

## Liquid Metal Plasma –Facing Components

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### Issues and Gaps for Plasma Facing Components

At present, the only solid material believed to be a viable option for plasma-facing components (PFCs) in a fusion reactor is tungsten. Operated at the lower temperatures typical of present-day fusion experiments, tungsten is known to suffer from surface degradation during long-term exposure to helium-containing plasmas, leading to reduced thermal conduction to the bulk, and enhanced erosion. Existing alloys are also quite brittle under 700°C. However, at a sufficiently high operating temperature (700 – 1000 °C), tungsten is self-annealing and it is expected that surface damage will be reduced to the point where tungsten PFCs will have an acceptable lifetime in a reactor environment.

The existence of only one potentially viable option for solid PFCs, though, constitutes one of the most significant restrictions on design space for DEMO and follow-on fusion reactors. In contrast, there are several candidates for liquid metal-based PFCs, including gallium, tin, lithium, and tin-lithium eutectics. The development of liquid metal PFCs is one approach to a resolution of Theme B, “Taming the Plasma-Material Interface”, identified by the Greenwald Panel. The two Tier 1 issues delineated in this report are PFCs and Materials.

A number of configurations have been considered for liquid metal PFCs, including fast flowing jets, fast open-channel flow of thick (~ cm scale) liquid metal layers, usually assisted by  $\mathbf{J} \times \mathbf{B}$  forces, and slow flow of thin liquid metal layers embedded in a porous metal substrate (capillary systems). All configurations exploit the ability of a liquid metal to continuously renew the surface. Whereas the erosion time scale for a solid PFC must be the first wall replacement interval (~1 year for a reactor), the time scale for replacement of a liquid metal is the residence time in the reactor (~seconds or less). The critical erosion rate for the two systems thus differs by 4-6 orders of magnitude. The liquid metal can be either self-cooled (in the case of rapidly flowing or evaporative systems), or cooled from behind (in the case of thin, capillary liquid metal systems). Note that the option of a thin first wall intensely cooled from behind, which forms the basis of various high-heat flux concepts such as the hypervapotron, is not available for solid PFCs due to the need for thick surfaces that can endure long term erosion. A liquid metal PFC however, restrained by capillary forces and separated from the coolant by a thin barrier layer, must only be thick enough to avoid full erosion on a single flow passage through the reactor. The working liquid metals themselves are not likely to be subject to neutron damage; however any supporting substrate for capillary or open channel systems will be.

Liquid lithium has received most of the attention as a candidate liquid metal PFC because it has a low Z, high thermal conductivity, low mass, and high surface tension with a strong chemical affinity for hydrogen. Lithium has the ability to retain hydrogen up to a 10 – 100% H – Li atomic ratio.<sup>1</sup> The minimum theoretical recycling level of deuterium or tritium on any surface is set by the probability of direct reflection of a deuteron or triton from the surface material.

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Lithium, by virtue of its low atomic mass, has the lowest probability for direct reflection of any material. Thus a liquid lithium surface is expected to have the lowest practical recycling coefficient of any candidate PFC, a property now being exploited to investigate the consequences of low recycling on confinement and energy transport.<sup>2,3</sup>

If low recycling walls prove to be unattractive for a fusion reactor, then high recycling liquid metals, which do not significantly retain atomic hydrogen, gain the advantage. Liquid gallium, for example, has good thermal conductivity and very low vapor pressure for  $T < 1,000$  °C with very little change in deuterium retention (about 5 ppm) for varying fluence and temperature making it a good candidate for a high temperature, high recycling first wall.<sup>4</sup>

There is also considerable synergy between intentionally introduced liquid metal PFCs with the behavior, dynamics and impact of unintentionally created metal melt layers during plasma events like disruption, mitigation via massive gas injection, VDEs, giant ELMS, etc. Melt layer mobilization can be the determining factor in the erosion lifetime of metal PFCs.

## **Scientific & Technical Requirements for Liquid Metal PFCs**

Liquid metal PFC development is in an early stage. Only a few liquid metal systems have been tested in tokamaks with a focus on lithium as a tool to reduce recycling predominantly in static or evaporative systems.<sup>5</sup> Fast flowing liquid metal jets, for example, have been tested in only one or two very small devices.

