Liquid Metal Plasma Facing Component Research for the ITER Era and Beyond
A White Paper to the FESAC Subcommittee on MFE Priorities

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In this white paper, we argue that the suitability of solid Plasma Facing Components (PFCs) (e.g. tungsten) for a reactor is far from certain. The only potential alternative is a liquid metal PFC. Furthermore, liquid metals have the potential to out-perform any solid-PFC approach in areas such as erosion lifetime and heat-flux handling. A US research program on liquid-metal PFCs could uniquely position the US to capture ITER burning-plasma physics while leading the world in a PFC technology that scales to a reactor.

The Plasma-facing Component Problem

The ITER project is already advancing fusion science and technology to a reactor-scale device. Several areas of research, however, are not the main focus of the project and are not likely to be resolved by ITER such as net erosion and redeposition of wall and divertor materials. Most design studies rely on the use of solid components, mainly tungsten, as the only plasma-facing material (PFM) likely to be available for a reactor. The issue here is that however one designs and shapes such a component, continued exposure to the plasma inside a fusion device will continually redistribute and reform those components due to sputter erosion and plasma transport effects. In addition, plasma transients may result in melting and permanent damage to solid, metal components. The strategy adopted for these issues is increasingly uncertain yet liquid metal PFCs can potentially resolve each of them.

Numerous tokamaks have performed experiments with high-Z, solid PFCs in recent years. Two have highlighted the issue of local melting due to excessive heat fluxes: Alcator C-Mod[1] and Textor[2]. Experiments on Alcator after severe melting of a W tile in the divertor have indicated that such damage events completely prevent reliable machine operation when the plasma is in contact with those damaged tiles[1]. The experiments further indicate that no “self-healing” effects which might return a damaged tile to the original net shape were observed during experiments. In essence, the experiments indicate that significant transient damage cannot be tolerated on solid PFCs. This position places severe limits on ELM size and frequency as well as on disruption size and mitigation techniques that are only now being developed and studied. We will point out below that liquid-metal PFCs eliminate this issue of transient melting and have already been demonstrated to handle disruption-level power loads.

Sputtering has long been understood as a process that must be mitigated for components to have significant lifetimes in a reactor environment. Most research in this area has focused on the divertor where particle and power fluxes are the most intense and there are indications that advanced scenarios such as radiative divertors, super-X or snowflake divertors may successfully reduce plasma temperatures to a level where sputter erosion is largely eliminated. Even so, recent papers have pointed out that wall erosion is likely to remain a problem and could result in *1000s of kgs per year* of circulating material in a power reactor[3 and references therein] even considering charge-exchange flux to the walls alone. There are significant uncertainties involved but this is likely to *underestimate*

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the true amount of erosion once the effect of ion bombardment is included[4]. It is speculated that the resulting net-reshaping and redistribution of PFC material will lead to a new equilibrium condition for the walls inside a confinement device. Such evolution to the new equilibrium would require enormous operating times to produce and the resulting operation of such a "self-regulating wall" has never been examined. In short, the extrapolation of a solid-PFC to a reactor is uncertain and may require a reactor-class device itself to understand. We will point out below that liquid-metal PFCs have the potential eliminate the net reshaping problem as well as significantly reduce the required pulse-lengths to study the evolution of the wall PFCs.

If the mission of a next-step device such as a Fusion Nuclear Science Facility (FNSF) is to demonstrate a significant duty-cycle, these issues indicate that significant risk is associated with the PFCs in that device. With so many uncertainties, associated not only with current knowledge of tungsten *but generally applicable to all solid-PFCs*, it seems that alternative lines of research are prudent.

The Potential of Liquid Metal PFCs

Liquid metals present numerous potential advantages when compared to solid tungsten PFCs. These include continuous renewal of the PFC surface, as part of the implementation of a liquid metal system. The liquid metals option already has been shown to be a viable PFC in laboratory experiments simulating fusion environments, as well as in tokamak experiments[5], and is a promising candidate for reactors. Liquid metal divertors avoid major issues of W surface damage and recrystallization, including dust formation due to He accumulation at grain boundaries, blister formation and subsequent bursting due to He bubbles, and the recently discovered tungsten "fuzz" that could be detrimental to successful plasma operation. A critical concern is that tungsten will not be able to withstand intense transient heat loads at levels expected in tokamak fusion systems, whereas similar power levels have already been tolerated by liquid metal systems[6]. These issues, furthermore, are complicated by neutron-induced damage to solid PFCs, which open them up to additional failure modes associated with changes in bulk material properties. The required resolution of the solid-PFC PMI issues represents a very large R&D effort, for which finally there may be no acceptable solution either for an FNSF or for an economical power reactor.

In a liquid metal system by contrast, the surface is continuously renewed, therefore long-term surface damage is not an issue compared to W or other solids. Only the substrate accumulates as high a neutron dose as W PFCs, but the substrate is not directly exposed to the plasma and the associated plasma-material interactions. Substrate development can proceed in non-nuclear thermomechanical and compatibility experiments and irradiation facilities such as IFMIF, or other materials testing facility, without needing to meet any requirements with respect to compatibility with plasma interactions. Development of the flowing liquid metal system itself likely only requires a D-D tokamak plasma, which need not be fully steady state. To establish proof of principal, the pulse length and duty factor need only be sufficient to allow several full flow cycles of the liquid metal PFC, including re-collection of material removed from high-temperature surfaces that will be continuously evaporated and sputtered. The chemical equilibrium in long-term experiments that include impurity filtration (for example) can be carried out in parallel. Such complementary facilities, for example, will be needed to extrapolate tritium burnup fractions, and successfully mitigate tritium retention in the chamber, by control of the lithium temperature, or use of other liquid metals. In contrast development of W plasma facing components requires high duty factor operation with realistic plasma conditions in order to assure the lifetime of the material and continuing favorable plasma operation. Much liquid metals PFC development could even proceed in NSTX-U, Alcator C-MOD and DIII-D. This last point is important because in a resource constrained environment, such as being considered by this sub-committee, it is important to note what can be tested with facilities operating today.

