Chapter Summary: Thin Liquid Wall Concepts and the CLiFF Design

The idea behind CLiFF, the *C̲onvective L̲iquid F̲low F̲irst-Wall* concept, is to eliminate the presence of a solid FW facing the plasma through which the surface heat load must conduct. This goal is accomplished by means of a fast moving (convective), thin liquid layer flowing on the FW surface (see Figure 7-1). This thin layer is easier to control than a thick liquid FW/Blanket, but still provides a renewable liquid surface immune to radiation damage and sputtering concerns, and largely eliminates thermal stresses and their associated problems in the first structural wall. The attractiveness potential and key issues for the CLiFF design are summarized in Table 7-1. The CLiFF class of liquid wall concepts is viewed as a more near-term application of liquid walls.

Details of the preliminary design, heat transfer, power balance, thermal-hydraulics, neutronics, activation and safety are included in this chapter. It is noted that the first several centimeters of various thick liquid FW/blanket concepts discussed in the preceding chapters will behave in a similar fashion to the CLiFF concept discussed here, and significant overlap with those analyses is seen in what follows.

Design Description

The majority of the work reported here was carried out for the tokamak. Specifically, the ARIES-RS geometry was utilized whenever possible, with modifications for the unique structures and high flowrates required for CLiFF. This means, however, that the ARIES-RS fusion power needs to be scaled-up to 4500 MW to give the 10 MW/m^2 peak neutron wall load and 2 MW/m^2 peak surface heat flux mandated in the APEX project. Tokamaks present a difficult challenge for liquid walls due to the fact that the plasma chamber is relatively closed with short scrape-off lengths, and so, vaporized liquid wall material must be screened by the edge plasma to keep it from penetrating to the core.

The general CLiFF design, as seen in Figure 7-1, is conceptually simple in its implementation. A thin fast liquid layer is injected near the top of the plasma chamber. The layer flows down the reactor walls without excessive slowing or thinning, and is removed in some fashion from the bottom of the chamber. Layer thicknesses *h* on the order of 0.5 to 2 cm, and velocities *U* on the order 10 m/s, are considered. The curved reactor wall fits the plasma shape and provides an adhesion force due to the liquid's centrifugal acceleration. The criteria for continuous attachment of the liquid layer is simply $U^2/R_c > g \cos\alpha$, where g is the acceleration of gravity, R_c is the radius of curvature of the first wall section and α refers to the angle of the outward surface normal to gravity vector (so 0° is completely inverted)

The velocity range is chosen quite high both to ensure adhesion to the back-wall, but also to keep the exposure time to the plasma short, and thus keep the surface temperature low. If one desires an inlet temperature that is > 300 C (for power conversion reasons), it turns out that it is this second restriction that is the more severe, based on the maximum surface temperature estimates provided by the preliminary plasma edge analysis. The high velocity requirements and the large coverage area results in volumetric flowrates in excess of 10 m^3/s compared to ARIES-RS in the 3 m^3/s range.

Table 7-1: Potential Advantages and Issues of CLiFF Concept for APEX

Potential:

- Removal of surface heat loads (greater than 2 MW/m^2 possible). Local peaking and transients can be tolerated
- FW surface protected from sputtering erosion and possibly disruption damage
- Beneficial effects on confinement and stability from conducting shell and DT gettering effects
- Elimination of high thermal stresses in solid FW components, having a positive impact on failure rates
- Possible reduction of structure-to-breeder ratio in FW area, with breeder material facing virgin neutron flux
- Integrated divertor surface possible where CLiFF flow removes all α heat
- Complex tokamak D-shape & ports can likely be accommodated

Issue:

- Hydrodynamics and heat transfer involve complicated MHD interaction between flow, geometry, and the magnetic field:
  - Suppression of turbulence & waves
  - LM-MHD drag thickenes flow and inhibits drainage from chamber
  - Effects of varying fields on LM surface stability and drag
- Evaporating liquid can pollute plasma, surface temperature limits unknown
- High flowrate requirement can result in low coolant ΔT or two coolant streams
- Effect of liquid choice on edge plasma gettering, tritium through-put, and tritium breeding
- Neutron damage in structure is only slightly reduced compared to standard blankets, blanket change-out required for high power density operation

The conceptual CLiFF design shown in Fig. 7-1 has an integrated droplet-type divertor. Some means (mechanical or electrical) is used to stimulate the breakup of the FW flow into a droplet screen. It is hoped that the droplet screen will have a higher heat removal capability due to the rapid rotation and internal circulation in the droplets, but this fact remains to be proven. In addition, for LMs, the droplet screen will be electrically isolated from the main FW flow and plasma currents will not be able to close. The liquid film can be removed from the vacuum chamber by gravity drainage or by an EM pump if the working liquid is an electrical conductor.

