APEX Interim Report - Executive Summary for Chapter 12

Executive Summary of Plasma-Interface Issues and Edge Modeling (Sec. 12)

A crucial issue for the use of liquid walls in fusion systems is their impact on the performance of the fusing plasma core. The thin layer of edge plasma provides the interface between the hot-plasma core and the liquid first-walls and divertor plates. The edge-plasma properties must be accurately determined to predict the coupling between the core plasma and the wall, and the edge-plasma itself is affected by both the core plasma and the wall.

The liquid surfaces can impact the edge and core plasmas by releasing impurities through sputtering, recycling, and evaporation. Such impurities degrade fusion core performance through enhanced radiation loss and fuel dilution. The tolerable levels of core impurity concentration owing to radiative energy loss and to fuel dilution are shown in Fig. s12.1 (also 12.1) for a tokamak. Changes in the edge plasma temperature and gradient scale-lengths can also affect the stability of the core-edge plasma, *e.g.*, the L-H transitions, ELMs, and possibly disruptions.

The edge plasma, in turn, influences the liquid surfaces through particle bombardment and line radiation from excited ions. The bombardment leads to sputtering and recycling, and both bombardment and radiation heat the surface that results in increased evaporation. The maximum tolerable evaporation rate specifies the maximum allowable surface temperature of the liquid and the sputtering analysis specifies the required edge-plasma properties through the plasma-induced particle flux to the walls.

A multi-faceted, self-consistent model is required to make a complete evaluation of these interactions between the edge-plasma and the liquid walls. We have made substantial progress in developing components of this general model and in using these components for initial evaluation of some of the critical issues. The progress is summarized below and presented in more detail in Sec. 12 for the following areas: 2-D fluid transport simulations of properties of the hydrogenic edge plasma; 2-D fluid transport simulations of impurity penetration to the core region arising from evaporating Flibe and Li-based walls; 1 1/2-D kinetic and 2-D fluid transport calculations of evaporated and sputtered impurities from liquid divertor plates; 2-D simulations of intense power deposition to a lithium divertor plate during a disruption; 1 1/2-D plasma core transport modeling, beginning simulations of the behavior of small liquid samples in the PISCES plasma divertor simulator and the DIII-D tokamak.

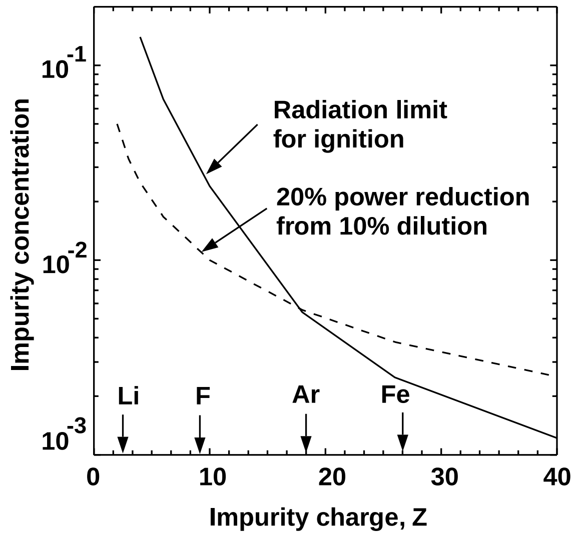

Fig. s12.1 Effect of core impurity concentration for different impurities in from radiation loss in a tokamak [12.1] and from simple fuel dilution.

We have used the 2D UEDGE code to obtain profiles of hydrogen ion density, parallel ion velocity, and separate ion and electron temperatures. The base-case is an ITER-like tokamak where the transport simulation sets boundary conditions of power and density a small distance inside the magnetic separatrix and calculates the resulting scrape-off layer (SOL) profiles. We have characterized 2-D plasmas profiles for both high-recycling regimes (Flibe or other non-recycling divertor) and low-recycling (lithium divertor which retains incident hydrogen). The low-recycling case results in high electron temperature at the divertor and low density, with the opposite being true for high recycling. An important consideration for the low-recycling case is the large particle flux out of the core that must be maintained by an edge particle-fueling source such as pellets.

The UEDGE calculations of the hydrogen edge-plasma is augmented by including a source of impurities from the first wall. There are a number of processes included in the modeling. The impurity gas is emitted from the wall in the form of atoms at typically 1 eV, although a range of energies have been used to assess the energy of the atoms after molecular dissociation which is not yet modeled in any detail. These neutrals diffuse by elastic collisions with ions until they are ionized by the electrons of the edge plasma. Once an ion, the impurity diffuses across the magnetic field with anomalous diffusion coefficient coefficients estimated from present experimental devices. Thus, the ions can diffuse radially into the core or back to the liquid wall where they are assumed to be absorbed. In addition, the ions can flow along the magnetic field and out of the system. The electron energy lost by ionizing the impurities through all of their charge states is included, so that the impinging impurities decrease the electron temperature, especially near the liquid surface. A typical set of charge-state profiles from a fluorine from a Flibe wall are shown in Fig. s12.2 (12.3).

