The high neutral densities and short neutral mean-free-paths in the Alcator C-Mod divertor have provided a unique testing ground for our understanding of the role of neutrals in a tokamak. The high neutral pressures found in the C-Mod divertor can be reproduced in models only by including such processes as ion-neutral and neutral-neutral collisions and neutral viscosity, as well as taking into account the plasma in the private flux region. After detachment, when the divertor plate ion flux has dropped by more than an order of magnitude, the divertor pressure still remains high. High neutral collisionality and the plasma in the private flux region again help keep neutrals in the divertor along with the large source of neutrals due to recombination. Likewise, diffusive neutrals are the explanation for the divertor neutral pressure’s insensitivity to strike point position. Closure of neutral leakage pathways did not lead to a decrease in neutral pressures in the region outside the divertor—the main chamber. This observation prompted further research, which showed that ion fluxes to main chamber surfaces rival those reaching the divertor plates; the main chamber pressure can be primarily determined by the level of ion transport perpendicular to the magnetic field. This finding has spawned a host of studies (active and passive) both at C-Mod and other tokamaks to understand how radial transport can be so large.

KEYWORDS: neutrals, Alcator C-Mod, divertor

NOTE: Some figures in this paper are in color only in the electronic version.

I. INTRODUCTION

The role of neutrals in the divertor and their sources, ionization, and control are emphasized in the Alcator C-Mod program. Divertor neutrals play a central role in divertor pumping throughput, in assisting divertor detachment, and in fueling the core plasma. It is less clear how they affect the core plasma performance (e.g., confinement, structure of the H-mode pedestal) and what the most important "neutral leakage" pathway is, i.e., via direct escape from the divertor or via leakage to the midplane/scrape-off layer (SOL). In addition, the role of neutrals recycling on main chamber wall surfaces needs to be considered.

Predictions of divertor plasma performance for a burning plasma experiment (BPX) such as ITER will remain uncertain unless the physics in the predictive codes can be checked against divertor experiments with relevant plasma conditions. The neutral mean-free-paths in ITER, normalized to the size of the divertor, are smaller than those for any currently operating tokamak. This is also true for the level of hydrogen resonance line radiation trapping (Lyα) in the divertor, which strongly affects the ionization/recombination balance. The plasma density (and accompanying ion fluxes and n_i) in the C-Mod divertor, and the Lyα trapping (proportional to n_iL), are closest to that predicted for ITER among existing tokamaks. Thus, the benchmarking of predictive codes against C-Mod plasmas is a crucial test. Until recently, the correspondence between code results and experiment has been poor in that the predicted divertor pressures for C-Mod were low by an order of magnitude. However, recent modeling of the C-Mod divertor plasma and neutrals has been more successful. This is due to the inclusion of a number of previously neglected physical effects and the forcing of a better match between an interpretive
plasma model and measured plasma background parameters. Yet, as will be discussed, this is just the first of many neutral modeling comparisons with C-Mod data that are needed.

Central to the discussion of the neutral species in Alcator C-Mod are measurements of the neutral pressure. Pressure gauges are placed at a number of locations in C-Mod, both toroidally and poloidally, as shown in Fig. 1. The pressure gauges used include absolutely calibrated baratron capacitance gauges and Bayard-Alpert gauges (nude, but magnetically shielded) on ports. In addition, there are a number of Penning gauges mounted on internal vessel surfaces. The inner divertor plate shape as shown in Fig. 1 was changed in 2002 (see Ref. 3 for a figure showing the new shape). The period prior to 2002 corresponds to the majority of the data included herein. In addition, the physics of neutral transport discussed herein does not appear to be affected by the change in geometry.

II. SCALING OF DIVERTOR NEUTRAL PRESSURES
IN SHEATH-LIMITED, HIGH-RECYCLING,
AND DETACHED REGIMES

Divertor characteristics vary considerably as the core conditions are varied. In the simplest ohmic-heated plasmas, the divertor plasma goes from sheath-limited to high-recycling to detached regimes as the core density is increased. Accompanying the changes in plasma characteristics are changes in the divertor neutral pressures. An example is given in Fig. 2 for the original C-Mod divertor geometry (Fig. 1). As will be discussed, modifications were later made to the divertor that increased the divertor pressure. In the sheath-limited regime the divertor pressure is found to be fairly constant or slowly increasing with plasma density, but it rises rapidly when the divertor transitions into the high-recycling regime. Finally, when the outer divertor detaches, the divertor pressure continues to rise, but much more slowly. The

![Fig. 1.](image-url)
neutral pressure dependence on density parallels the non-
linear variation in plasma characteristics measured at
the divertor plate up to the density of detachment onset. Thus,
as the detachment threshold is modified (e.g., by chang-
ing input power or injecting impurities), the curve shown
in Fig. 2 shifts to lower or higher densities. We
note particularly that as the power flowing to the divertor is
increased, the detachment threshold and maximum di-
verter pressure increase as well.