Supply nozzles will form the desired liquid flow at the top of the reactor. These nozzles will likely present a limited amount of solid surface to the plasma, but since they are at the top of the reactor chamber, the surface heat load and nuclear heat will be lower than the peak mid-plane values. Liquid removal from the plasma chamber is accomplished through a combined vacuum pumping and liquid drain port. It is envisioned that the liquid flow itself will pump a portion of the implanted plasma particles into the pumping ducts by convection, thus aiding in impurity removal.

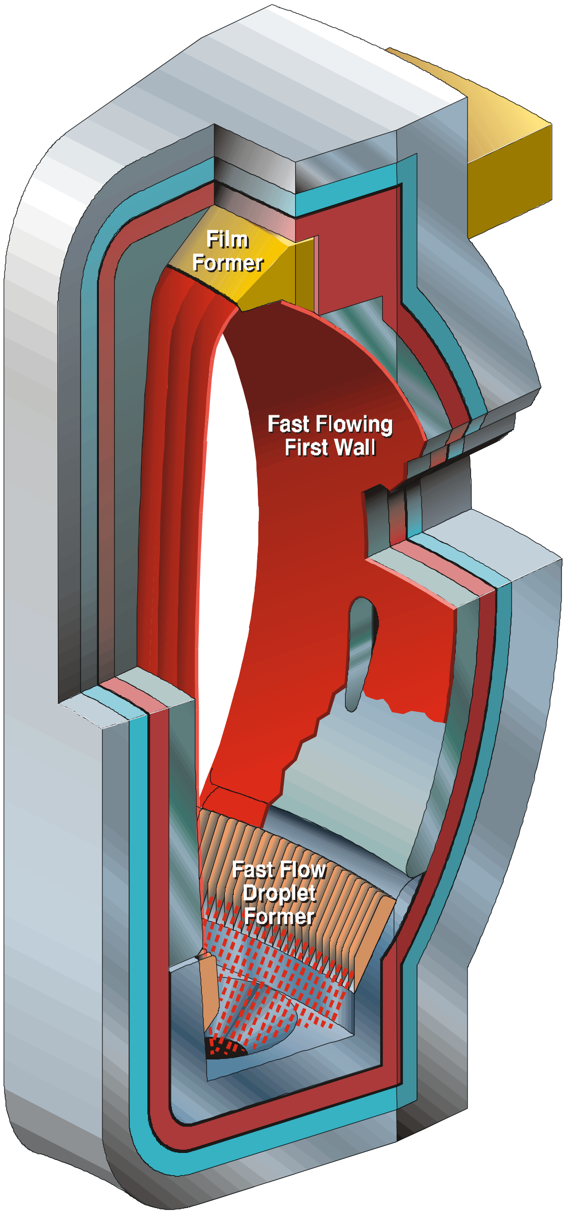

Figure 7-1: Conceptual sector schematic of CLiFF implementation in ARIES-RS reactor.

The working liquid should be a tritium breeding material like lithium, tin-lithium or Flibe. Thus the liquid removed from the reactor can be recirculated to the blanket as the main tritium breeder and coolant. The bulk nuclear heat is added on top of the

FW/divertor heat before the liquid is sent to the power conversion system. In this manner, the FW and divertor power is converted at relatively high thermal efficiency.

Penetrations for various heating, fueling and diagnostics functions will be provided as much as possible in the lower half of the outboard FW. Flow can be guided by means of submerged grooves around the penetration, and close again downstream to form a continuous surface protection. Cooling of the penetration structures themselves will be aided by the CLiFF flow. It is likely that for LMs, the penetrations will have to be electrically isolated from the flow by means of an insulator coating. This will be true in supply lines and nozzles as well.