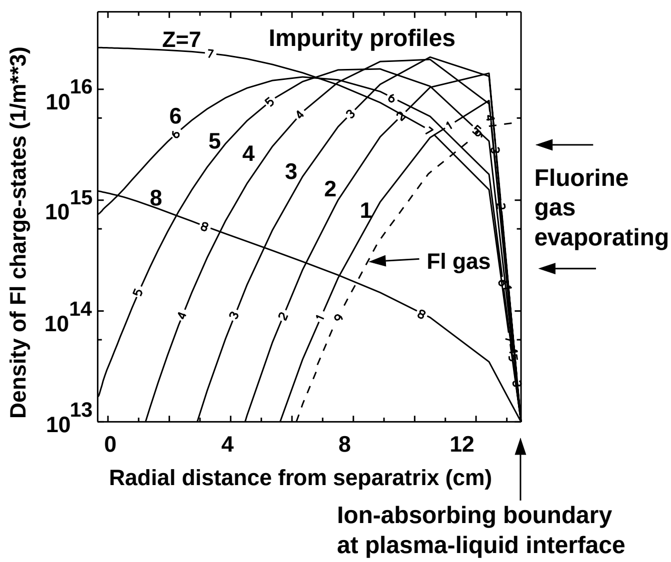

Fig. s12.2 Density of fluorine charge-states at the outer midplane for a gas wall flux of 8e18 $m^{-2}s^{-1}$ in the ITER-like geometry.

Similar calculations have begun for SnLi walls where only Li is evolved from the surface; it is assumed that evaporation of Sn is negligible. Lithium penetrates less easily to the core due, in part, to its lower first-ionization potential of 5.4 V compared to 17.3 V for fluorine from Flibe. Secondly, if one considers a SnLi, its evaporation rate is less than that of Flibe at a given temperature.

The comparison between the fluorine (Flibe) cases and the lithium (Li, SnLi) cases with respect to impurity concentration is shown in Fig. s12.3 (12.5). This figure quantifies what core impurity core density should be expected for a given gas flux, which can be determined from known data of the evaporation rate at a given liquid surface temperature.

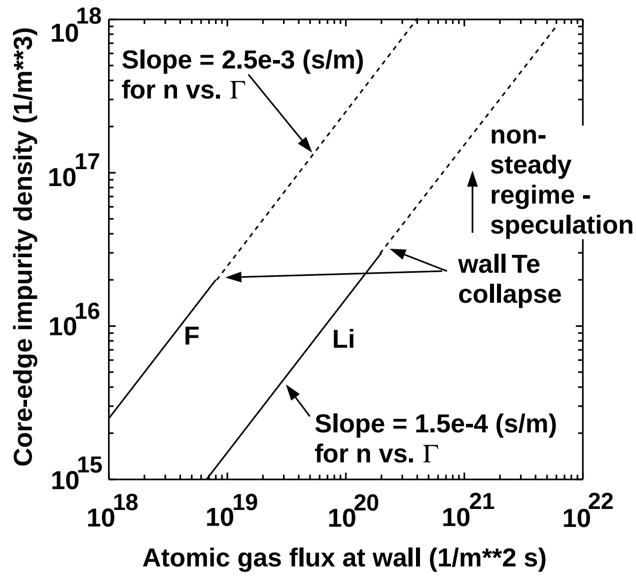

Fig. s12.3 Comparison of fluorine and lithium densities at the core boundary for different gas fluxes at the first wall. The dotted lines are extrapolations owing to non-steady solutions which arise with a collapse of the electron temperature just in front of the wall for larger gas fluxes.

From Figs. s12.1 and s12.3, one can deduce that for an ITER-like tokamak with 150 MW of plasma power flowing into the scrape-off layer, impurity penetration to the core may be kept to an acceptable level if the liquid surface temperature for Flibe is 540 C or less, while for SnLi it is 740 C or less. However, these results a quite preliminary with one of the most important uncertainties being the fact that the transport simulations have not yet found steady state solutions at the larger gas flux regions of Fig. s12.3 shown by the dotted lines. These dotted line portions of the curves are just those being used to make the estimates of the maximum surface temperature quoted above. Thus the highest priority of our present research is to better resolve and understand the non-steady solutions. Such solutions correspond to where the electron temperature near the surface abruptly drops below a few eV owing to impurity radiation and particle energy losses to the wall. This is a “detached” type of plasma, but here the detachment is from the side wall rather than the divertor plate.

The calculations for impurity influx from side walls have been mostly performed in a tokamak geometry. More simulations are needed for alternate geometries such as the Field-Reversed Configuration (FRC), spheromak, spherical torus, etc.

