6. Electromagnetically Restrained Lithium Blanket (Woolley, et al)

6.1 Introduction

Whereas conventional solid plasma-facing materials for a magnetic fusion blanket's first wall restrict maximum power density and require frequent replacement, a liquid has no crystal structure to be damaged by thermal stress or neutron bombardment. To advance objectives of higher power density and reduced maintenance, thick liquid flowing walls blanket concepts eliminate solid plasma-facing materials and instead present a liquid free-surface directly to the plasma with no intervening solid material. One thick liquid concept is the Electromagnetically Restrained (EMR) Lithium Blanket, in which an approximately one meter thick shell of liquid lithium metal almost completely surrounds a fusioning tokamak's toroidal plasma discharge, absorbing plasma particles, neutrons and other radiations while breeding tritium and collecting high temperature heat for power generation. The layer's thickness is chosen based on considerations of tritium breeding, of absorbing most of the fusion power, and of minimizing activation and damage to the solid chamber walls located behind the liquid. The liquid lithium is flowing, and circulates in a loop through external equipment which removes chemically bound hydrogen isotopes, entrained helium, and high temperature heat. Of all possible liquid materials, pure lithium metal has the advantages of

a)high abundance,
b)superior tritium breeding,
c) low chemical toxicity, and
d) almost zero neutron activation.

Lithium's high electrical conductivity may also permit efficient, compact MHD power generation. However, it also introduces challenges due to MHD interactions with the free-surface liquid metal flow.

The EMR concept convers MHD difficulties introduced by the liquid metal's electrical conductivity into MHD advantages by deliberately injecting controlled electrical currents to influence liquid flow dynamics. A strong toroidal magnetic field is unavoidably present in the liquid lithium layer, since it is needed to confine the adjacent plasma. A force field pushing the liquid against the chamber's walls is generated by injecting current to flow through the liquid lithium in the poloidal direction. The injected poloidal current interacts with the toroidal magnetic field to generate an internal "J X B" body force helping to keep the liquid lithium away from the plasma.

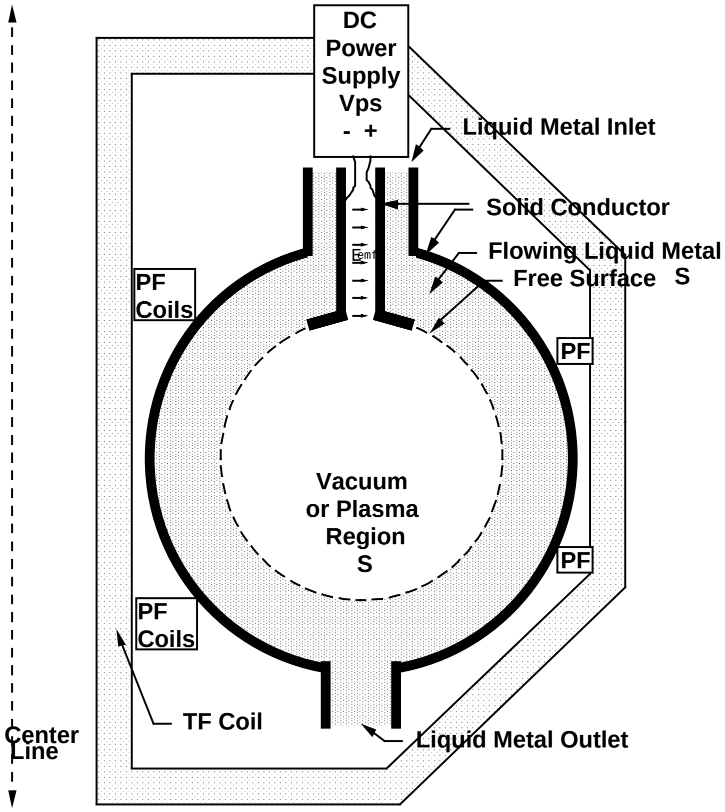

Figure 6.1: Electromagnetic Restraint (EMR) Lithium Blanket Concept

The electromagnetic forces developed within the liquid lithium are similar to the forces within a toroidal field coil magnet. Within a toroidal field coil, current flows in the poloidal direction through winding "turns", generating a magnetic field in the toroidal direction, The turn currents also interact with the toroidal magnetic field to produce a radial force on the turns, pushing the turns away from the enclosed toroidal volume. In the EMR Lithium Blanket concept, the lithium layer carries current in the same direction and sense as do the turns in the nearby toroidal field coils which enclose the plasma and blanket. The lithium layer thus functions as an additional toroidal field coil “turn” and is subject to typical TF turn forces.