Prominent issues for both high and low recycling liquid metals include the initial problem of introducing the liquid metal to, and removing it from, the reactor, and inducing stable flow to transport the fluid from inlet to outlet. MHD effects caused by the excitation of electrical currents in the liquid metal PFC must not cause macroscopic influx of the liquid metal into the plasma. Sputtering and evaporation must be kept to acceptable levels. Heat removal must be effective. The underlying substrate must be completely covered by the liquid metal since it will not be designed for exposure to plasma. Splashing and surface variations must be eliminated for systems using jets or open-surface channel flow. Clogging and nonuniform coverage must be avoided in capillary systems. The design of inlet manifolds and fluid collection systems is a challenge for either type of system. Tritium migration through the liquid metal into underlying coolant channels must be investigated; since different liquid metals have differing affinities for hydrogen, this work is specific to each candidate liquid metal and eutectic. Finally, for lithium, the physics consequences of low recycling walls for tokamak equilibria must be thoroughly explored since the consequences for reactor design can be considerable.

## **Research Thrusts for Liquid Metal PFC Development**

### **Theory and modeling**

Understanding basic properties of free-surface MHD flows is still in its infant stage. The outstanding questions include (1) how turbulence is influenced by free surface and magnetic field with an arbitrary angle to the surface, (2) how convection is influenced by heat deposited on the free surface and magnetic field, and (3) how the heat transfer rate depends on these two effects. To answer these questions, a strong theory and modeling effort is required. In addition, state of the art MHD modeling of open channel and capillary flow in the presence of reactor relevant magnetic fields is required.<sup>6</sup> Self-consistent electric currents in the liquid metal arising from both its motion through magnetic field and from coupling with the plasma must be

considered. Simultaneous treatment of thermal transfer must be included due to convective flow driven by temperature dependent surface tension (Marangoni effect), thermoelectric effects, and induced  $\mathbf{J} \times \mathbf{B}$  turbulence. A model of the influx of the liquid metal into the plasma due to off-normal events (ELMS, MHD)<sup>7</sup> as well as disruptions are needed. Surface modeling of free-flowing liquid metals is also important; in particular, retention of hydrogen and helium under reactor-level conditions must be examined. Equilibrium and transport modeling of tokamaks and stellarators with low recycling boundaries is a vast area. All are complex problems requiring significant computational resources.

### **Test stand experiments**

Well-diagnosed basic research experiments are needed to investigate the fundamental questions listed above in this long-term project. Close interactions with theory and modeling are essential to achieve fundamental understanding. Much of the preliminary development and feasibility assessment of flowing liquid metal PFCs can be done on dedicated MHD flow test stands with strong magnetic fields.<sup>8</sup> However, the final integration and testing of a system requires a tokamak environment. Inlet/outlet systems for slow and fast flow systems, transport approaches for movement of the fluid along the tokamak wall, or across the divertor strike point, thermal transfer measurements (using e-beams or other intense heat sources), etc. can be tested, understood, and used for code validation.

### **Experiments in tokamaks**

Ultimately, coupled liquid surface/plasma experiments will be required. Experiments involving the use of static liquid lithium as a PFC are presently underway, and are expected to yield information on tokamak equilibria with low recycling walls. Experiments in existing tokamaks with static high recycling liquids to quantify sputtering and evaporative flux into the core plasma are not planned, but are required to qualify these candidate materials. Similarly, experiments with fast flowing liquid metal PFC systems are not planned, but are needed to explore the coupled plasma physics and liquid metal MHD motion, control, and heat transfer problems inherent in such a concept. In the next few years upgrades of present U.S. facilities are expected to increase pulse lengths to  $\sim 10$  seconds, which should be sufficient to test flowing liquid metal PFCs once designs have been qualified on test stands. If a long-pulse tokamak or ST facility for the testing of PFCs becomes available, then an all-liquid-metal wall and divertor experiment would provide a comprehensive test.

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