At first glance the observed neutral pressure behav-
ior appears quite straightforward. For the lowest densi-
ties, the low ion fluxes incident on the divertor plates
(source of neutrals) and their long mean-free-paths allow
them to easily escape the divertor; both effects lead to
low neutral densities in the divertor. In the high-recycling
regime, the combination of rapidly increasing ion fluxes
and shorting neutral mean-free-path leads to a positive
feedback mechanism, raising the neutral pressures. Power
flow to the divertor is what supports the increase in di-
verter ion recycling and neutral pressures observed. On
the other hand, in detached regimes the divertor ion fluxes
drop by a factor of 10 or so, yet the divertor pressure
continues to increase. This lack of connection between
the neutral source (ion fluxes) and the neutral pressure
during detachment indicates that additional physics plays
a role in this regime.

It has been pointed out that the divertor plasma is
very cold over a large region ($T_e < 5$ eV) in C-Mod
detached plasmas. In this limit, the neutral mean-free-
path for ionization, $\lambda_{\text{ioniz}}$, is larger than that for
momentum transfer (charge exchange and elastic collisions),
$\lambda_{\text{mt}}$. In addition, the mean-free-path for momentum trans-
fer is short compared to the divertor dimension $L_D$, which
means that the neutral transport through the background
plasma is diffusive ($\lambda_{\text{mt}} < \lambda_{\text{ioniz}} < L_D$). In this regime,
the albedo $A$ of the divertor plasma for neutrals trying to
penetrate through it can be approximated as $A = 1 -
\lambda_{\text{mt}}/L_D$. Thus, as the plasma detaches, the albedo of the
divertor plasma increases, reducing the leakage of neu-
trals from the divertor plasma, allowing a similar divertor
pressure to be sustained with a smaller source of neutrals
(i.e., ion flux to the divertor target). The model used did not include the effect of recombination in the plasma,
which, because it is an additional neutral source, would
increase the neutral pressure in the divertor further. How-
ever, it was hypothesized that it would have a significant
effect. Later volume recombination estimates derived from
spectroscopic measurements of the Balmer series showed
that the recombination neutral source (sink for ions) can
be large when the outer divertor is detached. However,
the recombination neutral source does not quite make up
for the large (factor of 10 drop) loss in ion current to the
divertor plate, and so the total neutral source in the di-
verter does indeed drop during detachment.

III. EFFECT OF GEOMETRY ON DIVERTOR PRESSURE

The neutral pressure in the divertor was found to be
remarkably insensitive to the divertor and strike point
geometry in Alcator C-Mod. The pressure measurement
data shown in Fig. 2 are indicative of the pressure in the
plenum located behind a “closed” section of the outer
divertor plate (see Fig. 1). Thus, with the outer divertor
strike point in its standard vertical plate position (Fig. 18a
of Ref. 4), the measurement plenum is connected to the
private flux zone (PFZ) below the x-point. As the outer
divertor strike point is shifted to the top of the outer
divertor plate (flat-plate divertor, Fig. 18c of Ref. 4), the
pressure gauge still samples the PFZ. However, in this
configuration, the recycling occurs on the top of the di-
verter such that neutrals are generally launched in a di-
rection toward the core plasma and away from the divertor.
If the strike point is shifted down past the bottom of
the outer divertor to the floor (slot divertor, Fig. 18b of Ref. 4),
the recycling still occurs in the divertor but the pressure
gauge samples the common flux zone of the SOL. Fig-
ure 3 shows the result of these variations in magnetic
geometry, with the x axis indicating the location of en-
trance to the plenum with respect to the separatrix, re-
ferenced to midplane. The pressure has a mild maximum
when the outer divertor strike point is located near the
entrance to the measurement plenum behind the plate (at
the bottom of the outer plate). The lack of a strong de-
pendence on strike point location is in contrast to results
from other lower-density devices, where, unlike in C-Mod plasmas, the neutral collisional mean-free-path
in the divertor (cx and elastic), $\lambda_{\text{MFP}}$, is long compared to
the divertor dimensions and ionization length, $\lambda_{\text{IONIZ}}$
($\lambda_{\text{MFP}}/L_D > 1, \lambda_{\text{MFP}}/\lambda_{\text{IONIZ}} > 1$); the neutral transport is “ballistic,” and neutrals reach the pressure measure-
ment plenum only if they enter it on the first bounce.

