head of the PDX group, Dr. Kees Bol, and also the PDX operators and technical staff for their efforts in keeping the machine running smoothly. We acknowledge the engineering and technical support of D. Hay, H. Feng, R. Mika, R. Mullen, G. Drozd, and G. D'Amico for their work on the FARM. This work supported by U. S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

APPENDIX

Here we derive the expression for the quasifluid model of impurity asymmetries. The impurity flow in a toroidally confined plasma may be described by the particle continuity and momentum equations:

$$\nabla \cdot n_I \mathbf{u}_I = S_I \quad (\text{i})$$

$$-\nabla p_I - Z_I n_I e \nabla \Phi + Z_I n_I e \frac{\mathbf{u}_I \times \mathbf{B}}{c} + \mathbf{R}_{II} = 0. \quad (\text{ii})$$

where $\mathbf{u}_I$ is the first order impurity flow velocity, S_I represents atomic rates, $p_I = n_I T_i(r)$, taking the impurity and proton temperatures to be equal and constant on a flux surface, Z_I is the ion charge, and $\mathbf{R}_{II}$ the friction force between impurities and protons. The magnetic field is assumed to be of the form

$$\mathbf{B} = \frac{B_0}{h} (\hat{\theta} + \Theta(r) \hat{\phi}) \quad (\text{iii})$$

with $h = 1 + \epsilon \cos \theta$. In general, there are N coupled equations of this type for an impurity with nuclear charge Z_N .

The friction force $\mathbf{R}_{II}$ is calculated from

$$\mathbf{R}_{II} = \int d^3 \mathbf{v} m_i v_i C_{II}(f_I, f_i) \quad (\text{iv})$$

where C_{II} is the linearized Fokker-Planck collision operator for impurity-proton collisions, and f_I and f_i the impurity and proton distribution functions, respectively. By expressing C_{II} in terms of the Rosenbluth potentials and expanding in powers of m_i/m_I , in the limit of large impurity mass it can be shown that

$R_{\parallel I}$ depends only on the two moments n_I and $u_{\parallel I}$ of f_I . Straightforward computation yields

$$R_{\parallel I} = \frac{m_i n_i}{r_{iI}} (u_{\parallel i} - u_{\parallel I} + u_{\parallel i}') \quad (\text{v})$$

where

$$u_{\parallel i} = \int d^3 v \frac{v_{\parallel} f_{i1}}{n_{i0}} \quad (\text{vi})$$

$$u_{\parallel I} = \frac{1}{n_I} \int d^3 v v_{\parallel} f_I \quad (\text{vii})$$

$$u_{\parallel i}' = \int d^3 v \left[\frac{3\sqrt{\pi}}{4} \left(\frac{v_{ti}}{v} \right)^3 - 1 \right] v_{\parallel} \frac{f_{i1}}{n_{i0}} \quad (\text{viii})$$

$$v_{ti} = \sqrt{\frac{2T_i}{m_i}} \quad (\text{ix})$$

$$r_{iI} = \frac{3\sqrt{m_i T_i^{3/2}}}{4\sqrt{2\pi n_I Z^2} \ln \Lambda} \quad (\text{x})$$

In the small aspect ratio limit ($\epsilon \ll 1$) we have

$$u_{\parallel i} = -\frac{cT_i}{eB_\theta} \left(\frac{n'}{n} + \frac{e\Phi'}{T} + 1 + g \frac{T'}{T} \right) - \frac{cT}{eB_\theta} \left(\frac{n'}{n} + \frac{e\Phi'}{T} + 1 - g \frac{T'}{T} \right) \epsilon \cos \theta \quad (\text{xi})$$

and $g=1.7, 0.5, -1.17$, respectively in the collisional, plateau, and collisionless regimes.^{14,15} To calculate $u_{\parallel i}'$ we employ previously derived expressions for the first order proton distribution function.¹⁶⁻¹⁸ Integrating f_{i1} over velocity, the terms which are proportional to a shifted Maxwellian vanish, and we are left with

$$u_{\parallel i}' = 2\epsilon \frac{ecT_i'}{eB_\theta} \cos \theta \quad (\text{xii})$$

where $\xi = 1, 1.5, -0.75$, respectively, in the collisional, plateau, and collisionless regimes.

