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** See annex of M.L. Watkins et al, "Overview of JET Results ", (Proc. 21st IAEA Fusion Energy Conference, Chengdu, China (2006)).*

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## INTRODUCTION

JET performed two dedicated migration experiments on the final run day of separate campaigns using $^{13}CH_4$ methane injected into repeated discharges. The $^{13}C$ deposition was measured by IBA and SIMS techniques on removed vessel components from one poloidal location [2, 3]. One experiment used localized injection into L-Mode plasmas from the vessel top. In the second, the methane introduction was dispersed toroidally near the outer strike point in Type I ELMy H-Mode plasmas (Fig.1). The EDGE2D/NIMBUS code has been used to model carbon migration in both experiments. The important migration pathways were: 1. Re-deposition and erosion near the injection location, 2. Migration through the main chamber SOL, 3. Migration through the private flux region, and 4. Neutral migration originating near the strike points. In H-Mode, the migration is influenced by the ELM cycle.

These JET experiments are ideal for modeling. Campaign integrated material migration has historically been difficult to analyze since the erosion and deposition measurements tend to be available on tiles removed after a campaign. Thus results featured a range of plasma types (L-Mode, H-Mode, and advanced scenarios) as well as plasma geometries (variety of inner and outer strike point locations) and divertor plasma parameters (temperatures, densities, radiation levels, and ELM types and strengths). Using the last run day of a campaign, $^{13}CH_4$ was introduced repeatedly into a single plasma type, with one divertor geometry, and a single ELM frequency and amplitude. Consequently, the modeling of the $^{13}CH$ migration in such experiments was more constrained than the modeling of sputtered carbon migration in campaign integrated experiments. This paper reports EDG2D/NIMBUS based modeling of the $^{13}CH$ transport in JET experiments. EDGE2D models the neutral carbon, it ionization, and it movement both parallel and perpendicular to the field lines. All ionization states of the carbon are followed. Many runs were required to isolate the dominant physics involved with the migration. EDGE2D has been used successfully to describe the contamination resulting from methane injection and the assumptions for methane simulations are understood. In the $^{13}CH$ migrations studies, an additional approximation is made since the $^{13}CH$ is simulated by $^{12}CH$ and no intrinsic sputtering was calculated. Calculations varying the injection level and using intrinsic sputtering indicate that the SOL and divertor gross behaviour were unaffected by these approximations.

The 2002 JET experiment injected $^{13}CH_4$ at one toroidal location at the machine top into a 2.4MA, 2.4T Ohmic plasma. Experimentally, $^1/_2$ of the $^{13}CH$ was found and was deposited on the inner divertor target above the inner strike point. Computationally, three factors accounted for the concentration on the inner target. In order of importance:

1. Erosion effects are larger on the outer target and tend to remove the deposits preferentially from the outer target.
2. The thermal force is larger near the outer divertor entrance causing the carbon to preferentially enter the inner divertor.
3. The experimental SOL flow is large, is directed towards the inner target, and is not understood. In the calculations, a force was added to either/or both the deuterium and

carbon in the main chamber SOL of a magnitude so that the calculated flow matched experiment.

Computationally, the SOL carbon transport coefficients are unconstrained by experiment and were adjusted to fit the deposition. With DC of 1 $m^2/s$, about $^1/_2$ of the carbon migrated to the inner target while the remaining C was deposited on the main chamber walls (i.e. reached the edge of the main chamber grid).

The 2004 JET experiment injected $^{13}CH_4$ 5cm above the outer strike point into a 1.4MA, 1.4T type I ELMy H-Mode plasma with 120Hz ELMs. Each ELM was associated with a 30kJ core energy drop. The ELM is a significant event in the H-Mode migration. We studied the ELM effects on carbon migration using the EDGE2D ELM model developed by Kallenbach. During the Elm itself, large power and particle flow into the main chamber SOL from the pedestal. Consequently, the inertia force on the carbon being injected into the divertor prevents the injected $^{13}C$ from migrating far. However, in the time immediately following the ELM, most of the power from the core heats the pedestal region and does not propagate to the SOL. The power replenishes the pedestal. During this time, the SOL and divertor are much cooler than at other times, and the $^{13}C$ injected during this time accounts for most of the long range migration. Nearly as effective for long range C migration is the recovery phase when the power flow into the SOL is in the vicinity of 75% of the steady-state values.

