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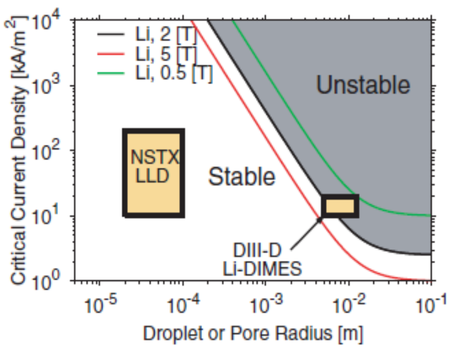
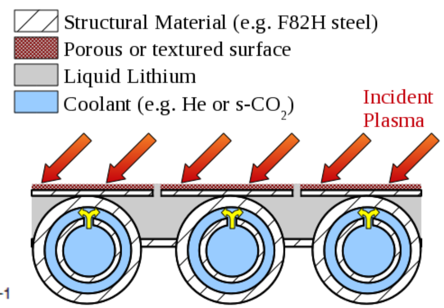
SAND2015-4399PE

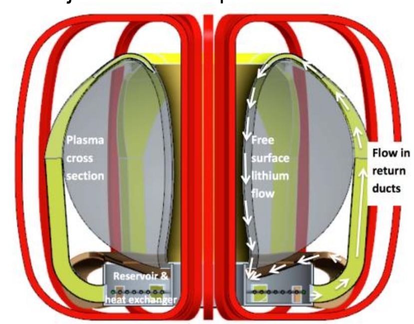
New after ReNeW: *increased emphasis on benefits of Li for plasma performance, rise of innovative ideas for Liquid Surface PFCs, experiments with JxB and thermo-electric drive*

Jaworski, Abrams, Allain ..NF **53** 2013





Majeski White Paper



White Papers

Currelli*, UCIC
Andruczyk*, UCIC
Jaworski*, PPPL
Majeski, Kaita, Zakharov
Ruzic, Morley, ...

** young researchers*

Understanding Design Integration to Confirm the Credibility of Liquid Surface PFCs

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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The perceived benefits of LSPFCs derive from several motivations.

Specific to Li and more recent is the improvement in plasma performance observed with Li is at the plasma edge of the plasma. Jaworski and also Hirooka have written excellent recent reviews with emphasis on Li.

The self-replenishing surface (implicit in LSPFCs for a DEMO) could eliminate several issues associated with solid surfaces, e.g., melting/recrystallization, ion damage, etc. This potential benefit was recognized much earlier, e.g., the UWMAK design in 1974 and a paper by Wells in 1981. These and other early efforts are summarized well by Mirnov.

Another motivation, one that could have significant impact but as yet is unexplored, is:

A plausible integrated solution for power exhaust with liquid surfaces may be the only solution for design in which the walls can conforming closely to an outer magnetic flux surface without the need for poloidal limiters to intercept transients that deposit high local power loads.

The last comment is speculative since we have not yet proven that (1) a solid wall solution will have to be non-conforming, and (2) liquid walls can provide this solution.

Consider the points below.

- We are now far beyond early simplistic concepts. Russians have pursued capillary pore system (CPS) since 1994 with tests in several tokamaks.
- Clever ideas are emerging, many since ReNeW, and being refined. However, the schemes are often at the cartoon stage.
- Deployments, including US modules for Asian tokamaks, are important steps. However the modules cover small areas.

We lack evidence that the schemes can be successfully integrated into the subsystems for an FNSF or a DEMO.

Clear solutions for solid walls to survive at high temperatures with high heat loads have not emerged. Troubling issues for C, W and reduced activation ferritic-martensitic steels (RAFMS) raise concern whether credible designs are possible without reduced operating temperature or component lifetimes.

Convected power to solid walls in an FNSF or DEMO has a big impact and will likely require shaped walls.

For example – earlier DEMO/FNSF design studies never evaluated provisions like poloidal limiters such limiters restrict volume for breeding tritium and complicate the challenges for injecting and exhausting power and remote maintenance.

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We need a credible vision of a path forward

Taming the plasma interface and harnessing fusion power are two critical challenges.

Developing at least one credible scheme to handle the power exhausted from the plasma is a critical step in our approach.

Confirming that liquid surfaces can provide robust heat removal, renewable surfaces and an alternative option to solid surfaces for any of the following applications would bolster the credibility of the program:

- divertors,
- wall protection (poloidal limiter, guard for RF launchers), or
- liquid first walls integrated in breeding blanket modules.