The first order perpendicular flow is obtained by taking the cross product of the momentum balance equation with $\mathbf{b} (= \mathbf{B}/B)$

$$n_I \mathbf{u}_{\perp I} = c \frac{\mathbf{b} \times (\nabla p_I + Z_I e n_I \nabla \Phi)}{Z_I e B} \quad (\text{xiii})$$

To obtain an expression for the impurity density we need to solve the particle continuity equation, which can be written

$$\mathbf{B} \cdot \nabla \left(\frac{n_I u_{\parallel I}}{B} \right) + \nabla \cdot n_I \mathbf{u}_{\perp I} + \nabla \cdot n_I \mathbf{u}_r = S_I \quad (\text{xiv})$$

where the third term on the left hand side accounts for "anomalous" radial transport processes. Expressing the parallel impurity flow velocity in terms of $u_{\parallel i}$ and $u_{\parallel i}'$ and substituting in Eq. (13) we obtain

$$\begin{aligned} & -\frac{\tau_{ii} T}{\sqrt{2} m_i Z_I^2} \frac{1}{R^2 q^2} \left(\frac{\partial^2 n_I}{\partial \theta^2} + n_I Z_I \frac{\partial^2 \chi}{\partial \theta^2} \right) - \frac{c T}{e B_T r} \left(\frac{n_i'}{n_i} + 1 + g \frac{T_i'}{T_i} \right) \frac{\partial n_I}{\partial \theta} - \\ & \frac{2 T c \sin \theta}{e B_T R Z_I} \frac{\partial n_I}{\partial r} + \frac{2 T c}{e B_T R} n_I \left[\frac{n_i'}{n_i} + \left(1 - \xi - \frac{1}{Z_I} \right) \frac{T_i'}{T_i} \right] \sin \theta - \frac{1}{r} \frac{\partial}{\partial r} r D_A \frac{\partial n_I}{\partial r} = S_I \end{aligned} \quad (\text{xv})$$

where

$$\chi = \frac{e \Phi_1}{T_i} \quad (\text{xvi})$$

$$e \left(\frac{1}{T_e} + \frac{1}{T_i} \right) \Phi_1 = -A e \rho_{i0} \frac{T_i'}{T_i} \sin \theta \quad (\text{xvii})$$

and

$$A = \begin{cases} \frac{1.3}{\nu_T \tau_{ii}} & \text{in the Pfirsch-Schlüter regime} \\ \frac{\sqrt{\pi}}{2} & \text{in the plateau regime} \\ 1.28\nu & \text{in the banana regime} \end{cases} \quad (\text{xviii})$$

where $\nu_T = v_i/Rq$ is the ion transit frequency, and Φ_1 the first order poloidally varying part of the electrostatic potential. The first term on the left hand side of Eq. (10) describes the diffusive spreading of impurities driven by parallel pressure gradients; the term involving derivatives of χ describes the repulsion of the impurities from regions of high electrostatic potential, an effect which tends to reduce the asymmetry. In the original model by Burrell and Wong⁵ the diffusive spreading term was balanced by the fifth term, which describes the effects of friction and thermal forces. Note that if the coefficient within the square brackets is negative, in other words, if friction forces predominate over thermal forces, or if the electrostatic potential term is sufficiently large, the asymmetry is opposite the vertical drift. On the other hand, if the coefficient within the square brackets is positive, (true for $L_T/L_n < 1 - \xi - 1/Z_I$) and the electrostatic term is small, the asymmetry is in the same direction as $v_{\nabla B}$.