The methane was introduced into the machine at 48 separate toroidal locations displaced uniformly. Some leakage occurs from the outer divertor gas injector. Possibly 25% of the injected methane entered the machine from the top of the baffle above the outer divertor and was injected directly into the main chamber SOL. The EDGE2D modeling indicates that the deposits on both the inner and outer baffles are dominated by this leakage flux (Fig.2). The deposit on the inner baffle travel the length of the main chamber SOL and are in the range of 1-5% of the injected $^{13}C$. The physics which describes their migration is the same as for the 2002 injection from the vessel top. EDGE2D indicates that 5-15% of the total injected 13C diffuses to the edge of the grid where it is supposedly lost to the main chamber walls. Experimentally, the deposits on the outer baffle was toroidally inhomogeneous, and was not measured close to the leakage location. The calculation is also difficult since the injection location is near the grid edge where it connects to the junction of the outer baffle and the main chamber vessel. Probably 5-30% of the injected carbon resides on the outer baffle.

The reciprocating probe was inserted at the machine top during the H-Mode experiment. The deposit on the inner target due to the leakage flux emitted from the top of the outer baffle passed the reciprocating probe location as the $^{13}C$ travelled the long path around the machine in the main chamber SOL. $^{13}C$ deposits were detected on the side facing the outer divertor. The EDGE2D calculations indicate a deposit consistent with the expected 13C flux reaching the inner target. However, the deposit was reduced on the probe tip (nearest the separatrix) in a manner consistent with erosion due to the hot plasma contact.

We believe that erosion is also important on the outer target where we have inferred that a sequential process of step-wise migration from the injection location to the separatrix occurred. We think that most of the freshly deposited $^{13}C$ can undergo erosion with a high probability in the vicinity of the outer strike point. Due to the angle of the field lines and the action of the inertial forces pushing the carbon ions back to the target, the subsequent ionization of the eroded $^{13}C$ caused it to be deposited nearer the separatrix until it crosses into the PFR and escapes the erosion/deposition cycle. EDGE2D does not follow the re-erosion, but by varying the location of the C injection, we determined that about 1/2 of the C eroded within about 1 cm of the outer strike point enters the PFR as neutrals. We think that 40-60% of the $^{13}C$ injected enters the PFR as neutrals and 5-20% enters as ions. A further 5-15% was lost to gaps and shadowed regions during the step wise migration along the outer target assumed proportional to the relative surface area of the tile gaps.

One consequence of the stepwise migration has been the large neutral carbon migration. The fact that such neutral migration occurred in the experiment is unambiguous due to the shadowing of the divertor tile structure on the deposits observed in the PFR. About 10% of the injected $^{13}C$ was observed as deposits on exposed regions of the PFR. The magnitude is less than the approximately 50% expected from the post processed EDGE2D calculations. Our present speculation is that the PFR deposits have undergone further erosion due to D neutrals originating from the core and the strike points. We think this erosion caused a further multi-step migration to shadowed regions.

The classical drifts are described in EDGE2D and, of these, the only significant one is the EXB force acting in the PFR close to the separatrix. The C ions that traverse (diffuse across) the separatrix and reside in the PFR can experience this force. The force induces a migration from outer to inner divertor legs with a deposition near the inner strike point (for the field orientation of this JET experiment). Since the multi-step erosion process at the outer target caused 10% of the carbon to enter the PFR as ions, then many of these ions are deposited in the vicinity of the inner strike point. We think that these deposits are further eroded from the inner strike point (primarily during the ELMs) and cause neutral migration to the PFR.

## SUMMARY

The JET $^{13}C$ migration experiments forced the models to include many phenomena. The understanding is not complete. However, one plausible migration picture is:

1. 25% of the $^{13}C$ was injected through a leakage location outside the divertor. This resulted in 14% deposition in the vicinity of the leakage location, 10% deposition on the main chamber walls and structures, and 1% deposition on the inner target above the inner strike point.
2. 75% of the $^{13}C$ was injected about 5 cm above the outer strike point. This injection location resulted in about 10% deposition in gaps on the outer target primarily between the injector and the strike point, 1% residual on the outer target, 1% residual near the inner strike point, and 60% deposited in the PFR at the bottom of the divertor. Only about 1/5 of the PFR deposit has been found and we assume that the remainder has migrated through multi-step processes into gaps and shadowed regions of the PFR.

