CARBON MIGRATION DURING JET ^{13}C EXPERIMENTS

J.D. Strachan[1], P. Coad[2], G. Corrigan[2], J. Spence[2], G.F. Matthews[2], M. Airila[3], J. Likonen[4], M. Rubel[5], R.A. Pitts[6], A. Kirschner[7], V. Phillips[7], A. Kallenbach[8], and JET-EFDA contributors[*].

[1]PPPL Princeton University, Princeton, NJ 08543

[2]Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, UK

[3]Helsinki University of Technology, Association Euratom-Tekes, Finland

[4]VTT Technical research Centre of Finland, Association EURATOM-Tekes, Finland

[5]Association EURATOM-VR, Fusion Plasma Physics, Stockholm, Sweden

[6], Ecole Ploytechnique Federale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association Euratom-Confederation Suisse, Ch1015 Lausanne, Switzerland
[7]Forschungszentrum Juelich GmbH, Institut fur Plasmaphysik, EURATOM-Assoziation, Trilateral Eurogio Cluster, D-52425, Juelich, Germany
[8]Max-Planck-Institut fur Plasmaphysik, EURATOM-Assoziation, Garching, Germany

JET performed two dedicated migration experiments on the final run day of separate campaigns using $^{13}CH_4$ methane injected into repeated discharges [1]. The ^{13}C deposition was measured by IBA and SIMS techniques on removed vessel components from one poloidal location (Fig. 1). 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. The EDGE2D/NIMBUS code modelled carbon migration in both experiments. The important migration pathways (Fig. 2) 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 modelling. 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 the deposits resulted from plasmas including a range of plasma types (L-Mode, H-Mode, and advanced scenarios), geometries (variety of inner and outer strike point locations) and divertor plasmas (temperatures, densities, heating power, 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 modelling of the ^{13}C migration was more constrained in comparison with the modelling of sputtered carbon migration in campaign integrated experiments. This paper reports EDG2D/NIMBUS based modelling of the ^{13}C transport in JET experiments. EDGE2D models the neutral carbon, its ionization, and movement both parallel and perpendicular to the field lines. All ionization states of the carbon are followed. EDGE2D has previously been used successfully to describe the core contamination resulting from methane injection experiments. The assumptions for methane simulations are listed in [2]. In the ^{13}C migration studies, an additional

---

[*] See appendix of M.L. Watkins, *et al*, Fusion Energy 2006 (21st IAEA Int. Conf. Chengdu)

approximation is made since the ^{13}C is simulated by ^{12}C and intrinsic sputtering effects were calculated on separate runs. Sensitivity analysis indicates 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, 50% of the ^{13}C was found in post mortem analysis 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 so that deposits are preferentially removed from the outer target.
2. The thermal force is larger near the outer divertor entrance allowing less carbon to enter the outer than the inner divertor.
3. The experimental SOL flow is large, and is directed towards the inner target.

In the simulations, the SOL carbon perpendicular transport coefficients are unconstrained by experiment and were adjusted to fit the deposition. With $D_C = 1\ m^2/s$, about 50% 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 simulation grid).

In the 2004 JET experiment, $^{13}CH_4$ was injected 5 cm above the outer strike point of an 8 MW, 1.4 MA, 1.4 T type I ELMy H-Mode plasma with 120 Hz ELMs. Each ELM was associated with a 30 kJ core energy drop. The ELM is a significant event in the H-Mode migration. Its effect is included in the simulations using the EDGE2D ELM model [3]. During the ELM itself, power and particles flow into the main chamber SOL from the pedestal. One consequence is that the inertia force on the injected carbon inhibits migration into the main chamber. 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. During this time, the SOL and divertor are much cooler than at other times, and the ^{13}C injected during this time (7 msec intra-ELM vs. 1 msec ELM duration) accounts for most of the long range migration.

In the H-mode experiment, the methane was introduced into the machine at 48 uniformly displaced separate toroidal locations. Some leakage occurs from the outer divertor gas injector. 15-50% of the injected methane entered the main chamber from the top of the baffle above the outer divertor and was injected directly into the SOL. The EDGE2D modelling indicates that the deposits on both the inner and outer baffles are dominated by this leakage flux (Fig. 1, 2). The deposit on the inner baffle results from carbon travelling the length of the main chamber SOL and are 1-5% of the injected ^{13}C. The physics which describes this migration is the same as for the 2002 injection from the vessel top. EDGE2D indicates that 5-15% of the total injected ^{13}C diffuses to the edge of the grid where, in the code, it is supposedly lost to the main chamber walls. Experimentally, the deposits on the inner baffle are assumed to be toroidally uniform, while on the outer baffle were measured to be toroidally inhomogeneous, and were not measured close to the leakage location. The calculation at the baffles is therefore difficult. A further complication is that the leakage location is near the grid edge where it connects to the junction of the outer baffle and the main chamber vessel. Possibly 5-30% of the injected carbon resides on the outer baffle.