What should we do now?

We should create a Liquid Surface Design Integration Task Group using limited effort from experts in design integration at PPPL, SNL, ORNL, INL and UCLA. The group would study the liquid surface PFCs in a set of selected concepts, uncover issues to be mitigated in the design integration (or fatal flaws), and assess their potential* to be realized in workable designs for an FNSF.

*Consider basic features such as the integral first wall structure with a breeding blanket, driving and managing the movement of a liquid along a first wall or divertor structure including the manifolds, provisions for filling and draining, and interfaces with the systems to recover power (electricity) and tritium fuel. The proposal complements the development of these innovative ideas in a way that will guide the development of these ideas in future.

Integration of Liquid Surface PFCs into a DEMO or FNSF

Richard E. Nygren, abstract for PFM

Many ideas for liquid surface PFCs are for divertors.

First walls are likely to be more challenging technologically because long flow paths are necessary for fast flowing systems and the first wall must be an integral structure with the blanket.

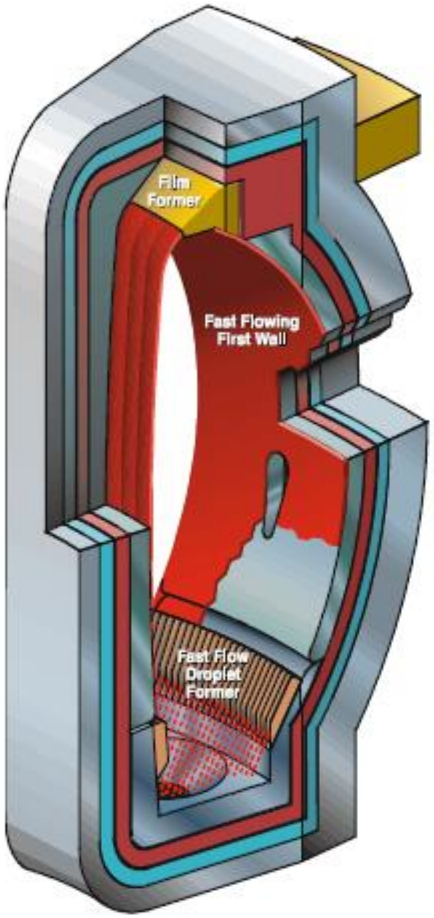
Maximum tolerable heat loads are a critical concern for the desired high power densities and heat loads in FNSF or DEMO.

A fast flowing system would seem to have an advantage, since CPS PFCs must transfer heat through the lithium and its host structure to the coolant in the substrate. However the slow flow in these systems diminishes the liquid metal MHD forces, but only at the wall.

This paper describes several processes at work in a wall with a liquid plasma-facing surface, and the considerations imposed by heat transfer and the power balance for the PFC as well as the structure needed for an integrated first wall and blanket ...

Table 7.2-1: Potential Advantages and Issues of CLiFF Concept for APEX

Potential:	Issue:
• Removal of surface heat loads (greater than 2 MW/m^2 possible). Local peaking and transients can be tolerated	• Hydrodynamics and heat transfer involve complicated MHD interaction between flow, geometry, and the magnetic field: – Suppression of turbulence & waves – LM-MHD drag thickens flow and inhibits drainage from chamber – Effects of varying fields on LM surface stability and drag
• FW surface protected from sputtering erosion and possibly disruption damage	• Evaporating liquid can pollute plasma, surface temperature limits unknown
• Beneficial effects on confinement and stability from conducting shell and DT gettering effects	• High flowrate requirement can result in low coolant ΔT or two coolant streams
• Elimination of high thermal stresses in solid FW components, having a positive impact on failure rates	• Effect of liquid choice on edge plasma gettering, tritium through-put, and tritium breeding
• Possible reduction of structure-to-breeder ratio in FW area, with breeder material facing virgin neutron flux	• Neutron damage in structure is only slightly reduced compared to standard blankets, blanket change-out required for high power density operation
• Integrated divertor surface possible where CLiFF flow removes all α heat	
• Complex tokamak D-shape & ports can likely be accommodated	