Conducting liquids flowing through magnetic fields can generate large MHD forces opposing their motion, if a closed path exists for electric current to flow in response to the motion-induced electric field. For flow through pipes, these MHD forces can be overcome by using high pumping pressure, but for free-surface liquid blankets, which inherently have a low pressure gradient, external pumping is not effective. The use of injected electric currents provides the possibility of compensating for some of the MHD effects in free-surface systems.

As depicted in Figure 6.1, two axisymmetric liquid lithium streams enter the toroidal chamber’s top. The two streams are electrically separated there, either by an electrical insulator or by a noninsulating structure in which some electrical dissipation is wasted via leakage. At the top, the two streams are biased to different voltages via electrodes connected to an external power supply. Poloidal current injected via these electrodes is conducted through the streams which meet and join at the bottom of the chamber. The resulting **J X B** electromagnetic forces push the streams against the chamber walls and thus help hold them away from the plasma. The EMR Lithium Blanket concept makes use of these electromagnetic forces in conjunction with the other natural forces that exist, including centrifugal(inertial) forces, contact forces, viscosity, and surface tension.

In a variation on the EMRconcept, a two-pass design using sublayers also is possible in order to simultaneously achieve high exit temperature of the heated lithium while keeping the maximum vapor pressure of the colder plasma-facing liquid lithium surface low. This useful capability to obtain a higher temperature inside a heated fluid than at its edge is a capability of thick liquid blanket concepts, but it may be most effective with the laminar characteristic of highly conductive free-surface liquid flows in a strongmagnetic field. It occurs since most lithium blanket heating is due to DT neutron interactions within the bulk fluid, because the sublayer with a free surface can transit through the chamber faster than layers closer to the chamber wall, and because typical liquid lithium flow fields in a strong magnetic field are laminar rather than turbulent, thus thermally equilibrating slowly via thermal conduction/diffusion. The liquid’s transit time from the top to the bottom of the chamber is determined by gravity, frictional losses and chamber geometry. Since centrifugal force does not act alone in producing the liquid blanket structure, slower liquid velocities may be tolerated for the bulk liquid, Optional nonaxisymmetric solid structures could be mounted on the chamber walls to slow the lithium’s rate of descent via induced eddy currents.

6.2 Comparison with other Thick Liquid Blanket Concepts

Other thick liquid blanket concepts differ in the material used but meet the same objectives regarding tritium breeding, absorbing most fusion power, and minimizing activation and damage to the solid chamber walls located behind the liquid. The two materials which have been considered by APEX are

1. Tin-Lithium, a mixture of liquid tin and lithium mixture, and
2. FLiBe, a mixture of molten salts BeF_2 and LiF.

The Tin-Lithium material is highly conductive and dominated by MHD effects. The EMR concept could be applied directly to Tin-Lithium, and probably would be necessary in a thick liquid blanket to help counter MHD difficulties. The EMR flow details for Tin-Lithium would be more sensitive to centrifugal force and weight than flows for pure lithium since its mass density is far higher. The Tin-Lithium could be operated at a higher surface temperature based on its lower evaporation characteristics, A thinner layer of Tin-Lithium would suffice because of its better neutron moderating properties, but the tritium breeding ratio of Tin-Lithium is poorer than that for pure lithium. Tin-Lithium is less likely to burn in an accident than pure lithium, but Tin-Lithium is more of a radiological biohazard for accidents or for waste disposal. Tin is sufficiently abundant to not limit the future deployment of fusion power plants.

The thick liquid blanket concepts for FLiBe do not need to contend with dominant MHD effects. Their configurations are maintained via centrifugal inertial effects, which require high velocities, high mass flow rates, and high pumping power. FLiBe has a higher melting temperature than lithium and has different evaporation characteristics and different impurity effects on a plasma; it may have a smaller window of acceptable operating temperatures than pure lithium. FLiBe like pure lithium would not pose a radiological waste disposal hazard, but would be a radiological hazard fro accident conditions. Unlike lithium, FliBe cannot burn. World resources of beryllium may limit the amount of FLiBe that can be produced, thus limiting the number of fusion plant blankets employing FLiBe which could be deployed