A reciprocating collector probe was inserted at the machine top during the H-Mode experiment. The probe intercepted some of the 13C leakage flux travelling through the main chamber SOL and eventually deposited on the inner target. Larger ^{13}C deposits were detected on the probe side facing the outer divertor. The deposit was consistent with the inner target deposit but reduced on the probe tip by erosion from the SOL plasma.

Erosion is also important on the outer target. A sequential step-wise migration from the injection location to the separatrix is inferred. Most of the freshly deposited ^{13}C must undergo erosion in the outer strike point vicinity. 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 and re-eroded nearer the separatrix until it crosses into the PFR and escapes the erosion/deposition cycle. EDGE2D does not follow the re-erosion, but runs varying the location of the carbon injection, indicated that 1/2 of the C eroded within 1 cm of the outer strike point enters the PFR as neutrals. Projections indicate 40-60% of the ^{13}C injected entered the PFR as neutrals and 5-20% as ions. A further 5-15% was lost to gaps and shadowed regions during the step wise migration along the outer target.

One consequence of the stepwise migration was large neutral carbon migration. This neutral migration is unambiguous experimentally due to the shadowing by the divertor tiles of the observed PFR deposits. About 10% of the injected ^{13}C was observed as deposits on exposed regions of the PFR. The magnitude is less than the ~50% expected from the post processed EDGE2D calculations. Probably, the PFR deposits have undergone further erosion due to D neutrals originating from the core and the strike points. This erosion might cause a further multi-step migration to shadowed regions in the PFR.

The classical drifts were included in the EDGE2D simulations and only the $\underline{E}x\underline{B}$ force (in the PFR close to the separatrix) was significant. The C ions that traverse (diffuse across) the separatrix into the PFR experienced 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. These deposits are further eroded from the inner strike point (primarily during the ELMs), leading to further neutral migration to the PFR.

The JET ^{13}C migration experiments forced the simulations to include many phenomena. The understanding is not complete. An example of a plausible migration picture is:

1. 25% of the ^{13}C was injected through a leakage location outside the divertor. The resulting deposition was 14% near the leakage location, 10% on the main chamber walls and structures, and 1% 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. The resulting deposition was 10% 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% in the PFR at the bottom of the divertor. Only about 1/5 of the PFR deposit was found experimentally, with the remainder assumed to migrate through multi-step processes into gaps and shadowed regions of the PFR .

[1] J. P. Coad, *et al*, Nuclear Fusion 46, 350 (2006)
[2] J.D. Strachan, *et al*, Nuclear Fusion 44, 772 (2004)
[3] A. Kallenbach, *et al*, Plasma Phys. Contr. Fus. 46, 431 (2004)

Acknowledgements: Supported by DOE and JET-EFDA.