REFERENCES

- [1] TERRY, J. L., MARMAR, E. S., CHEN, K.I., MOOS, W. H., Phys. Rev. Lett., **39**, (1977) 1615.
- [2] SUCKEWER, S., HINNOV, E., SCHIVELL, J., Rapid Scanning of Spatial Distribution of Spectra Line Intensities in PLT Tokamak, PPPL-1430.
- [3] ALLEN, S., MOOS, W. H., RICHARDS, R. K., TERRY, J. L., MARMAR, E. S., Nucl. Fusion **21**, (1981) 251.
- [4] HOGAN, J. T., XII International Conference on the Physics of Electronic and Atomic Collisions, Proceedings, Gatlinburg, Tenn., (1981) 769.
- [5] BURRELL, K. H., WONG, S. K., Nucl. Fusion **19**, (1979) 1571.
- [6] HUGHES, M. H., POST, D. E., J. Comp. Phys. **28**, (1978) 43.
- [7] HULSE, R., Numerical Studies of Impurities in Fusion Plasmas, PPPL-1917, (1982).
- [8] BOTTCHEER, C., HEIL, T. G., XII International Conference on the Physics of Electronic and Atomic Collisions, Abstracts, Vol. 2, Gatlinburg, Tenn., (1981) 676.
- [9] OLSON, R.E., SHIPSEY, E. J., BROWNE, J. L., J. Phys. B **11**, (1978) 699.
- [10] SHIPSEY, E. J., BROWNE, J. L., OLSON, R. L., J. Phys. B **14**, (1981) 869.

- [11] BUTLER, S. E., Phys. Rev. A **20**, (1979) 2317.
- [12] HEIL, T., DALGARNO, A., J. Phys. B Lett. **12**, (1979) L557.
- [13] PHANEUF, R., XII International Conference on the Physics of Electronic and Atomic Collisions, Abstracts, Vol. 2, Gatlinburg, Tenn., (1981) 688.
- [14] HAZELTINE, R. D., Phys. Fluids, **17**, (1974) 961.
- [15] HIRSHMAN, S., SIGMAR, D. J., Nucl. Fusion, **21**, (1981) 1079.
- [16] HAZELTINE, R. D., HINTON, F. L., Phys. Fluids, **16**, (1973) 1883.
- [17] WONG, S. K., BURRELL, K. H., Phys. Fluids, **25**, (1982) 1863.
- [18] ROSENBLUTH, M. N., RUTHERFORD, P. H., TAYLOR, J. B., FRIEMAN, E. A., KOVRIZHNIK, L. M., (1971), in Plasma Physics and Controlled Nuclear Fusion Research (proc. 4th Int. Conf. Madison, 1971) Vol. 1, IAEA, Vienna (1971) 495.

FIGURE CAPTIONS

- FIG. 1.** PDX Fast Rotating Mirror (FARM) diagnostic.
- FIG. 2.** Cross section of magnetic field geometry in standard PDX circular (rail limited) discharge.
- FIG. 3.** Nonsymmetric radial scan of C III.
- FIG. 4.** Chordal profiles of C III and C V for $R_{\text{maj}} = 143$ cm (solid curves) and $R_{\text{maj}} = 152$ cm (dashed curves) circular discharges.
- FIG. 5.** Time evolution of $n_e t$ (upper figures) and radial scans of C III (lower figures) for two PDX circular discharges. During density flattening as, asymmetry of C III reverses direction.
- FIG. 6.** Chordal profiles of O III, C III, O V, and C V.
- FIG. 7.** (Left) Radial scans of C III during inner wall discharges for opposite directions of the vertical ion drift. (Right) Schematic of C III distribution in inner wall discharge illustrating positions of intensity maxima.
- FIG. 8.** Radial scans of C III and C V in circular discharges. The dashed (solid) curve corresponds to a vertical ion drift directed upward (downward).
- FIG. 9.** Experimentally observed values of η for C V plotted versus different quantities. (a) Quasi-neoclassical fluid theory scaling, main ions assumed to be in plateau regime: $L_T = 10$ cm, $L_n = 12$ cm, (b) same as above, but main ions in banana regime.
- FIG. 10.** Experimentally observed values of η for C V plotted versus different quantities. (a) η_{exp} versus $\bar{n}_e$. (b) η_{exp} versus η_{kin} .
- FIG. 11.** Density, temperature, and q profiles of discharges used in numerical modeling.
- FIG. 12.** Asymmetry parameter η of $\text{C}^{+1} - \text{C}^{+5}$ (triangles) vs. minor radius from numerical modeling using 2-D transport code. In Figs. (b) through (d) ν_n has been increased by factors of 3, 10, and 100, respectively, and