The EMR Lithium Blanket may result in the lowest possible inventory of radioactive materials for all DT fusion power plant designs. It thus is appealing from a radiological/safety point of view. Pure lithium is a near-zero activation material, with essentially zero activation in most circumstances. Its tritium breeding byproduct, helium, is inert for both nuclear and chemical reactions. Although its tritium breeding product is radioactive, tritium's only radiation is a low energy electron with no accompanying gamma rays. In a fusion reactor employing the EMR concept, the blanket should be continuously scrubbed of its bred tritium, resulting in a low tritium inventory susceptible to release in an accident. Bred tritium would be consumed in the plasma as it is produced. Lithium itself has no radioactive isotopes with significant half-lives. There is one "nearby" short half-life radioactive isotope of beryllium which beta decays with an accompanying gamma ray, but there are no single-step reactions capable of converting lithium to it, and multi-step reactions are not significant. This situation is in contrast to FLiBe which would contain products from nuclear reactions involving fluorine, Whereas conventional blanket designs using a solid first wall typically includes a substantial amount of material which becomes activated by the neutron bombardment, the EMR concept has no first wall in front of the liquid to become activated. By designing the lithium layer to be sufficiently thick, activation of the wall behind the lithium can also be minimized. Thus, the EMR concept's only activated material results from neutron irradiation of the unprotected solid plasma-facing materials located between the two lithium streams' entrance ports.

From a chemical biological perspective, lithium is not especially toxic. Lithium compounds have even been administered as medication. This is in contrast to FliBe, considered a poison due to its Be content.

Lithium may improve the plasma performance Lithium is low-Z (after hydrogen and helium) and so is expected to have the smallest possible impact on plasma radiation losses, as compared to Fluorine and even higher Z elements. Some experience and theory suggest that lithium impurities may even improve plasma performance. It has been suggested that because of their complete absorption of incident hydrogen, lithium walls may end hydrogen recycling, leading to higher plasma edge temperature, better energy confinement, and improved fusion plasma performance. Lithium walls are expected to simplify vacuum pumping. Axisymmetric flowing liquid lithium are also expected to disallow penetration of nonaxisymmetfric magnetic flux, and so may tend tooppose the growth of nonaxisymmetric magnetic islands in the plasma which cand lead to disruptions.

Use of a single element, lithium, may simplify chemical processing of the blanket, This is in contrast to FLiBe, which is likely to develop various soluble impurities like hydrofluoric acid after some of the lithium and beryllium is consumed by neutron reactions.

6.3 Flow Phenomena with Injected Electric Current

Significant forces can be generated in liquid lithium metal without excessive electrical power. The threshold for significance may concern levitation. Lithium's mass density is about half of water's, so its gravitational weight density on Earth is about 5000 Newtons/m^3. With the approximately 5 Tesla toroidal field typical of many tokamak reactor designs, to generate a force field matching lithium's weight density requires a current density of $J=\rho g/B=1$ kA/m^2 in the lithium, which implies an electric field of 350 micro-volts/meter and an electric power dissipation of 0.35 watts/m^3. These are modest parameters. At this "one-gee" force-field level, a lithium EMR blanket surrounding an ITER-sized plasma would require a total current of 50 kA, implying a loop voltage of 0.01 volts, and a power of 500 watts. Increasing power to 1 MW would increase the lithium force field to the equivalent of 45 "gees".

6.4 Axisymmetric LMMHD Analyses

If highly conductive liquid metal were flowing in nonaxisymmetic patterns beside a tokamak plasma, MHD effects would produce nonaxisymmetric currents in the liquid, which in turn would produce nonaxisymmetric magnetic fields and which would perturb the plasma. Tokamaks and several other plasma confinement schemes require precisely axisymmetric magnetic fields to maintain nested internal flux surfaces. They have very little tolerance for departures from axisymmetry and develop “magnetic islands” which deteriorate plasma confinement at very small levels of nonaxisymmetric magnetic field “ripple”. A reactor blanket must therefore avoid doing harm to the plasma equilibrium, so strict axisymmetry is an important requirement for the portions close to the plasma of a highly conductive, fast moving, liquid blanket.