Off-normal plasma events like disruption can possibly induce large currents in LM CLiFF flows and cause the layer to be splashed or torn-off the wall altogether. For poorly conducting Flibe, the effect of the disruption is not as clear. It is hoped that, in any case, splashing will turn out to be an allowable response, and that the liquid wall will just be restarted following the disruption. For an all-liquid wall system, this seems a reasonable assumption, except for possible damage to antennae and sensitive diagnostics. It is hoped that “liquid tolerant” antennae could be designed that could accept the occasional splashing of liquid metal, but this certainly remains to be demonstrated.

Hydrodynamic and Heat Transfer Analysis

Aside from plasma compatibility, one of the key issues for CLiFF is related to finding a feasible hydrodynamic configuration. A significant amount of design analysis has been done so far on CLiFF in order to answer the three basic questions: How do you form it? How do you drain it? How do you maintain it? It is noted that liquid metals and Flibe behave very differently in the magnetic environment of a tokamak. The low thermal and electrical conductivity of Flibe leads to a FW flow that will still be turbulent, and have heat transport at the free surface and flow drag at the back-wall that depend heavily upon this turbulence. For LMs the converse case occurs, where it is expected that the MHD effects will dominate the drag, and the thermal conduction dominates heat transfer.

Turbulent Flibe Flow

Several models have been applied to predicting the flow profiles for Flibe, ranging from simple hydraulic models for the steady state equilibrium flow profile, to more complex two- and three-dimensional non-steady codes for studying phenomena like surface waves and penetrations. The 1.5D hydraulic calculations indicate that flow depth equilibria in the range of 2 cm can be achieved for Flibe flows in the 10 m/s range (see Figure 7-2). A more sophisticated, low-Reynolds number k-ε model of turbulence was also applied to the CLiFF flow in order to study the effect of MHD turbulence on the flow profile. In comparison to the ordinary k-ε model, the present one was extended to the MHD case by means of additional terms in the closure equations. Due to turbulent viscous friction, the layer thickness increases rapidly over the initial flow section (see again, Figure 7-2). This is in contrast to the results presented earlier where the simple friction factor formulation predicts nearly constant flow height and velocity profiles for CLiFF. This contradictory result is cause for concern because if the layer slows down significantly, the transit time through the plasma chamber will go up, as well as the surface temperature. Attempts to benchmark the k-ε and friction factor against available data from the UCLA Mega-Loop Experiment are inconclusive – the data splits the difference between the k-ε and friction factor model.

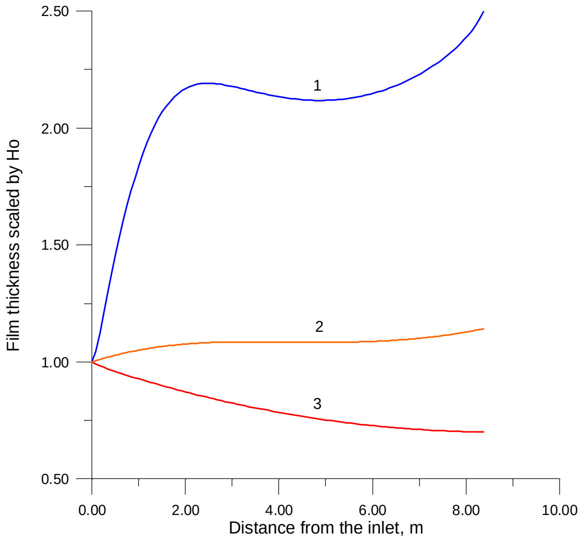

Figure 7-2: Surface height predictions for Flibe with various models: Line 1. k-ε, 2. Darcy-Weisbach friction factor = 0.025, and 3. laminar

The effect of the magnetic field on the flow parameters is negligible if the Hartmann number is less than about 1000, and hence for CLiFF with Ha = 500, we conclude that there is no strong impact of MHD on the Flibe flow hydraulics.

Heat transfer calculations using this same model indicate that depending on surface turbulence assumptions, the temperature rise at the surface can be quite low. For a 10 m/s, 2 cm thick Flibe flow, the surface temperature rise is in the range of 30 to 160 C depending whether optimistic or pessimistic assumptions are used. The effect of the magnetic field again appears to be small. When considering the thermal hydraulics, it is seen that the temperature window for Flibe is limited (see Flibe system diagram in Figure 7-3), and so the surface heat transfer is critical for feasibility. There are, however, no experimental data, and this issue needs closer study and experimental validation.

