Liquid-Lithium as a Plasma Facing Material for FusionReactors
D. N. Ruzic1, J. P. Allain1, D. Curreli1 and D. Andruczyk1
1Center for Plasma Material Interactions, Department of Nuclear, Plasma and Radiological Engineering, University of Illinois Urbana-Champaign, Urbana IL, 61801 USA
Email: druzic@illinois.edu

One disruption or a few larger-than-predicted ELMS could very likely melt a portion of the divertor surface in a DEMO-scale fusion energy device, if it is a scaled-up version of ITER. Such melting would destroy the surfaces conformity to the contours of the last-closed-flux-surface and require replacement and extensive downtime. Even without such a possibility an ITER-scaled DEMO would have such an enormous cost per kW-hr of electricity produced that it would never be seriously considered by a utility company. If fusion is to become a usable, economically-competitive energy source, the envisioned future device must cost significantly less. The easiest way to accomplish such a cost reduction is a reduction in size.

1. Technology to be assessed
A liquid lithium surface has unique advantages over a solid surface. Liquids are self-healing, and lithium is the lowest-Z material possible, allowing higher impurity concentrations in the core. Furthermore, lithium has the unique property of absorbing most of the hydrogenic species which impinge upon its surface, as long as the lithium is clean[1]. This leads to a low-recycling surface, where cold (divertor-plate-temperature) deuterium and tritium are NOT returned immediately to the plasma.

2. Application of the technology
In the high-recycling regime, wall-temperature molecules leave the surface in equal numbers to the hotter ion flux impinging on the divertor plate. Such a return of recycled hydrogenic species cools the edge of a fusion device, and therefore shrinks the portion of the confined plasma which reaches temperatures high enough for fusion. A device operating in the low-recycling regime can maintain the same volume of fusing plasma as a standard-ITER-like fusion device with a dramatically smaller major radius, and thus smaller overall volume.[2] Volume equals cost. A low-recycling lithium-surface machine could cost an order-of-magnitude less and still produce the same electricity output. While the average heat flux to the surface would be higher in a smaller machine, liquids also allow the possibility of tolerating that flux. After all they are already melted!

3. Critical variable
There are four critical variables that need to be taken into account with these liquid metal technologies in particular lithium. These will be mentioned below and their design variables and risks will be evaluated in sections 4 and 5.
   a. Lithium Gets Contaminated/Saturated: The reactivity of lithium means that it may quickly passivate through reactions with impurities in the plasma vessel. This will negate the advantageous effects of lithium, eventually it will look like any other high recycling wall.
   b. Lithium Absorbs all the Tritium in the World: If a machine the size of ITER had a fully flowing lithium 1st wall and divertor, it can be shown that within the space of a several hours all the tritium will be absorbed. Thus being able to extract this in a timely manner will be critical
c. **Lithium is Too Corrosive and Difficult to Handle:** Indeed, lithium is corrosive, however the metals that are resistant to lithium attack are fortunately ones that are fusion compatible and active systems to control the lithium flow will be needed.

d. **Lithium Gets Too Hot:** Lithium has a high vapour pressure and has a limited operating temperature range between 180°C (melting) and 400°C (evaporation).

4. & 5. **Design variables risks and uncertainties**

Here each of the topics discussed above will be addressed in terms of the design parameters needed.

a. **Lithium Gets Contaminated/Saturated:** To combat this potential the problem, the lithium must be both molten and flowing. That way a constantly clean new surface is exposed to the plasma. One such scheme which accomplishes this is LiMIT (Liquid Metal Infused Trenches) [3] which utilizes the TEMHD effect, the plasma’s heat flux, and the toroidal magnetic field, to self-pump molten material across the divertor strike point as shown in Fig. 1. This was first shown to work at Illinois in laboratory experiments[4], and then placed in Magnum-PSI to determine heat flux limits[5], placed in HT-7 to illustrate its compatibility with tokamak relevant fields[6], and in DeVEX to show how droplet emission could be eliminated by proper spacing of the trench components[7]. Other flowing lithium concepts are also possible such as FLiLi[8] and CPS[9], as long as continuous replenishment and removal of the lithium takes place. This class of flowing liquid lithium systems – at use in many fusion devices around the world – are important innovative technological breakthroughs.