Although exact 3-D MHD equations for an incompressible liquid are complicated, they can be simplified without any approximation for the EMR Lithium Blanket concept by this requirement for axisymmetry. In deriving exact axisymmetric LMMHD equations with independent variables (r,z,t), it is convenient to express magnetic field via the poloidal magnetic flux stream function, Ψ, and the total poloidal threading current stream function, I (including any Toroidal Field coil system current). (One could also employ a velocity stream function and vorticity formulation, but that does not appear to simplify the equations.) Denoting fluid velocity $\vec{u} = u_r \hat{a}_r + u_\varphi \hat{\varphi} + u_z \hat{a}_z$, the resulting six time-dependent scalar PDEs which apply to Figure 6.1 are

$$\boxed{\frac{\partial I}{\partial t} = -u_r \frac{\partial I}{\partial r} - u_z \frac{\partial I}{\partial z} + \frac{1}{\sigma\mu}\Delta^* I + \frac{2u_r I}{r} + \frac{r}{\mu} \nabla\Psi \times \nabla(\frac{u_\varphi}{r})} \tag{1}$$

$$\boxed{\frac{\partial \Psi}{\partial t} = -u_r \frac{\partial \Psi}{\partial r} - u_z \frac{\partial \Psi}{\partial z} + \frac{1}{\sigma\mu}\Delta^* \Psi} \tag{2}$$

$$\boxed{\begin{aligned} \frac{\partial u_r}{\partial t} = \frac{u_\varphi^2}{r} - u_r \frac{\partial u_r}{\partial r} - u_z \frac{\partial u_r}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial r} + \nu(\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial u_r}{\partial r}) + \frac{\partial^2 u_r}{\partial z^2} - \frac{u_r}{r^2}) \\ - \frac{\Delta^* \Psi}{4\pi^2 r^2 \rho\mu}\frac{\partial \Psi}{\partial r} - \frac{\mu I}{4\pi^2 r^2 \rho}\frac{\partial I}{\partial r} \end{aligned}} \tag{3}$$

$$\boxed{\begin{aligned} \frac{\partial u_\varphi}{\partial t} = -\frac{u_r u_\varphi}{r} - u_r \frac{\partial u_\varphi}{\partial r} - u_z \frac{\partial u_\varphi}{\partial z} + \nu(\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial u_\varphi}{\partial r}) + \frac{\partial^2 u_\varphi}{\partial z^2} - \frac{u_\varphi}{r^2}) \\ + \frac{1}{4\pi^2 r^2 \rho}(\frac{\partial I}{\partial z}\frac{\partial \Psi}{\partial r} - \frac{\partial I}{\partial r}\frac{\partial \Psi}{\partial z}\} \end{aligned}} \tag{4}$$

$$\boxed{\begin{aligned} \frac{\partial u_z}{\partial t} = -u_r \frac{\partial u_z}{\partial r} - u_z \frac{\partial u_z}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial z} + \nu(\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial u_z}{\partial r}) + \frac{\partial^2 u_z}{\partial z^2}) \\ + g_z - \frac{\Delta^* \Psi}{4\pi^2 r^2 \rho\mu}\frac{\partial \Psi}{\partial z} - \frac{\mu I}{4\pi^2 r^2 \rho}\frac{\partial I}{\partial z} \end{aligned}} \tag{5}$$

$$\boxed{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right) + \frac{\partial u_z}{\partial z} = 0} \tag{6}$$

where $\Delta^* := r\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}$ is the Grad-Shafranov operator, where $\Delta := \hat{a}_r\frac{\partial}{\partial r}+\hat{a}_z\frac{\partial}{\partial z}$ is the gradient operator, where ν is kinematic viscosity, ρ is density, σ is conductivity, and μ is permeability.

The spatial boundary conditions for Eq (1) are that I = the TF coil system's ampere-turns at the exterior of Figure 1's conductor region and $I = I_s$ at the liquid metal's inner plasma-facing free-surface, where I_s is given by

$$\boxed{I_s = \frac{2\pi}{\mu}\frac{\Phi}{\oint_{\partial S}\frac{z}{r}dr}} \qquad (7)$$

EMR performance partly controlled by the power supply voltage, which affects the boundary condition for Equation (1). In Eq (7) the contour integration path is the time-varying free-surface's shape, ∂S (See Figure 6.1), and the enclosed flux variable, $\Phi(t)$, varies over time according to the following ODE:

$$\boxed{\frac{d\Phi}{dt} = V_{PS} - \frac{1}{2\pi\sigma}\oint_{\partial S}\left(\frac{\partial I}{\partial r}\frac{dz}{r} - \frac{\partial I}{\partial z}\frac{dr}{r}\right) + \frac{\mu I_s}{2\pi}\oint_{\partial S}\frac{(u_r dz - u_z dr}{r}) + \frac{1}{2\pi}\oint_{\partial S}\frac{u_\varphi}{r}d\Psi} \qquad (8)$$

These integrals are also evaluated around the liquid metal's free-surface contour. V_{PS} is the possibly time varying dc control voltage galvanically applied to the liquid metal by the external power supply in Figure 1. (Note Eq (8) neglects plasma poloidal current effects, but is exact for a true vacuum region.) The "no-slip" boundary condition, $\vec{u} = 0$, applies to velocity on liquid/solid interfaces. Velocity is unconstrained on the free-surface but the pressure is $p|_{FreeSurface} = \gamma(\frac{1}{R_1}+\frac{1}{R_2})$ (9)

where γ is the liquid's surface tension parameter, R_1, R_2. are local surface curvature radii.