Fig. 2. Divertor neutral pressure versus line-averaged plasma
density, spanning different divertor plasma regimes. From Ref. 7.
IV. MODELING OF THE DIVERTOR NEUTRAL PRESSURE

The development of numerical tools to model the C-Mod divertor, and by extension the ITER divertor, is still in its infancy. As mentioned, the effort to match the C-Mod divertor conditions\(^1\) led to simulated divertor pressures that were a factor of 10 below the measurements. That effort relied on a simple model for the divertor plasma.

More recently, the problem has been attacked again with the aim to develop a more accurate plasma description for the C-Mod divertor and to include a more extensive set of neutral physics, including radiation trapping effects.\(^2,14\) This effort led to a better match between model and experiment. The plasma under investigation was a medium-density C-Mod discharge (also used in Ref. 1) in which the inner divertor and PFZ plasmas were detached but the outer divertor plasma was attached. The EIRENE neutral transport code was used.\(^15\) The modeled divertor plasma solution was reconstructed from experimental measurements using the onion skin method.\(^16\) In particular, a simple, parameterized model for the profile of plasma conditions along the flux tube through the detached region was used. The plasma solution was forced to match, in an overall sense, the data from a host of plasma diagnostics ranging from Langmuir probes in the plates to spectroscopic measurements of D\(_2\) emissivity, which is indicative of the occurrence of volume recombination, and the local density and temperature in the detached/recombining regions. The match of D\(_2\) emission between experiment and modeling is shown in Fig. 4. The two recombination zones correspond to the high-emission regions in the PFZ paralleling the inner and outer legs.

A number of factors were found to be essential to obtain the observed high neutral pressures in the divertor. Neutral viscosity (arising from neutral-neutral collisions) is important inside the pressure measurement plenum; it supports a gradient in the D\(_2\) density that extends from the PFZ into the plenum volume. However, neutral viscosity was found to be significantly less important outside the plenum, where plasma-neutral interactions dominated instead.

D\(^{+}\)–D\(_2\) elastic collisions in particular were found to be a necessary element for achieving higher divertor neutral pressures. Molecules traveling to the PFZ from the plenum volume have a high probability to scatter off the...
cold, dense plasma in the PFZ. This leads to an effective albedo $A$ of the PFZ plasma to the incident molecules. A flux balance can be assumed between hot neutrals entering the plenum and cold neutrals returning from the plenum to the PFZ. For a given primary influx of neutrals into the PFZ from the plenum (particles entering the PFZ for the first time), $\Phi_0$, a fraction $A\Phi_0$ is reflected back into the plenum. That flux then tries to enter the PFZ again, leading to $A^2\Phi_0$ returning toward the plenum. This infinite series can be expressed as the total influx $\Phi_{tot}$ by

$$\Phi_{tot} = \frac{\Phi_0}{1 - A},$$

which is highly nonlinear as $A \to 1$. We can see evidence of the plasma-neutral collisions in the gradient in the density profile, Fig. 5. The density gradient at the entrance to the plenum is due to

1. the conversion of D to D$_2$ via wall collisions
2. the temperature gradient between the higher-energy molecules outside the plenum (which have partially thermalized with the plasma via D$^+$-D$_2$ elastic collisions) and the colder gas inside the plenum that has thermalized with the walls
3. the higher-energy neutrals “pushing” on the colder plenum gas via neutral-neutral collisions.

While neutral viscosity and plasma neutral collisions are important for increasing the divertor plenum pressure in the model, photon trapping has an important effect in lowering the divertor pressure. If a Lyman series photon emitted during a volume recombination event leaves the system either directly or through multiple absorptions and reemissions, the result is the creation of a ground-state neutral atom. We call this a complete recombination.\textsuperscript{17} However, if that photon is absorbed by a neutral atom before leaving the system and that neutral is ionized before reemitting the photon, then there is no net gain in neutrals due to the volume recombination event (no complete recombination). This is termed photon trapping. Thus, for a fixed plasma solution, which is the case here, proper accounting of the radiation transport and subsequent reionization leads to a reduction in the calculated recombination rate compared to the untrapped case. The modeling of the photon transport was done with EIRENE and included Doppler and natural broadening, taking into account Ly$_{\alpha}$ through Ly$_{\epsilon}$ trapping. Zeeman splitting and Stark broadening have recently been incorporated into the modeling but are expected to introduce only a 10 to 20% change in trapping rates. Finally, the existence of openings (leakage) in the outer divertor structure was included in EIRENE, which lowered the divertor pressure by roughly 60%. The relative importance of three of the above effects is shown in Fig. 6.