Fast Flow FW-Divertor				Blanket			Mat.	
	FW	Divertor	Press.			Press.		
	surface	surface		breeder	coolant			Comments
A	Li[A1] or Li-Pb[A2]	Li or Li-Pb	L	Li-Pb[A1]	He	H	RAFS	If Li-Pb formed a Li layer at the free flowing surface (due to the free energy of this system), then the FW and blanket could share the same working fluid.
B	Li	Li	L	Li-Pb	He	H	SiC[B1]	
C	Li	Li	L[C1]	solid	He	H		The FW may be a low pressure system but the blanket coolant is high pressure He (or CO2).
D	Li – HX[D1]	Li	Li – L HX – H[D1]	solid	He			*Li fast flow with an in-vessel heat exchanger
E	Ga	Ga	L	solid	He	H		FW low pressure, blanket high pressure as above. Ga has excellent heat transfer but does not provide beneficial interaction at the plasma edge like Li.
E	molten salt	molten salt	L	molten salt	molten salt	L		Liquid surface[5] is mixture of Li, Na and Be fluorides from the APEX program is the only low pressure system listed in the table.
	CPS FW & Div.			Blanket				
	surface	coolant		breeder	coolant			
G	Li	He	H	solid	He	H		Many favor solid breeders over liquid breeders, e.g., in earlier EU DEMO designs [EU DEMO]

I am trying to create a table like this for a review paper and my paper at PFMC.

A1. Current paths for JxB drive currents in fast flow FWs. Where JxB currents drive the fast flow of a free surface of liquid metal (e.g., Li), the needed containment of all or most of the driving current within the liquid metal requires that any alternate routes for the current have significantly higher electrical conductance. The conductance depends upon both the conductivity of the material and the cross section integrated along the current path. Inconel 600, ferritic steel and lithium have respective resistivities in micro-ohm-m of ~1.30, 0.6 and 0.36 (??0.32 at 400 °C).

When the FW is part of an integral structure with the breeding blanket, the current introduced to drive the FW will also distribute into the blanket structure unless there is some provision for electrical insulation. Relying simply on the higher resistance, for example of a RAFS, may not be sufficient. If we assume the flowing lithium is 10 mm thick and the wall thickness of the structure is 5 mm, then

If the structure is a ferritic-martensitic steel with , even becomes is arrangement probably requires either (1) a solid breeder because a liquid breeder, suh as the dual coolant lithium-lead system (A in the table) would provide a low conductance current path in parallel with the first wall without the use of an insulator, or (2) use of an insulator. Blanket liners, e.g., SiC flow channel inserts, have been proposed and might serve this purpose. Confirming this solution would require a detailed 3-D flow model that accounted for the LMMHD effects.

A2. If Li-Pb formed a Li layer at the free flowing surface (due to the free energy of this system), then the FW and blanket could share the same working fluid.

A first wall with fast flowing liquid system continuously accumulates heat as it flows along a relatively long flow path. A complication is that liquid metal MHD (LMMHD) dominates the flow characteristics and these systems require propulsion and stabilization using electric currents and JxB forces and, in some proposed applications, thermo-electric currents.

The altered flow distributions affect not only the required pressure to drive flow but also heat transfer and corrosion. Design integration of such systems must deal with these factors as well as the complications of flow redirection and redistribution in manifolds and with gradients in the magnetic fields.

After the flow down (or across) the first wall, the flow path must either (a) return within the vessel and transfer heat to another coolant through a heat exchanger, as proposed by Majeski[4], or (b) exit the vessel and transport the heat to an external heat exchanger. The latter option requires flow across both the strong toroidal field and the poloidal field as well as through field gradients.

Even with the return flow path inside the vessel, LMMHD effects will dominate the flow during the redistribution of flow through the heat exchanger and manifolds.

We may find we need to combine the elements from several different concepts to complete an integrated system.

CPS PFCs must transfer heat through the liquid (lithium) through the host structure to the coolant in the substrate although some heat may be transported by evaporation at one location and deposition elsewhere. While a CPS eliminates some concerns about liquid MHD at the plasma facing surface, a CPS requires both a secondary coolant to remove heat and must have some approach for removing impurities (slag) on the surface and processing tritium, and must mitigate tritium migration into the secondary coolant. The substrate walls for cooling passages must handle pressure (4-10 MPa) and thermal stresses.

A driving system that would sustain net migration of lithium down or across a wall may not be the same technique needed to drain the lithium from a collection reservoir or manifold and move it to a lithium purification system and the tritium recovery loop.