It should be noted that Equations (1)-(9) are not closed because they do not completely describe the poloidal flux boundary conditions on the surfaces of the liquid and solid metallic conductors. These time-varying boundary conditions depend on the plasma and poloidal field coil currents, which depend on the plasma scenario. For the case of no plasma or PF coil currents, the above equations are closed and are ready to be solved for specific cases. For cases including a plasma and/or PF coil current histories, additional data is needed to conduct an analysis.

Although greatly simplified from the 3-D case, the above equations (1) through (9) are not amenable to direct analytical solution unless many approximating assumptions are made. That has not been done, but perhaps it would be useful.

The equations are amenablet to numerical solution. No commercially available simulation code was identified capable of such a simulation, so one was coded. However, the code's debugging was not complete at the time of this report, so no detailed numerical studies of the EMR concept could be included herein.

Some observations can be made directly about the equations. They follow:

1. The toroidal swirl motion, $\frac{\partial u_\varphi}{\partial t} \neq 0$ is characterized by Equation (3), which predicts that toroidal swirl motion could remain identically zero as long as $\frac{\partial I}{\partial z}\frac{\partial \Psi}{\partial r} - \frac{\partial I}{\partial r}\frac{\partial \Psi}{\partial z} = 0$, i.e., as long as the poloidal current in the liquid metal is aligned to follow poloidal flux surfaces.

2. For a familiar solid conductor, Equation (1) becomes $\frac{\partial I}{\partial t} = \frac{1}{\sigma\mu}\Delta^{*} I$, which describes the diffusion of current into the conductor and relaxing to its steady-state configuration. For a liquid there are other terms, including:

a) $u_r \frac{\partial I}{\partial r} + u_z \frac{\partial I}{\partial z}$ which is nonzero if the injected current is misaligned from the velocity,

b) $\frac{2u_r I}{r}$ which generates "diamagnetic drag" in conjunction with Eq.(3)

c) $\nabla\Psi \times \nabla(\frac{u_\varphi}{r})$ which is zero unless a non-uniform swirl is misaligned with poloidal flux surfaces,

3. If liquid velocity injected current were both aligned to poloidal flux surfaces, Equations(3) and (5) show that velocity along streamlines would be unaffected by the variables, I and Ψ.

6.5 Electromagnetic Interactions with Tokamak Plasma

The equations (1)-(9) of the previous section include all interactions with an axisymmetric plasma, except for galvanic halo currents flowing between the plasma and the conducting surface, which are not predicted by these equations. There will be causal inteactions in both directions between the plasma's magnetics and the lithium blanket's magnetics, which ideally would necessitate integrated analyses. The choice of variables, I and Ψ, matches the magnetic variables typically used in plasma simulations, and was chosen to simplify the later task of marrying a plasma simulatio code with an EMR blanket model,

For a passive solid conductor, Equation (2) would become $\frac{\partial\Psi}{\partial t} = \frac{1}{\sigma\mu}\Delta^{*}\Psi$, which describes current penetration ito a conductor and its relaxation to a steady-state configuration, which is zero in the case of eddy currents. For the moving liquid we have the additional term, $u_r \frac{\partial\Psi}{\partial r} + u_z \frac{\partial\Psi}{\partial z}$, which is zero if the liquid velocity follows poloidal flux surfaces but could be permanently nonzero if they are misaligned.

6.6 Necessary Departures from Axisymmetry

It is not possible to design an entirely axisymmetric blanket system since the flowing liquid must cross between structural supports at some location, and in most versions of the concept need to exit and reenter the TF coil region. Analyses of these nonaxisymmetric regions will be more complex. There may be significant MHD pressure losses and pumping problems in the nonaxisymmetric regions.

6.7 Key Issues and R&D.

The key issues with the EMR Lithium Blanket concept all are based on the difficulty of predicting its performance. At the present time, there are no computer tools or other methods to design such a system. At this time, the key issues are all associated with developing methods to predict how it and variations of it would behave, and experiments with the goal of benchmarking those experiments.