Progress in a US-based Liquid Metal Plasma-Facing Component Design Activity for a Fusion Nuclear Science Facility

R. Maingi[1], D. Andruczyk[2], D. Curreli[2], J. Jun[3], J.D. Lore[3], C.E. Kessel[3], A. Khodak[1], E. Kolemen[1], D. O'Dea[2], B.A. Pint[3], S. Smolentsev[4], Z. Sun[1], D.L. Youchison[3]

[1] Princeton Plasma Physics Laboratory, Princeton NJ, USA
[2] Univ. of Illinois – Urbana/Champaign, Urbana IL, USA
[3] Oak Ridge National Laboratory, Oak Ridge TN, USA
[4] Univ. of California – Los Angeles, Los Angeles CA, USA

Lead author email: *rmaingi@pppl.gov*

Executive Summary: We present new results from a US-based liquid metal divertor plasma-facing component (PFC) design program that was initiated in late 2019. There are two sets of activities: (1) design calculations of heat transfer and liquid metal (LM) flow for candidate PFC designs for a fusion nuclear science facility (FNSF)[1]; (2) experiments in test stands to close LM technology and science gaps, and experiments in a linear flow configuration with applied magnetic fields. The design calculations[2, 3] have identified an operating window with gas-cooled, flowing liquid Li PFCs that exhaust 10 MW/m^2 with 7-8 m/s driven velocity, while maintaining a Li surface temperature at 450 °C. Calculations of the scrape-off layer (SOL) and divertor plasma response to lithium evaporation have been initiated with the SOLPS-ITER package, including the injection of neon gas to reduce incident heat flux to the LM PFC. These calculations indicate the Li is well confined in the divertor region[4]. Experimental tests of wetting, corrosion and embrittlement have been initiated. Finally new experiments on the Liquid Metal eXperiment Upgrade (LMX-U) were initiated, (1) to test predictions of the liquid metal MHD computational fluid dynamics models used in the FNSF design above, and (2) to develop a new flowing divertor concept: "divertorlets"[5].

Design calculations: a generic flowing liquid lithium PFC is modeled, where a 10 MW/m^2 incident heat flux is removed by a thin flowing lithium layer with a gas-cooled substrate (Figure 1).

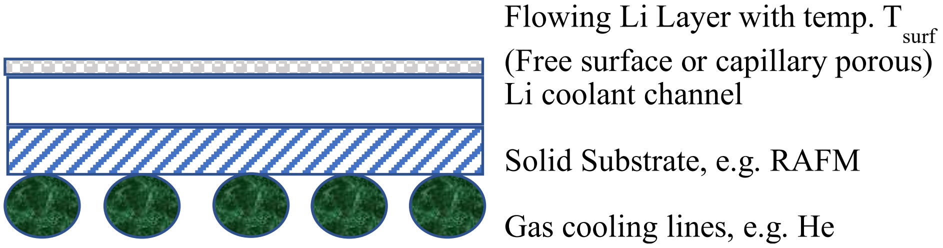

Figure 1: Schematic of flowing liquid Li PFC. There is a coolant channel, either a free surface or one that sits under a solid structure, e.g. a capillary porous layer or a thin-walled tube. Under the Li channel is a substrate, typically RAFM steel or tungsten. On the back side of the substrate, there are gas cooling lines with e.g. He.

The target maximum surface lithium temperature is 450°C or below, close to the temperature where Li surface evaporation increases to perturbative levels.

Several different top-surface options were evaluated: a free-surface boundary, infusion of the liquid Li in a capillary-porous system (CPS), and fast flow of Li in a thin-walled solid structure. For the free-surface boundary calculation, three heat removal modes and the regimes where they dominate were identified[2]: dominant convective cooling by flowing Li for fast velocities, by the He gas coolant with slow Li velocity, and intermediate Li flow velocity regimes. Further numerical computations suggest that of the three regimes, the best heat transfer is via Li flow, and the required Li flow speed to achieve 10 MW/m^2 heat flux removal is about 7 m/s. Tripling the flow speed to 20 m/s removes about 16 MW/m^2. The He-dominated cooling provides low cooling capability <0.5 MW/m^2 in the case of a reduced-activation ferritic Martensitic (RAFM) steel substrate and <2.5 MW/m^2 in the case of a high conductivity copper-like substrate.

In addition, a new divertor cooling concept using liquid lithium coolant channels in a CPS was analyzed[3]. In this concept liquid lithium is propelled through the magnetic field with MHD pumping, i.e. a current is induced through the liquid Li. By using the FNSF toroidal magnetic field B_t, the resulting j x B_t force can propel the Li to speeds ~ m/s, which acts as the sole coolant. Meanwhile the CPS enables wicking of the Li to the plasma-facing surface. The concept was inspired by the large channel reservoirs designed into 3D-printed W targets that were tested in MAGNUM-PSI[6]; when aligned properly, the j x B forces can propel the liquid Li through those channels. Analytical and numerical computational fluid dynamics models were created, with the latter including the effect of surface lithium evaporation on heat transfer. At a Li flow velocity of 7 m/s, 10 MW/m^2 heat flux removal is accomplished with a surface temperature ~ 450°C (Figure 2). In addition, the required power to pump liquid lithium through a cooling channel was computed to be < 5% of the incident power to the PFC from the plasma, which should be readily achievable.