The surface stability for Flibe CLiFF Flows was also analyzed using a linear stability analysis technique for infinitesimal disturbances. For CLiFF, the results show that whenever the flow is adhered, it should be stable as well. The effect of finite size perturbations may alter this picture. The primary source of large disturbances comes from the turbulence of the flow itself. The fluid dynamic behavior of the first-wall flow system may be effected due to these eddy generating mechanisms including boundary layer relaxation near nozzles, Gortler-type instabilities, structural vibrations, *etc*.

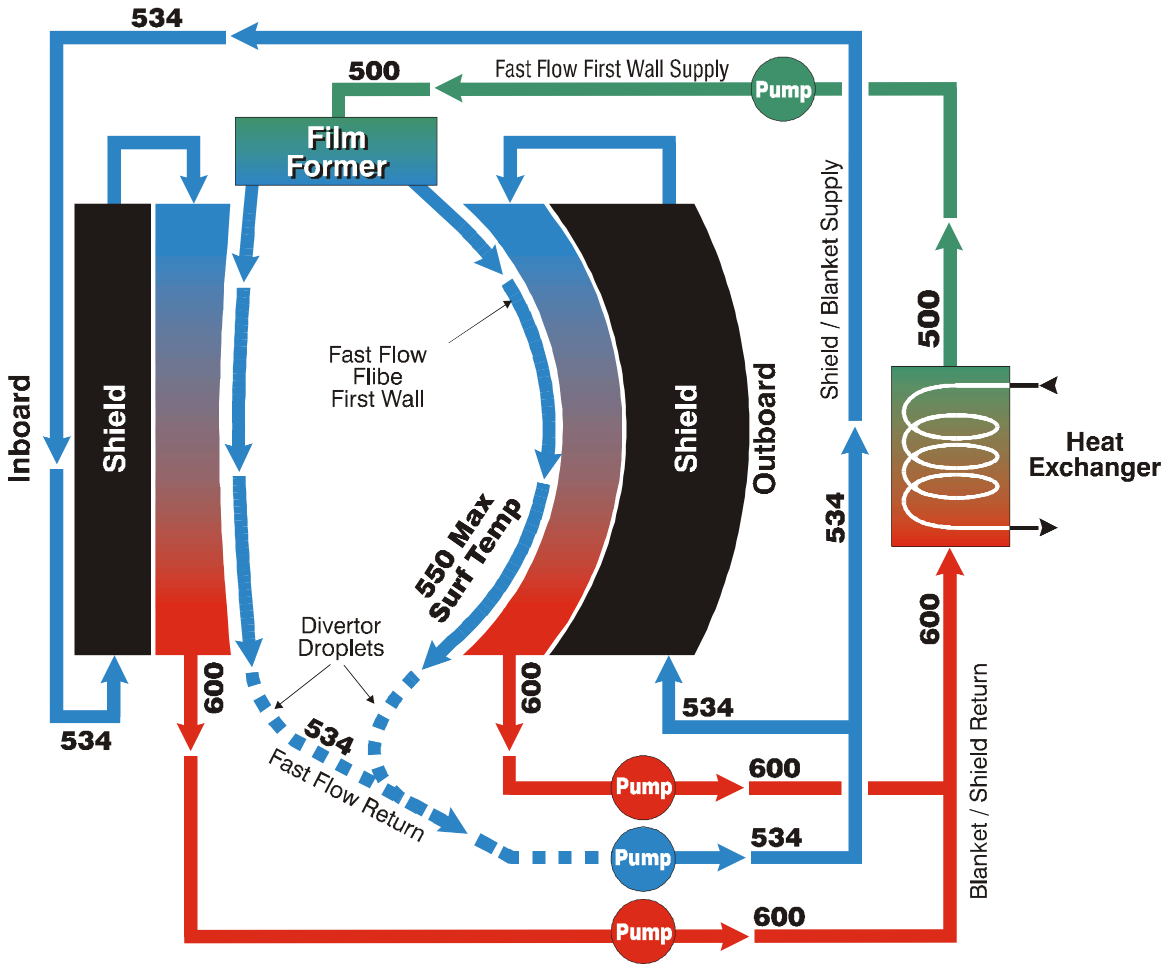

Figure 7-3: CLiFF – Flow / Temperature Schematic-Flibe option.