Overall, the modeled discharge produced pressures around 11 mTorr, a factor of 5 above what was achieved previously\textsuperscript{1} but still a factor of $\sim$2 below that measured in experiment ($25 \pm 3$ mTorr). It is unclear at present whether the remaining discrepancy is due to deficiencies in the neutral model or inaccuracies in the plasma solution. This effort is continuing with improvements to the
plasma and radiation transport models as well as modeling of higher-density discharges where the outer divertor is detached, leading to a higher level of photon trapping and shorter mean-free-paths (neutral and plasma). These divertor plasma conditions are even closer to an ITER-like device and provide an important test for the code’s capabilities.

V. EFFECT OF DIVERTOR CLOSURE ON NEUTRAL PRESSURES

A high divertor neutral pressure is desirable in a reactor since He ash removal is required and gas throughput is proportional to pumping speed times neutral pressure. One would expect that any neutral leakage from the divertor might lower the pressure below that of the ideal “sealed” divertor. In addition, it is desirable to minimize the neutral pressures in the main chamber. In reducing the neutral levels near the vessel walls outside the divertor, the main chamber impurity sources arising from charge exchange neutral sputtering of the wall should be reduced. Moreover, better control of core fueling should result. In practice, any divertor structure has intrinsic pathways (e.g., gaps for thermal expansion) through which neutrals can “leak” out of the divertor. These pathways are difficult to seal because of the complex mechanical structure. Nevertheless, the overall expectation has been that any success in reducing those leaks should lead to increases in the divertor pressure simultaneously with decreases in the main chamber pressure. With this view in mind, efforts were undertaken in C-Mod to close these intrinsic neutral pathways. However, the efforts led to some unexpected results.

Based on the simple modeling of divertor pressures outlined in the previous section, it was predicted that if the toroidally semicontinuous gap (poloidal gap) between the largest major radius edge of the outer divertor and the vessel wall were closed (see Fig. 1a), then the divertor pressure should rise by a factor of 1.7 and the midplane pressure should be halved. A further suggestion was made that if one changed the outer divertor geometry such that a larger fraction of the outer SOL impacts the vertical-plate section of the divertor, then more neutrals would be created in the divertor instead of the main chamber and thus increase the divertor pressure (and lower the midplane pressure).

Acting on the first of the above suggestions for modifying the divertor, the poloidal gap between the outer divertor and the vessel was filled with fiberglass insulation that, when compressed, drops the conductance through the gap to a small fraction of its original value. In fact, the closure of the poloidal gap did lead to an increase in the divertor-to-midplane neutral pressure ratio by a factor of 2 to 3 (see Fig. 7b). This increase was almost entirely due to an increase in the divertor pressure; there is little or no evidence for a corresponding decrease in main chamber pressure as a result of closing the leak (Fig. 7a), suggesting that the main chamber neutral pressure is set primarily by some other physical mechanism. The leakage through the poloidal gap represented approximately half the overall leakage out of the divertor, with the remaining leakage due to the toroidal gaps between sections of the outer divertor plate required for diagnostic access.

VI. MAIN CHAMBER RECYCLING

The minimal, if any, reduction in main chamber pressures after the closure of the divertor leakage foreshadowed a radical rethinking of the plasma transport physics in the C-Mod SOL, in particular, the relative strengths of cross-field versus parallel ion transport. Based on Mach probe measurements at the entrance to the outer divertor, the integral ion flux into the throat of the divertor is small compared to the amount of ionization occurring outside the divertor and fueling the plasma. Since any neutrals escaping from the divertor must return as ions or neutrals back into the divertor, the level of divertor neutral leakage could not by itself account for the level of neutral ionization observed in the main chamber. The implication was that the source of neutrals in the main chamber must be from ions recycling on main chamber surfaces. To support these conclusions, it was argued that there must be very strong radial ion transport in the SOL, with an effective diffusion coefficient increasing strongly with distance from the separatrix.