$$D_A = 10^4 \text{ cm}^2/\text{sec}, v_A = -10^3(r/a) \text{ cm/sec.}$$

FIG. 13. Plot of η for $C^{+1} - C^{+5}$ versus minor radius in 2-D modeling of charge exchange recombination theory of poloidal asymmetries. In (b), (c), and (d) $n_0(r)$ has been increased by factors of 2, 5, and 10, respectively.

#83X0426

SCHEMATIC OF THE FAST ROTATING MIRROR SYSTEM (FARM)

Fig. 1

#82P0124

Fig. 2

Fig. 3

#83X0206

Fig. 4

Fig. 5

Fig. 6

PDXToroidal
Bumper Limiter

Fig. 7

#03X0265

(a)

(b)

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

EXTERNAL DISTRIBUTION IN ADDITION TO TIC UC-20

Plasma Res Lab, Austro Nat'l Univ, AUSTRALIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. D. Palumbo, Dg XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.M. Saksanaka, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Telchmann, Univ of Montreal, CANADA
 Dr. H.M. Skersgaard, Univ of Saskatchewan, CANADA
 Prof. S.R. Greenlavan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Hannes Barnard, Univ British Columbia, CANADA
 Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
 Zhengou Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, SW Inst Physics, CHINA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-CEP, FRANCE
 AM Dupes Library, AM Dupes Library, FRANCE
 Dr. Tom Mui, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. A.K. Sunderam, Physical Research Lab, INDIA
 Dr. S.K. Trahan, Panjab University, INDIA
 Dr. Indre, Mohan Lal Das, Banaras Hindu Univ, INDIA
 Dr. L.K. Chavda, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Var Ruchi Haro, INDIA
 P. Kaw, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Cuperman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ DI Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Clelia De Palo, Assoc EURATOM-CNEN, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Prof. M. Yoshikawa, JAERI, Tokai Res Est, JAPAN
 Prof. T. Uchida, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sigeru Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Tech Info Division, Korea Atomic Ener., KOREA
 Dr. R. England, Ciudad Universitaria, MEXICO
 Bibliotheek, Fom-Inst Voor Plasma, NETHERLANDS
 Prof. B.S. Liley, University of Waikato, NEW ZEALAND
 Dr. Suresh C. Sharma, Univ of Calabar, NIGERIA
 Prof. J.A.C. Cabral, Inst Superior Tech, PORTUGAL
 Dr. Octavian Petrus, ALI CUZA University, ROMANIA
 Dr. R. Jones, Nat'l Univ Singapore, SINGAPORE
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Atomic Energy Bd, SO AFRICA
 Dr. J.A. Tagle, JEN, SPAIN
 Prof. Hans Wilhelmsson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Dr. Erik T. Karlson, Uppsala Universitet, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. W.L. Weise, Nat'l Bur Stand, USA
 Dr. W.M. Stacey, Georg Inst Tech, USA
 Dr. S.T. Wu, Univ Alabama, USA
 Prof. Norman L. Olsson, Univ S Florida, USA
 Dr. Benjamin Ma, Iowa State Univ, USA
 Prof. Magnus Kristiansen, Texas Tech Univ, USA
 Dr. Raymond Askew, Auburn Univ, USA
 Dr. V.T. Tolok, Khar'kov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. M.S. Rabinovich, Lebedev Physical Inst, USSR
 Dr. G.A. Eliav, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Prof. T.J. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universität, W. GERMANY
 Nuclear Res Estab, Jülich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Dr. H.J. Kaeppeler, University Stuttgart, W. GERMANY
 Bibliothek, Inst Plasmeforschung, W. GERMANY

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.