b. **Lithium Absorbs all the Tritium in the World:** A low-recycling divertor solution requires fast tritium removal and re-injection. Fortunately this could be possible, since most of the hydrogen stays in solution with molten lithium [10] as opposed to forming hydrides. It is critical to test this hypothesis with experiments. Some of those are underway at Illinois starting with LiH and determining the equilibrium curves between the solution and hydride phases shown in figure 2. Next fast-distillation of the hydrogen-filled lithium will be demonstrated, and then a fully-flowing lithium-loop will be constructed on the Illinois Stellarator HIDRA[11], where a full accounting of D-recycling, removal and recovery by a flowing lithium surface will be documented for the first time under realistic conditions. Preliminary calculations show that it may be possible to recirculate the tritium with a time constant less than 1 hour. More experiments along these lines should be encouraged across the world. It should be noted that it also has been shown that liquid lithium can pump helium and this may be useful as a method for removing the helium ash from future devices.[16]
c. Lithium is Too Corrosive and Difficult to Handle: Indeed lithium is corrosive and difficult to handle, which is why an active technology program is essential. Handling lithium safely is paramount, but quite possible. One concern is the ability to get lithium to wet some surfaces, and not to wet others.[12] Towards this goal, femtosecond-laser texturing of materials have shown that the lithium wetting temperature is pushed at least 100°C higher as shown in Fig. 3. Complete integrated systems with molten lithium need to be tested under realistic conditions before they can be adopted in large-scale machines. HIDRA serves as a lithium-technology test-bed, where the actual lithium-containing structures will be tested before being placed in EAST. Fig. 4. shows that they all fit and will be hit by a realistic edge plasma.[13] These are only a few examples of the work that needs to be done for lithium readiness, but they show that such work is possible and is in progress. In fact, the surface chemistry of lithium can be studied in-situ through a device such as the HIDRA Materials Analysis Tool (HIDRA-MAT) shown in Fig. 5. containing XPS, TDS and DRS diagnostics operating while the plasma is in progress.[14]

![Figure 3. Femtosecond-laser texturing creates nanostructures which resist wetting.](image)

![Figure 4. EMC-Eirene modeling of HIDRA plasmas, and equilibriums which allow full-size placement of EAST components in the HIDRA edge-particle-flux.[13]](image)

![Figure 5. The MAPP facility installed on LTX at PPPL diagnoses plasma-material interactions with in-situ surface analysis instrumentation.](image)

d. Lithium Gets Too Hot: Lithium has a very high vapor pressure above 400°C. This does not mean the thermal cycle of a lithium-containing fusion device is limited to 400°C. Since 80% of the energy from fusion exits through the neutron channel, thermodynamic efficiency is largely determined by the blanket parameters. However, it is quite possible to have the divertor plate colder while the walls of the vessel are at much higher temperatures. As long as the heat removal rate is greater or equal to the heat input rate, a thin structure can be maintained at any temperature. There may be an easier way to still have an active lithium surface able to achieve low local recycling, while escape the stringent temperature limits. Molten Sn-Li eutectics made at Illinois (see Fig. 6) have been shown to have a few atomic layers of Li segregate to their surfaces,[15] thus presenting a lithium PFC to the plasma, while maintaining bulk Sn properties such as vapor pressure and boiling points. Research into this and other liquid metals is critical to enable an alternate materials path for fusion.

6. Maturity
In general, the liquid lithium technologies are somewhere between the TRL4 and TRL 5 stages. TRL 3 has been completed. All of the systems mentioned above, LiMIT [3], FLiLi [8] and CPS [9] have been shown to work in several locations and on different machines. TRL4 has been done to some
degree. The systems have been tested in different environments but the heat removal and also hydrogen and circulation integration need to be completed.

7. Technology development for fusion applications

There are several areas that need to be developed before we see liquid lithium technologies be accepted as a viable PFC.

a. The need to determine how quickly deuterium and tritium is absorbed by lithium and how quickly it can be separated and reused. This will require in situ environments and diagnostics to be established based around XPS, SEM and RGA capabilities within flowing liquid lithium systems that are installed on actual machines like HIDRA, EAST, NSTX-U etc.

b. Devise and develop techniques to safely handle and utilize liquid lithium and tin-lithium. This includes assessing the wetting of liquid metals with surfaces and investigating surface treatment where we can control the surface wetting and the way the liquid metal behaves. This includes exploring the merits of Sn-Li technologies.

c. Further testing of flowing liquid lithium concepts like LiMIT and FLiLi with technology development and testing on devices like HIDRA and then full scale experiments on machines like EAST. Proof of concepts development for high-heat flux “fas” flowing lithium across the target.

d. 3-D modeling of the full lithium flows, including MHD effects

Liquid metals offer a superior alternate approach to the most demanding PFC challenges of fusion. Not only could they withstand high and off-normal heat fluxes without permanent damage, they offer entire new regimes of fusion device operation. The low-recycling wall, if it can be made to work, could reduce the size and cost of fusion energy devices ten-fold. To realize this awesome potential, further innovative technology development is required. The US is the present leader in this field. It is imperative to the future of fusion energy that such programs continue and grow. Liquid-lithium surfaces are an innovation which could fulfill fusion’s promise.

[13] D. Curreli et. al., Fusion Engineering Design (to be submitted) 2017