Modeling, using UEDGE (Ref. 20), was brought to bear on the above set of experimental data with the same end result—divertor leakage (and thus divertor closure) does not have a large effect on main chamber neutral levels. An example of the match to experimental data is shown in Fig. 8. As stated, the amount of main chamber ionization, which is equivalent to the total flux of neutrals “attacking” the plasma, is much greater than the...
ion flux into the divertor. It can certainly be argued that for scenarios where the divertor neutral leakage is very large, it could indeed affect the observed main chamber neutral levels. However, the action of closing the divertor to neutral leakage beyond a point where the leakage is small relative to the integral of ion fluxes to main chamber surfaces obviously has little effect on the main chamber pressure. This appears to be the case in C-Mod and for high densities in JET (Ref. 12). Modeling of ASDEX-Upgrade plasmas led to a similar conclusion regarding the role of radial plasma transport. More recently, studies of DIII-D and JET SOL transport also indicate that strong radial transport exists in a number of devices and that the main chamber–recycling effect can be an important contributor to neutral pressures outside the divertor.

VII. ACTIVE EXPERIMENTS TO DETERMINE THE IMPORTANCE OF MAIN CHAMBER RECYCLING

Even though the concept of main chamber recycling appeared to explain the disparity between the effect of divertor closure on the midplane and divertor pressures, doubts remained. In particular, there was a concern that conditions of the chamber walls (neutral retention characteristics, wall-recycling levels) or of the plasmas themselves could have been different between the run periods with and without the divertor closure. Based on this concern, a divertor bypass valve system was designed and built (see item 8 in Fig. 1). The conductance between the divertor plenum and the main chamber is altered by the bypass, which consists of 10 discrete structures equi-spaced in the toroidal direction. The locations in the divertor structure are shown in Fig. 1. A single unit consists of seven louvered flaps. The total area of the bypass is 0.08 m², giving a free-molecular conductance of ~23 m³/s. This amount of conductance is comparable to the intrinsic leakage conductance through the open ports as well as the leakage through the toroidally semicontinuous gap that had been closed. The bypass is controlled using a small embedded coil. When energized, the resulting interaction with the ambient toroidal magnetic field

![Fig. 7.](image-url) (a) Main chamber and divertor neutral pressures before and after closing a neutral leakage pathway in the C-Mod divertor. (b) Compression ratio of divertor-to-midplane pressures.

![Fig. 8.](image-url) Rough estimates of ionization fluxes in the main chamber from midplane Dₐ (closed diamonds), ion fluxes toward the divertor from the scanning Langmuir/Mach probe (closed stars), and ion fluxes onto divertor surfaces from divertor probes (squares) as a function of an estimate of the neutral flux from the wall. UEDGE simulations of two discharges yield similar results: Fluxes from the main chamber ionization (open diamonds) are much higher than fluxes directed toward the x-point (open stars). From Ref. 22.
produces a torque that rotates all seven flaps of the bypass. The bypass can open or close in a time as short as \( \sim 20 \) ms.

Experiments showed that the bypass valve affected only the divertor pressure, not the midplane pressure—the same response seen previously when the toroidally, semicontinuous leakage gap (item 11 in Fig. 1a) was closed by a “glass-sock” material. Figure 9 shows the divertor and midplane pressures as a function of \( \bar{n}_e \) for both open and closed bypass conditions. All plasmas are with ohmic heating only. The midplane pressure increases strongly with \( \bar{n}_e \), roughly as \( \bar{n}_e^4 \). The divertor pressure also increases strongly. We see that the opening of the bypass lowers the divertor pressure by a factor of \( \sim 2 \). The saturation in divertor pressure above \( \bar{n}_e = 1.8 \times 10^{20} \text{ m}^{-3} \) is due to detachment.

The divertor and main chamber plasma parameters were carefully compared with and without the bypass open. There were no significant differences seen in the profiles of the plasma across the divertor plate, the plasma across the SOL, or the flows in the SOL.

One initial aim of the bypass experiment was the investigation of the effect on the main chamber SOL of changing the flux of neutrals escaping the divertor. Measurements of \( D_a \) just above the bypass indicated that a portion of the flux of neutrals through the bypass is ionized in the main chamber relatively close to the bypass. Such a particle flux must recirculate as ion flow in the SOL in steady state, ultimately returning to the divertor. The probe at the entrance to the divertor shows a well-defined net flux into the outer divertor, which does not depend on the state of the valve. In addition, that flux into the divertor is smaller than, but similar to, the flux estimated (based on molecular flow) to pass through the bypass. The probe and \( D_a \) measurements suggest that most of the particles going through the bypass return directly to the outer divertor and are not transported as ions around the plasma periphery. Apparently, the influence of the bypass valve state tends to be lost in the presence of a relatively large amount of main chamber recycling.