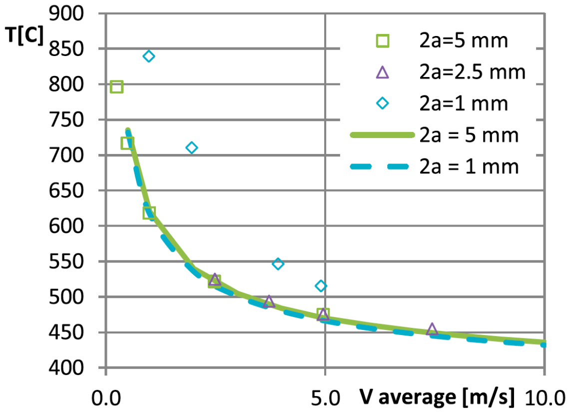

Figure 2: Computed surface temperature on CPS-like mesh with Li coolant channel as a function of flow velocity. Analytical calculations are shown by the lines with differing channel widths '2a', while the points are from numerical analysis [3].

Finally a computational fluid dynamics calculation of heat transfer with fast flowing liquid Li through a thin-walled W tube to maximize heat transfer was initiated. Heat fluxes of 20-60 MW/m^2 were removed by this design, with operating temperatures between 450 and 1550 °C, the latter just above the boiling pint of Li.

Preliminary calculations of plasma response to liquid Li vapor liberated in the divertor from plasma-surface interactions were initiated[4]. A simplified target plate geometry with several candidate impurity injection locations was adopted (Figure 3). This geometry facilitates liquid Li flow along flat surfaces. The base case used Ne gas seeding for upstream cooling. Li vapor was added from the target, with a refined temperature-dependent evaporation rate determined by new sheath calculations with the HPIC code. Initial results indicate that the Li can exhaust 10 MW/m^2 of plasma heat flux, with an upstream Li concentration less than a few percent. The addition of divertor baffling to reduce the upstream Li contamination is being investigated.

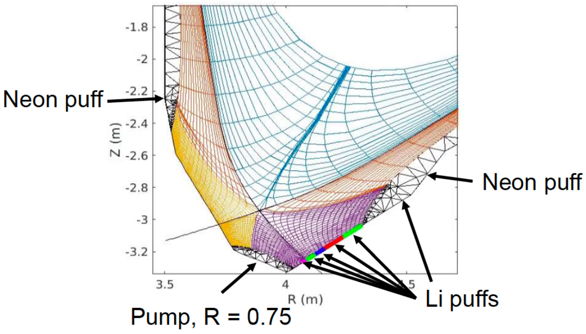

Figure 3: Mesh used for SOLPS calculations for FNSF. Three flat plates are used to simplify liquid metal flow designs. Ne puffs and fixed Ne impurity fractions are used to reduce heat flux. Li is injected at the target [4].

Experimental activities in test stands: Several experiments on wetting, erosion, corrosion, and embrittlement are being carried out in this program. At UI-UC, the mock-up entry module (MEME), a large flexible vacuum chamber, was assembled for experimental tests of liquid Li fill injectors, Li wetting, and Li corrosion studies. In steady-state a liquid Li fill system is required to replenish Li that is deposited in the plasma chamber, due to surface evaporation at high temperatures, surface ejection due to transient plasma loads, and surface removal due to plasma-wall interactions. Some of this Li will be mobilized via subsequent plasma-material interaction processes and swept back into the divertor due to scrape-off layer flow. That Li may be in the form of compounds which must be removed via Li flow and purified for re-use in experiments. A liquid Li refill design injector concept is shown in Fig. 4a.

Measurements of liquid Li embrittlement of a RAFM steel were initiated at ORNL. Three hollow tensile specimens made of F82H steel were prepared, two filled with Li and one empty, to be used as a control sample (Figure 4b).