The non-Li liquid metals have attractive upper operating limits in temperature (~1200ºC for Sn, Ga, as opposed to the ~650°C limit observed for lithium in FTU). All have operating temperature ranges that overlap with RAFM steel. Although only lithium is chemically compatible with steel over the entire projected temperature range, platings (e.g. chromium) form effective barriers and can prevent liquid tin or gallium from attacking steels. Importantly, many of the research topics associated with implementing LM-PFCs are common to all (e.g., MHD stability of the free-surface), so that much of the research and development effort applied to any one liquid metal (e.g. lithium) can be transferred to the others. Also, the portfolio of liquid metal options offers a wide choice of D-T trapping and recycling options, e.g., Li traps hydrogen isotopes whereas Sn does not. A liquid metal PFC system can include a spectrum of liquids tailored to different functions.

A final, but important, point relates to the strategy for the US to quickly and uniquely contribute to the development of solutions to the PFC question, in the larger context of the world fusion program. Numerous facilities exist around the world that can meet (or will be able to meet with upgrades) the materials research needs for solid materials (excepting those requiring a full confinement device for material transport studies). These facilities are already actively engaged in solids research (primarily W, but also Be and C in support of ITER). Liquid metal PFC solutions are at an earlier stage of development around the world, at only a few places including Red Star in the Russian Federation, ASIPP in China, PPPL, U of Illinois, Purdue University, UCLA and Sandia National Laboratory in the US. Even under the current budgetary pressure on fusion research in the U. S., we argue that with a modest investment in liquid metals, the domestic program could quickly establish a leadership position in this promising technology, with large impacts on world fusion research. The liquid metals option could be most viable and economical approach to guarantee the continuity of a successful path of PFC development.

Research Needs for Liquid Metal PFCs

A demonstration of the basic science and technology tied to liquid-metal PFCs can be accomplished in the next 5-7 years in laboratory test stands and high-power toroidal confinement device with a modest level of support. The research needs to be obtained leading up to and obtained from such a demonstration fall into four broad categories:

- Liquid metal stability and flow in the divertor and first-wall of a confinement device (e.g. mitigation of ejection under quiescent and transient events),
- Thermal-hydraulics of the liquid metal PFC, control of evaporation and condensation locations and power-cycle integration,
- Robust operation for long-term use in reactor environments (e.g. corrosion of PFC substrate and other components), and
- Plasma response and impurity production.

Concepts for liquid metal PFCs can be generally grouped under two categories: fast-flow, self-cooled systems and slow-flow, thin-film systems. Both require development in all of the categories above if either is to be demonstrated in a reactor. For instance, capillary forces provide a powerful means of stabilizing surfaces against various instabilities and could provide a general design strategy for slow-flow, thin-film systems to avoid ejection into a confinement device. For the fast-flow, self-cooled systems, the heat transport in the liquid metal itself can potentially be enhanced by turbulent mixing of the fluid, but such mixing is inherently difficult to achieve in strong magnetic fields. By contrast, the energy transport in thin-film, slowly flowing systems becomes conduction-dominated[7] and can leverage cooling technologies already developed for solid-PFCs. Plasma response studies can be split into two length scales: near-PFC and whole-machine. In the first case, near-PFC interactions such as sputtering, prompt redeposition and local transport can be studied on linear plasma devices available today. In the second case, studies of overall transport and the impact of a given liquid-metal PFC on operation can only be accomplished in a confinement device and would have to wait for an integrated PFC to obtain this information. In all the elements listed above, however, a path-forward exists on a number of topics that can be examined in off-line facilities while preparations are made for integration in a confinement device. A set of research programs covering thin-film concepts, fast-flow concepts and modeling of these schemes could utilize $5M/yr and have a group of concepts available for integration in a confinement device in 5-7 years.

This program would be an aggressive and innovative endeavour studying the science and engineering of the *simultaneous* interaction of all four phases of matter. It has clear break-out potential and would resolve the pressing plasma-material interaction issues facing fusion energy science in ways unavailable to the conventional, solid-PFC approach.

Complementing ITER and Looking to a Reactor

At present, there is no technically demonstrated, steady-state liquid metal PFC option, though such systems are currently under very slow development with extremely modest funding. If a liquid metal PFC is to be considered for an FNSF or other future device, however, significant research and development is needed to establish the technical basis for such PFCs and the associated systems. If an FNSF planning activity is to occur about 2018-2020, R&D working toward demonstration of a full system on a US confinement device needs to begin now. Such would represent a complementary research program to existing work supporting ITER and examining the solid-PFC option. *In particular, if the ITER experience bears out the expected difficulties of solid-PFCs, then having a liquid-metal PFC option uniquely positions the US to capture the burning-plasma physics obtained on ITER, while leading the world in the engineering and science of liquid metal PFCs in a reactor.*

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