Alternatively, the observation that the midplane pressure and flux into the divertor is insensitive to the bypass valve state might be explained by a tendency for the plasma to maintain a constant leakage flux from the divertor plenum to the main chamber. In other words, when the bypass is opened, the conductance out of the divertor increases, the divertor pressure decreases, and the net flux (conductance times pressure) might stay approximately constant. It was argued that such a “fixed flux” of neutrals might be set by a rate-limiting process, such as the ion flux to the divertor, which is the primary source of neutrals in the divertor.\(^{29}\) Based on these considerations, the relative contributions to the midplane pressure of main chamber recycling and neutral leakage from the divertor remained uncertain.

As a result of this ambiguity, further experiments were conducted in an attempt to unfold the relative roles of divertor leakage and main chamber recycling.\(^{30}\) These involved a comparison of the pressures in the upper divertor (locations 1 and 2 of Fig. 1), the midplane (location 5), and the lower divertor (locations 9 and 10). Location 9 corresponds to the toroidal location where the lower divertor is fully “closed,” i.e., with no local toroidal opening, while location 10 is at a diagnostic port opening (“open”)—a location where a 6 deg toroidal sector of divertor is removed for diagnostic access. Figure 10 summarizes the results. Midplane pressure is plotted as a function of the three divertor pressure measurements (lower divertor closed and open and upper divertor). These data exhibit a linear correlation between the midplane pressures and the lower open divertor and/or the upper divertor pressures; a nonlinear relationship between midplane and closed divertor pressures is found.\(^{30}\) Thus, it is unlikely that the closed divertor plays a direct role in determining the midplane pressure, except indirectly through neutrals traveling to the open divertor. We note that the upper divertor neutral pressure is the result.

![Fig. 9. (a) Midplane and (b) divertor pressure and (c) their ratio as a function of line-averaged density for cases with bypass valve open and closed. From Ref. 28.](image-url)
of recycling there of plasma on flux surfaces in the SOL far outside the separatrix, in the region of the second separatrix. The gap between first and second separatrix, mapped to the midplane, SSEP, is in the range 1.5 to 2 cm for most C-Mod experiments.

The linear scaling between the lower divertor (open port) pressure ($P_{LD}$), the upper divertor pressure ($P_{UD}$), and the midplane pressure ($P_{0,\text{Mid}}$) is consistent with a simple model\cite{30} that balances the number of neutrals outside the divertor attacking the core plasma per unit time ($\Gamma_{1,0}$) through the plasma surface area $A_{\text{Plasma}}$ with the neutral flux through lower (open) and upper divertor leakage areas, $A_{L,\text{Leak}}$ and $A_{U,\text{Leak}}$:

$$P_{0,\text{Mid}} = f (P_{UD}R_{UA} + P_{LD}R_{LA}) + P_{\text{MCR}}.$$  \hspace{1cm} (2)

The contribution of main chamber recycling at outer wall surfaces to the midplane pressure is denoted by $P_{\text{MCR}}$. The ratio of $A_{L,\text{Leak}}$ to $A_{\text{Plasma}}, R_{LA} = 0.0136$, and $R_{UA} \sim 8 \times R_{LA}, f$ is the probability that an escaping neutral will reach the midplane before being ionized.

Since $P_{LD}R_{LA} \sim P_{UD}R_{UA}$, then the contribution to the midplane pressure due to main chamber recycling at the top of the chamber is already similar to the effect of leakage from the lower divertor. Allowing main chamber recycling at the outer wall ($P_{\text{MCR}}$) will reduce the relative contribution of lower divertor leakage still further.

Using a plausible upper limit for $f$ (0.5), $P_{\text{MCR}}$ was estimated. Substituting in the scaling relationships of Figs. 10b and 10c between $P_{UD}, P_{LD}$, and $P_{0,\text{Mid}},$ we find $P_{\text{MCR}} \sim 0.67 \times P_{0,\text{Mid}}$. If we assume that the upper chamber contribution to the midplane pressure is really just part of main chamber recycling, then main chamber recycling contributes $\sim 80\%$ of the midplane pressure.