Penetration have also been analyzed for the Flibe case using a 3D free surface code that allows the introduction of arbitrarily formed structures. The penetrations considered are elongated into ellipses in order to be more hydrodynamically streamlined. The specific case considered has dimensions 20 cm wide and 90 cm long (in the flow direction). The back-wall in the vicinity of the penetration is tailored to guide the liquid around the penetration itself, and to aid in closing the liquid again downstream of the penetration. Figure 7-4 indicates that such a design solution can successfully guide the flow around penetrations, but additional work and optimization is needed for their design.

Magnetohydrodynamics for Lithium and Sn-Li Flows

Mathematically these types of flows can be described by a set of Navier-Stokes equations for incompressible fluids and Maxwell’s equations for electromagnetic phenomena. The numerical tools used to analyze this system of equations are based on two-dimensional, simplified magnetohydrodynamic equations and can be performed in practice for any values of governing parameters for ducts of various geometries. This is an extreme simplification of the physics and assumes that all currents close in their own cross-sectional plane. This type of calculation is accurate for well-behaved, nearly fully developed flows with simple geometries, but ignores significant effects near field gradients and developing regions.

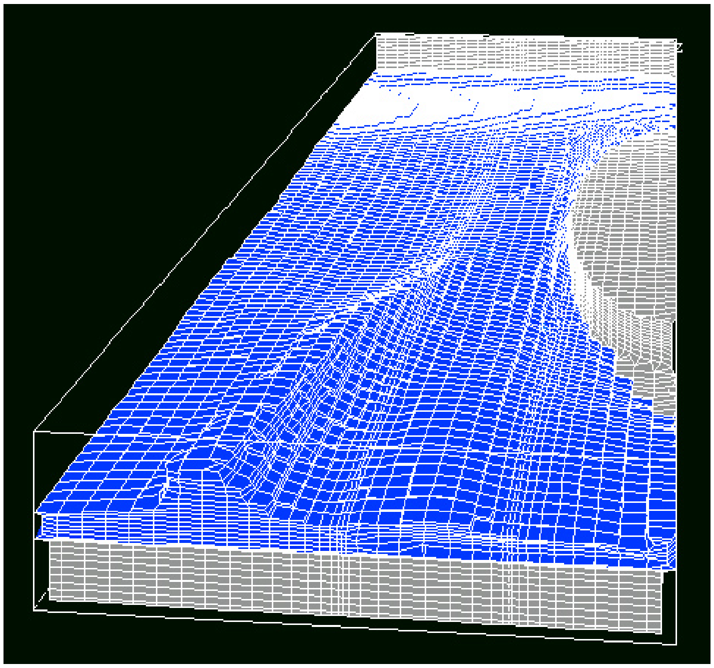

Figure 7-4: Persective view of flow around a 20 cm wide penetration with the gradually tailored back-wall**.**

It is well known that the presence of electrically conducting walls can lead to larger electrical currents in the flow domain and, as a result, to a significant increase in the MHD drag effect. In the case of free surface MHD flows this effect manifests itself in the increase of the layer thickness with the accompanying reduction in the velocity. Ideally, if the liquid layer is assumed to be completely axi-symmetric in the toroidal direction, flow along poloidal flux surfaces with no field gradients, no MHD drag will occur. This ideal case, though, is not possible in practice and we look at two variants to gauge the relative effects of the MHD. One case is the presence of fins, side-walls or penetrations breaking up the flow toroidally, and the other is a slight deviation of the flow path from the flux surfaces resulting in a small surface-normal field component. Figures 7-5 and 7-6 illustrate the results for these two cases for lithium, where we assume that a doubling of the initial height represents an unacceptable result.

For the case of side-walls, it was found that electrically insulated side-walls are acceptable only if they are no closer than 1 m toroidally, and that low conductivity walls like SiC (thickness = 1 cm, assumed $\sigma = 10^3\ \Omega^{-1}m^{-1}$) are acceptable provided they are no closer than 8 m. Bare metal walls (thickness = 2 mm, $\sigma = 10^6\ \Omega^{-1}m^{-1}$), even if very thin, can be no closer than 110 m, and so are not feasible for CLiFF. For the case of a small radial field it was found that if the back-wall is bare metal the allowable field is only $B_r <$ 0.1 T. This value goes up to $B_r < 0.5$ T if the backing wall is insulated. These calculations assume that there are insulated side-walls present at some distance to break up the toroidal electric path (but they are separated by enough distance that they don't add appreciable drag). If complete axi-symmetry is assumed, where induced currents close on themselves, the allowable radial field is $B_r < 0.015$ T! These calculations indicate that serious work is needed in the area of LM-MHD analysis and experiments to prove that passive flow schemes like CLiFF are possible.