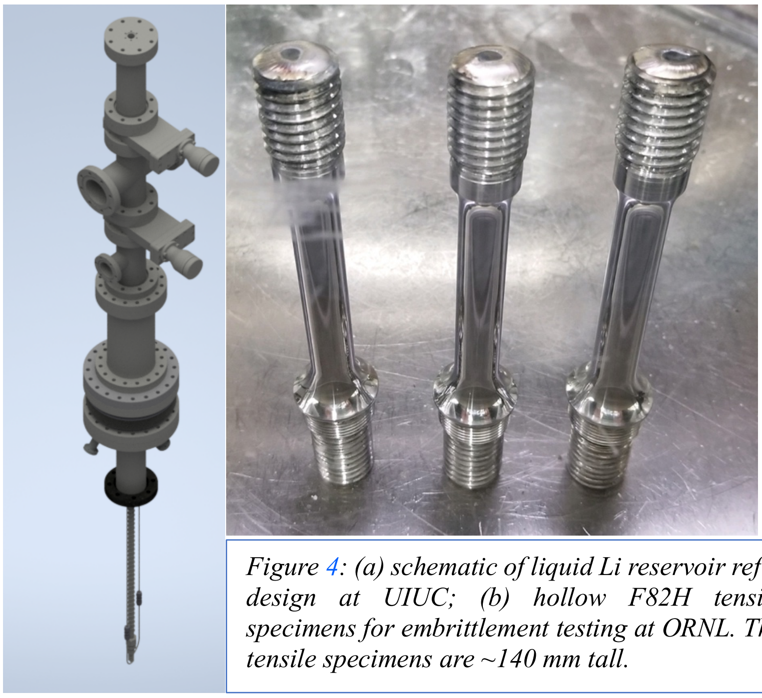

Figure 4: (a) schematic of liquid Li reservoir refill design at UIUC; (b) hollow F82H tensile specimens for embrittlement testing at ORNL. The tensile specimens are ~140 mm tall.

Experimental activities in prototypical flow experiments: Liquid metal flow experiments on the Liquid Metal eXperiment Upgrade (LMX-U) aim at validating model calculations in the design studies. In fact, a new set of MHD flow calculations for LMX-U was completed, investigating the impact of insulating walls vs. conducting walls, operating flow speed, and inclination angle relative to the magnetic field. Each of these will be tested in upcoming experiments. LMX-U is also used to develop new flowing liquid metal concepts, such as "divertorlets"[5]. In this concept, electrodes of alternating polarity drive flow along short flow paths to minimize the amount of time a mass of liquid metal spends in contact with the plasma. This allows the achievement of high heat flux ~ 10 MW/m^2, with a maximum flow speed ~ 1 m/s, i.e. significantly less than the fast flow in the design concepts described above. An example of a module built and tested with Galinstan (Ga-In-Sn), a surrogate liquid metal for Li, is shown in Fig. 5.

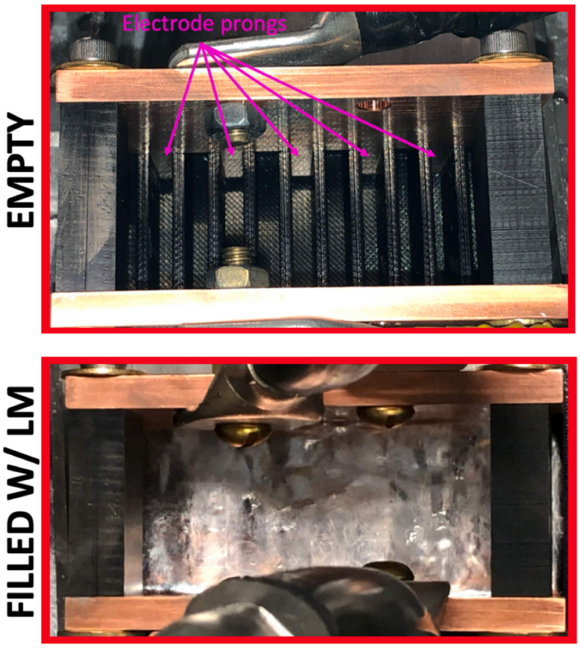

Figure 5: Pictures of an experimental test of the "divertorlets" concept in the LMX-U, using Galinstan as the liquid metal [5].

Outlook: These calculations have successfully identified design windows with simplified flow geometries for an FNSF, with required liquid Li flow speeds ~ 5-10 m/s to exhaust 10 MW/m^2 at surface temperatures near 450 °C. The next step in the program is to investigate higher surface temperatures that will lead to higher Li evaporation rates and stronger divertor heat flux dissipation. As concepts mature for US-specific fusion pilot plants, our calculations will migrate toward evaluating liquid metal PFCs for those designs, eventually aiming to test PFC concepts in a high power tokamak.

* This research was supported in part by the U.S. Dept. of Energy Contracts DE-AC02-09CH11466 & DE-AC05-00OR22725, and grants DE-SC0020642 & DE-SC0020979. The United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

References

1. C. E. Kessel *et al.*, 2019 *Fusion Sci. Techn.* **75** 886
2. S. Smolentsev, 2021 *Fusion Sci. Technol.* at press
3. A. Khodak, and R. Maingi, 2021 *Nuclear Materials and Energy* **26** 100935
4. J. D. Lore *et al.*, 2021 *IEEE Trans. Plasma Sci.* in preparation
5. A. E. Fisher *et al.*, 2020 *Nuclear Materials and Energy* **25**
6. P. Rindt *et al.*, 2019 *Nucl. Fusion* **59** 054001