The data of Fig. 10 show that it is difficult to separate out the effects of the different divertor geometries (lower or upper) on the midplane pressure because of the strong correlation with $\dot{n}_p$. One strategy used to separate out the effects of the different divertors is to vary the magnetic equilibrium from single-null x-point at the lower divertor (LSN) to double-null (symmetric up-down x-points). We use SSEP as a measure of x-point balance. Figure 11

![Fig. 10. Correlations between midplane pressures and (a) lower, closed divertor, (b) lower open divertor, and (c) upper divertor pressures. From Ref. 30.](image)

![Fig. 11. Dependence of neutral pressures on the x-point balance (SSEP) in otherwise identical discharges. SSEP = 0 corresponds to a balanced double-null case. SSEP < 0 corresponds to LSN divertor. Symbols indicate measurements. Lines indicate model results. See Fig. 1 for locations of pressure gauges. From Ref. 30.](image)
includes data from the upper divertor, midplane, and lower divertor (closed and open ports) pressures versus the SSEP parameterization. The curves in Fig. 11 show the result of fitting the pressure data from the divertors and using that as input to the model prediction [simpler version of Eq. (2)] of the midplane pressure. The contributions to the midplane pressure are $P_{\text{MCR}}/P_{0,\text{Mid}} \sim 0.9$ and $P_{\text{L},\text{Leak}}/P_{0,\text{Mid}} \sim 0.1$. We note that this estimation of $P_{\text{MCR}}/P_{0,\text{Mid}}$ is not dependent on knowing the values of $f$, $R_{\text{LA}}$, and $R_{\text{UA}}$.

Finally, a third method of determining $P_{\text{MCR}}/P_{0,\text{Mid}}$ was used in this study. The lower divertor pressure was changed by changing the inner wall gap (keeping the gap to the outer limiters constant). This lowered the lower divertor pressure by a factor of 4 with $\sim 10$ to 25% drop in the midplane pressure. This again shows that the lower divertor leakage plays a minor role in determining the midplane pressure. In summary, the techniques utilized for examining the relative effects of divertor leakage and main chamber recycling in determining the midplane pressure give essentially the same result, $P_{\text{MCR}}/P_{0,\text{Mid}} \sim 0.8$ to 0.9 and the transmission of neutrals to the midplane, $f$, in the range 0.1 to 0.5.

Although the preceding analysis examines the role of divertor leakage in determining the midplane pressure, the question of the relative roles of mechanical (baffling) versus plasma blockage (or “plasma-plugging”) of the neutral flows was not addressed. Neutral pressures in the toroidally and poloidally open upper divertor during upper $x$-point discharges are found to be comparable to neutral pressures in a short (toroidally) open section of the lower divertor during lower $x$-point discharges. These results suggest that plasma baffling must make a significant contribution in reducing the overall leakage conductance (i.e., “effective conductance”). A study was undertaken to address this question. A novel experimental technique was employed, using capillaries to puff known flow rates of $D_2$ gas into different parts of the lower divertor (open and closed sections) as well as the upper, open divertor with and without plasma present. Localized pressure measurements were also made nearby, allowing the gas conductance and flow through the various structures to be measured directly. It was found that the presence of an LSN in the vacuum vessel lowers the effective neutral conductance out of the open sections of the lower divertor (diagnostic openings) by a factor of $\sim 4$ relative to the vacuum conductance value. Conductances out of the closed sections of the lower divertor are also reduced by the presence of this plasma, but only by a factor of $\sim 2$. The LSN plasma was even found to influence the overall neutral conductance from the upper divertor chamber, dropping the conductance there by a factor $> 2$. When the plasma magnetic equilibrium was switched to upper single null, a dramatic drop in effective leakage conductance from the upper divertor was seen—a reduction of a factor of $\sim 5$ relative to the vacuum conductance value. Recently, Stotler and LaBom-

VIII. SUMMARY

The divertor characteristics of Alcator C-Mod lead to neutral densities and mean-free-paths approaching those predicted for ITER, thus providing essential tests of neutral and plasma models. C-Mod research shows that in addition to divertor recycling, three-body recombination can be an important neutral source affecting divertor pressures. Experimental results and simple models show that the diffusive nature of neutrals in C-Mod reduces their chance of escape from the divertor during detachment. That together with recombination are key reasons the divertor pressure does not drop even though the ion flux to the divertor plates drops by a factor of 10. The short neutral mean-free-path in C-Mod (normalized to the size of the divertor), approaching that of ITER, leads to an absence of an effect of divertor strike point geometry on neutral pressure, unlike in other tokamaks, where neutrals are more kinetic in nature. The testing of plasma-neutral codes on C-Mod divertor conditions proved very difficult since they had only been tested under kinetic neutral conditions. Careful comparison of the models with experiment showed that the physics associated with short neutral mean-free-paths (e.g., viscosity) and trapping of hydrogenic Lyman alpha radiation play an important role in determining the neutral pressure. Of equal importance is the result that the private flux region must be modeled properly, including detachment effects, to recover the neutral pressure.