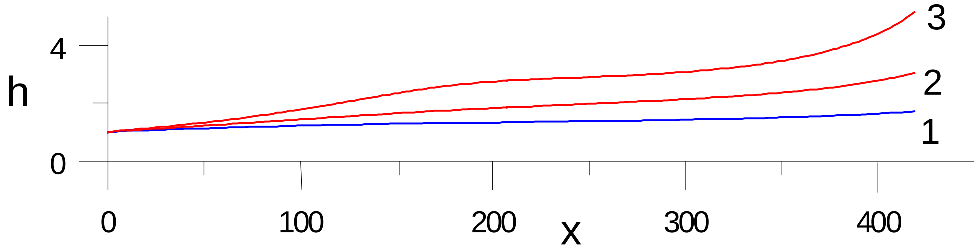

Figure 7-5: Influence of the wall conductance ratio on the layer thickness increase (2b=1 m). Line 1- c_w=0; 2- c_w=1.0 10^{-6}; 3- c_w=2.0 10^{-6}

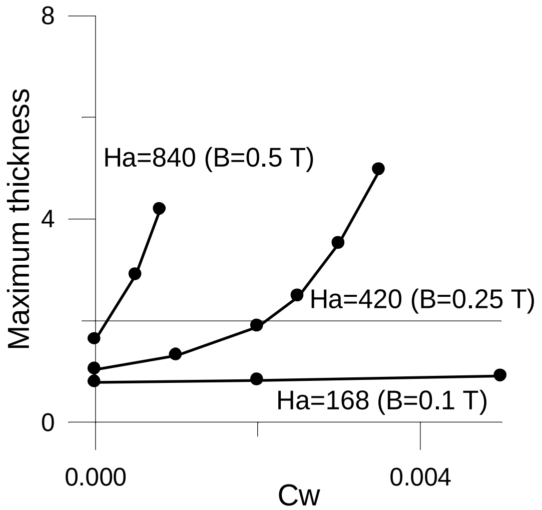

Figure 7-6: Influence of the radial magnetic field and the wall conductance ratio on the maximum thickness of the layer (for axi-symmetric case, $C_w = \infty$)

Heat transfer at the surface is calculated for Li and Sn-Li using only conduction, but assuming some penetration of X-ray photons in the case of lithium. The conclusion is that at 10 m/s the temperature rise will be on the order of 150°C for Li, and 300°C for Sn-Li. The thermal-hydraulic calculations utilizing these numbers result in a blanket outlet temperature around 650°C for the Sn-Li, but much lower for the lithium, possibly necessitating a two-stream approach, where only part of the Li flow is sent to the blanket.

The results of stability computations are in a good agreement with the linear stability analysis conclusions. Long wavelength initial disturbances grow very rapidly on the inverted surface under the effect of gravity and centrifugal acceleration and then propagate down with slowly decreasing amplitude. The growth rate and the maximum amplitude depend on the wavelength. The short waves (< 20 cm) are suppressed rapidly by the surface tension, while the long wave disturbances (1.5 – 2 m) are not suppressed over the whole flow length. The most dangerous disturbances are those having the long wavelength of about 2 m, for which the amplitude can reach 40-50% of the initial flow depth, however, layer disintegration, flow separation, and/or excessive increase in the thickness do not accompany the wave propagation. Therefore, special means to suppress surface instability are not needed provided inlet fluctuations are at a level < 5-10%

Due to the complexity of the problem, no detailed work has yet been done in the area of accommodation of penetrations with liquid metals. Such penetrations represent in MHD flow both a disturbance to the hydrodynamic flow field via the physical diversion of liquid from its initial course, and also, and more significantly, a disturbance to electrical current paths that potentially can overwhelm the flow with local and global MHD drag. Preliminary conclusions, gleaned from the discussion of side-walls above, is that any penetration will require an insulator coating to isolate the structure from the free surface flow.