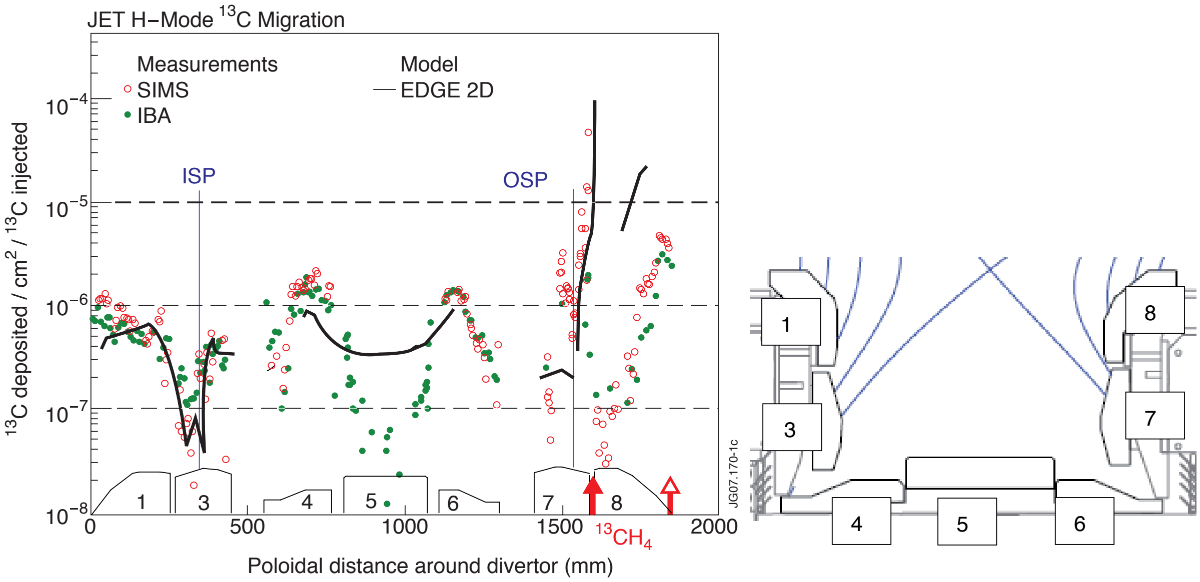


*Figure 1. The SIMS (solid green points) and IBA (hollow red circles) indicated the deposited $^{13}C$ / surface area per injected $^{13}C$ for the case with $^{13}CH_4$ injected at the outer target (about 1600mm) into a 1.4 T, 1.4MA type I ELMY H-Mode plasma. Possibly 15-50% of the methane entered the vessel through a leakage location near the outer baffle (around 1800mm). The strike points were at 350 and 1550mm. The solid line is the EDGE2D based calculation of the deposit modified by post processors for erosion and neutral transport effects.*

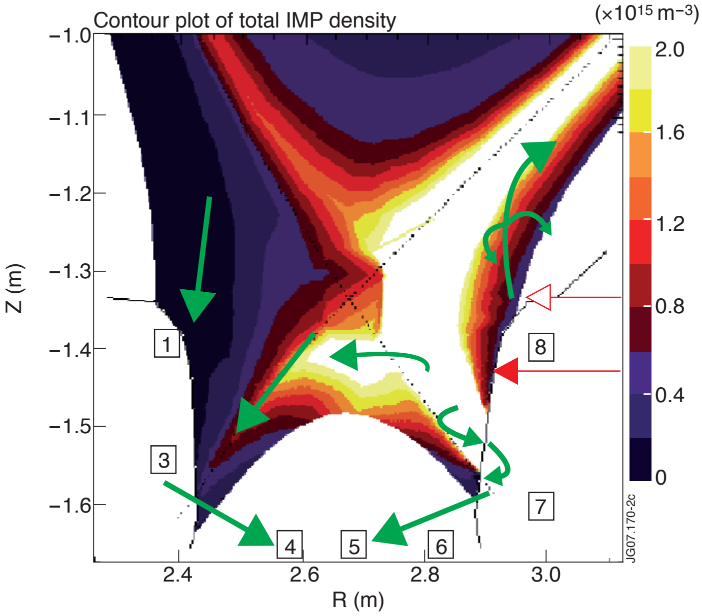


*Figure 2. EDGE2D calculated Carbon densities when all the carbon originates by injection at the red arrow. The green arrows indicate the migration pathways.*