Neutrals studies of regions outside the divertor proper have also led to groundbreaking results. The minimal reduction of the C-Mod main chamber pressure after leaks of neutrals from the divertor were significantly reduced (and the divertor pressure increased) became essential to the shift in understanding of the role of perpendicular transport in the SOL: Only larger than expected ion fluxes to surfaces outside the divertor could support recycling and neutral sources comparable to that in the divertor. This realization led to a number of active and passive experiments and modeling to support this hypothesis. The end result is that the C-Mod research has played an important role in characterizing the phenomena of radial transport and its consequences.

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REFERENCES

1. D. P. STOTLER et al., J. Nucl. Mater., 290, 967 (2001).
2. S. LISGO et al., J. Nucl. Mater., 337–339, 139 (2005).
3. J. L. TERRY et al., “The Scrape-Off Layer in Alcator C-Mod: Transport, Turbulence, and Flows,” Fusion Sci. Technol., 51, 342 (2007).
4. B. LIPSCHULTZ et al., “Divertor Physics Research on Alcator C-Mod,” Fusion Sci. Technol., 51, 369 (2007).
5. B. LaBOMBARD, Phys. Plasmas, 2, 2242 (1995).
6. B. LIPSCHULTZ et al., J. Nucl. Mater., 220–222, 50 (1995).
7. A. NIEMCZEWSKI et al., Nucl. Fusion, 37, 151 (1997).
8. B. LIPSCHULTZ et al., J. Nucl. Mater., 241–243, 771 (1997).
9. A. NIEMCZEWSKI, “Neutral Particle Dynamics in the Alcator C-Mod Tokamak,” PhD Thesis, Massachusetts Institute of Technology, Nuclear Engineering Department (1995).
10. B. LIPSCHULTZ et al., Phys. Plasmas, 6, 1907 (1999).
11. R. MAINGI et al., Nucl. Fusion, 39, 1187 (1999).
12. A. LOARTE, Plasma Phys. Control. Fusion, 43, 183 (2001).
13. H. TAKENAGA et al., Nucl. Fusion, 41, 1777 (2001).
14. S. LISGO, “Interpretive Modeling of the Alcator C-Mod Divertor,” PhD Thesis, University of Toronto, Aerospace Department (2003).
15. D. REITER, S. WIESEN, and M. BORN, Plasma Phys. Control. Fusion, 44, 1723 (2002).
16. P. C. STANGEBY, The Plasma Boundary of Magnetic Fusion Devices, Institute of Physics Publishing, Bristol, England (2000).
17. J. L. TERRY et al., Phys. Plasmas, 5, 1759 (1998).
18. B. LaBOMBARD et al., J. Nucl. Mater., 241–243, 149 (1997).
19. M. V. UMANSKY et al., Phys. Plasmas, 5, 3373 (1998).
20. T. D. ROGNLIEN et al., J. Nucl. Mater., 196–198, 347 (1992).
21. M. V. UMANSKY et al., Phys. Plasmas, 6, 2791 (1999).
22. B. LaBOMBARD et al., Nucl. Fusion, 40, 2041 (2000).
23. B. LaBOMBARD et al., Phys. Plasmas, 8, 2107 (2001).
24. H. S. BOSCH et al., J. Nucl. Mater., 220–220, 558 (1995).
25. B. LIPSCHULTZ et al., “A Study of JET SOL Radial Transport Based on Particle Balance,” in Controlled Fusion and Plasma Physics, St. Petersburg, Russia, Vol. 27A, p. 3.197, European Physical Society, Geneva (2003).
26. B. LIPSCHULTZ, D. WHYTE, and B. LaBOMBARD, Plasma Phys. Control. Fusion, 47, 1559 (2005).
27. D. WHYTE et al., Plasma Phys. Control. Fusion, 47, 1579 (2005).
28. C. S. PITCHER et al., Rev. Sci. Instrum., 72, 103 (2001).
29. C. S. PITCHER et al., Phys. Plasmas, 7, 1894 (2000).
30. B. LIPSCHULTZ et al., Plasma Phys. Control. Fusion, 44, 733 (2002).
31. B. LaBOMBARD and C. J. BOSWELL, “In-Situ Gas Conductance and Flow Measurements Through Alcator C-Mod Divertor Structures With and Without Plasma Present,” PSFC/RR-03-06, Massachusetts Institute of Technology Plasma Science and Fusion Center (2003).
32. D. P. STOTLER and B. LaBOMBARD, J. Nucl. Mater., 337–339, 510 (2005).