Nuclear Heat, Tritium Breeding, and Activation

The thin layer of liquid does not significantly alter the radial build of ARIES-RS, however, the choice of working liquid plays a big role in the neutronics. Analyses of the nuclear heating and activation have been carried out using the ARIES-RS radial build at higher power density and with different coolants. The conclusions are that waste and damage issues in the vacuum vessel, the shield and magnets are minimized when Flibe is used, as compared to Lithium. Solid walls damage parameters are reduced by ~ 10-15% with the 2 cm Li-layer and ~20-30% with 2 cm Flibe or Sn-Li layers. Lithium coolant offers the best tritium breeding potential at natural Li-6 enrichment. Lithium and Flibe coolants have maximum tritium breeding ratio (TBR) at 25% Li-6 enrichment (local TBR ~1.5 for Li and ~1.2 for Flibe) whereas it keeps increasing with Li-6 enrichment in the Sn-Li coolant (~TBR ~1.3 at 90% Li-6). The inclusion of beryllium drastically enhances TBR in the Flibe and Sn-Li cases (local TBR~1.7 in Flibe at 25% Li-6 and ~1.4 in Sn-Li at 90% Li-6 enrichment) which indicates that tritium self-sufficiency condition could be met with Flibe or Sn-Li breeder. With regard to power deposition however, the Sn-Li offers the largest power multiplication (PM) among the several breeders. PM is ~1.4 for Sn-Li, ~1.14 for Li and ~1.02 for Flibe. The Sn-Li breeder therefore could offer better plant thermal output for the same fusion power.

Key Issues and R&D

There are several dominant issues that go directly to the feasibility of this concept, and many more issues that weigh heavily on the ultimate attractiveness. The amount of allowable evaporation must be determined for all liquid candidates. This is both a feasibility issue and an attractiveness issue. We recognize that a fully consistent answer to this question will require a considerable amount of research in modeling and analysis of plasmas with liquid wall boundaries, as well as experimental research in various confinement devices.

In addition to the plasma compatibility, the issue of establishing a viable hydrodynamic configuration threatens feasibility. The issues in this category differ significantly for molten salts versus liquid metals. For Flibe, the main issue concerns the penetration of heat at the free surface and the availability of a robust operating window. Other issues as to the formation and removal of the liquid flow in the plasma chamber, and the accommodation of penetrations are also serious, but in our opinion solvable via numerical modeling and scaled experiments with Flibe simulants (such as water). The heat transfer issue is a more serious unknown, as current limits on surface temperature for Flibe are estimated by the plasma interface group at about 560°C. Also a serious issue for Flibe, is the behavior in the divertor region, where direct plasma contact occurs. The amount and nature of the material sputtered and redeposited needs to be determined before accurate plasma modeling of the region can take place.

The main issue facing liquid metals is of course that of MHD interaction. The CLiFF flow itself is very sensitive to changes in drag since the only forces governing the flow are gravity and friction. Without toroidal axi-symmetry of the flow and field, reliable insulator coatings will be required on all surfaces in contact with the LM layer. MHD forces from surface normal components of magnetic field can upset this balance, even when complete axi-symmetry is assumed in the toroidal direction. Additionally, gradients in toroidal field can exert a significant drag on the free surface flow. LMs however, offer the potential for active control that is not present with the molten salt. By biasing and applying electric currents, the LM can be pumped or pushed against the back-wall *in-situ* – offering the chance to “confine” the liquid wall just as we confine the plasma. All these effects need to be analyzed in greater detail, with both modeling and small-scale experimental efforts to see if a suitable flow is indeed possible in the real fields of a tokamak or other plasma confinement device.

Apart from the free surface flow itself, MHD issues exist in the LM supply and drain lines and blanket flows as well. Insulator coatings are needed for these structures. Additionally, due to the large LM flowrates required for CLiFF, large pressure drops are expected in the entrance regions between toroidal field coil legs. These pressure drops can theoretically be overcome by *in-situ* LM pumping, but lead to very large pumping powers for the CLiFF designs with LMs. A clever design of inlet piping may help reduce this effect, as would a reduction in the LM flowrate as well.

Impact of liquid wall implementation on other reactor systems is another category of issues for the CLiFF concept. In particular, it will be likely that heating and diagnostic ports must be redesigned to allow flow to pass around the penetration. Pumping systems with a considerable amount of vapor from liquid evaporation will need to be modified. Tritium recovery (especially with hydrogen *getters* like lithium) will be even more challenging, and material selection and compatibility to help optimize liquid wall performance must be addressed. Flibe and Sn-Li database issues must be addressed for all liquid wall and blanket options as well.