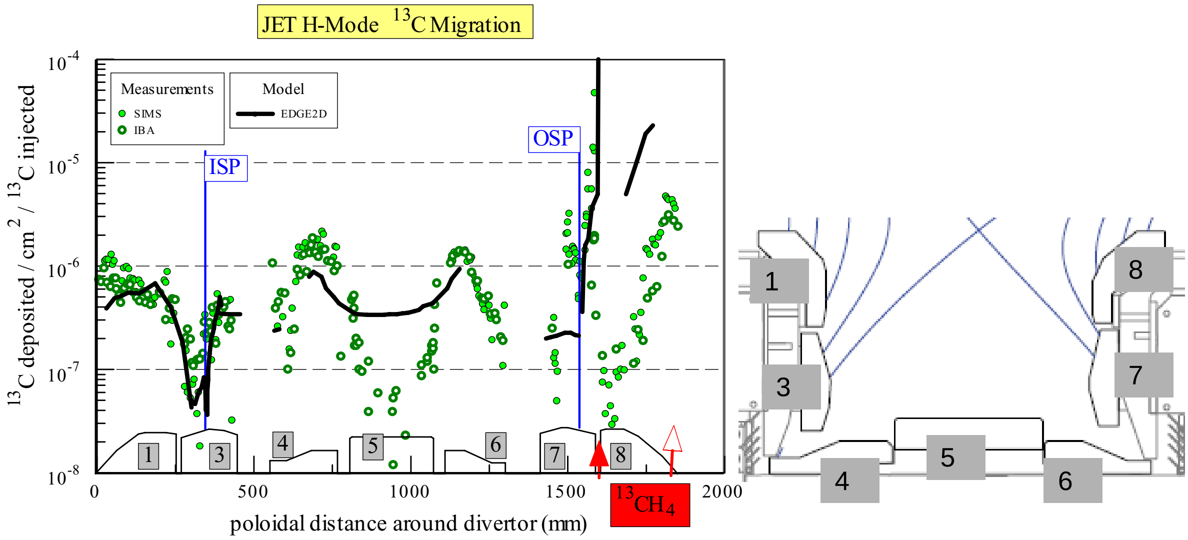

Figure 1. The ^{13}C deposition when $^{13}CH_4$ was injected at the outer target (arrow) into a 1.4 T, 1.4 MA type I ELMY H-Mode plasma. Possibly 15-50% of the methane entered the vessel through a leakage location (hollow arrow) near the top of tile 8. The solid line is the EDGE2D based calculation modified by post processors for erosion and neutral transport effects.

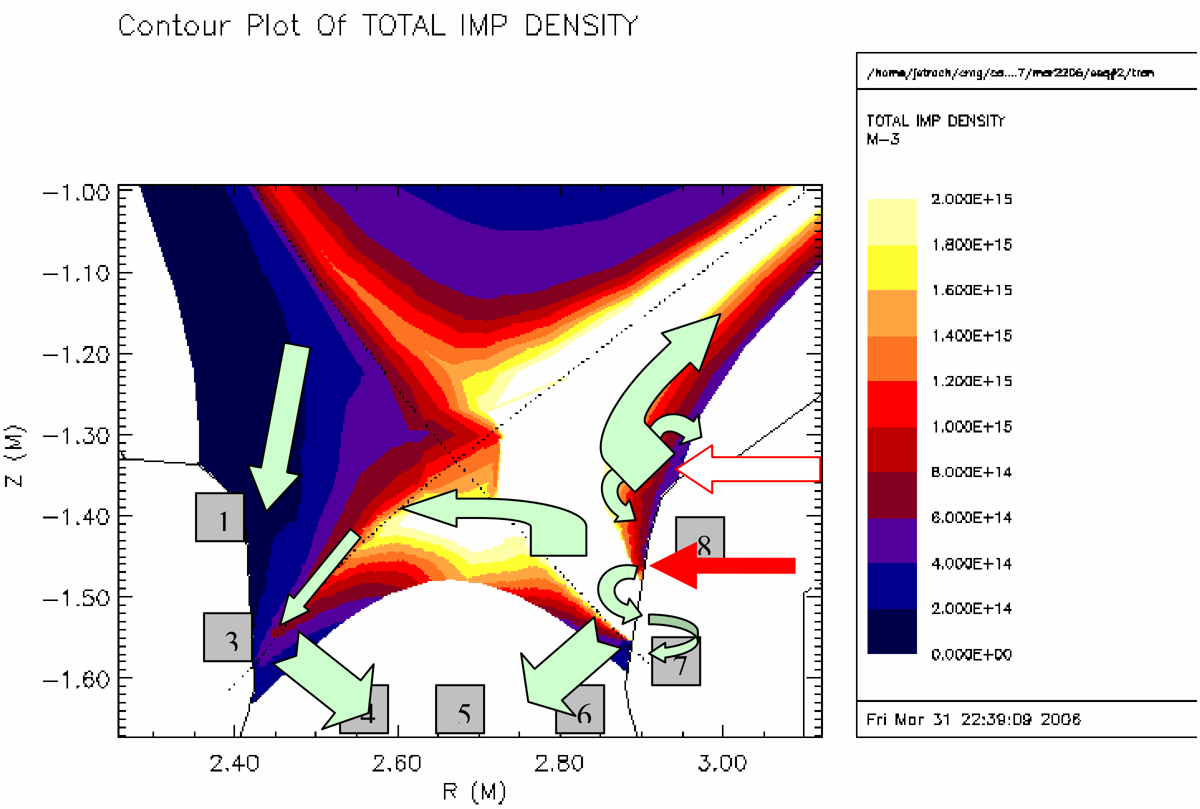

Figure 2. EDGE2D calculated Carbon densities when all the carbon originates by injection at the red arrow. The green arrows indicate the migration pathways.