Kinetic simulations are performed for the region near liquid divertor plates using the test-particle codes BPHI and WBC codes with Monte Carlo collisions. BPHI focuses on the sheath region, including ionization within the sheath whereas WBC uses a reduced sheath model and includes the presheath region ~10 cms in front the plate. Both codes begin with a hydrogen plasma from a 2-D fluid transport code, but then trace sputtered and evaporated impurities from the plates made of Flibe or lithium until they escape upstream or are redeposited on the plates.

For the WBC code lithium analysis, The following is observed: (1) very high near-surface lithium redeposition rate (~100%), (2) high redeposited average energy with highly oblique Li ion impingement. Result (1) is favorable showing low potential for plasma contamination by sputtered lithium, even for the low-collisionality, low-recycle regime. Result (2) gives rise to concerns about runaway self-sputtering although preliminary estimates using initial ALPS/APEX project data show that this will probably not occur.

WBC calculations for Flibe assessed the near-surface transport of the individual sputtered Flibe constituents of F, Li, and Be. As with the lithium surface calculations, a highly preliminary sputtering model was used. Results using a hydrogen plasma in the high-recycle regime (T_e = 30 eV, n_e =$3x10^{20}$ m^{-3}) show a high redeposition fraction for each element. There is a lower potential for self-sputtering runaway due to lower redeposition energies and less oblique incidence.

BPHI sheath code calculations were performed for a low-recycle plasma divertor regime with a lithium surface. Preliminary results, for one particular low-recycle regime, show that a majority of slow-moving, evaporated lithium atoms will be ionized in the sheath and will be returned to the surface due to strong sheath electric field. On the other hand, the sheath heat transmission factor will increase due to reduced sheath potential resulting from the extra electrons and ions produced by in-sheath ionization. The resulting increase in heat flux is of concern in terms of a runaway effect but this may be mitigated by the transient nature of the overheating and the fact that the lithium is flowing.

In the coming months, a self-consistent sputtering erosion/redeposition analysis of a lithium divertor surface is planned, using coupled UEDGE/WBC/VFTRIM (plasma SOL fluid code/Monte Carlo kinetic impurity code/vectorized fractal-TRIM sputtering code) codes. This will better compute plasma contamination potential, tritium codeposition, and self-sputtering runaway potential.

Another important question is the response of a liquid divertor plate to a tokamak disruption. A number of physical processes have been included in the HEIGHTS package and simulations performed for a liquid lithium plate. The incoming power to the plate is taken as 100 GW/m^2 which is typical of what would be expected in a reactor-sized tokamak. As this high particle energy strikes the plate, material is ablated in the form of a gas vapor, which is subsequently ionized by the incoming electrons. The energy required to ionization of the vapor can decrease the incoming energy to the plate by an order of magnitude to less than 10 GW/m^2 while this partially ionized vapor cloud becomes optically thick. An additional reduction of the power to the plate comes from the splashing of plate material into droplets due to Kelvin-Helmholtz or Rayleigh-Taylor instabilities in the vapor. The power loss in vaporizing these droplets can result in another factor of 5 reduction in power reaching the plate. The mass loss of the liquid lithium plate can likewise be reduced by about two orders of magnitude from the combined shielding of the vapor and the droplets from slashing. As a result, the effect of a disruption on the lithium plate is not thought to be limiting.

Further assessment is needed to determine how the incoming disruption power, which is initially absorbed by the vapor and droplets but then re-radiated, effects nearby structures. Also, the vapor and splashing that result from the disruption will migrate to other surfaces in the machine. If all surfaces are moving liquids, they will self-clean, but using the same liquid for the plate and the walls will eliminate the problem altogether.

The impact of different edge-plasma conditions on the performance of the fusing core plasma is being studied with the 1 1/2-D core transport code ONETWO which has been used extensively for analyzing DIII-D experimental results. As an initial case, an ITER-like tokamak is being considered with a 20 keV operating point since a lot of previous analysis has been done on this configuration which provides a good simulation benchmark. The effect of the low-recycling edge conditions using lithium plates will be contrasted with the normal high-recycling edge (which would likely arise if Flibe were used). Given this background, a similar analysis will be done for the ARIES-RS design.

Finally, it is important to benchmark models of how liquid surfaces emit impurities in the presence of plasma discharges, and how the impurities transport in the plasma. At present, small samples of lithium and gallium have been used in the linear plasma device PISCES, and lithium has just been used on the DiMES probe for the DIII-D tokamak. Sputtering data is also available from particle beam measures on the Univ. of Ill. experiment. The sputtering data from these various experiments are being tabulated and will be used as input for the fluid and Monte Carlo codes which follow the subsequent ionization and transport of the impurity ions. A challenge impurity transport modeling for the DiMES probe is that the probe is localized to one toroidal location, so 3-D effects do enter which can only be estimated by the present codes. Nevertheless, these calculations will begin to force reality checks on the models. Larger-scale samples in experiments will improve this benchmarking. There are discussions to use liquid divertor surfaces in other devices such as CDX-U. This type of activity is important to provide the experimental data base to validate models predicting the influence of such walls in fusion-related devices, and close collaboration will be maintained.